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ADVANCES IN AGRONOMY

VOLUME II

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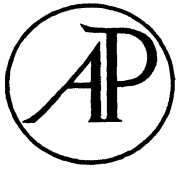
VOLUME II

Edited by A. G. NORMAN

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1950

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Preface

In the preface to Volume I it was pointed out that the pressure of progress in the many sub-fields that collectively constitute agronomy tends to produce specialists who find it difficult to keep abreast of newer developments somewhat removed from their immediate interests, yet of professional importance to them. It was further explained that the editors were not inclined to quibble about the precise definition of the word "agronomy." In selecting topics for treatment they would be guided more by the consideration of what might be useful to agronomists than what constitutes agronomy. The authors are urged to present, as far as possible, unified, complete and authoritative accounts of the recent developments in their particular fields. Topics will reappear from time to time as new material and new viewpoints develop.

This is the mid-century year. It would be presumptious on the part of a publication so recently established as *Advances in Agronomy* to prepare a mid-century number delineating and weighing the achievements and accomplishments of the first half of this century. The editor had no difficulty in resisting the urge to follow the lead set in this matter by long-established and more popular publications. However, this thought did set in train some speculations as to what topics might have been selected for a similar volume had one been prepared fifty years ago. Largely, this amounted to a realization of the topics which would not have been included because their development has taken place almost entirely since 1900. Crop improvement through genetics, soil physics, and soil genesis are examples. A cursory glance at the contents of this volume will show that about half of them would not have appeared in any form in a 1900 edition. Thus fast has agronomy grown.

Speculation in another direction is possible. One might consider the extent of the agronomic achievements of the past half century in terms of the changes in U. S. agriculture and agricultural practice. These are dramatic enough. Here is a nation which in fifty years has doubled in population but has no more farms now than then. Twenty-five per cent more acres are harvested, meat production has been doubled, fertilizer consumption has increased eight-fold, but there are fewer sheep, and far fewer horses and men on farms now than at the turn of the century. Perhaps in the last lies a clue to much that has been accomplished by the mechanization of many operations through the availability of power equipment.

What can be anticipated in the remainder of this troubled century?

Have the easy things been done? Will the tempo of progress be slowed? Are the land use systems that have developed stable or exploitive? Will the crop surpluses of domestic production be absorbed in meeting the deficits elsewhere, or are they merely a temporary feature soon to be dissipated by population increase? Should production be curtailed in the interests of conservation? Will there be changes in food habits on the part of the consumer that will call for great shifts in types of farming? Will the era of surpluses even give way to a period when the demands for food will be such that exploitive land use is forced upon us?

The resolution of many vital questions such as these will not primarily lie in the hands of those practicing the profession of agronomy, yet they will be required to use all their skills and ingenuity and resourcefulness in providing the solution to the innumerable practical problems that taken together will determine the answers to such major questions. Subsequent volumes of the *Advances* will record and summarize their methods, recount their achievements and measure their accomplishments.

A. G. NORMAN

Frederick, Md.
October, 1950.

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Texas Agricultural and Mechanical College System, College Station, Texas

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I. Introduction

J. E. ADAMS

Texas Agricultural and Mechanical College System, College Station, Texas

Cotton is the most important cash crop grown in the United States, and is the only major crop which produces the 3 products, fiber, food and feed. When all phases of the industry are considered, some 20 to 25 million people are wholly or partially dependent on cotton as a source of income. Of these, approximately 1,500,000 are engaged in production and 3,000,000 in ginning, marketing and processing.

The fact that the entire fruit of the cotton plant is used makes it an unusual crop. In addition to lint, the embryos or "meats" of the seed furnish both a protein concentrate and a high-grade oil. The "hulls" or seed coats are used as feed, as well as the concentrate. The fuzz left on the seed after normal ginning is removed mechanically and these short fibers known as "linters" are used in upholstering, low-grade mattresses, and as a source of cellulose for synthetics.

The present status of cotton is both artificial and in a state of flux. Although cotton lint is the most versatile fiber known when all end-uses are considered, economic conditions since the early thirties, with intermittent acreage control and price subsidies, have resulted in increased competition of old and new synthetic fibers. Unrestricted production during and following the war, with impending acreage controls, is reflected in Table I, released as of December 8, 1949, by the Bureau of

Agricultural Economics, Austin, Texas. Every cotton-producing state shows an increase in acreage in 1949 over 1948. In spite of lower production per acre in some areas, there was a net increase of 1,157,000 500-lb. gross-weight bales in 1949, as compared with 1948. More striking is the increase of 4,728,000 bales in 1949 over the average of 11,306,000 bales in the 1938-1947 period. The increase in production in the irrigated areas, particularly California and also New Mexico and Arizona, is phenomenal.

Although the sections on production treat mechanization of the cotton crop in many of its details, it is to be emphasized that mechanization for all areas really dates to the World War II period, during which there was an intensification in research and more ready acceptance by the farmer due to the dearth of labor. Development of flame cultivation, rotary hoes, efficient fenders for cultivation equipment, along with the culmination of years of research on harvesting machinery, resulting in usable harvesters, has made full mechanization of the crop a reality in some sections. Remaining difficulties for other areas and particular seasons are yielding to intensified research.

Estimates furnished by the National Cotton Council indicate that approximately 2900 spindle-type pickers were used in 1949. Mississippi led with 990. California used approximately 850, Arkansas, 350, and Louisiana, 200. The acreage harvested would be difficult to estimate, but probable harvest per machine varied from 100 to 250 acres. A total of better than 7000 strippers were used, with the Texas High-Plains area accounting for at least 6000. Oklahoma was the only other large user, the estimated number being 950. The capacity per machine ranges from 125 to 400 acres, depending on local conditions.

Considering that practically all of the cotton harvesters have become available since the war, the increase in use of machinery is outstanding. The general feeling that costs of production for cotton must eventually be radically lowered, leads to the conclusion that production per acre must be increased. Better fertility practices, control of insects and diseases, better varieties of cotton for mechanical harvesting, along with more complete and assured defoliation are of prime importance.

All of the cottons of the world, whether cultivated or wild, belong to the genus, *Gossypium*. They may be divided into 3 main groups: (1) Old World or Asiatic cultivated (n = 13), (2) New World or American cultivated (n = 26), and (3) wild, (n = 13, with one anomalous exception). Though the reported number of species of Gossypium varies widely, depending on the classification system employed and the inclination of the taxonomist, a recent work by Hutchinson *et al.* (1947) (see References in IX) recognizes twenty. These writers place the cultivated

cottons under four species: *G. arboreum* L., *G. hirsutum* L., and *G. barbadense* L. The first two are designated as Asiatic and the last two as American cottons, and all bear spinnable seed hairs, called lint, which distinguishes them from the wild cottons which do not have spinnable lint. American cultivated cottons (n = 26), according to the theory advanced by Skovsted (1937) (see References in IX) and confirmed independently by Beasley (1940) and Harland (1940) (see References

TABLE I

Cotton Production in United States

State	Acreage Harvested			Lint Yield per Harvested Acre			Production (Ginnings)[a] 500 lb. gross wt. bales		
	Average 1938-1947, 1000 acres	1948 (revised), 1000 acres	1949 (Dec. 1 est.), 1000 acres	Average 1938-1947, lbs.	1948 (revised), lbs.	1949 (Dec. 1 est.), lbs.	Average 1938-1947, 1000 bales	1948 Crop (revised), 1000 bales	1949 Crop (Dec. 1 est.), 1000 bales
Missouri	375	555	583	451	436	377	356	506	460
Virginia	30	26	32	348	447	300	22	24	20
North Carolina	743	725	815	355	447	270	549	678	460
South Carolina	1,118	1,120	1,270	309	372	211	716	871	560
Georgia	1,608	1,289	1,550	235	279	189	779	751	610
Florida	46	29	44	164	249	196	14	15	18
Tennessee	684	770	830	368	417	375	523	669	650
Alabama	1,691	1,630	1,810	262	353	229	901	1,197	865
Mississippi	2,397	2,560	2,770	318	441	258	1,588	2,353	1,490
Arkansas	1,916	2,220	2,450	334	428	325	1,329	1,982	1,660
Louisiana	968	950	1,060	261	382	294	528	756	650
Oklahoma	1,491	1,025	1,300	163	175	229	521	374	620
Texas	7,642	8,610	10,725	170	176	264	2,722	3,153	5,900
New Mexico	115	209	310	497	542	394	119	236	255
Arizona	200	281	373	423	558	641	174	328	500
California	352	804	957	602	576	651	447	968	1,300
Other States[b]	18	18	19	413	435	383	16	16	16
UNITED STATES	21,396	22,821	26,898	254.0	312.6	285.8	11,306	14,877	16,034
Amer. Egypt[c]	63.5	4.0	6.3	279	434	327	29.5	3.6	4.3

[a] Allowances made for interstate movement of seed cotton for ginning.

[b] Illinois, Kansas, and Kentucky for all years and Nevada for 1948 and 1949.

[c] Included in State and United States totals. Grown principally in Arizona, New Mexico, and Texas.

in IX), are tetraploids which have arisen by amphidiploidy from hybrids of Asiatic (n = 13) and American Wild (n = 13) parentage.

This paper will present important aspects of the production of cotton each of which, because of space limitations, can be treated only briefly.

II. Competitive Position of Cotton Among Fibers

M. K. HORNE, JR.
University of Mississippi, University, Mississippi

1. Cotton Loses Markets

Except for the abnormal experience of the war and early postwar years, it can be said that over the past 4 decades the per capita consumption of cotton in this country has shown no tendency to rise. Over this long period, it has gravitated around a central figure of 25 or 26 lbs. a year, displaying no trend either up or down. In net effect, the entire new market created by rising standards of living has been captured by rayon, paper, and to a smaller extent, other materials. In this fact we have an indication of what competition has done to the cotton market down to the present time, and why the students of the demand for cotton are engrossed in its competitive position.

There are at least 35 materials which give cotton substantial competition. The more interesting ones include rayon in its various forms, paper, glass fiber, nylon and the other fibers of synthesized polymers, the synthetic protein fibers, plastic film, and jute, ramie and the other bast fibers.

In seeking the competitive meaning of these numerous materials, it seems helpful, and in some degree defensible, to think primarily in terms of rayon. This fiber is not only cotton's biggest, but by a wide margin its most serious, most threatening competitor. In Project IV of the cotton fact-finding program, "A study of the agricultural and economic problems of the Cotton Belt," presented in 1947 before the Cotton Subcommittee of the Committee on Agriculture, U. S. House of Representatives, it was found that some form of rayon was cotton's closest competitor in 65 out of a group of 106 end-uses analyzed. In 25 years, rayon has advanced from a trivial position among all fibers to second place in the volume consumed in the United States. In 1948, 1,124,000,000 lbs. of rayon were produced in this country. Factory capacity has now reached an estimated 1,235,000,000 lbs., or the equivalent in usable fiber of about 2,900,000 bales of cotton. This amounts to 48 per cent of the average annual consumption of cotton in this country during the

decade of the 1930's, and to 35 per cent of the cotton consumption in the best year of that decade, which was 1937. Two-thirds of this rayon capacity has been built since the end of that decade. With the return to a buyer's market for textiles in the United States, cotton is inevitably feeling a terrific impact from a competitor which has grown so rapidly and become so large. In foreign lands, the tendency is for rayon to assume an even stronger competitive position than in the United States.

2. End-Uses of Cotton and Other Fibers

Every end-use market for cotton has a separate pattern of requirements in price and in the scores of distinct qualities which characterize a fiber product. Likewise, there is a separate price and quality pattern for every competing material. Most materials are quite different from cotton in price and quality, and they must compete in a more limited number of end-uses where their special characteristics give them an advantage. As competitors of cotton they are specialty materials, concentrating upon and limited to some segment of cotton's end-use markets.

Paper, for example, is cotton's second most aggressive competitor today. It has a big advantage in price and a few small advantages in quality. Within a limited range of uses, these factors can sometimes overcome the important advantages of cotton in other properties. Paper is a formidable competitor in the great bag market, and in large sectors of the towel, cordage, napkin, and handkerchief markets. Its quality is being steadily improved through research. But paper's differences in texture, strength, and absorbency quite obviously restrict it to a fraction of the cotton market.

For a second example, the leading synthetics other than rayon are considered. They are all far above the price range of cotton. One may be tempted to reason that since rayon came down to the price of cotton, these other materials can eventually do likewise. Any such reasoning would seem to be premature, at least for the better fibers. In the strong, resilient synthesized polymers, including nylon, the textile scientists point out that basic differences in the chemical approach seem to invalidate the idea of ever bringing costs down to the level of rayon. At the same time, these various synthetics are quite superior to cotton in some qualities, and quite inferior to it in others. There are certain uses for cotton in which their patterns of quality can overcome the price handicap, but again these uses are limited.

Rayon is distinguished by the fact that to an ever-increasing degree it competes for markets, not because of its differences from cotton, but because of its similarities to cotton. Its price and quality pattern has relentlessly shaped itself toward the price and quality pattern of cotton.

Very generally, it can be said that today rayon is in the same price range with cotton. In reference to quality, there still are sharp differences between the two fibers, but rayon has made marvelous progress in overcoming its quality handicaps through research. That progress can be seen in the development of staple fiber, in delustering, in crimping, in higher wet and dry strength, in softer yarns, and in better finishes for dimensional stability. Several of rayon's biggest quality handicaps remain, but we cannot overlook the fact that the extensive research program of the rayon industry is going vigorously forward. As a competitor of cotton, rayon looks less and less like a specialty fiber and more and more like a fiber which eventually may contend for virtually all of cotton's markets.

The two chief weapons with which rayon might be expected to improve its present competitive position are: (1) the lowering of price; and (2) the improvement of quality. Which of these two possibilities is the more threatening to cotton? From the excellent research in recent years, it now seems fairly clear that the rayon industry is likely to rely primarily on improved quality to buttress its competitive position. The era of continual price reductions in rayon, year by year, seems to have ended in 1938. The average production cost of viscose staple at a recent time was 29 cents a pound. This of course was before any allowance for income tax. The selling price of viscose staple was 35 cents in March, 1950. Obviously it is unlikely that any drastic price reduction will be achieved by reducing profits unless market conditions take a serious turn for the worse. On the side of cost reductions, it must be recognized that real technical progress is still being made, but the nature of the cost is such that the further reductions are likely to be much more gradual than in the past. Therefore, it seems that any declines in the selling price of viscose staple are likely to be modest in amount unless a serious business recession occurs. For types of rayon other than viscose staple, the possibilities of cost reductions, through technical advances, may be somewhat greater, but nowhere can any reductions of major proportions be foreseen.

On the other hand, the rayon industry is spending large sums of money on research, a major part of it apparently aimed at the improvement of quality. It is perhaps a reasonable guess that the present rayon research and technical-service programs of the 5 leading companies are costing ten million dollars a year. We can never predict what research laboratories may bring forth, but we must be impressed with the success of the rayon research program down to the present time. A continued, and perhaps an accelerated, improvement in the quality of the various rayons appears to be the greatest threat to the market for cotton. A continuing

trend toward general equality in the price and quality patterns of the two fibers is therefore to be expected.

3. A Static vs. a Dynamic Position for Cotton

In the face of this trend, how shall we appraise the competitive position of cotton?

Although the situation is essentially dynamic, let us examine it first under assumed conditions which would make it static. The assumptions include the following: (1) no change from the situation of 1946 in the relative qualities of cotton and rayon products; (2) no change in the relative merchandising efficiency of the two fibers; (3) no war-created shortages or deferred demands; (4) a level of economic activity represented by 7 million unemployed; and (5) the price levels prevailing in January, 1946.

The two most interesting price assumptions for cotton are, first, the price actually prevailing in January 1946, or about 25 cents, and second, a price about half as high, or 12 cents.

With these assumptions a group of textile economists made a systematic effort to estimate the amount of cotton that would be consumed in 127 end-uses, representing about 83 per cent of the domestic market. For the other 17 per cent, made up of countless small uses, it was assumed that changes would follow the pattern of the 83 per cent. The sources of information already available were supplemented by field trips, in which numbers of the best informed business executives were questioned with regard to each end-use. The estimates which came out of this work were as follows: first, that at 25 cents per lb. cotton would find a domestic market for about 7,700,000 bales; second, that at 12 cents per lb. cotton would find a domestic market for about 9,600,000 bales.

Since prices in general, and rayon prices in particular, are now about 40 per cent higher than in January, 1946, the assumed cotton price may logically be increased to this extent. With this revision, and under the other assumptions stated, the study indicated that, at today's general price level, the domestic market for cotton would tend to be 7,700,000 bales at 35 cents, compared with 9,600,000 bales at 17 cents.

Two lessons from these figures are outstanding:

First, by cutting the higher price in half, the quantity consumed would be increased by less than two million bales. The demand, considered in this sense, is inelastic, even when allowance is made (as it was in Project IV) for enough time lapse to permit a given price to exert a real influence on an end-use market. For certain end-uses (notably tire cord, bags, insulation, and plastic laminates) the demand is elastic, but in the great bulk of the domestic market the differences in consump-

tion at the two price levels would be quite small, so small as to make the overall domestic demand rather inelastic. The inelasticity results chiefly from two facts: (a) the price of raw cotton is a small factor in the average retail price of cotton products, and (b) under the assumption of no change in quality, the substitutability of other materials is quite limited.

Second, at either price, cotton still seems to have the competitive strength to hold a very substantial domestic market. Even at the higher price, the quantity consumed would be no smaller than in 1939. The explanations are: (1) the increase in population; (2) some assumed improvement in business conditions; and (3) a decisive margin of quality advantages for cotton in many important uses. Despite rayon's gains, cotton still holds firmly to many markets by the strength of some very real quality advantages, most of which can be summarized under the headings of launderability, durability, and versatility. Cotton is endowed with a remarkable combination of qualities, all present in the same fiber at the same time: they include wet and dry strength, abrasion resistance, good absorbency and dyeing properties, vapor permeability, chemical stability, softness, pliancy, and ease of preshrinking.

In view of this finding and of what we have already said about rayon, it seems that two facts should be made equally emphatic on the vital point of quality: (1) (a static concept) at a very recent time, cotton's quality advantages were strong enough to protect most of its domestic markets from rayon. Since that time there has been no drastic change in the quality picture. If cotton could hold its present position in quality, the great part of its domestic market would appear to be reasonably safe from competition, even at a high price; (2) (a dynamic concept) there is little reason to hope that under the present circumstances cotton is holding its position in quality. Over the past 25 years, rayon has made enormous gains on cotton in quality, and the research and development program which produced those gains is now being pushed forward on a record scale. Cotton does not have a research and development program of equal size and scope. Some excellent advances are being made in cotton research, but the program is simply too small to give it a reasonable chance of equalling rayon's achievements. It is essentially a mere token of what is needed.

4. Need for Expanded Research

On the dynamic side of the quality problem, however, one further point needs emphasis: cotton's lag in quality improvement results from the lack of an adequate research program and not from the lack of opportunities in the fiber. The Project IV report outlined 41 broad fields of quality in which cotton's markets might be strengthened through

research. Cotton is a promising subject for quality improvement at every stage from plant breeding through production, ginning, spinning and weaving, finishing and fabricating. Cotton has the opportunity to become a dynamic fiber like rayon, matching rayon's progress with progress of its own, and thereby postponing indefinitely the day when rayon will overtake it in quality. The opportunities exist, but in spite of recent expansion, an adequate program does not.

Let us now attempt to summarize the significance of two competitive factors, price and quality, and their interrelationship with one another, in the domestic market for cotton. There seem to be 3 points which deserve attention: (1) as long as cotton holds its present quality advantages, the demand on the domestic market will be rather inelastic in response to price change. There will be a very substantial market for cotton at what has usually been regarded as a high price; (2) if rayon continues to improve in quality more rapidly than cotton, in the course of time the amount of cotton that can be sold at any price will decline; (3) if rayon continues to improve in quality more rapidly than cotton, in the course of time the significance of price as a competitive factor will increase. As rayon becomes more substitutable for cotton, the demand for cotton will become more elastic in its response to price change. If rayon ultimately becomes as launderable and as durable as cotton, and cotton makes no offsetting gains in quality, it will then be out of the question for cotton to sell on the domestic market at a figure which would not give it a marked price advantage over rayon.

Thus, from the standpoint of the cotton economy, the largely neglected opportunity to build an adequate research and development program for quality improvement presents a vital problem. The cost of such a program would be large, but it could be measured in millions of dollars annually. If, through the lack of such a program, it becomes necessary to make sharp reductions in the price of cotton, that loss will have to be measured in hundreds of millions of dollars annually.

In this statement many factors which bear upon the competitive position of cotton have been omitted. In actual practice, the important place of merchandising in the domestic market cannot be overlooked, nor can the special nature of the export market. In the limited space available, however, attention has been concentrated upon the great economic significance of quality improvement.

III. Physiology of the Cotton Plant

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1. Floral Initiation and Plant Development

a. Branching Habits of the Cotton Plant. Some of the most important physiological responses of the cotton plant find their expression and basis in the type of branches which are produced. According to conditions of growth, the branches arising from the main stalk may be exclusively vegetative branches or exclusively fruiting branches. In the axil of each leaf on the main stalk, and also on vegetative branches, there are two buds. One of these buds, if it develops, will produce a vegetative branch and the other a fruiting branch; both buds may develop. Morphologically, the vegetative branches, or limbs, are like the main stalk. Only fruiting branches develop flowers and bolls. A flower bud, even though it may abscise while still a millimeter or two in diameter, develops in the axil of each leaf of the fruiting branches. Although there are various complexities, American Upland cottons, unless planted too closely, typically develop from their main axes one or several vegetative branches between the first and eighth nodes. Thereafter, starting between the seventh to tenth nodes, only fruiting branches are developed from the main-stalk nodes. In addition to developing from the main stalk and from vegetative branches, vegetative branches may also develop from fruiting branches. There are important early papers by O. F. Cook on the morphology of the cotton plant.

Gaines (1947) has found that, in the absence of insect control, a loss of 50 per cent of the floral buds during the first 30-day period of fruiting is without effect on final yields. This is in conformity with earlier agronomic and physiological observations showing that the loss of some of the early floral buds aided in the maintenance of plant development and that new buds were developed to replace those that were lost. Under some conditions, the removal of early buds and flowers has resulted in increased yields. Data are occasionally presented to show that the flowers at fruiting-branch nodes near the main stalk are more apt to develop into bolls than are those farther out. But if these first buds and bolls are lost they are replaced by those that might otherwise have shed, environmental conditions permitting.

The types of branches produced by the cotton plant are influenced by temperature and by length-of-day (Fig. 1). Also the number of vegetative branches may be influenced by closeness of spacing, defruiting,

darkening the tips of plants (Eaton and Rigler, 1948) and by treatments with growth substances which cause buds to shed. Whether or not there is some one chemical of hormone-like entity, which is responsible for the determination of which type of branch shall develop under a given circumstance, remains one of the most intriguing aspects of cotton physiology. Some of the reactions of the cotton plant provide a basis for regarding the fruiting branch as being homologous to the inflorescenses of other plants.

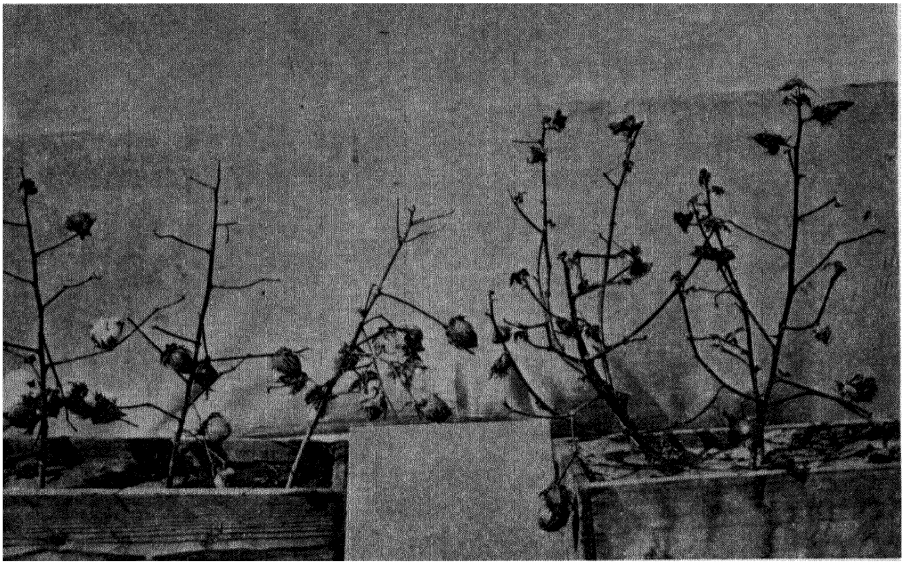


Fig. 1. On the left are cotton plants with fruiting branches only, and on the right, plants with a preponderance of vegetative branches. The latter plants had some short fruiting branches with floral buds but so far none had produced bolls. These plants all received 13-hour days and represent the difference between hot nights (left) and cool nights (right) at San Diego, California, where the days are cool. Certain photoperiodic cottons would give this same response to short days, left, but produce only vegetative branches under long days. (Eaton, 1924).

b. Photoperiodism. No work on the photoperiodism of the cotton more extensive than that of Konstantinov (1934) has appeared in the literature. By that work it was shown that the length of day may alter the fruiting activities of some, but not all, of the perennial arborescent cottons, particularly those from equatorial regions, and to a slight extent, also, varieties of Egyptian and of medium and late Uplands. He concluded that the early (determinant) American Upland cottons, as well as some of the wild forms from Mexico and elsewhere, were without length-of-day reactions. The author states that when length-of-day reactions were found, the basic change consisted in a lowering of the

position of the first fruiting branches. All cottons exhibiting photoperiodism are those requiring short days, *i.e.*, cottons are unknown that require long days for flowering.

c. Temperature. The striking influence that temperature may exert on the kind of branches produced, and, therefore, on the fruiting of cotton plants, is illustrated in Fig. 1. Dastur (1948) makes mention of observing lower temperatures to be conducive to the development of vegetative branches. At Shafter, California, where mean nightly temperatures for the summer months averaged about 60°F., Acala p-18-c was observed in 1947 (unpublished data) to develop 10 times as many vegetative branches per 20 feet of row as did the same variety similarly spaced at Sacaton, Arizona, where the average minimum nightly temperatures are about ten degrees higher. Laying a soil heating cable under a dust mulch along the two sides of a row of cotton plants at Shafter increased the nightly temperature by a few degrees 4 inches above ground and in turn lessened the development of vegetative branches.

d. 2,4-D and Hormone Responses. Attention was first directed by Staten (1946) to the high sensitivity of the cotton plant to wind-carried traces of 2,4-dichlorophenoxyacetic acid and its derivatives. The outstanding symptom of an excess of this material was shown by Staten and by Dunlap (1948) to be the growth repression of the mesophyll of leaves and involucral bracts which gave these organs a ligulate appearance in which the veins were especially prominent. Brown *et al.* (1948) illustrate, also, the pronounced swelling of the stems of cotton plants at ground level. Each of the foregoing investigators has shown that dusts and fine mists of 2,4-D can be carried many miles in sufficient concentration greatly to reduce cotton yields. Dunlap pointed out that if the injury was not too severe the cotton plant could put out new branches of normal appearance and develop late bolls. He also showed that the seed of plants injured by 2,4-D might upon germination have swollen hypocotyls and typical aberrations of the true leaves.

Ergle and Dunlap (1949) found that more than 0.002 mg. of 2,4-D per plant reduced the yield and increased the height and number of vegetative branches of cotton plants. Changes were found in the concentrations of several organic constituents of the leaves that were associated, possibly, with the altered proportions of vein and mesophyll tissue. The highest concentration used (0.04 mg.) appeared to reduce somewhat the tensile strength of fiber.

Singh and Greulach (1949) concluded from a carefully planned green-

house experiment that sprays of α-naphthaleneacetic acid and α-naphthaleneacetamide, although altering several plant characters, caused no effects of agronomic significance.

In California, in either of two years, during periods when 60 to 70 per cent of the bolls were shedding, Eaton (1950) could find no evidence of any effect on boll retention by dusting cotton plants with 1000 p.p.m. napthaleneacetic acid, with 100 p.p.m. sodium 4-chlorophenoxyacetate, or with the two in combination. Of weekly sprays with 10 and 20 p.p.m. 4-chlorophenoxyacetate, β-naphthoxyacetate, and α-naphthaleneacetate, only the 20 p.p.m. concentration of 4-chlorophenoxyacetate altered growth or fruiting. This latter material reduced significantly the number of bolls per plant and bolls per 100 g. of fresh stems and leaves, and increased significantly the height, and the number of main stalk nodes and vegetative branches. The increased height and number of vegetative branches were regarded as probably the result of reduced fruiting caused by extra bud shedding. As a part of this work, attempts were made both in winter and summer to alter the types of branches produced by day-length sensitive and day-length neutral cottons by treatment with various of the presently available synthetic growth substances. These efforts were not successful, but the investigations are regarded as deserving of continued effort as new materials become available, particularly any that influence floral initiaton or repression.

2. Mineral Nutrition

Knowledge of the mineral nutrition of plants has gained important impetus during the past ten years from rapidly developing evidence and views on the exchange of cations between the plant and soil. A recent review by Wadleigh (1949) deals extensively with the relations represented. The order of ease of release of cations from soil colloids by exchange reaction is headed by sodium which is released most easily followed by potassium, magnesium, calcium and hydrogen. As measured on clay membranes, the activity of sodium adsorbed on montmorillonitic clay is 20 to 25 times that of calcium. The activity of adsorbed sodium relative to calcium is always greater than the ratio of adsorbed sodium to adsorbed calcium, but the calcium on kaolinitic clay may be 10 or 20 times as readily available to plants as that on montmorillonitic clay. Calcium may be unavailable to plants if it constitutes only 50 per cent or less of the bases retained by the clay, *i.e.*, high levels of adsorbed potassium or sodium may prevent calcium uptake. Hydrogen ions released from plant roots provide the critical exchange ion for the release of calcium, potassium, etc., from clay. Carbon dioxide arising from root metabolism is the antecedent agent in the transfer of hydrogen from root

to clay. Of like recognized importance, but less well understood, are the processes and intensities of adsorption of nutrient cations on root surfaces and their relative rates of transference inwardly.

Investigations by Jacobson and Overstreet (1947) indicate that energy arising from respiration is directly involved in the intake of anions whereas the CO_2 product of respiratory activity functions in the hydrogen transfer that is instrumental in cation accumulation by exchange. Lundegardh's review (1947) deals extensively with this phase of mineral nutrition. In the instance of cotton, Eaton and Joham (1944) found that defruiting to increase sugar concentrations resulted in significant increases in both bromine and potassium in the fibrous roots; there was also an increase of both elements in the leaves, but the potassium increase was slight and not significant.

a. Constant Sum of Cations. Recent papers by van Itallie (1948) and Wallace *et al.* (1948b), who worked with oats and alfalfa, respectively, have added support to a conclusion reached earlier that the sum of the cation equivalents per unit of dry weight at a given stage of plant development tends to be uniform even though the species is grown on substrates of widely varied composition. Within what limits this conclusion can be extended to cotton is not yet clear. Cooper *et al.* (1948) thought that it might not be applicable to cotton where there is a wide variability in hydrogen-ion concentration. As grown on 7 plots at Florence, South Carolina, the sum of equivalents of K, Na, Ca, and Mg varied from 112 to 218. The two highest values were on limed plots (pH 6.7 and 6.5). On plots with pH values of 5.1 and 5.2 respectively the values were 159 and 112.

b. Sodium and Potassium. The interest that has been attached in the South to the roll of sodium as a plant nutrient for cotton has applied also in an important manner to other plants in other regions. Although no one has assumed, or concluded, that sodium is an essential element, there is now a wealth of evidence that it can make up in part, in varying degrees in different plants, for a deficiency in potassium supply. Furthermore, in some plants, such as the beet (Sayre and Vittum, 1947), sodium applications have resulted in yield increases over and above those that could be obtained by potassium alone. Plants which tend to accumulate more sodium than potassium, such as beets, cabbages, carrots, and spinach (Wallace *et al.*, 1948a) tend also to be tolerant to sodium and perhaps are more often benefited by sodium.

Collander (1941) has reported sodium to be higher in the roots than in the shoots of a number of plants whereas K was higher in the shoots.

Cotton contains much less Na than K above ground, and, as found in the expressed leaf sap (Eaton, 1942), there was only a fifth or less as much Na as K (Table II). Cooper *et al.* (1947) have considered the

TABLE II

Influence of Sodium Equivalent to 100 lbs. per Acre of Na_2O on 10-Year Average Cotton Yields and 3-Year Average Ca, K and Na Accumulations in Plants Equally Supplied with Nitrate on Norfolk Sandy Loam [a]

Lbs. of K_2O and N source	Seed Cotton Yield, lbs. per acre		Cation concentration in plants meq. per 100g. dry weight		
	Actual	Na gain	Calcium	Potassium	Sodium
No potash					
Cal-Nitro	306		70.00	19.63	1.42
Sodium nitrate	521	+ 215	60.00	17.43	11.27
15 lbs. potash					
Cal-Nitro	742		74.67	22.47	1.12
Sodium nitrate	943	+ 201	64.50	21.97	11.01
45 lbs. potash					
Cal-Nitro	1093		76.33	31.00	1.29
Sodium nitrate	1280	+ 187	60.83	32.57	10.75
60 lbs. potash					
Cal-Nitro	1201		74.85	35.57	1.69
Sodium nitrate	1383	+ 182	57.67	36.73	9.65

[a] Cooper and Garman (1942).

agreements and discrepancies between the order of accumulation of mineral nutrients in higher plants and the order of the same ions when arranged on the basis of their electrode potentials measured in equivalent volts. Spiegelman and Reiner (1942) have called attention to the selective accumulation of potassium from K and Na mixtures by sand columns and by myosin, and have suggested that considerations based on chemical mechanisms offered more promise than those based on physical relations. The possible fit of preferred ions in the lattice structure of the solid phase has been pointed to as one explanation.

Potassium is customarily credited with promoting not only the utilization of nitrogen in protein formation but with a catalytic activity in the assimilation of carbon dioxide and the synthesis of carbohydrates and oils. It is evident that sodium cannot perform all functions of potassium in cotton, *or in cotton does not accumulate in the right places in sufficient concentrations.* This is indicated by Volk's (1946) observation that Na alleviated but did not eliminate cotton rust. Leaf rust is the

important symptom of potassium deficiency in cotton. Biddulph's (1949) radioautographs show K concentrations in cotton leaves to be much more dense in and near the veins than outward in the more distant mesophyll. Similar radioautographs of sodium distribution would be of interest. In the Georgia Coastal Plain, Turner (1944) found that potash deficiency great enough to cause marked leaf symptoms, heavy leaf loss, and a 25 per cent reduction in the yield of American Upland cottons decreased the weight of seed per boll by only 10 per cent.

Gains from sodium applications have been common in field experiments with cotton (Andrews and Coleman, 1939; Mathews, 1941; and Holt and Volk, 1945). As yet there is insufficient evidence for concluding that the same yield increase might not have been gained from additional potassium. When ample potassium was supplied, the last mentioned investigators obtained no benefit from Na additions in greenhouse tests, using both sand and potted soil cultures. In the field, however, they obtained gains of 98 to 213 lbs. of seed cotton per acre in plots supplied with sodium in addition to 24 to 48 lbs. K_2O. Mathews (1941) found both sodium and potassium responses on Clarksville soils in Georgia, but neither element gave a response on Decatur soil. The availability of K (but not of Na) having been determined in both soils, it was concluded that the lack of benefit from sodium on the latter soil was due to the abundance of K. On the Clarksville soil, Na was estimated as being worth 40 per cent as much as K as a fertilizer.

Data by Cooper and Garman (1942) are notable in showing nearly uniform gains of approximately 200 lbs. of seed cotton per acre from applications of 100 lbs. Na_2O per acre, when K_2O applications were increased from none to 60 lbs. per acre. At all K_2O levels the added sodium caused nearly uniform increases in accumulation of Na from about 1.5 to 11 meq. per 100 g. of plant tissue. Adding but 60 lbs. of K_2O was sufficient to increase K accumulation from 19 to 35 meq. per 100 g. At the high levels of supply, there was 3 times as much K as Na in the above-ground portions of the plants.

Skinner *et al.* (1944) observed that extra K fertilization increased the percentages of K and reduced the percentages of Mg and Ca, and also of N and P in cotton plants. Like Cooper (1945), they concluded that the requirements of the cotton plant for Mg is less than for K or Ca and will be satisfied if dolomite is used in the manufacture of non-acid forming fertilizers.

c. Phosphorus. In each of 5 years Brown and Pope (1939) reported that heavy applications of phosphorus caused average increases of 30 per cent to 40 per cent in the proportion of flowers produced during the

first two weeks of the flowering period. With heavy P_2O_5 applications, there was also a large increase in the percentage of the seed cotton gathered at the first picking. Potassium on the other hand appeared to decrease the determinateness of the plant and to increase ultimate yields.

Radio-phosphorus injected into a leaf vein by Biddulph and Markle (1944) moved via the phloem to other parts of the plant. The downward rate of 21 cm. per hour was thought too high to be accounted for by diffusion. The upward movement was slower than the downward movement. From 30 days before to 25 days after anthesis, Biddulph and Brown (1945) found that the accumulation of both tagged and untagged phosphorus in floral buds and bolls was at rates nearly proportional to the gain in dry weight. Mason and Phillis (1944) supplied cotton plants with phosphorus in amounts from that causing acute starvation to an excess, and found that both the soluble and insoluble fractions in the main-stalk leaves increased throughout the full range; the former increase was linear whereas the latter tended to flatten.

In citrus, tomatoes, soybeans, pineapples and peanuts, various investigators have found high levels of nitrate to depress the uptake of phosphate. Similarly, reduced growth on soils low in nitrate has resulted from heavy phosphate fertilization. This also applies to cotton (unpublished work by H. E. Joham).

The use of radio-phosphorus has permitted some significant conclusions on the availability to cotton of various types of phosphate fertilizer. Measurements by Hall *et al.* (1949), showing the proportion of accumulating phosphorus derived from the soil and from the tagged fertilizer, have been made with a number of crops under various conditions. On Norfolk sandy loam, cotton derived most phosphorus from calcium metaphosphate and least from dicalcium phosphate, but the source of phosphate was without effect on yield. In Alabama, Ensminger and Cope (1947) concluded that, on old fertilizer plots, the responses to various phosphates were dependent upon the calcium and sulfur deficiences that had resulted from previous fertilizer practices.

d. Sulfur. By classical interpretation, sulfur is essential to the synthesis of proteins and when sulfur is deficient various plants become as chlorotic as they do when nitrogen is deficient. With insufficient sulfur, there is often an accumulation of NO_3, as well as of other soluble forms of N; starch and hemicelluloses also tend to accumulate. Little work on the biochemical reactions of the cotton plant to insufficient sulfur has been published, but the plant requirements are known to be fairly high. In the leaf sap from cotton (Eaton, 1942), much more sulfur and much less phosphorus were found than in that from the other plants examined.

During the last war, the substitution of rock phosphates for superphosphate resulted in poor cotton yields in some localities. Willis (1936) has reported finding that sulfur-free fertilizers produced crops equal to those supplied with sulfur only on soils which had had heavy previous applications. Younge (1941) noted that sulfur deficiency reduced the number and delayed the development of cotton bolls on a Coastal Plain soil. Tests of cotton responses to sulfur at scattered locations in Florida by Harris *et al.* (1945) show that there may be a widespread area that would benefit from its inclusion in fertilizers. Were it not for the large amount of sulfur in superphosphate and in the gases released to the atmosphere by some industries, more information on the sulfur metabolism of cotton might now be available.

e. Boron. This element, which is now thought to be involved in oxidative enzyme systems, is essential to the formation of meristematic tissues, and when deficient the fruiting branches of cotton are short and the flower buds fail to develop. Boron has continued to be regarded as an important constituent of cotton fertilizers under some conditions. Coleman (1945) reports beneficial results from applying boron at the rate of 20 lbs. per acre to Grenada silt loam in Mississippi. Boll size and number of bolls were increased, but no effects were found on percentage of oil in the seed. In representative Georgia soils with 0.05 to 0.55 p.p.m. of water-soluble boron, Olson (1942) failed to obtain increased yields by adding boron.

f. Copper. Like iron, copper functions as a coenzyme in oxidation and reducing systems. It has been shown by Manns *et al.* (1937) to produce substantial increases in yields of cotton when added to fertilizers in North and South Carolina and Virginia. Gaines *et al.* (1947) has found copper applications to cotton in Texas to produce greater yield increases when applied to the leaves as a dust with insecticides than when applied in the soil. The extensive literature on copper as a nutrient has been reviewed by Somner (1945), but no indication is afforded as to how extensively benefits might accrue from its more general use in cotton production.

g. Chemical Composition. There have been a good many investigations of the accumulation of minerals in the cotton plant by the various State Experiment Stations in the South. One of the most recent is that reported by Olson and Bledsoe (1942). Their data include 3 soils and 4 stages of growth. Relative to the seedling stage, the plants at maturity were about half as rich in P_2O_5 (0.44% on dry weight), CaO (2.08%)

and MgO (0.99%), and four-tenths as high in percentage of N (1.60%) and K_2O (1.39%). As calculated from data from plants on Cecil sandy loam, the proportions of N, P, K, Ca and Mg in the mature cotton plants, including squares and bolls, correspond closely with the proportions of the mineral nutrients supplied by Hoagland's solution, which was developed on the basis of analyses of barley plants. The efficiency of the cotton plant in fruiting activities is relatively high. The squares and bolls of mature cotton plants were found to constitute 65.8 per cent of the total dry weight of the plant and to contain 57.3 per cent of nitrogen, 78.7 per cent of the calcium, and 53.1 per cent of the magnesium.

According to data by Phillis and Mason (1942) the percentage composition of K, Ca, Mg, P, Cl and N in cotton leaves rises during the day and falls at night through losses. Collections of dew on attached leaves made about midnight contained an abundance of potassium and only traces of calcium. The authors regard the results as being in harmony with the view that the mineral elements enter the leaf in the wood, and, with the exception of calcium, are translocated from it in the phloem.

3. Nitrogen

In the Sudan, Crowther (1934) found 60 per cent or more of the total nitrogen of the cotton plant to be in the squares and bolls from the time the first bolls had started to open until the plants were mature. Notwithstanding continued leaf development, the movement of nitrogen from leaves to buds and bolls was at a greater rate than the movement into the leaves. This progressive exhaustion of leaf nitrogen continued from the peak of flowering onward. In American Upland cotton, Olson and Bledsoe (1942) found nearly the same proportion of the total nitrogen to be in the buds and bolls at plant maturity as did Crowther. By Wadleigh's (1944) extensive inquiry into the forms of nitrogen and nitrogen metabolism of the cotton plant, it was shown that protein constituted from two-thirds to three-quarters of the total nitrogen in all the plant fractions examined. At the stages of plant development selected for sampling both total nitrogen and protein nitrogen were much higher in leaves and immature seed than in other parts. This proportion of protein is in accord with earlier results by Rigler *et al.* (1937) who studied the dialyzable constituents of entire plants. In Wadleigh's experiment nitrate nitrogen varied from 3.1 per cent of the total nitrogen in the leaves (low nitrogen plants) to 37.5 per cent in the fibrous roots (high nitrogen plants). Mason and Phillis (1945) obtained a high linear correlation between soluble and protein nitrogen in leaves until a relatively high level of supply was reached, beyond which there was no further increase in protein. Potassium and phosphorus starvation both

caused reductions in the proportion of protein. The total nitrogen of cotton fibers has been found to be correlated directly with the soluble nitrogen of cotton leaves and inversely with the protein nitrogen (Eaton, 1947). Fine fibers are higher in nitrogen than are thick-walled fibers, reflecting, probably, a higher ratio of protoplasmic residue to wall weight in the former than the latter.

From a series of greenhouse comparisons of ammonium and nitrate salts in water cultures, Holley and Dulin (1943) concluded that there were no wide or very consistent differences in the yield benefits, or in effects on growth, between the two forms of nitrogen. They pointed out that ammonium fertilization initiated more flowers, but more of these flowers were shed. Although these conclusions are valid, the data through the 7 experiments reported in their Tables V, VII and XII show trends in favor of the ammonium salts in fresh weight of plants and in bolls per plant, and also in relative fruitfulness (computed by the writer) that seemed worthy of testing by analyses of variance. As summarized in Table III, ammonium salts produced a nonsignificant increase in combined weight of leaves and stems, but highly significant increases in bolls per plant and in relative fruitfulness; the latter amounted to 12 per cent. All of these effects are in the direction to be expected on the

TABLE III

Relative Fruitfulness of Cotton Plants in Several Experiments Involving Nitrogen

	Nitrogen source meq. per l.	Fresh stems and leaves, g.	Bolls per plant, number	Relative fruitfulness [a]
Holley and Dulin (1943)	NH_4	1997	77.6**	4.4*
(7 experiments)	NO_3	1868	70.3	3.9
Wadleigh (1944)	NO_3— 0.6	145[b]	5.3[c]	3.6
	NO_3— 1.8	289[b]	10.1[c]	3.5
	NO_3— 5.4	652[b]	18.6[c]	2.8
	NO_3—16.1	662[b]	23.1[c]	3.5
Eaton and Rigler (1945)	NO_3— 0.5	128	5.7	4.5
Low light	NO_3— 4.0	319	11.4	3.8
	NO_3—16.0	328	11.2	3.4
	NO_3—64.0	239	9.6	4.1
High light	NO_3— 1.0	107	7.2	6.8
	NO_3— 4.0	328	22.9	6.4
	NO_3—16.0	367	22.9	6.4
	NO_3—64.0	252	18.4	7.6

[a] Bolls per 100 g. of fresh stems and leaves.

[b] Green weight at time of second sampling.

[c] Number of bolls contributing to seed cotton.

*,** Significant at 0.05 and 0.01 level, respectively.

basis of the extra energy required for the reduction of nitrate ions. The literature on nitrate and ammonium nutrition, as well as many other features of nitrogen nutrition of green plants, has been extensively reviewed by Nightingale (1948).

4. Carbohydrates, Nitrogen and Fruitfulness

As fruit setting progresses, the cotton plant may become a victim of its own morphological development. As fruiting progresses, nitrogen is translocated to the bolls at a greater rate than it is taken up from the soil. As the reserves within the plant are exhausted there is a yellowing and a progressive reduction in the size of leaves and length of internodes; with heavy fruiting all terminal growth may stop. The diversion of sugars to the bolls reduces the flow into the fibrous roots thereby reducing nitrogen uptake as a consequence of the lessening of the essential metabolic activity. The onset of nitrogen exhaustion is delayed as the external supply becomes more abundant, and also when the variety is indeterminant in its growth habit. Wadleigh (1944) believed that high respiratory activity and reduced carbohydrate supply was involved in the low productivity of plants grown in a greenhouse with high temperatures and low light intensity. The level of starch and dextrin decreased with increased nitrate supply. Crowther (1944), in accord with some of his earlier colleagues, concluded that the number of flowers produced by the cotton plant depends on nitrogen supply, but that their continued growth (*i.e.*, boll retention) depends on carbohydrate supply.

Experiments by Eaton and Rigler (1945) were conducted with the objective of learning whether in cotton there are particular relations between nitrogen and carbohydrate levels that are conducive or nonconducive to fruitfulness. Plants were grown in sand cultures supplied with 1, 4, 16, and 64 meq. nitrate per liter: (1) in a greenhouse in the winter where daily maximum light intensities were arranged to average about 1000 foot-candles, and (2) freely exposed outdoors in the summer where the light averaged about 10,000 foot-candles at midday. Between the low and high light intensities there was an increase in sugar and starch at all nitrate levels. In the plants supplied with 16 meq. NO_3 per l. this increase was 4-fold in the leaves and 2-fold in the root bark. The weight of leaves and stems in the high and the low light experiments (Table III) were alike, but the plants under high light produced twice as many bolls as did those under low light. Factors associated with very low light thus caused decreased fruitfulness, *i.e.*, influenced the partition of growth materials between vegetative and fruiting activities in favor of the vegetative. Compared with light, the effects of level of nitrogen supply on the partition of carbohydrate utilization between

the two growth activities were found to be minor, *i.e.*, in this experiment, as in Wadleigh's (Table III), additional nitrogen, when not in excess, caused proportional increases in growth and fruiting. At both very low and very high nitrate levels relative fruitfulness was increased slightly. This may be partially accounted for by a tendency toward smaller bolls at these levels, but primarily by a repressed development of vegetative branches. The plants supplied with 16 meq. NO_3 per l. accumulated more nitrogen and contained more starch than those supplied with 4 meq. NO_3, but they set no more bolls.

In the foregoing experiment there was much floral bud shedding under low light and much boll shedding under high light. An important but as yet unanswered question arises from this experiment: If carbohydrate deficiency is a general cause of boll shedding why were the supplies found in the high light plants not more nearly utilized before these plants started to shed? Any satisfactory explanation of the cause of boll shedding on nutritional grounds will evidently need to go beyond the often repeated carbohydrate and nitrogen theory. This is not to imply that an adequate and continuous supply of carbohydrate is not essential for the maintenance of boll growth and for boll retention, but rather that within the nutritional interpretation there are significant points of plant composition including enzymes and hormones, that have not yet been brought to attention by laboratory analyses. One of the most direct supports for the nutritional interpretation of shedding is the fact that defruiting of heavily laden cotton plants increases carbohydrate levels, causes renewed vegetative growth, and renewed boll setting.

Rather extreme or prolonged reductions in light intensity have been found by Dunlap (1945) to result in shedding, but he also noted that short periods of heavy shading and longer periods of light shading did not produce this result. It seems a little improbable that any but the most unusually long or intense periods of cloudy weather are much of a factor in shedding. This conclusion is in accord with early data by E. C. Ewing in Mississippi and by Mason and Maskell in Trinidad. It is even possible that short periods of overcast skies may favor carbohydrate utilization and thereby boll retention. It is now generally recognized that, as late as midsummer, an occasional burst of shedding may be compensated for by the setting of new flowers. But in cotton, as in other plants, periods of dark weather cannot be considered apart from the rankness of the growth of the planting. Five per cent, or less, of the light intensity at the top of the plants may be found near the ground under a heavy growth of cotton.

5. Effect of Drought on Plant Composition and Fruiting

Drought, as studied by Eaton and Ergle (1948), was found to cause an increase in hexose sugars in cotton leaves and large reductions in starch. In the stems and roots, on the other hand, there were always moderate to large increases in hexoses, sucrose, and starch. The data show that the utilization of photosynthetic products in growth is curtailed more by drought than is photosynthesis. Although the results have as yet not been published, measurements by the same investigators have shown that reduced water supply, even though decreasing vegetative growth by half and reducing boll periods and boll sizes, was without appreciable effect on relative fruitfulness.

In an investigation of the organic acids of the cotton plant, Ergle and Eaton (1949) found relatively high concentrations in the leaves and lesser amounts elsewhere. The concentrations of these acids changed little in leaves during prolonged respiration and they were not extensively translocated. Drought caused an extensive reversible shift from citric to malic acid. Little, if any, correlation was observed between the organic acids and other determined organic constituents. Defruiting had little effect on these acids.

6. Drought and Other Factors Affecting Boll Development and Lint Properties

The effects of nitrogen and mineral deficiencies that are so marked on the plant are not necessarily reflected in effects on fiber properties. Instead, the influences on the latter are inclined to be minor or irregular. Once the ovules have been fertilized and their growth has been initiated, the boll occupies a favored nutritional position.

Increases in nitrogen supply under certain conditions (Wadleigh, 1944 and Nelson, 1949) have resulted in increases in length of fiber. This response, however, does not seem always to occur (Sturkie, 1947), and length reduction has been accredited to the use of nitrogen alone (Brown, 1946). Nelson (1949) reported that phosphate applications increase boll size, but have little effect on the lint. Under conditions where potash greatly increased yield, it also increased fiber length, weight per inch, and x-ray angles, and there was an accompanying decrease in fiber strength; yarn strength was reduced 5 to 15 per cent by 90 lbs. per acre of K_2O. Fertilizer studies in Texas by Hooton *et al.* (1949) showed that a high level of phosphorus increased fiber length in comparison with a high nitrogen fertilizer, but not when compared with no fertilizer.

Drought, as reported by Barker (1946) and Sturkie (1947), has been observed repeatedly to decrease the length of cotton fibers and usually,

but not always, to increase their strength. Berkley *et al.* (1948) show that the increase in tensile strength associated with drought is accompanied by a narrowing of the angle between the long axes of the cellulose crystallites and that of the fiber, *i.e.*, reduced x-ray angles.

According to investigations by Eaton *et al.* (1946) immaturity and drought have similar effects on the composition of cotton seed. Both drought and disease injury reduced substantially the percentage of oil in seed and weight per seed, but left unchanged the percentage of protein. Earlier investigators have shown that oil is synthesized in seeds during the late stages of development whereas the input of nitrogen is continuous from anthesis.

In a number of cottons, Berkley (1945) has found the fiber strength per unit weight to increase only gradually after it is 35 days old and that this increase is about what might be expected on the basis of changes in the x-ray angles.

Anderson and Kerr (1943) have shown the enlargement of young bolls to be uninhibited by severe wilting of the plant, but full size bolls shrank during plant wilting and regained their size during the night. They concluded that a lack of equilibrium between osmotic pressures and diffusion pressure deficits in cottonseed was more apparent than real. Kerr and Anderson (1944) concluded that imbibition is largely responsible for water absorption by developing seed.

7. Oxygen Requirements for Root Growth

Leonard (1945), having observed marked correlations between oxygen supply, texture and moisture content of Mississippi soils and the distribution of cotton roots, undertook more extensive controlled laboratory experiments (Leonard and Pinckard, 1946). Young cotton plants were grown with their roots extending into glass tubes of nutrient solutions through which various gas mixtures were bubbled. The minimum oxygen in the gas mixture required for elongation was between 0.5 and 1 per cent. The optimum range was found to lie between 7.5 and 21 per cent. The greatest root growth in any experiment was observed to be with 21 per cent oxygen and 10 per cent carbon dioxide. The elongation of the tap root was similar whether nitrate or ammonium nitrogen was supplied. The absence of carbon dioxide did not affect root growth and 60 per cent of this gas prevented growth.

IV. Diseases of Cotton

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Cotton disease investigations have been in progress in the cotton-growing areas of the United States since before the turn of the century. Pammel (1888) reported that the root-rot disease of cotton was caused by a fungus and was not a result of unfavorable soil conditions or of chemicals or other materials in the soil. Atkinson (1892) reported that cotton wilt was caused by a vascular-invading Fusarium. Orton (1900) was the first to breed for wilt resistance in Upland cotton (*Gossypium hirsutum*) and produced two wilt-resistant varieties, DILLON and DIXIE.

Since these early disease investigations in cotton, numerous workers have studied the various diseases attacking the cotton plant and have made notable contributions to an understanding of the disease problems and to methods of control.

1. Seed Treatment

Workers in most of the cotton-growing states have cooperated during the past several years in developing a uniform seed-treatment program. As a result of this work, we are now able to recommend with confidence the seed treatment that a farmer should use, regardless of his location in the Cotton Belt. Those most commonly used are ethyl mercury p-toluene sulfonanilide, 7.7 per cent active ingredient (Ceresan M), at 1½ oz. per bushel for fuzzy seed and 3 oz. per 100 lbs. of delinted seed, and zinc trichlorophenate, 50 per cent active ingredient (Dow 9-B), at 1½ oz. per bushel of fuzzy seed and 3 oz. per 100 lbs. of delinted seed. In addition to controlling pre-emergence and post-emergence damping-off, these materials will disinfect the surface of the seed and eliminate seed-borne diseases such as bacterial blight and anthracnose.

2. Phymatotrichum Root Rot

The first systematic work on the cause and control of cotton root rot was done by Pammel (1888, 1889). Various causes for the disease were suggested, such as certain chemical or physical conditions of the soil, an excess of humic acid, an excess of lime, an excess of sulfuric acid, insufficient drainage, or an impervious stratum of clay or limestone underlying the plants that arrested the growth of the taproots.

Pammel (1889) isolated the causal organism from diseased cotton plants and definitely established the fact that root rot is caused by a fungus. A series of experiments was then set up to determine whether

the disease organism was seed borne, and to find methods of control. It was concluded that the disease organism is not seed borne. Recommendations made for the control of the disease were: good cultural practices and rotation with nonsusceptible crops such as corn, sorghum, millet, wheat, and oats; trench barriers, particularly in orchards and vineyards; various chemicals; and heavy applications of barnyard manure.

Many methods of control have been tried by every worker since Pammel but none of them has been satisfactory for the entire region where the disease is a problem.

A variety of intensive chemical treatments ranging from common table salt to kerosense oil have been used with varying success. Only a few of the more promising ones will be mentioned here. King (1923) found that a solution of formalin in dilutions of 1¼ to 2 per cent was effective in eradicating the disease from small areas. The soil should be saturated to a depth of more than a meter. Streets (1938) recommended applications of ammonium sulfate or ammonium phosphate, at a rate of one lb. of ammonium salt to 10 square feet of surface, for treating and protecting ornamental shrubbery and shade trees. Neal *et al.* (1932) used ammonium hydroxide with good results. The soil around affected plants was saturated with a 6 per cent solution by flooding or by pressure methods.

Clean fallow, followed by deep tillage and rotation with nonsusceptible crops, is effective in reducing the disease, particularly in Texas. McNamara and Hooton (1930) state that, in a plot where more than 90 per cent of the plants were infected from 1919 to 1921 inclusive, no diseased plants were found after a 2-year continuous fallow.

Numerous types of barriers have been developed to check the spread of the disease. The more common types are: open trenches 12 to 20 inches in width and 18 to 30 inches in depth dug just in advance of the front lines of infection; trenches filled with mixtures of sand and heavy motor oils or sand and chemicals; strips of sheet metal or roofing paper placed vertically in the soil; and as used by Taubenhaus and Ezekiel (1935), barriers consisting of 2 or 4 rows of sorghum (a nonsusceptible plant) planted in advance of the line of infection. The most effective is the trench barrier containing mixtures of soil and heavy oils, salt, ammonia, and sulfur.

Fertilizers high in nitrogen were shown by Jordan *et al.* (1939) to reduce the incidence of root rot under some soil conditions. The results of various cultural practices employed in Texas are summarized by Jordan *et al.* (1948).

No promising results in the direction of disease resistance have been

reported from breeding experiments on cotton, but some of the selections of grape and citrus in Texas appear to be resistant.

Control of root rot has been obtained by the use of stable and corral manures where heavy applications of these and other organic materials have been made in deep furrows during the fall and winter, and cotton has been planted over them. King (1937) states that, in 1935, on plots treated with manure 1.6 per cent of the plants died, while on the untreated plots 56.2 per cent of the plants died. For one acre, 20-40 tons of green alfalfa or 8-15 tons of barnyard manure were used. More recently, Lyle *et al.* (1948) reported a practical control for Phymatotrichum root rot in Texas by use of a sweet clover and cotton rotation.

By the use of organic materials, soil conditions are created which favor the rapid development of certain soil organisms which in turn hinder the development of the root-rot fungus. Since these organisms are present in almost every type of soil, the author believes that this method of control will apply to all the areas affected by the disease. The only problem will be to find the most efficacious method of applying the organic materials for each locality or soil type.

3. Fusarium Wilt

A cotton wilt caused by a form of Fusarium was reported by Atkinson (1892); the disease was described as *Fusarium vasinfectum* n. sp. It was observed to be of general occurrence on the lighter soil types of the Southeastern cotton-growing states. At the present time, the disease is known to occur in all parts of the world where cotton is grown.

Orton (1900) is credited with breeding the first wilt-resistant Upland cotton. For a period of 8 years, healthy plants were selected from wilt-infested fields where most of the plants had been killed. The selections were tested under wilt conditions in the field and from these the two resistant varieties, DILLON and DIXIE, were developed. Lewis and McLendon (1917), working in Georgia, developed several resistant varieties. Apparently most of the original resistant varieties were of the late-maturing type since many of them have been discontinued. Also, as a result of boll weevil damage to the late varieties, as Sherbakoff (1949) points out, breeding work in the U.S. Dept. of Agriculture, became directed to the production of earlier and more productive wilt-resistant varieties by crossing resistant DILLON and DIXIE with the earliest and most productive susceptible varieties such as TRIUMPH, COOK, COLUMBIA, COKER, WEBBER, and FOSTER.

Shortly after the beginning of the wilt-resistance work in the United States, Fahmy (1929) started the breeding of a resistant Sakel cotton (*Gossypium barbadense*) in Egypt. About this same time Uppal *et al.*

(1941) began similar work in India. All of these workers, through the results which they obtained and through the influence which their work had upon subsequent investigations, have contributed materially to the ultimate success in obtaining a satisfactory wilt-resistant cotton. An outstanding example of this relatively recent work is the development of COKER 100 WILT and COKER-4-IN-1 by the Coker Pedigreed Seed Company. These cottons have been widely accepted and planted on wilt-infested soil and as a result the losses from Fusarium wilt have been reduced to a minimum. The most recent contribution in this field has been the EMPIRE cottons developed by Smith and Ballard (1947) at the Georgia Experiment Station. In respect to resistance, earliness, and productivity EMPIRE stands near the top of all the commercial Upland cottons.

4. Verticillium Wilt

Verticillium wilt of cotton caused by *Verticillium albo-atrum* R. & B. was first reported by Carpenter (1914). No further mention of this disease was made in the United States until it was reported by Sherbakoff (1929) as causing considerable damage to cotton in Tennessee. Miles and Persons (1932) reported the disease as occurring on cotton in the Mississippi Delta, and Herbert and Hubbard (1932) reported the disease in cotton at the U.S. Field Station, Shafter, California.

Shortly thereafter, Brown (1937) reported the disease as occurring in all of the cotton-growing areas of Arizona. At the present time, Verticillium wilt is known to occur in cotton across the entire Cotton Belt from South Carolina to California.

In the early stages of Verticillium wilt investigations, the disease appeared to be more of a novelty than a potential destructive disease. Beginning about 1937 to the present time, however, the disease has increased in severity and in the total area affected to the point where it is recognized as one of the major diseases of cotton. Certain areas of the irrigated Southwest suffer losses that range up to 50 per cent, with overall losses ranging up to 20 or 25 per cent. Efforts were made by Rudolph and Harrison (1939) to control this disease by the application of chemicals or soil amendments, but at the present time none of these practices appears to be very promising. Breeding for disease resistance offers the most practical method of control. Rudolph and Harrison (1939), Presley (1946), and Barducci (1942) have contributed to this phase of the problem. Salter (1946) reported the release of a resistant strain of ACALA 1517 which was developed by Leding at the U.S. Cotton Field Station, in New Mexico. Strains of COKER 4-IN-1 and EMPIRE appear to have considerable tolerance to the disease in Mississippi, whereas the

cottons developed in the irrigated Southwest are very susceptible. The breeding and selection work is being continued in California, Arizona and New Mexico, as well as in Mississippi, where a variety, HARTSVILLE, has been found to be highly resistant to wilt under conditions which obtain in the Mississippi Valley. The late maturity and low yield of HARTSVILLE renders it undesirable commercially, but it offers excellent possibilities in a back-cross program for transferring resistance to the desirable commercial types. A selection and hybridization program has been under way for the past 4 years in Mississippi and notable progress has been made. At the present time progenies are ready for yield trials in Mississippi and for further resistance tests in other cotton-growing areas.

5. Bacterial Blight

Bacterial blight caused by *Xanthomonas malvacearum* (E. F. Sm.) Dowson is one of the most common diseases of the cotton plant. It attacks practically all varieties of Upland cotton and it is especially severe on varieties of Sea Island and Egyptian cotton (*G. barbadense*). The disease was first described by Atkinson (1891). Atkinson (1892) published a rather complete description of the disease and called it angular leaf spot. Smith (1901) reported that the disease was caused by a bacterium. Xanthomonas is capable of affecting all above-ground parts of the cotton plant and, according to the organ affected, the disease is known as angular leaf spot, black arm, or bacterial boll rot. Although the disease is present in all cotton-producing countries, crop losses vary with varieties grown, seasonal conditions, and with the region in which the cotton is produced. In the irrigated valleys of the Southwest, the disease is especially severe and crop losses ranging up to 25 per cent are not uncommon in certain areas.

Since the bacterium was found to be carried on the lint and on the surface of the seed, Rolfs (1915) recommended the use of sulfuric acid as a means of removing the lint and disinfecting the seed surface. Brown and Streets, University of Arizona, perfected and patented a sulfuric acid process for delinting cotton seed in 1934. Although the bacteria which are carried on the lint and seed surface are removed by the sulfuric acid treatment, carefully controlled experiments by many workers have demonstrated that there is a certain amount of infection carried inside the seed coat which is not controlled by the sulfuric acid or other seed treatments. Results of the Uniform Seed Treatment Studies which have been conducted for many years in most of the cotton-growing states demonstrate that the recommended seed protectants are also effective in controlling the surface-borne seed infections of bacterial blight. Seed treatment reduces primary infections, but cannot be expected to entirely

control the disease inasmuch as a small percentage of infection is carried within the seed. The centers of infection resulting from the internal infection may pass unnoticed in the field, but if favorable conditions arise considerable spread may be expected. Much work has been done on survival, dissemination, and spread of the causal organisms (Faulwetter, 1917; Hansford *et al.*, 1933; Hare and King, 1940; Massey, 1930; Rolfs, 1935). Stoughton (1933) has described the effects of environmental conditions upon the disease.

It is obvious that the most practical approach to complete control of bacterial blight is through the development of disease resistant varieties. Fortunately, a resistant variety of Upland cotton has been found. Simpson and Weindling (1946), working with many varieties of cotton, found one selection of STONEVILLE to be resistant. This resistant selection was designated STONEVILLE 20. Since the release of STONEVILLE 20 many workers have used it in transferring resistance to many other varieties of Upland cotton. Blank, at College Station, Texas, has transferred resistance to the commercially desirable varieties of cotton which are grown in Texas. Other workers in Tennessee, Mississippi, New Mexico, Arizona and California are using STONEVILLE 20 in their breeding programs in order that resistance to bacterial blight may be transferred to the new varieties which are being developed.

6. Root-Knot

Root-knot caused by *Heterodera marioni* (Cornu) Goodey was early recognized by Gilbert (1914) as a serious disease of cotton in itself, and also as a contributing factor to the losses in wilt-infested soils, due to the fact that Fusarium wilt of cotton is much more severe where the disease is associated with root-knot. Godfrey (1923, 1943) recommends clean fallow, rotation with nonsusceptible crops, and summer plowing for controlling root-knot. Watson and Goff (1937) and Watson (1945) in Florida, reported control by use of mulches. Cuba (1932) suggests the use of a carbon disulfide emulsion in controlling the disease and recently almost innumerable reports have been made of the success of other chemicals in controlling the disease. Jacks (1945) used formaldehyde, carbon disulfide, chloropicrin, and a mixture of 1-3 dichloropropane and 1-2 dichloropropane (Shell D-D), and found that chloropicrin and Shell D-D gave the most promising results. Smith (1948) found that ethylene dibromide (Dow W-40) gave considerable increases in yield when used on wilt-sick soil infested with nematodes. Presley (1949) also obtained consistently high yields from plots treated with ethylene dibromide on wilt-infested soil also infested with root-knot nematodes.

Through the use of a simplified method of application and row treat-

ment rather than blanket application, the chemical control of nematodes is economically feasible. Studies conducted at the Mississippi Agricultural Experiment Station have shown considerable carry-over effect of the soil fumigant from one year to the next. Cotton grown in 1949 on plots fumigated in 1948 produced more than double the nonfumigated plots. At the present price of cotton, soil fumigation should be a profitable practice wherever nematodes are a serious problem.

7. Summary

Although many of the fundamental principles of disease control were pointed out and investigated by earlier workers, it has been during the past 10 to 15 years that outstanding progress has been made in developing control measures for the most important diseases of this crop. At the present time practical control measures are available for the seedling-disease complex commonly referred to as damping-off, for Phymatotrichum root rot, for Fusarium wilt, for bacterial blight, and considerable progress has been made in controlling Verticillium wilt. Controls have also been developed for the root-knot nematode.

V. Insect Pests

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Statistics released by the Bureau of Agricultural Economics and the National Cotton Council indicate that insects cause an estimated average annual loss of $208,727,000 to cotton planters of the South. The boll weevil has been the most damaging insect for many years. Bollworms, leafworms, fleahoppers, aphids, thrips, stinkbugs and other insects are also responsible for much injury.

In recent years, research entomologists have made considerable progress toward the development of chemical controls by employing better laboratory techniques plus the latest designs for field experiments. Newly developed insecticides are tested first in the laboratory, under controlled conditions, and later are placed in field tests. The field tests are designed for statistical analysis of the infestation data as well as yields, in order to evaluate the materials.

1. Thrips

As soon as cotton emerges in the spring, injurious insects begin their attack. Several species of thrips, *Frankliniella tritici* (Fitch), *Frankliniella fusca* (Hinds) and *Thrips tabaci*, Lind. cause similar injury to

cotton. Wardle and Simpson (1927) stated that thrips cause premature and excessive defoliation. They found no evidence, however, that the salivary secretion of the insect was toxic. Eddy and Livingston (1931) showed that thrips retarded the growth of cotton seedlings and that unfolded leaves were perforated and had marginal erosions. Gaines (1934) observed that thrips transferred in large numbers from weed fields to cotton early in the spring, and that later populations increased on cotton at a rapid rate. Watts (1934, 1936) reported the biology of several species of thrips known to attack cotton in South Carolina. Thrips injure the tender leaves, destroy buds and retard fruit production. The injury becomes so severe at times as to result in loss of stands.

Chapman *et al.* (1947), Fletcher *et al.* (1947) and Gaines *et al.* (1948) have conducted thrips control tests. The results show that thrips may be controlled with several organic insecticides; however, increases in yield were not significant. Losses in stands can be prevented by use of insecticides.

2. Cotton Aphid

Aphids, *Aphis gossypii,* Glov., also attack seedling cotton and are especially injurious during cool damp weather. This pest retards growth and fruit production and often results in loss of stand. Aphids may be controlled with benzene hexachloride, but insecticidal control applied to seedling cotton rarely proves economical except in cases where losses in stands are prevented.

Infestations of aphids resulting from the use of calcium arsenate later in the season cause excessive shedding of leaves, difficulty in ginning and deterioration in the grade of the lint. R. C. Gaines *et al.* (1947) reported that control of aphid infestations by the addition of nicotine to the calcium arsenate used for weevil control proved economical.

3. Cotton Fleahopper

The fleahopper, *Psallus seriatus* (Reut.) also attacks cotton early in the season. Howard (1898) reported this insect as a pest of cotton. Hunter (1924) gave a brief account of severe injury to cotton in South Texas caused by the then-called "cotton flea." Reinhard (1926a, 1926b, 1927) described the various stages of the insect and suggested the use of sulfur to control the pest. The injury to the cotton plant is characterized by an excessive blasting and shedding of small squares, a reduction in the number of fruiting branches, and either a tall whiplike growth of the main stem or an increased number of vegetative branches. Several workers (Gaines, 1933, 1942; Hunter and Hinds, 1904; Reinhard, 1926b) have shown that the fleahopper migrates from horsemint to

cotton early in the spring and migrates from cotton to croton early in July. Ewing (1929) and Painter (1930) investigated the possibility of the fleahopper being a vector of a plant disease. They concluded that the material injected into the plant by the insect did not spread far from the point of injury and that both the disturbance and shedding of squares was due to the multiplicity of bites. The fleahopper occurs throughout the Cotton Belt, causing the greatest damage in the western part of the area. Ewing (1931) noted that a mixture of Paris green and calcium arsenate killed a higher percentage of adult fleahoppers than did sulfur; however, sulfur proved the more effective in killing nymphs. Later, Ewing and McGarr (1936, 1937) showed that Paris green-sulfur (10:90) was more effective against this pest than sulfur alone.

Most of the newer organic insecticides have proven highly effective against all stages of this pest. Low concentrations of either toxaphene or DDT applied as sprays or dusts are effective and have proven practical for the control of the fleahopper.

4. Boll Weevil

The boll weevil, *Anthonomus grandis*, Boh., crossed the Rio Grande near Brownsville, Texas, on or before 1892, and by 1894 it had spread through several surrounding counties in Southern Texas. The weevil gradually spread to the northwest and eastward and by 1922 had covered practically the entire Cotton Belt. Several workers (Fenton and Dunnam, 1928; Gaines, 1942; Hunter and Hinds, 1904; Hunter and Pierce, 1912) have shown that there are two principal periods of dispersal and spread during the season. The first period occurs when the hibernating weevils leave their winter quarters and go in search of food. The second period is dependent on several factors: (1) large weevil population; (2) abundance of fruit; (3) high percentage of infested fruit; and (4) high temperatures. The hibernating weevils migrate to cotton early in the season, feeding on the leaves and small squares. When the squares become half-grown or larger, the female deposits an egg in a cavity which has been formed by eating into the square or boll. The cavity is then sealed by secreting a mucilaginous substance from accessary glands of her female organs. The feeding punctures are never sealed, thus differentiating between those containing eggs. Either kind of puncture soon causes the squares to flare and fall. Heavy weevil infestations result in serious boll injury as well as square injury caused by the grubs feeding on the contents of the fruit.

Newell and Smith (1909) recommended powdered arsenate of lead for the effective control of weevils. Later, Coad (1918) and Coad and Cassidy (1920) reported that calcium arsenate afforded good control

of the weevil without causing injury to the cotton. Research work has been conducted on the boll weevil in practically all Southern States and numerous reports of this work have been issued by various Experiment Stations and the Bureau of Entomology and Plant Quarantine. Calcium arsenate, since discovery of its applicability, has been the recommended control for this pest throughout the South. Since the use of this insecticide often results in aphid infestations and is not effective against the sucking type of insects which are injurious to cotton, an effort has been made to find a desirable substitute by both manufacturers and entomologists. The development of organic insecticides during World War II offered several possibilities. A number of workers (Becnel *et al.*, 1947; Dunnam and Calhoun, 1948; Ewing and Parencia, 1947, 1948; Gaines and Dean, 1947, 1948; Gaines and Young, 1948; Ivy and Ewing, 1946; Ivy *et al.*, 1947; Parencia *et al.*, 1946; Rainwater and Bondy, 1947; Watts, 1948) have shown that toxaphene or a mixture of benzene hexachloride and DDT were effective against the boll weevil, as well as most of the other cotton insect pests. Calcium arsenate or calcium arsenate mixed with an aphicide such as nicotine is still recommended for weevil control in all the cotton states. However, 20 per cent toxaphene-40 per cent sulfur or 3 per cent gamma benzene hexachloride-5 per cent DDT-40 per cent sulfur are preferred to calcium arsenate, particularly in those states where the bollworm causes injury.

Spraying cotton with arsenicals for weevil control has not proven profitable. Results of tests conducted in several states in 1949 indicate that some of the organic insecticides applied as spray emulsions at a low pressure and volume per acre were effective against the weevil. This method of application is being rapidly explored by cooperative efforts of agricultural engineers and entomologists.

Several years ago, when the pink bollworm spread to the southern counties of Texas, strict regulations were imposed on the planters regarding planting dates and early fall destruction of stalks. The fall stalk destruction date was set sufficiently early to starve the boll weevil before it hibernated. During the years following adequate fall destruction of stalks, the boll weevil was greatly reduced and the need for chemical control was practically eliminated. Gaines and Johnston (1949) reported the results of a fall stalk destruction program which was conducted in Williamson County, Texas, during 1947. In this county, the stalks were destroyed early by all planters and the weevil infestations were greatly reduced the following year. Apparently a well executed fall destruction program will greatly reduce the losses resulting from the weevil.

The so-called "Florida Method" involved the removal and destruction

of all infested squares early in June after the hibernating weevils had emerged, followed by dusting the plants with calcium arsenate to destroy the adults. Several factors made this method impractical. The pre-square poisoning method was developed and used to some extent in the eastern portion of the Cotton Belt and proved more effective in communities where all the planters cooperated in the program. However, neither method has been generally accepted by cotton planters.

Since several of the organic insecticides have proven effective both in the form of sprays and dusts for controlling such insects as thrips, aphids, fleahoppers and boll weevils which usually attack cotton early in the season, the control of these insects appears both practical and promising. Spray equipment is being developed which will allow the insecticide to be applied when the cotton is cultivated. By combining insecticidal applications with the usual cultivation practices the expense of early-season control should be greatly reduced. In certain communities where planters have cooperated in an early-control program, the results have been favorable. During dry years this program should prove profitable. In wet years and in areas where the bollworm causes injury later in the season, however, several applications of insecticides will be necessary to protect the cotton and the early season control may be an added expense. In either case, early season control is a good investment to insure early fruiting of cotton. The Texas Extension Service suggested the early-season control program during 1949. In some areas, it was well received and proved profitable. In other areas, where bollworm infestations occurred, additional applications were necessary to protect the crop during July and August. Cotton receiving the late applications produced as much as the cotton receiving both early and late applications. Additional research is being conducted to evaluate the various programs in different areas.

5. Bollworm

The bollworm, *Heliothis armigera* (Hbn.), occurs over the entire Cotton Belt as a pest of many crops. This insect overwinters in the pupal stage and the moth emerges early in the spring. The first brood feeds on legumes and corn, while the second brood attacks corn causing considerable injury to the ears. In the Southwest, corn matures early in July and the moths emerging from the mature corn fields migrate to cotton fields and severely damage the more succulent cotton. Sporadic occurrences of this pest have been reported throughout the entire Cotton Belt. Riley (1885) studied the bollworm and recommended London purple and Paris green for its control. Later Quaintance and Brues (1905) recommended arsenicals, the use of trap crops, and cultural prac-

tices to control the pest. Moreland and Bibby (1931), Gaines (1941, 1944) and Moreland *et al.* (1941) presented results of insecticidal tests which indicated that calcium arsenate applied at the proper time gave economical control of the pest. Parencia *et al.* (1946), Ewing and Parencia (1947), Gaines and Dean (1947) and Gaines *et al.* (1948) reported the results of field tests in which DDT, 3 per cent gamma benzene hexachloride-5 per cent DDT-sulfur and 20 per cent toxaphene-sulfur were compared with calcium arsenate. The organic insecticidal mixtures proved more effective in controlling the bollworm than calcium arsenate.

Unpublished results of tests conducted in 1949 indicate that toxaphene and toxaphene-DDT, when applied as spray emulsions, are effective in the control of the bollworm.

6. Pink Bollworm

The pink bollworm, *Pectinophora gossypiella* (Saund.) is a worldwide pest of cotton and causes severe injury to the fruit. The greatest damage caused by this pest is the destruction of bolls or rendering them unfit for picking. Cotton produced under heavily infested conditions is inferior in grade because of staining, shorter staple and less tensile strength.

The pink bollworm was first described from specimens collected in India and is believed to have spread by means of seed shipments to Egypt around 1906. According to Hunter (1918, 1926b) the pink bollworm was introduced into Mexico in 1911 through shipments of seed from Egypt. The infestations in this country were introduced from Mexico likewise through seed shipments, and also by moths drifting across the border from heavily infested areas.

The biology of the pink bollworm was carefully studied in Mexico by Loftin *et al.* (1921) and Ohlendorf (1926). Hunter (1926b) reported on steps taken to prevent this pest from establishing itself in the United States. The pink bollworm has been a potential danger to the cotton industry in this country for the last 28 years.

Latest reports issued by the Bureau of Entomology and Plant Quarantine indicate that the pink bollworm has been found to occur in 127 counties in Western Texas, 8 in Oklahoma, 15 in New Mexico and 7 in Arizona. It has been effectively controlled by the use of cultural practices including regulated dates for planting and destruction of stalks as specified by the State Departments of Agriculture.

During the past few years, considerable research has been carried on in Mexico by workers in the Bureau of Entomology and Plant Quarantine to effect a chemical control for the pink bollworm. The results

of these tests indicate that DDT is effective in reducing the worm population.

7. Hemipterous Insects

A number of hemipterous insects attack cotton, particularly in the western areas of the Cotton Belt. According to Cassidy and Barber (1939) the most important species of stink bugs causing injury to cotton are *Euchistus impectiventris* Stal, *Chlorochroa sayi* Stal and *Thyanta custator* (F.). Three species of plant bugs, *Lygus hesperus* Knight, *L. pratensis oblineatus* (Say) and *L. elisus* Van D. are also injurious to cotton. The most conspicuous injury resulting from hemipterous insects is the blasting of young squares and bolls and the puncturing of bolls followed by severe lint staining due to invading pathogenic organisms.

Increases in yields have been obtained with applications of Paris green-sulfur or calcium arsenate-sulfur. Later work conducted by Stevenson and Kauffman (1948) proves that the organic insecticides are more effective than the arsenical-sulfur mixtures. Either DDT, a mixture of DDT-benzene hexachloride or toxaphene is recommended for control of plant bug and stink bug.

8. Cotton Leafworm

The leafworm, *Alabama argillacea* (Hbn.) is one of the oldest known insect pests of cotton. Since this insect cannot overwinter in any part of the United States, infestations originate from flights of moths from Central or South America. Almost every year this pest has been reported from some section of the Cotton Belt. It was once thought that periods of maximum infestations occurred in 21-year cycles, but this is not now generally accepted. The conditions affecting the increase of this pest in its native habitats, and the conditions existing in this country at the time the moths appear, govern the injury produced.

This pest is primarily a leaf feeder. After the leaves have been destroyed, however, it may also devour the fruit. Due to its feeding habit, the leafworm is easily controlled with almost any kind of arsenical. It has been found that, with the exception of DDT, the organic insecticides used to control other cotton insects are also highly effective against this pest.

Leafworms have not developed to injurious numbers in the last few years, due perhaps to the thorough dusting programs which have been generally followed in the coastal area of Texas. However, unfavorable conditions for leafworm development in South and Central America may also have been a contributing factor.

9. Spider Mites

Sporadic infestations of spider mites have been reported throughout the Cotton Belt. This pest attacks the underside of leaves and causes a

TABLE IV

Insecticides Recommended by the Various States for Cotton Insect Control during 1949

Insects	Insecticides	Rate of application, lbs. per acre
Thrips	10 per cent toxaphene	12 to 15
	3-5-40 [a]	7 to 10
Aphids	3-5-40	7 to 10
Fleahopper	5 per cent DDT	10
	10 per cent toxaphene	10
	20 per cent toxaphene	10
	3-5-40	10
Boll Weevil	Calcium arsenate alternated with calcium arsenate—2 per cent nicotine or 3-5-40	7 to 10
	Calcium arsenate	7 to 10
	3-5-40	10 to 15
	20 per cent toxaphene	10 to 15
Bollworm	20 per cent toxaphene	10 to 15
	3-5-40	10 to 15
	10 per cent DDT	10 to 15
	Calcium arsenate	10 to 15
Leafworm	Calcium arsenate	7 to 10
	Lead arsenate	7 to 10
	20 per cent toxaphene	10
	3-5-40	10
Plant Bugs	5 per cent DDT	10 to 15
	3-5-40	10 to 15
	10 per cent toxaphene	10 to 15
Stink Bugs	2-5-40 [b]	15 to 20
	3 per cent G. BHC	15 to 20
	10 per cent DDT	10 to 15
	3-5-40	10 to 15
	20 per cent toxaphene	10 to 15
Red Spider	Sulfur	20 to 25

[a] 3 per cent gamma benzene hexachloride—5 per cent DDT—40 per cent sulfur.
[b] 2 per cent gamma benzene hexachloride—5 per cent DDT—40 per cent sulfur.

discoloration and subsequent defoliation of the plants. Sulfur has been recommended for a number of years as a control for this pest, but the results obtained by planters have not always been favorable. In a recent article, McGregor (1948) determined the species of spider occurring on cotton in Texas as *Septanychus sp.* The two-spotted spider mite, *Tetranychus bimaculatus* Har., is known to be widely distributed in the southeastern section of the Cotton Belt.

When organic insecticidal mixtures were first used without sulfur, a decided increase of spider mites was noticed, particularly in the Southwest. It was found that the addition of sulfur to the insecticidal mixtures averted increases. Results of tests conducted by Iglinsky and Gaines (1949) indicate that sulfur effectively controls the *Septanychus sp.* spider mite.

10. General Recommendations for Chemical Control

The insecticides or insecticidal mixtures generally recommended by the various states for cotton insect control during 1949 are given in Table IV. The recommendations issued by the Extension Services of Arkansas, Mississippi, Missouri, North Carolina, South Carolina and Tennessee do not include sulfur in the organic mixtures. The entomologists in Alabama, Arizona, California, Georgia, Louisiana, New Mexico, Oklahoma and Texas suggest that the organic mixtures should contain at least 40 per cent sulfur to prevent red-spider increases.

VI. Improvements in Production Practices

1. In Humid Areas

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The rapid advancement of mechanized practices in the humid areas of the Cotton Belt, due to the shortage of farm labor and to the improvement in equipment, has brought about many changes and improvements in farming techniques. These can best be described in the order in which the operations are carried on. Space will not permit any lengthy comparisons between the most modern practices and those of past years.

a. Field Layout and Water Control. A water control program, whether terracing for erosion control or a drainage system to remove surplus water, or possibly a combination of the two, is an absolute necessity where modern tractors with pneumatic rubber tires are used. In order to obtain the best in control measures, it is necessary to give

careful attention to field planning. Fields should be so arranged as to give the longest rows possible with a minimum of short rows. It may be well, therefore, to take certain parts of a field from row crops in order to increase the efficiency of the operation. This field planning may possibly require the moving of tenant houses and other buildings from the field, as well as relocation of roads and ditches. Low spots, or pockets, lend themselves readily to "spot-plowing operations" and in areas where heavy equipment is available land levelers are being used.

b. Disposal of Crop Residues. The modern power-driven stalk shredders have greatly simplified the problem of crop residue disposal, allowing the stalks to be cut to very small pieces, thereby increasing coverage during the plowing operation and hastening the incorporation of vegetation into the soil. Many of these same machines are used on cover crops to shred thoroughly the green growth so that it can be completely and easily incorporated into the soil. In some instances the use of the stalk shredder on cover crops will allow the planting date to be advanced a week to 10 days.

c. Preparation of Seedbed. The manner of seedbed preparation varies widely with the area; heavy disk harrows, mold board plows, disk plows, wheatland plows, and middle breakers, are all standard implements. Regardless of the machine used, a good seedbed is essential. Improvements in farm equipment enable the farmer not only to increase efficiency, through the coverage of more acres per day, but improve the seedbed produced in the plowing operation. Any plant, whether grown in the garden as a shrub or in a 1000 acre field, retains its characteristics and requires the same seedbed regardless of the acreage. Farmers realize the importance of good seedbed preparation and increasingly are making use of the modern equipment at their command.

d. Fertilization. The use of fertilizer has been on the increase for a number of years and remarkable strides have been made in both machines and methods of application. In those areas where complete fertilizer is used at planting time, equipment is now available in units for one, two, or four rows which apply fertilizer according to the placement recommendations, simultaneously with the planting operation. This not only saves labor, but assures a more positive placement in relation to the seed with better moisture conditions, thereby giving greater efficiency and more complete utilization of the fertilizer by the plant. Throughout the humid areas, nitrogen is the principal fertilizer used for sidedressing the crop, and in some areas is the only fertilizer used. It is then applied

both prior to planting and as a sidedressing. One of the newer nitrogenous fertilizers is anhydrous ammonia, which in some areas is used in extremely large quantities for direct application to the soil. Other areas of the Cotton Belt, particularly in the Southeast, are using a complete fertilizer at planting followed by anhydrous ammonia as a sidedressing with excellent results. This particular form of fertilizer has advantages for sidedressing, inasmuch as deeper placement is possible than when granular fertilizers are used. The use of anhydrous ammonia is one of the most important developments in cotton fertilization in recent years.

e. Planting. Increased efficiency in mechanical, acid, and gas delinting of cotton seed has allowed the farmers to attain greater precision in planting than ever before. Many farmers are now planting their cotton to a stand, either by hill dropping or in some instances light drilling, thereby eliminating the costly operation of thinning as well as attaining a saving in seed planted per acre. Cross plowing or check-row planting, while seemingly attaining popularity several years back, has become less popular due to decreased efficiency of the mechanical picker. It still retains its place, however, in areas badly infested with grass and weeds, as a means of cheap control of these pests in the cotton crop. Recent tests from several Experiment Stations indicate that the extreme precision necessary in planting a crop such as corn is not necessary in the growth of cotton. The various methods of planting do affect, however, the fruiting habits of the plant and increase or decrease, as the case may be, the efficiency of the weed-control measures, which in turn affect yield and operation of mechanical harvesters.

f. Cultivation. Cultivation rightfully is divided into 3 periods, early, midseason, and late. It should be borne in mind that cultivation is primarily for weed control and that the breaking of the land has been accomplished during seedbed preparation. Rotary hoe attachments, cited by Gull and Adams (1945) are mounted between the cultivator gangs and independent of them, and have greatly speeded up and increased the efficiency of early cultivation. Many farmers are setting their machines on the floor of their shop by the line-diagram method, and with the use of rotary hoes are attaining speeds up to 5½ miles per hour during the early cultivation period, when timeliness is so important. It should be pointed out that these speeds have been possible through the cooperation of the Farm Equipment Industry in developing and making available ground-working equipment suitable for high-speed operations.

During the second stage in the cultivation of the cotton crop, flame

cultivation is brought into the picture and is carried on simultaneously with the regular shovel cultivation. Pioneer work with flame by Neely and Brain (1944) was extended by Gull and Adams (1945). Through the development of more efficient burners for the flame cultivator in later years by Meek and other workers of the Mississippi Delta Branch Station, it is now possible to begin the operation of these machines when the cotton plant is much smaller than has heretofore been possible. These new burners, using a standard spray nozzle for an orifice, allow the size of the orifice to be changed at will, thereby permitting small orifices to be used on young cotton, and the size of the opening increased as the cotton plant increases in size. The burners also furnish a longer exposure of the plant to the flame, which permits higher operating speeds than has ever been obtainable before. Probably one of the greatest advantages of these new burners is that they are set at an angle of 45° to the surface of the ground and when once set do not require further adjustment. Clods and ridges do not particularly affect the action of the flame and, as a consequence, the flame cultivator has been made more adaptable to the Cotton Belt as a whole. The price of fuel, which is either butane or propane, will be the determining factor in the use of these machines. With flame cultivation controlling the grass and weeds in the row and the regular shovels of the standard cultivator giving control in the middles, a greater degree of efficiency is now attained for humid regions than ever before. Mid-season control is, for the modern farmer equipped with modern equipment, a comparatively simple matter.

Where mechanical harvesters are used, the late control of grass and weeds in cotton is vitally important. The grass in particular must not only be killed, but destroyed above ground. Farmers have found this extremely difficult to do due to the size of the cotton plant. Great damage has been done in the past by machines moving through the dense vegetation. Wheel fenders for the tractor, developed at the Mississippi Delta Branch Experiment Station, now allow cultivation by shovels and flame much later in the season than ever possible before. In many areas, it is necessary in the late stages of control to remove the standard shovel cultivators and continue with the flame alone, particularly when rains occur during the late growing season. These fenders, while invaluable in the grass- and weed-control program, also allow the farmers to make insecticidal applications, and then later to use his own tractor in applying a defoliant, either dust or liquid.

g. Application of Insecticides. Insect control is of vital importance, not only from the standpoint of yield, but also because it affects the mechanical harvesting program. One of the newest developments is the

attachment of spray rigs on supports of the regular shovel cultivator, whereby organic insecticides are applied during the early stages of growth, as a control for thrips and other insects. This early spraying apparently causes the cotton to fruit earlier, which gives more uniform distribution of the bolls on the plant and allows the mechanical harvesters to be started sooner in the fall and so do more work. Control of boll weevil and other insects is carried on, where sprays are used, with the same unit used in early applications. These machines are developed to the stage that the gallonage per acre applied approximates that of airplane application, and preliminary results indicate that the control to be obtained by the two methods is comparable. By the use of the fenders on the tractor wheels, this insecticide treatment may be applied either as sprays or as dusts well toward the harvest season, or to a point after which further control is not considered profitable. Insect control, during the middle and latter part of the season, can greatly affect the efficiency of the mechanical harvester. Where control is not obtained, the plant has a tendency to grow tall and rank due to the dropping of the fruit, and as a consequence, more vegetation must be handled by the harvesting equipment and its efficiency is thereby reduced.

h. Defoliation. Defoliation in the humid areas is carried on principally with calcium cyanamid dust applied either by airplanes or ground machines. This practice greatly increases the efficiency of the mechanical harvester and allows cotton of a higher grade to be produced. Where hand picking is practiced, defoliation permits the pickers to enter the field earlier when heavy dews are prevalent, and also increases their efficiency. The use of sprays in the humid areas appears to be limited. In many instances, farmers defoliate their crop in order to remove the leaves and allow sunlight to penetrate into the plant, thereby reducing rot of the lower bolls. In other instances farmers may defoliate rather early in order to reduce the damage from boll weevil or leaf worm, that is, they discontinue their insect control program in favor of defoliation.

i. Harvesting. Cotton strippers are seldom used in the humid areas due to the extreme difficulty of passing the large amount of vegetation through the machines, and also to the inability of the gins to remove the large amount of trash resulting from stripping the longer-staple varieties common to the areas. The spindle-type pickers are the machines used and are attaining great popularity under humid conditions. Their operation at the present time is, however, restricted, as no machines are made for entirely satisfactory performance in the Southeast in contoured

fields, or where rocks are often encountered. On the more level lands, however, the mechanical pickers are operating most satisfactorily and large numbers of them are being used. Two spindle-type pickers were in production commercially in 1949. There is every indication that at least two more will be placed on the market in 1950, with possibly a third being available.

Farmers are realizing that every phase in the production of the cotton crop is of vital importance and that no one operation can be slighted without affecting those which follow. From field layout and water control on through crop-residue disposal, seedbed preparation, fertilizing and planting; and thence through cultivation for weed and grass control, every single operation, including the insect control and defoliation program, affects harvesting, and may have a decided effect both on yield and quality of cotton produced. Better machines and better methods are increasing the efficiency of the cotton farmer, permitting him to produce a higher quality product with fewer man hours.

2. In Low-Rainfall and Subhumid Areas

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Low-rainfall cotton is that which is grown where the average annual rainfall is less than 25 inches and where the rainfall distribution is such that irrigation will materially increase yields. That grown west of a line drawn from Corpus Christi, Texas, to Oklahoma City, Oklahoma, will be, approximately, in the low-rainfall area. This area includes the western halves of the states of Texas and Oklahoma and all of New Mexico, Arizona and California. Bonnen and Thibodeaux (1937) show that the approximate western limits of dry-land farming is a line drawn from Raymondville, Texas, to Lovington, New Mexico.

Although a large part of the cotton produced in the subhumid area is grown as dry-land cotton, approximately 3 million acres of cotton are irrigated. The acre yields of dry-land grown cotton range from failures, in exceedingly dry years, to a bale of 500 lbs. per acre in years of ample rainfall. Acre yields of irrigated cotton range from one-half to 3 bales in some cases. Government estimates indicate that approximately 3¼ million bales of cotton were produced in 1949 from the irrigated acreage.

Cultural practices for low-rainfall cotton, both dry-land and irrigated, differ from the practices of the humid areas; therefore, they are discussed separately.

a. Field Layout. Fields that are to be irrigated must be carefully surveyed, slopes determined, irrigation ditches located and lateral ditches planned so that water can be properly applied, as discussed by Thomas (1948). The land must be leveled with land-leveling machines and "Fresnos" so that water will flow down the furrows in a uniform manner. Borders are sometimes thrown up and the entire field flooded to facilitate planting and insure subsoil moisture.

b. Disposal of Crop Residues. In the High Plains area of Northwest Texas and Western Oklahoma, crop residues such as cotton stalks and sorghum stubble are left until January or February as a protection against wind erosion. Just prior to listing the land, 4- and 5-row shop-made rolling stalk cutters are used to cut the stalks. The dry stalks and stubble do not decompose readily in the dry climate, and subsequently cause frequent stoppages of cultural machines, particularly of mechanical cotton strippers. In the Lower Rio Grande Valley area, governmental regulatory measures require that all cotton stalks be cut and plowed under by the first of September. Power-operated stalk cutters and shredders are being used in this and other areas to chop and shred cotton, sorghum and corn residues, and also green cover crops. A tandem disk harrow hitched behind a rolling stalk cutter is a popular method of cutting and disposing of crop residues throughout the low-rainfall area. A knife arrangement, similar to that on a peanut digger, to cut the stalk under the surface of the ground immediately above the root crown, makes land preparation easier, and permits the use of modern mechanized tools, such as the rotary hoe.

c. Preparation of Seedbed. Under dry-land farming conditions, land is usually listed with tractor-mounted middlebreakers to form beds. Under irrigation, however, Thomas (1948) states that land must be carefully leveled, broken flat with one-way plows, floated, ditches made and often borders thrown up for an application of water before the final seedbed is prepared. Some farmers list forming a bed for each row, while others throw up a wide bed to accommodate two rows. The wide double beds are called "cantaloupe beds." The beds are harrowed down and sometimes "boarded" off a few days before planting. In the High Plains where cotton is planted in the furrow, the beds are "knifed" with long knives just before planting to destroy weeds. Where cotton is planted on low beds in Central Texas, rolling stalk cutters are frequently used to chop the beds to break up clods and destroy weeds.

In some areas where a sandy topsoil is underlain by a clay subsoil, chiseling and subsoiling is practiced to aid the infiltration of water.

d. Fertilizer Responses. Fertilizer is not generally used in the low-rainfall area because of the low crop response. Magee *et al.* (1944) state that, in the High Plains of Texas, the natural soil fertility has not been depleted to the extent that commercial fertilizers can be profitably used. Hinkle and Staten (1941) found that the heavy soils of New Mexico are inherently fertile and may be expected to produce satisfactory cotton yields without fertilizers. Light soils, however, may give profitable responses when fertilizer is applied, especially manure. Staten and Hinkle (1942) found that, where cotton followed two or more years of alfalfa, considerably higher yields of cotton were obtained. Unpublished results from Texas indicate that profitable increases in yields are obtained in Central Texas when nitrogenous fertilizers are used.

e. Planting. Planting practices in the subhumid areas differ for dryland and irrigation farming. Jones (1948) discussed practices in the High Plains where the seed is planted in the furrow with a lister type 2- or 4-row planter. A small amount of seed is drilled and little or no thinning is done. Where rains wash excess soil over the seed, rotary-hoe attachments mounted on sled cultivators are used to loosen the soil to aid the emergence of seedlings. In Central and South Texas, planting is done on low beds with 2- or 4-row tractor-mounted planters, as discussed by Alsmeyer (1949). Presswheels are left off the planters and special rollers are used a few hours after planting to compact the soil over the seed. Planting on either flat-broken or bedded land is a general practice under irrigated conditions. Where cotton is planted on flat land, many farmers use a double-disk furrowing attachment in combination with a runner or knife opener. Throughout the low-rainfall area most cotton is drilled, but there is a trend toward the use of hill-drop attachments. Rotary and electrically actuated valves are satisfactory for hill-dropping cottonseed. There is also a definite trend toward the use of delinted seed. One concern in Central Texas annually furnishes farmers 70,000 bushels of certified mechanically-delinted and treated seed.

f. Thinning. Cotton farmers of the High Plains area of Texas and Oklahoma have long followed the practice of planting to a stand, that is, only enough seed is planted to give a stand of plants. Where cotton is hill-dropped with an average of 4 to 5 seeds per hill, spaced 14 to 18 inches, no thinning is necessary. Where cotton is drilled to a thick stand, the most common method of thinning is chopping with a hoe. The average rate of pay for hand chopping in 1949 was $4.00 per day per laborer. Many farmers use mechanical choppers and some practice cross-plowing to reduce "chopping" costs.

g. Cultivation. Fairbank (1948) has pointed out that weed and grass control is one of the major problems in cotton mechanization. Cotton has been produced entirely by mechanical means under humid conditions, as reported by Gull and Adams (1945). Limitations under dry-land and irrigation culture, as given by Smith (1949a) emphasize the problem of control of weeds and grasses in the crop row. Cultivation is not only necessary to destroy weeds, but also to conserve moisture and to put the soil in better condition for plant growth. The rotary-hoe cultivator attachment is an excellent tool for breaking soil crusts and for the destruction of young weeds in the first two months of crop growth. When the sweeps on each side of the rotary hoes are set flat and run shallow, cultivation can be done 40 per cent faster than where the customary fenders and sweeps, and sweep setting, are used. The rotary-hoe attachment can be used either in the listed furrow or upon beds. Current work shows that an integral-mounted 4-row tractor lister cultivator with rotary hoe attachment may reduce hoeing hours from 60 to 100 per cent in the High Plains area. The regular 2- and 4-row tractor-mounted cultivators are used except where cotton is planted in the furrow.

The number of cultivations required for weed control varies from an average of 3 to 6 per season. Extremes may range from 1 to 10 per season. The first cultivation of cotton may often be before seedlings emerge and the last cultivation may be delayed until bolls begin to open.

Flame cultivation has not been used extensively in the low-rainfall areas because of the different farming practices, and climatic conditions and because the low moisture level in the surface soils retards germination of seeds of annual weeds.

h. Application of Insecticides. Tractor-mounted dusters, and also airplanes, are used for applying insecticides to cotton. There appears to be a trend toward the use of spray equipment in some sections. Where the pink bollworm is found, stalk cutters, disk harrows, and plows are important tools in cutting and burying of the crop residue. The distribution and relative importance of cotton insects is discussed in V.

i. Defoliation. Jones and Jones (1945) stated that defoliation of cotton plants at harvest time in the subhumid areas is more difficult to obtain than in the humid areas. Usually the weather is dry and hot, the soil is deficient in moisture for plant growth and the plants are semi-dormant, and in stress from lack of moisture. Under most conditions, plants and foliage must be approaching maturity to obtain rapid defoliation. Smith (1949b) points out that an active plant and atmospheric

moisture in the form of dew are two essential factors to complete defoliation of cotton.

Where cotton is defoliated, hand pickers can easily see and pick bolls that would ordinarily be hidden by the foliage. The trash in mechanically-picked cotton is dry and can be more easily removed, without chlorophyll stain, by the cleaning equipment of the gin, and thus a higher quality cotton obtained than where the plants have not been defoliated.

j. Harvesting. Smith *et al.* (1946a) discuss 4 methods of harvesting cotton in general use in the subhumid areas. These methods are termed hand-picking, hand-snapping, machine-stripping, and machine-picking. The practice of snapping cotton began in the High Plains of Texas about 1912 and since that time has spread to all sections of Texas, and to other states. Mechanical stripping also started in the High Plains area. Home-made sled strippers were used from 1914 to 1930, but were practically abandoned during the period 1931 to 1940. Two-row tractor-mounted strippers were introduced in 1943. Cotton growers in Texas and California are adopting the spindle-type picker, but some farmers who grow the fine-textured, long staple cottons in New Mexico and Arizona contend that this quality type of fiber is injured when machine picked. The mechanical stripper requires a storm-proof type cotton while the picker requires an open boll with fluffed locks, and a staple length sufficient to allow the lint to wrap around the picking spindle. Smith *et al.* (1939, 1946b) showed that varietal characteristics generally affect field losses of mechanical harvesters more than the mechanical factors. Williamson and Rogers (1948a, 1948b) point out that cultural practices materially affect field losses of both the stripper and picker. The quality of yarn manufactured from machine-stripped and picked cottons of Texas production was not affected by the method of harvest when compared with hand-harvested cottons, except for a slight lowering of the appearance grade for the longer and fine-fibered cottons, as discussed by Smith *et al.* (1946b) and Grimes (1947).

k. Irrigation. McDowell (1937) and also Barr (1949) have pointed out that the proper use of water is perhaps the most fundamental problem in cotton production in regions where the crop is grown under irrigation. Irrigation practices are influenced by the nature of the soil, amount and distribution of rainfall, temperature, and evaporation. These factors or conditions vary widely in different areas and the practice for one area will not apply, as a whole, to another area. The 3 principal sources of water for irrigation are those impounded in reservoirs, pumped from rivers, and pumped from wells. Under Arizona conditions, Harris

(1947) found that the average amount of irrigation water required to produce a crop of cotton ranges from 20 to 30 acre-inches. The amount and distribution of the annual rainfall will influence the irrigation requirements. Where cotton is grown under irrigation, there are 3 critical periods of cotton growth: (1) planting to heavy fruiting; (2) fruiting; and (3) the maturity period. Experiments in Arizona by Harris and Hawkins (1942) and Harris (1947) show that, in general, the more rapid the growth of the cotton plant prior to heavy fruiting, the higher the final yields.

The application of water to cotton late in the season will delay maturity. Cotton plants require and use more water during July, August, and September than at other times. The cost of producing cotton under irrigation is higher than under rain-grown conditions and yields must be higher to obtain profitable returns.

VII. Improvements in Ginning Practices

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The ginning processes are of vital importance to all who are engaged in the cotton industry, because the few-minute period that is required to gin a bale determines the grade and staple sample for selling the bale, and this sample may reward or punish those who have contributed to its production.

The United States leads in improvements in ginning, and competitors quickly copy them, either by purchase of better machinery, or by efforts to provide home-made substitutes. This is evidenced by some 17 patents, with others pending, pertaining to ginning machinery and processes.

"Ginning" includes several important stages of processing, each having a special function and bearing upon the end result, namely, the quality of the finished bale. Without being too technical, it may be said that there are about seven of these stages, usually operated in the following order: (1) conditioning; (2) cleaning and extracting; (3) distributing and feeding to the gin stands; (4) separation of the fiber from the seed, either by saws or rollers within the gin stands; (5) lint cleaning; (6) disposition of freshly ginned seed and foreign matter; and (7) packaging the lint into bales.

1. Regulation of Moisture

Regulation of optimum moisture content has not yet been satisfactorily achieved. There are various regional conditions that call for

different treatment of the seed cotton and the fiber. The restoration of moisture in the arid regions is a much slower and more difficult operation than is the mere drying necessary in humid areas. Approximately 30 lbs. of seed cotton must reach each saw-gin stand per minute, and conditioning must therefore be done in bulk streams, or in the final distribution to the gin stands. Modern gins attempt to do both, insofar as drying is concerned, but neither methods nor controls have yet been devised for optimum regulation of the moisture content of the seed cotton

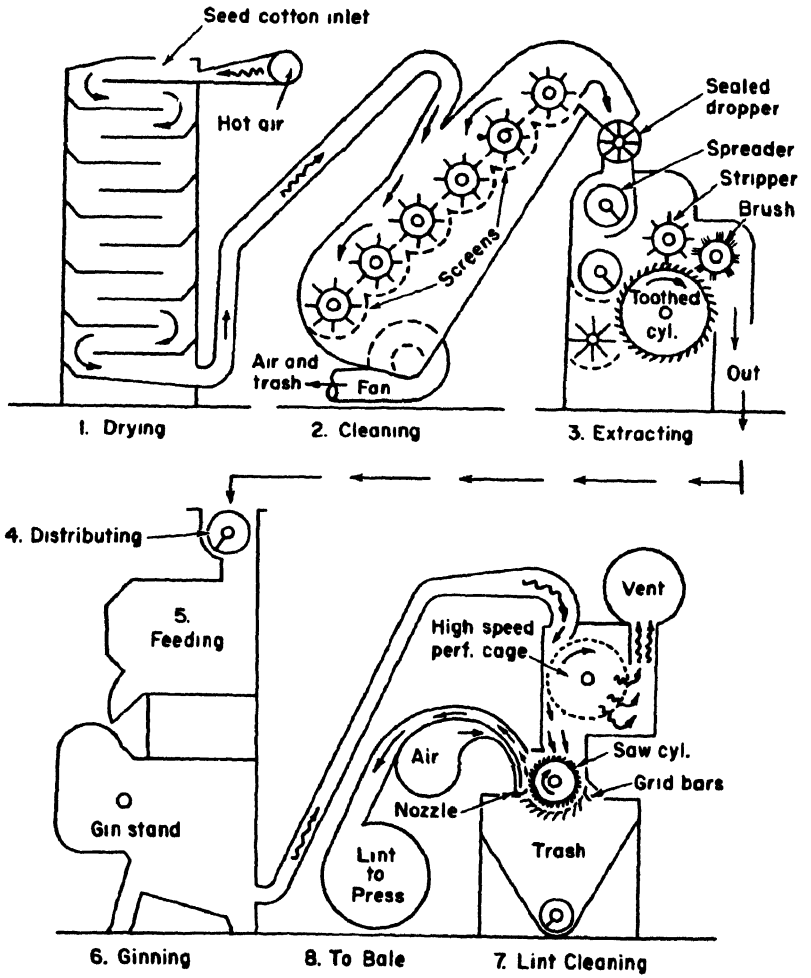


Fig. 2. Diagrams of the several processes of cotton ginning, except pressing and packaging. In normal order of sequence, beginning at upper left hand corner, they are (1) drying; (2) cleaning; (3) extracting, which is usually followed by more cleaning; (4) distribution; (5) feeding; (6) ginning or the separation of the fiber from the seed; and (7) lint cleaning during which the freshly ginned fiber is centrifuged and scrubbed.

(principally the fiber) in the high-speed transit of the material through the several processes ahead of the actual ginning or fiber separation from the seed.

Figure 2 depicts in diagram form the several preliminary processes of drying, cleaning, and extracting; it also shows the cleaning of the ginned fiber or lint immediately after it leaves the gin stand. No lint cleaning devices are as yet available for roller-types of cotton gins.

It will be noted from Fig. 2 that the drying involves a pneumatic method; that the cleaning involves a threshing method which employs both beaters and screens (or grids of some sort); and that the extracting depends upon a carding method which is accomplished by toothed cylinders and strippers. Drying fluffs up the cotton and liberates the ordinary small particles of foreign matter, and at the same time it appears, in rain-grown regions, to enhance the subsequent action of the cleaners and extractors. If means can be developed for adding moisture quickly to the seed cotton as it passes through gins in the arid regions, much will be accomplished.

Drying is now a multistage process in itself at the more completely-equipped gins, because several driers may be used in succession. They may be all of one type, or mixed, and intermingled with them may be auxiliary jets of hot air to the cleaners in lesser air volumes than are employed in the regular dryers. Seed cotton may be conveyed through the dryers by pneumatic or mechanical means. The Government design (Fig. 2), developed by the U. S. Department Agriculture Ginning Laboratory, is pneumatic, and consequently somewhat automatic in action because the cotton moves in proportion to its fluffiness and dryness, rather than by positive rate of travel from a belt or auger.

2. Cleaning

The "cleaners" have a unique function in the modern cotton gin, whether they achieve the maximum removal of finer trash or not. First, they open and fluff up the cotton as it comes from the dryer, often comprising the receiving chamber for this material in a very simple and effective way. Fig. 2 shows this in a modern "blow-in" delivery of dried cotton to the cleaner. Second, this fluffing is a mechanical agency that loosens larger pieces and fragments of burs, hulls, leaves, and other unwieldly foreign matter, so that the portion passing to the extractors may be the more readily removed. That part of the foreign matter that can be screened out, is, of course, usually discharged in the cleaners, but not always at the first one. After the main extracting stage, the finishing cleaners perform a "cleanup" job. All-in-all, cleaners generally take out about 30 per cent of the foreign matter that comes into the gin with the

seed cotton, although sometimes 20 or more cylinders are required to accomplish this.

3. Extraction and Interrelated Processes

The extractors exist for the purpose of extracting sticks, stems, burs, hulls and larger pieces of foreign matter. Like the dryers and cleaners, they too involve a series of individual extractions, interspersed here and there between cleaners and driers, or between cleaners and gin stands. Foreign matter removal by extractors is also approximately 30 per cent, taken as a whole for all extraction processes that may be employed in the modern gins, beginning with overhead machinery and ending right within the huller fronts of the gin stands themselves. Huller fronts are primitive extractors, from which the large modern counterpart has arisen. The U. S. Department of Agriculture is now conducting research on better removal of green, unopened bolls, and of heavy plant sticks and stems that are very troublesome when machine-stripped cotton is being ginned.

Figure 3 depicts a cross-section of a modern cotton gin with a chain of processes frequently used. Any similarity between the diagram and

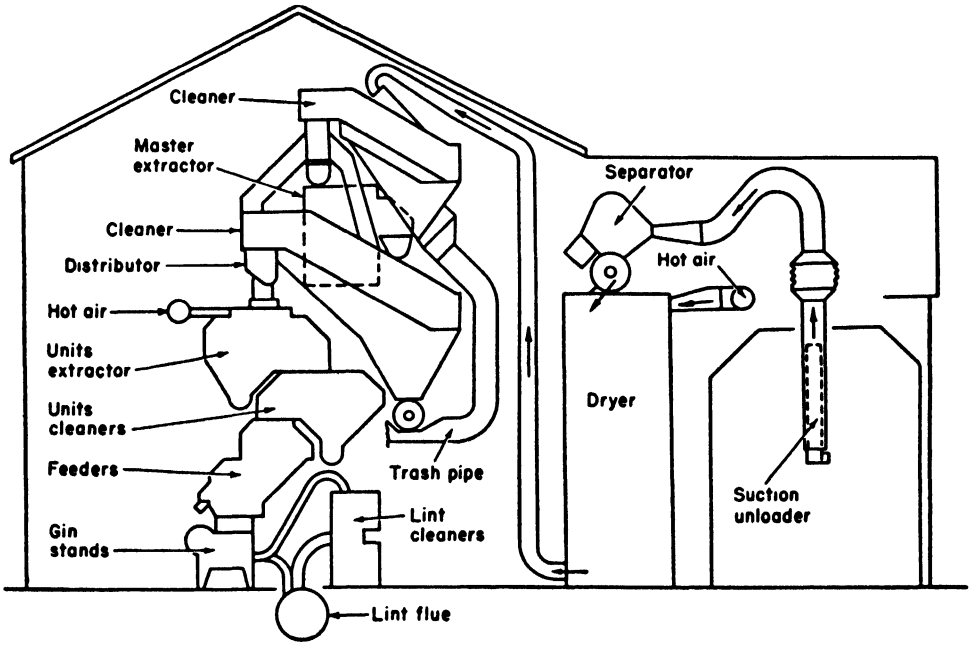


Fig. 3. Diagram of a section through a modern cotton gin equipped to handle machine-picked and roughly hand-harvested cottons. This diagram is for informative purposes only and does not conform in cross section to the majority of cotton gins that have suction telescopes at the front of the stands. The equipment, however, is comparable.

special brands or makes of machinery is strictly coincidental and does not comprise Governmental endorsement. It will be noted (Fig. 3) that some of the various processes are repeated, except those within the gin stands and lint cleaners, and that the seed cotton now does rather extensive traveling on its way from storage bin or vehicle to the bale press (not shown in the figure).

Figure 4 depicts a somewhat different arrangement of dryers, cleaners and other units than used in Fig. 3, both being representatives of improved types of cotton gins now in use in humid and arid regions of the Cotton Belt.

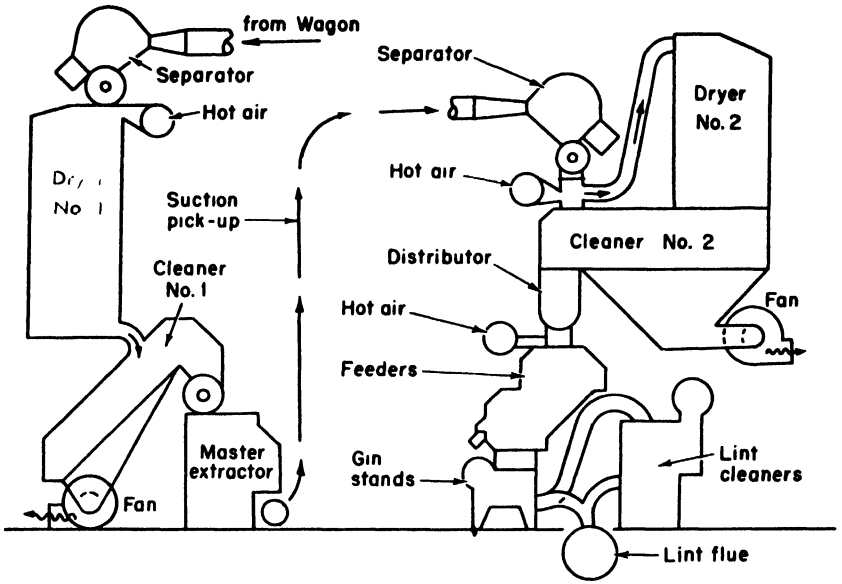


Fig. 4. Elevation diagram of a modern cotton gin with drying, cleaning and extracting equipment on left side of the ginning aisle; and with a conventionally equipped, standard gin for hand-picked cotton on the right hand. The "Annex," or equipment to the left, is usually employed on machine-picked and other roughly harvested cottons.

From previous statements, it will be noted that the combined action of cleaners and extractors, under optimum conditions, takes out about 60 per cent of the foreign matter from the seed cotton. The lint cleaners remove up to about 13 per cent more. There is still room for improved efficiency and simplification in both cleaning and extracting.

There is fairly definite information on moisture removal, but little data on restoration because of the many variables involved. Usually the first drying process can remove approximately 3 per cent of the moisture in the seed cotton, most of it coming from the fiber rather than

from the seed. In succeeding stages of drying, which may be concurrent with cleaning as is indicated in Fig. 4, somewhat less moisture may be removed than in the first stage, but the final result may bring the fiber to 5 per cent moisture content, or less. Static electricity is then likely to appear, with an attendant sequence of troubles. Likewise, too much heat and too many cylinders of cleaning may cause the fibers to become brittle, "neppy," "nappy" and roped. Rapid indicators and controls are now needed to improve the present crude regulation of moisture content to percentages best suited for each succeeding process.

Drying aids the cleaning process, and accordingly the moisture content of damp cottons should be reduced to 10 per cent. Cleaning assists the extracting; extracting enhances the feeding and the ginning; and lint cleaning "pronounces the benediction" on processing, if other steps in processing have been good. With these modern processes, machine-picked cotton may be brought very close in grade to hand-picked cottons, but the gin cannot turn out a bale of machine-picked cotton as quickly as it can gin clean hand-picked cotton; neither can it do it as cheaply, nor with as small amount of machinery and labor.

Preservation of pure seed is possible at the most modern gins, if correct methods of handling and clean-up are employed. Sterilization of seed and incineration of trash can also now be accomplished without causing community nuisances.

4. Summary

The modern cotton gin frequently represents an investment of many thousands of dollars. True progress and improvements are coming through better trade association practices and methods, through more scientific appraisal of the engineering and economic aspects of the business, and through the cooperation of scientists and collaborators in all the elements of the cotton industry, from producer to cotton mill and spinner.

The 7 processes, listed at the beginning of this section, are all working in the modern cotton gin to enhance and preserve the coordinated efforts of the agronomist, geneticist, agricultural engineer, and cotton technologist to produce cottons more acceptable to the trade and cottons of maximum performance. The team-work of those engaged in research on the ginning process is paying large dividends, as mechanized production increases. Improved ginning practices and methods make for better cotton and greater profit and will continue to contribute to the competitive position of cotton as a fiber, food or feed.

VIII. Fiber Properties and Their Significance

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Significant recent advances have been made in this country in developing instruments and applying techniques for measuring the fiber properties of cotton. Some of these advances are so new that their significance is not generally understood. Many workers have made important contributions to these advances. The objects of this brief summary are to outline some of the recent advances and to emphasize their significance to cotton breeders who are striving to develop better cottons, and to others who are interested in more effectively utilizing the various combinations of fiber properties that exist in this remarkable natural fiber.

It has been known for a long time that the spinning performance of cotton depends upon certain fiber properties such as length, strength, structure, and fineness. Within the past few years a great deal more has been learned about each of these properties, and how their interrelationships affect yarn and fiber quality. As modern technology widens the range of raw materials and as improved methods of processing these raw materials into textiles are developed, it is inevitable that the trend will be more and more toward the selection of cotton on the basis of fiber quality. As evidence of this trend, attention is called to the increasing number of fiber laboratories with modern equipment for measuring fiber properties which are being installed by merchants and spinners.

1. Fiber Structure and Development

Basic to a better understanding of fiber properties, their interrelationships, and their significance is the recent work on the origin and nature of cotton fibers and the factors that affect fiber properties.

Each fiber, as reviewed by Anderson and Kerr (1938), is an outgrowth of a single epidermal cell of the cotton seed. This cell first elongates as a thin-walled tubular structure to its maximum length and the fiber wall is then thickened by deposition of cellulose, within, until it matures.

The elongation phase of fiber growth begins on the day the flower opens and pollination takes place. Elongation continues for a period of 13 to 20 days depending on variety and growth conditions. It is slow at first, more rapid for a few days, then slows down near the end of the growth period. The short-fibered varieties generally elongate over a shorter period of time than the long-fibered varieties. Length of the

fiber is influenced also by environmental factors, especially water stress within the plant. A slowing down in the rate of elongation results in the production of short fibers. The thin membrane which encloses the protoplasm is known as the primary wall. It is the outer layer of the mature fiber, and is made up of waxes, pectins, and cellulose.

The thickening phase of fiber-wall growth begins after elongation has ceased. Deposition of the secondary wall in most varieties takes place within a period of 25 to 40 days. It may continue over a longer period for long-staple varieties, as is true for elongation. Cellulose in the secondary wall of the fiber is laid down in a spiral formation. The spirals in the first layer of the secondary thickenings are conspicuous because they lie in a direction opposite to those in succeeding layers (Kerr, 1946). Some details of minute fibrillar structure of this wall are visible through the ordinary microscope (Fig. 5). Examination of a prepared cross section of the matured fiber shows alternating light and dark rings in the inner thickening. According to Anderson and Kerr (1938), each pair of adjacent light and dark rings represents the cellulose deposited during one day's growth. Although variety largely determines characteristics of a secondary-wall structure, environment may modify them considerably. Water stress, for example, which slows down the elongation of the primary wall during the first 13 to 20 days, if continued through the phase of secondary thickening, results in thinner, more dense layers in the secondary wall.

Many workers (Barre *et al.*, 1947; Berkley *et al.*, 1948; Hermans and Weidinger, 1949; Hessler *et al.*, 1948; Nelson and Conrad, 1948) have contributed to providing the answer as to why the cotton fiber has a tensile strength greatly exceeding that of man-made fibers. It has been shown that this is determined by the character of the minute structure of the secondary wall. This structure is determined by the chemical constitution of the fiber and the location of the various components in the different parts of the wall.

Cellulose makes up 88 to 96 per cent of the mature cotton lint and forms the skeletal framework of the fibers of average thickness. The cellulose is composed of many glucose anhydride units arranged in the molecule in a threadlike chain. There are at least 3,000 to 4,000 glucose units in a molecule of cellulose. These straight chains are deposited in the wall parallel to the protoplasmic surface and more or less parallel to each other. The ends of the chains overlap. In many regions of the wall, 50 to 100 chains may be truly parallel to each other. In this case the molecules are held in a fixed position and are kept together by so-called valence bonds. Such groups of parallel chains behave as minute crystals and are called crystallites. Not all chains are truly parallel. When the

distance between the cellulose molecules exceeds the effective distance, the molecular structure is said to be "amorphous." Even a single chain may pass from a region of crystallinity to a region that is amorphous in nature. In a dried cotton fiber, at least 70 per cent of the total cellulose is in the form of the minute crystallites. Groups of crystallites in turn form the fibrils. The long axis of the molecules, the crystallites, and the fibrils coincide.

Sisson (1937), Berkley *et al.* (1948), and others have shown that the properties of the cotton fiber may be profoundly influenced by: (1) the general direction of the chains and crystallites with respect to the fiber axis; (2) the average length of the chains; and (3) the relative percentage of crystalline and amorphous cellulose. While it is not possible to see the molecular chains, the direction of the molecules may be determined accurately by means of x-ray diffraction patterns.

Though the chains themselves cannot be seen, a large number of parallel crystallites form the so-called fibrils that are visible under the microscope. The direction of these fibrils to the fiber axis affects the strength of the fiber. The more nearly they parallel the long axis of the fiber, the stronger is the cotton. The organized crystalline cellulose makes up the more dense parts and its arrangement is associated with the tensile strength of the fiber. The amorphous, or unorganized, parts are less dense and probably account for the flexibility or the efficiency with which the fibers bend and form themselves into position.

The average length of the chains, as they are deposited within the cotton hair, is apparently about 3,000 glucose units. Variations in the average length of cellulose chains resulting from growth conditions have not been shown to affect the fiber properties significantly. When mature cotton is exposed in the field and damaged by the weather, the average length of the chains is usually reduced. The action of ultraviolet light reduces chain length and may affect fiber strength. Microorganisms that frequently develop during field exposure leave many of the chains unaffected, as judged by fluidity tests, but apparently produce localized destruction of a high percentage of the chains with consequent reduction in fiber strength.

2. Fiber Length

The oldest and most widely known property for evaluating cotton fiber is fiber, or "staple," length. Until recently, spinners who wanted yarns of a given strength specified the length of staple that should be used to produce the desired strength.

One of the early methods of measuring fiber length was to sort out the various length groups from a sample and measure them with a rule.

A mechanical device that gives a more nearly accurate measurement is the Suter-Webb duplex sorter, developed by Webb (1932). The fibers are removed from the sorter in order of length and placed in groups differing one-eighth inch in length. Each group of the same length is weighed. On the basis of these data, it is possible to compute the length of the longest 25 per cent of the fibers by weight and also to calculate the average length of the entire sample. Though accurate, the Suter-Webb duplex sorter is slow and tedious and therefore expensive to operate.

A device that measures fiber length more rapidly has now come into general use. This instrument, known as the Fibrograph, was developed by Hertel and Zervigon (1936). It is a photoelectric device for scanning a fiber sample and tracing a length-frequency distribution curve from which fiber lengths are readily obtained. In operation, a small quantity of ginned lint is placed upon one of a pair of combs. Several transfers from comb to comb parallel the fibers. The combed sample then consists of parallel fibers evenly distributed over the length of the two combs, with the fibers caught at random points by the teeth, and extending from the combs. The two combs bearing the fibers are placed in the Fibrograph, and the length distribution curve is traced directly upon a card by manipulation of the instrument. Tangents drawn to the resulting curve give two fiber-length measures: (1) the average length of the longer half of the fiber population, upper half mean, which compares roughly with staple length as judged by commercial classers; and (2) the mean length of all fibers in the sample.

3. Fiber Strength

Though methods for determining fiber strength with considerable precision have been known for several years, most of them have been, until recently, extremely time-consuming. The most laborious of the traditional methods, the breaking of individual fibers, is now used only for specialized research.

The Chandler bundle method, using the pendulum-type Scott tester, was the most widely used procedure for testing fiber strength for many years. In operation, as described by Richardson *et al.* (1937), a bundle of parallel fibers about a millimeter in diameter is wrapped with thread of known size and length so the cross-sectional area can be calculated from measurement of the circumference. The wrapped bundle is placed in the test jaws of the breaker, in which the weight required for breaking is determined. The tensile strength of the sample is calculated as pounds per square inch of cross-sectional area.

A rapid breaking-strength method using the Pressley (1942) strength

tester, an instrument that can be operated much more easily and rapidly, has largely replaced the Chandler bundle method. The Pressley breaker is essentially a lever system activated by a weight rolling down a graduated inclined plane. A parallel tuft of fibers is placed in two jaws lying against each other, and the protruding ends of the fibers are cut off. One of the jaws is held fast and the other is pulled away by the rolling weight on the lever. The weight automatically locks in position when the bundle breaks. A scale indicates the load required to break the sample. The broken tuft is weighed and the strength of the sample is computed in lbs. per milligram of cotton of a given length. The method is reasonably accurate, even though there is inadequate control over the speed at which the breaking load is applied, and the portion of tuft between the two jaws where the break occurs is short.

4. Fiber Fineness

The term "fiber fineness" is well established in cotton literature. Unfortunately it is a loose term even though useful in describing the number of fibers that can be packed into a yarn of a given count. More precisely it depends on two properties: (1) fiber perimeter, which is largely an inherited characteristic; and (2) fiber wall thickness, which is dependent on both genetic and environmental influences.

Cotton technologists in this country have, for many years, expressed fiber fineness in terms of weight per inch as described by Richardson *et al.* (1937). A sorter is used to make a length array. Usually 200 fibers are counted from each length group and weighed. The weights are then used to prorate the various length groups and, finally, a weighted mean for the entire sample is computed and expressed as "micrograms per inch of fiber." This method, though difficult and time-consuming, gives an accurate measure that represents the composite effects of perimeter and cell-wall development.

A much more rapid method for determining a different composite effect of perimeter and cell-wall thickness was developed by Sullivan and Hertel (1940); the instrument is called the Arealometer. It provides a measurement of the surface area of a given mass or volume of fiber. Because it is so much more rapid than the weight per inch method, it or some other air-flow method, such as that developed by Pfeiffenberger (1946) or Elting and Barnes (1948), is now widely used in research and industrial laboratories.

The Arealometer uses an aerodynamic principle governing the flow of gas through a porous medium. The measures that were used up to the fall of 1949 were as follows: in operation, a line sample of 100 mg. is rolled into a plug and compressed in a tube of standard bore until

resistance to air flow is equal to a standard resistance. The amount of compression indicated by the length of the plug is read directly from the instrument. By means of a calibration chart, plug lengths can be converted to the specific surface in square centimeters per milligram. Although the Arealometer is rapid and provides a very useful composite measure of fineness, it, like weight per inch, does not provide information on cell perimeter and cell-wall thickness.

Fiber perimeter varies with different varieties and species of cultivated cottons. At present, no rapid precise method has been worked out for measuring fiber perimeter. Pearson (1950) developed a microscopic technique for obtaining the comparative perimeters of different varieties. In this technique, the fibers are measured in the primary-wall stage and thus the errors and complications associated with attempts to measure mature fibers are avoided. Tufts of young fibers are stained, fanned out on a glass slide and allowed to dry. As there apparently is no readily detectable shrinkage during the drying process, the widths of the collapsed dried fibers as viewed longitudinally are equal to half the fiber perimeter at the position measured.

Kerr (unpublished paper presented at the April, 1949, meeting of the Fiber Society) has devised an indirect method of calculating perimeter from surface area and weight-per-inch data. The weight-per-inch data are recalculated in terms of weight (in micrograms) per centimeter and the reciprocal of this quantity is divided into the Arealometer reading (surface/mg.). In using this method, data from the "Annual Varietal and Environmental Study of Fiber and Spinning Properties" for the crop years 1943, 1944, 1945, and 1946, are compared. Strangely enough, the characteristic perimeter of different varieties was found to be little affected by varying environmental influences.

A newly designed Arealometer has been released to a number of laboratories. Prior to September 20, 1949, results obtained with the Arealometer have been reported in terms of $cm.^2/mg.$ Because of the difference in density among textile fibers, it has been deemed desirable to change the unit in the new instruments so that the same reading will be reported on all fibers having the same geometrical size. The new unit selected is "square millimeters per cubic millimeter."

Since the average density of cellulose is 1.52, and the new calibration data give results that are three per cent higher, a cotton heretofore reported with a specific surface of 2.00 $cm.^2/mg.$ will now read 314 $mm.^2/mm.^3$ in the new units ($2.00 \times 1.03 \times 152 - 2.00 \times 157 = 314$). Results prior to September 20, 1949, must therefore be multiplied by 157 to give results in terms of the new unit which was adopted September 20, 1949. The factor 157 is based on the average of 12 readings for each of 18 cottons

covering a wide range of specific areas, and may be used as an average conversion factor.

Several fiber characters other than those mentioned above are known to exist and may be important in spinning performance but, in general, are not well understood. Luster, drag, convolutions, reversals, and bends are some of the properties that have not been extensively measured and evaluated. For genetic variability in spinning performance, good predictions may now be made from data on fiber length, fiber strength, and surface-area measurements. Measurements of environmentally-induced variations in fiber properties, however, result in less accurate predictions. This is interpreted as evidence that important properties other than length, strength, and fineness may be associated genetically with one of these three properties, but varies independently when modified by environment.

5. Significance of Fiber Properties

The significance of fiber properties in relation to end-use value has been exceedingly difficult to determine. This is due to many causes. One of these is the complexity of fiber-property interrelationships. Another is that, in processing cottons of varying properties, many processing adjustments are required to obtain optimum results. It is difficult, therefore, to ascertain whether an adjustment that was made on the basis of experience in dealing with a given property, such as length, is actually optimum for some other property such as perimeter or cell-wall development. In studying the interrelationships of fiber properties and their significance in long draft spinning, Barker and Pope (1948) presented correlation data on 447 samples.

Multiple-correlation studies established that about 80 per cent of the varietal differences in skein strength may be accounted for by four measured fiber properties obtained from the Fibrograph, Pressley breaker, and Arealometer. For environmental effects, however, only about 55 per cent of the skein strength was accounted for by these 4 properties.

From the standpoint of the practical breeder whose main interest is in genetic differences, R^2 is nearly as high for two properties, upper-half mean length and Pressley index, as it is when all 4 or 5 fiber measurements are evaluated. That Arealometer measurements can usually be dispensed with, in estimating varietal differences in skein strength, is apparently due to the fact that genetic differences in fiber length are rather closely associated with differences in surface area.

For environmentally induced differences in fiber and spinning properties, however, a very different condition exists. In the first place, mean length supersedes upper-half mean length as the important length meas-

urement, and surface-area measurements become of greater importance. The latter cannot be omitted without causing appreciable reduction in R^2 values.

For yarn appearance grades, multiple-correlation coefficients showed that upper-half mean length and surface area differences significantly affect yarn appearance grade.



Fig. 5. Spiral structure of outer layer of secondary thickening. Where the fibrils change direction is referred to as the spiral reversal (photomicrograph). × 850.

IX. Breeding and Improvement

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1. General

The cotton plant bears complete flowers. Cultivated varieties generally are placed in the "usually" self-fertilized category with respect to crossing habit under natural conditions, but the per cent of crossing may vary from less than 5 to approximately 50 (Kime and Tilley, 1947; Simpson, 1948a). The amount at any one location is proportional to the number of wild and domesticated bees which visit the field. Since the cottons of commerce are propagated by seeds, there is more or less of a tendency toward inbreeding, depending on the breeding methods employed, the isolation of increase plots, the precautions taken against mechanical mixtures, and many other factors.

Vavilov (1927) has shown that stable populations of crop plants exist (or existed) in certain limited areas called "centers of origin," that variability in such centers is high, and that variability diminishes toward the periphery of the distribution. There are at present two centers of origin for American cultivated species, one for American Upland, *G. hirsutum,* in Southern Mexico and Central America and one for Sea Island and

related types, *G. barbadense,* in the Andean region of Peru, Ecuador and Colombia. The American species have proved to be remarkably plastic genetically and it has been possible through selection to develop agricultural varieties of a significant range of types, many of which have been widely adapted geographically.

The advances in breeding and improvement in cotton, as presented in this section, will be confined almost entirely to the American cultivated cottons and wherever possible, to American Upland, *G. hirsutum,* which is the predominant cultivated variety in the United States.

2. The Breeding Problem

The observation that cotton varieties or strains often lose in vigor and productivity under a regimen of selfing or close inbreeding, such as that resulting from the progeny-row breeding systems, in vogue soon after the rediscovery of Mendel's papers, has led many farmers and breeders to consider "running out" of strains to be characteristic of cotton. Excluding genetic abnormalities such as balanced lethals, homogeneity is a natural consequence of prolonged inbreeding. The observed fact of reduction in productivity following inbreeding in a given strain is attributable to a number of factors chief among them being: (1) the degree of heterogeneity of the original parent stock; (2) the mathematical probability against accumulating all (or even most) of the favorable genes for yield in one homozygous line; (3) mechanical mixtures and cross pollination with other varieties; and (4) selection for one (or a small number) of characters without regard to other characters which have an important function in the genetic complex. The last factor is of utmost importance and often determines the success or failure of a breeding program.

On theoretical grounds there is no reason to suspect that pure lines of cotton are different in behavior from pure lines of any other crop. The practical consideration of a pure line involves both uniformity and superior performance. Both cannot be sought rapidly and at the same time. Selection for high yield "on a broad genetic base," which is necessary if decreases in production are to be avoided, involves the simultaneous handling of a number of characters over a relatively long period; such a procedure does not lead rapidly to homogeneity. Failure to observe the "broad base" concept and the desire for rapid development of uniformity in one character at the expense of all others has taught many cotton breeders the severe lesson that the probability of obtaining a "uniformly bad" strain is much higher than that of obtaining a "uniformly good" one.

It has been shown that the germ plasm, which constitutes the genetic reservoir, from which present agricultural varieties have arisen, has yielded a number of productive types which are well adapted to their respective geographic areas of growth. Particularly has this been true of American Upland stocks. Reselection within varieties, and even within the progeny of varietal hybrids, over a period of many years, inevitably has resulted in severe inbreeding and the elimination of many beneficial as well as deleterious genes which were present in the native stocks. Since American Upland varieties in the United States are all interrelated and probably descended from not more than a dozen original introductions, it is doubtful that future requirements of special fiber properties, disease, insect and drought resistance, mechanical harvesting, and other specialized uses and properties can be met by the usual selection methods entirely within present cultivated varieties (Richmond, 1947).

Two approaches or combinations of two approaches to further progress and improvement come to mind immediately: (1) development of more precision in the breeding program through refinements in method and design to provide more discriminatory statistical tests, and the establishment of indices which will measure the genetically potential performance rather than the actual end-result behavior; and (2) introduction of new germ plasm into the breeding material. In the first, the goal is to determine the amount of genetic variability in the material and to distinguish this variability from the variability due to environment. In the second approach, genetic variability is increased purposely by the addition of new genes. Genetic variability outside the range of that now present in current agricultural varieties is available from 3 principal sources: (1) obsolete agricultural varieties; (2) primitive stocks in or near the center of origin; and (3) the wild species of the world. In the United States, under a regional project in cotton genetics made possible by the Research and Marketing Act of 1946, the Mississippi Agricultural Experiment Station has the major responsibility for collecting and maintaining stocks from the first source, and the Texas Agricultural Experiment Station is responsible for the stocks from the last two sources.

The importance of genetic variability in the primary breeding material cannot be over-emphasized, for it is axiomatic that the breeder cannot bring out in his selections anything more than is present in the raw stock. Modern breeding methods are designed to preserve and control genetic variability, to guard against serious loss of favorable genes through the restricted selection of only a few superior plants or progenies in any one season. It follows that such methods must keep genetic variability high in relation to environmental variability, particularly in the early stages of the breeding program.

3. Breeding Systems

Less than 20 years ago Cook (1932) advocated renewed emphasis on "type" as the prime consideration in cotton breeding and in the maintenance of seed stocks. Under that "type selection" system, groups of progenies, instead of single progenies, were propagated and maintenance of the stock was carried out by reselection within the groups. Selection and testing of progenies under different conditions "as a means of preserving the adaptive characters of varieties which otherwise may be lost even without being recognized" was recommended. The value of stable mixtures of strains or varieties in providing "greater flexibility of response" was recognized by Hutchinson (1939). In his genetic interpretation of plant breeding problems, Hutchinson (1940) observed the association of rapid degeneration with the more closely bred varieties and recommended that "the effort at present devoted to achieving purity may profitably be used to increase the efficiency of selection."

Hutchinson and Panse (1937) introduced randomization and replication into the progeny-row system of breeding. The system, which has been designated as the "replicated progeny-row method," provides all the information on means of progenies, and means of plants within progenies, obtainable by earlier progeny-row methods and, at the same time, makes possible additional valuable information. In the design employed by Hutchinson and Manning (1943), the progeny of each selected plant was tested in 10 randomized blocks, each plot of which contained 5 plants. Where strains from a number of families were to be tested in one lay-out, "compact family blocks" were arranged within the main experiment to provide more precision in the interfamily comparisons. Not only does the design reduce the environmental contribution to the variance, but it makes possible the partitioning of the total variance into its genetic and environmental components, thus, minimizing "environmental fluctuations while maintaining genetic contrasts." The writers point out that selection on progeny means is as many times more efficient than mass selection in the same material as there are plants per progeny.

To avoid some of the dangers inherent in progeny-row breeding when rigid selection is practiced on relatively few characters, Harland (1943, 1949) inaugurated a breeding system which he terms "mass-pedigree selection." In practice, the system involves: (1) the growing of progeny of a large number of selected plants; (2) determining the mean of each progeny for the characters under consideration; (3) arraying the progeny means for each character and selecting progenies whose means fall on a certain segment of the distribution curve (the segments to be chosen

by the breeder on the basis of the relative importance of one character as compared to the others, and to the original variability of the material, etc.); and finally, (4) massing of all the selected lines to form a bulk planting from which another selection cycle may be started. According to Harland (1949) "continuous selection by this method for any measurable character tends to produce a system of gene frequencies resulting in the manifestation of the character at a higher level through the elimination of alleles, the combinatory effects of which are ordinarily antagonistic to the standards laid down for the character." The "mass-pedigree selection" system makes full use of the principle of progeny testing, and at the same time is designed to preserve genetic variability through the use of a large number of lines and a broad adaptation base by propagating massed lines under varying seasonal and other environmental conditions. Furthermore, the method would preserve certain genes for vigor as heterozygous loci, a condition which, in Harland's view, would give the stock an advantage over strains in which the same genes were homozygous. Used with considerable success in rehabilitating Tanguis cotton, the method is recommended by Harland for wider application and use instead of pure line selection systems. The system is similar in principle to the older "type selection" methods, but recognizes, defines, and measures the component characters of the type, and provides a much more critical progeny test. Actually, the method is not at odds with the progeny-row method as employed by many contemporary plant breeders, in which a number of tested lines of generally similar characteristics are massed at certain stages in the testing procedure, and the seed stock distributed as an agricultural variety. The "mass-pedigree selection" method obviates detailed records of families and lines, while the "replicated progeny-row" method would seem to give a more precise test of the all-important primary selection.

The American Upland cotton-breeding program of the Texas Agricultural Experiment Station largely employs varietal hybrids. Because of the wide range of soil and climatic conditions in Texas, the breeding program must emphasize particularly the conservation and maintenance of genetic variability in progeny tests extending over a number of years. Probably in no other cotton-growing region is the maintenance of a "broad adaptation base" so important. The system involves: (1) selection of single plants in F_2; (2) "duplicate progeny-row" evaluation in F_3; (3) replicated tests of within-family bulks from F_3 to F_{6-8}; and finally, (4) reselection within families followed by massing of seed from similar lines of superior performance.

Breeders have taken renewed interest in the native American Upland cottons of Southern Mexico and Central America as a source of new germ

plasm. Inasmuch as present cultivated varieties were derived from these native stocks, important new economic characters—if found in native cottons, should be relatively easily transferred to cultivated stocks. In 1946, T. R. Richmond and C. W. Manning made a preliminary exploration trip to the area. The next year S. G. Stephens, who was then employed by the Empire Cotton Growing Corporation, explored the area; and in 1948, J. O. Ware and C. W. Manning made a rather extensive survey of a wide area including parts of San Salvador, Guatemala and Mexico. As a result of these recent expeditions, more than 640 stocks have been collected.

The backcross method of breeding is clearly indicated, when the objective is to transfer a character which is conditioned by one simple gene, or a small number of such genes, from one variety or type to another without deleteriously affecting the desirable characters of the latter. Only a small number of plants per progeny is required in each backcross cycle when such characters are available. Unfortunately, in cotton, only a very few such simply inherited and easily distinguished characters have been recognized. The genes controlling resistances to certain cotton diseases are the best examples, but more will doubtless be discovered as the work of "sifting" recent foreign introductions proceeds.

The backcross method has been employed in varietal hybrids in attempts to transfer characters which are inherited according to a quantitative scheme. This approach should not be entirely discouraged, but in its application the low probability of success should be pointed out. Knight (1945) goes so far as to state that the backcross "system is valueless in intraspecific (varietal) crosses because such hybrids, by the first backcross, are normally very similar vegetatively to the backcross parent—(thus)—the hybrid may look like the backcross parent but it still contains a large proportion of the donor genotype and is unlikely to breed true for the various qualitative and quantitative characters desired."

Certain modifications or adaptations of the backcross and the straight hybrid systems, or combinations of systems, may prove useful in American Upland cotton breeding. Richey's (1927) "convergent improvement" method is a case in point. Another method suggested by Sprague (1946) and recommended for use in certain cotton experiments by Richmond (1949) is called "cumulative selection." In this method, lines bearing the character under study, from as many diverse sources as possible or practical, are selected in F_2. After isolating relatively good complexes, but without carrying on selection in each line to its ultimate conclusion (complete uniformity), the selected lines are immediately crossed in all possible combinations and carried to a new F_2 in bulk.

Selection for the character is then practiced again, and the cycle repeated until the level of acceptability is reached.

The greatest range in variability in cotton exists among the wild and cultivated taxonomic species; these are fairly well distributed over the tropical and sub-tropical areas of the world. The two cultivated American species, *G. hirsutum* and *G. barbadense* cross readily and give fertile progeny, as do the two cultivated Asiatic species, *G. arboreum* and *G. herbaceum.* Though, literally, thousands of attempts have been made, there has not as yet been selected from the progeny of a species cross, a strain in which two quantitatively inherited characters have been combined in the full expression of their original parental form. It is extremely difficult, in fact, to find good examples of satisfactory intermediate expressions of quantitative characters. The work of Harland (1936) has shown that stable complexes of interrelated genes are built up within each species. When such species are crossed, the "genetic balance" is disrupted in the F_2 generation giving a maze of abnormal and unbalanced types. Stephens (1950) presents evidence to show "that multiple gene substitution, such as that suggested by Harland, is not sufficient to explain the cytological, genetic and breeding phenomena encountered in critical studies of fertile interspecific hybrids and their progenies in Gossypium." It is stated that "recent evidence from studies of amphidiploids which casts doubt on the validity of 'normal' chromosome pairing and hybrid fertility as indices of structural homology." The structural (cryptic) differences to which Stephens refers are considered to involve much smaller 'pieces' of chromosome than those involved in the gross structural changes which may be recognized cytologically, and which may cause partial or total sterility in the hybrid progeny.

The process of cotton improvement by breeding from species hybrids will unquestionably be of long duration. Future requirements of the cotton industry are likely to be such that they can be met more readily by the introduction of characters outside the range of present cultivated varieties. Not only does it seem important to continue research in those inter-specific hybrids which cross readily, but methods of utilizing the wealth of new germ plasm in the wild species of the world should receive special attention.

Crosses between many of the cotton species with 13 pairs of chromosomes and all of the crosses of 13 by 26 paired species, if successful at all, gave sterile hybrids, until recently. Little more than 10 years ago Beasley (1942) induced fertility in a cross of Arizona Wild (*G. thurberi* Tad. by *G. arboreum*) by doubling the chromosomes of the sterile hybrid by treatment with colchicine. The resulting amphidiploid (n =

26) was partially fertile with American Upland (*G. hirsutum*, n=26) and a high degree of fertility was reached after the first backcross to Upland. A vast new field of cotton improvement was thus opened up, but it is, as yet, only barely explored. When this backcross was made, it was found that fiber strength increased materially over anything previously known in the cultivated Upland cottons. This, of course, was quite unforeseen, as the Asiatic parent was by no means outstanding in respect to fiber strength and the American Wild parent had no spinnable fibers at all. Subsequent studies have shown that the fibers of the new hybrid have narrow cross-sectional areas (narrow perimeters), a character introduced from the apparently worthless wild cotton from Arizona. Hence, in species crosses, the apparent valuable characters available for transfer are probably only a fraction of the important qualities yet to be discovered.

Breeding experiments with the so-called triple hybrid (Asiatic x American Wild (doubled) x American Upland) have been in progress at the Texas and North Carolina Stations from the time of Beasley's first induced amphidiploid. Eventual success in these and other studies involving species hybrids appears to rest on the not altogether vain expectation that a favorable crossover in a given differential segment will occasionally occur. Knight's (1946a) transference of blackarm (bacterial blight) resistance from one species of cotton to another is sufficient to demonstrate the tremendous benefits to be enjoyed when success is finally achieved.

4. Hybrid Vigor in F_1 and Advanced Generations

The substantial increases in yield and improvement in other economic characters obtained in first generation and double crosses in corn, and the almost universal acceptance of hybrid seed as the propagating material for commercial corn production, has led some cotton investigators to re-examine the possibilities of similar methods in cotton. In recent years several experiments, designed primarily to study hybrid vigor, have been undertaken. Three inbred lines from varieties of American Upland cotton and the 6 possible F_1 and F_2 hybrids from the lines were studied by Kime and Tilley (1947) for a period of 3 years. The F_1 seed was produced by hand pollination and the F_2 by selfing. Significantly higher yields were reported, for a 3-year period, for each of the hybrids as compared to its highest yielding parent. The important economic consideration was, however, the finding that by no means did all of the hybrids excel significantly in the single years. Clearly, the significant increases obtained for the 3-year means resulted, in all but one case, from the additive effects of small single-year differences which were nearly always

in favor of the hybrid. Significant increases in the yield of the advanced generation (F_2) over the most productive parent were recorded for only two crosses, and these occurred in only one year.

Simpson (1948a) reported on the heterosis exhibited in the progeny of varieties and strains propagated by open pollinated seed from a production area in which natural cross pollination approximated 50 per cent. The progenies of 7 varieties were tested, seed of which were produced under two conditions, *i.e.*, (1) open pollination (crossed) in a 25 entry variety test, and (2) in isolated blocks (inbred). It was reported that the yields of the 7 progenies from the crossed seed exceeded those of "inbred" seed by 5.7 to 44.2 per cent, or an average of 15.4 per cent. The practical significance of the data lies not so much in the average increase of 15.4 per cent attributed to hybrid vigor, but in a comparison of the "crossed" stocks with the highest yielding agronomic variety. When such comparisons are made, it is seen that significant yield differences in favor of the "crossed" stocks occur in only an occasional instance. Simpson (1948b) also conducted an experiment to measure the amount of heterosis resulting from natural crossing in test plots at several locations in the Cotton Belt.

The great handicap to the practical utilization of hybrid vigor in cotton is the difficulty of producing the hybrid seeds. Two methods have been proposed by Simpson (1948a), both of which require natural crossing by bees. For certain conditions in India, Balasubrahmanyan and Narayanan (1947) have proposed vegetative cuttings as a method of propagating F_1 cotton hybrids on a commercial scale. Probably the most hopeful method now on the horizon is the use of male steriles as "mother" plants. Male-sterile stocks, when interplanted with normal lines in areas of high natural cross-pollination, would yield hybrid material of known composition. The difficulty so far has been the discovery of a suitable male-sterile type. Recently several apparently male-sterile lines have been studied and found to be only partially, or periodically, so.

5. Special Phases

a. Fiber Properties. The development of suitable instruments and methods for testing and predicting fiber and spinning properties, as discussed under VIII, has given great impetus to breeding for improved or special fiber properties.

The data from regional variety studies have pointed to one salient fact; that is, *the variety (genetic constitution) is the single most important consideration in the determination of quality of cotton fibers.* That considerable genetic variability for fiber properties must have been present in certain of the relatively modern varieties of American Upland

cotton is evident by the fact that breeders have made significant improvements in fiber strength and related characters by selection within varieties and varietal hybrids. The value of the wild and primitive cottons of the world as a source of fiber properties which are outside the range of American Upland types already has been emphasized. Strains with fibers 20 to 30 per cent stronger than the better Upland types have been extracted from species hybrids at the Texas Station, and continuing yield trials show that perceptible, though slow, progress is being made in the transference of great fiber strength to acceptable Upland stocks. A wealth of untried fiber characters remains in the base material.

b. Resistance to Disease, Insects, and Unfavorable Environments. The important problems in breeding for resistance to cotton diseases have been referred to under IV, and will not be further discussed here.

Though insects annually take a toll of millions of dollars from the American cotton crop, scientists in this country have given scant attention to the extremely important problem of breeding for insect resistance. Evidence obtained to date from a number of sources supplies a basis for optimism as to the distinct possibilities for cotton improvement which lie in this long neglected field. According to Knight (1946b), who referred to previous reports, "*G. thurberi* appears, at Shambat, to be immune to pink bollworm (*Pectinophora gossypiella*), and *G. armourianum* itself shows very marked pink bollworm-resistance." British cotton investigators have worked extensively on Jassids (*Emposca ficialis*) and have found resistance to be associated with plant pilosity, the more resistant types showing the greatest degree of "hairiness" on the under side of the leaf (Parnell *et al.*, 1949). Dunnam (1936) and Dunnam and Clark (1939) found that, under dry conditions, hairy varieties retained significantly more calcium arsenate dust than glabrous varieties; on undusted cotton, the aphid population increased in direct proportion to the number of hairs on the lower leaf surfaces.

Probably no more remunerative use can be made of the extensive collections of wild and primitive cottons now available to breeders than to subject them and certain of their hybrids to critical study for resistance to major cotton insect pests. The same material should prove useful as a source of new or unfamiliar genes for drought resistance, cold tolerance, high oil and low gossypol content of the seeds, and many other economic characters.

c. Adaptation to Mechanical Harvesting. Harvesting is an expensive cotton production operation. Currently, about 90 per cent is performed by hand. The recent development of machines which will perform this

operation represents a great technological advance in the mechanization of cotton production. As discussed under VI, mechanical cotton harvesters are of two general types: (1) picker; and (2) stripper.

The choice of variety is a very important consideration in planning a mechanized-production program. Fortunately, several of the modern, rapid fruiting, early maturing, American Upland varieties are fairly well adapted to spindle-type picking, particularly when grown under planned systems of spacing and culture. Future work is being directed along two lines: (1) the achievement of more mechanical efficiency in picking, *i.e.*, obtaining a higher per cent of the cotton harvested as compared to the total available open cotton; and (2) obtaining raw cotton which is equal or superior in grade and other lint qualities to that of hand-picked cotton, *i.e.*, freedom from leaf, stem, and bract trash and other foreign matter, and with a minimum of discoloration and staining due to exposure to weather.

The present "type ideal" for spindle picking seems to be a plant (1) that will grow in a more or less upright position but at the same time be early in fruiting habit and fairly determinate in growth habit, (2) that will set its fruit in an evenly spaced manner all over the plant but beginning well off the ground, (3) that will have bolls which will allow the cotton to fluff and at the same time cause it to stick in the burr strongly enough for good storm resistance, (4) that will mature its fruit early and in a very short space of time, and (5) that will shed its leaves readily when the major portion of the bolls have matured. Even a casual consideration of such an "ideal" plant will reveal several physiological and morphological antagonisms. The idea of obtaining early fruiting and at the same time a set of bolls well off the ground, may be mentioned as one.

The "ideal" plant type for stripper-machine harvesting is a dwarf or semi-dwarf, with short to medium fruiting branches, which will fruit rapidly and mature its fruit early and well off the ground. The last allows the lifters of the machine to slip under the lowest branches and engage the cotton without picking up dirt and extraneous plant materials. The seed cotton should be closely held in the boll at maturity as all or most of the bolls on the plant must be mature before the stripper enters the field; but the locks need not fluff. Reference has been made elsewhere in this paper to a mutant boll character in which the seed cotton is closely held in bolls which open only partially. According to Lynn (1949), this stormproof-boll type suggests a complex of modifiers that operate in connection with the main gene to cause varying expressions of the characters. Uniform lines have been extracted which range from the extreme mutant expression to types indistinguishable from the F_1.

The stormproof-boll character has been established in high yielding strains adapted to stripper-type harvesting by workers at the Texas Agricultural Experiment Station's substations at Lubbock and Chillicothe.

Regardless of the type of mechanical harvester employed, any new character, or refinement of existing characters, which would result in less foreign matter in the harvested cotton and ginned lint would be a valuable contribution to the problem of mechanical harvesting. Varieties with many large, spiny plant and leaf hairs give lower grades of ginned lint from machine-picked cotton than those with fewer and shorter hairs. A variety, designated as DELTA SMOOTH LEAF, which is almost free of leaf and stem hairs has been developed by workers at the Mississippi Delta Branch Station. The variety gives significantly higher grades of machine-picked cotton and work is under way at several locations to improve its yield and other agronomic properties, or to transfer the character to other varieties. The prominently-toothed bracts (bracteoles), characteristic of Upland cotton, are known to contribute materially to lint trash. Attempts are being made through breeding to reduce the size of the bracts or to eliminate them entirely. Two sources of breeding material are worthy of mention: (1) the small, almost toothless bracts of some members of the *marie galante* group of Upland cottons; and (2) a deciduous-bract type, first studied at the Mississippi Delta Branch Station, in which the bracteoles fall from the boll at maturity.

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Soil Nitrogen

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I. Introduction

Records of ancient Chinese civilization, as well as early Greek and Roman writings, refer to the use of animal manure as a means of increasing plant growth. The general acceptance of this practice as well as the growing of leguminous green manure crops offers strong evidence that nitrogen has been a deficient element in the cultivated soils of the world since the beginning of agriculture. Since the time of Liebig and Lawes, there has been an increasing awareness of the acute nature of this deficiency in many soils. A better understanding of the problem and the availability of commercial forms of nitrogen has resulted in a rapid increase in the use of nitrogen in fertilizers during the past few decades. The world-wide use of nitrogen fertilizers, which according to Parker (1946) increased from 720,000 tons of nitrogen in 1913 to 2,766,000 tons

in 1937, is also a result of a changing agriculture. An indication of this trend is shown in Pierre's (1949) statement that there has been an increase of over 2 million acres of row crops in Iowa alone since 1941. Such changes have been accompanied by a decrease in legume-grass acreage which has resulted in an accelerated decline in soil fertility and a marked increase in response obtained from additions of nitrogen. The increasing use of hybrid corn, *Zea mays,* L., and improved varieties of other crops has further widened the gap between the soil's nitrogen supplying power and potential crop yield. Recent research in the South has shown that corn responds to much higher levels of nitrogen applications when plant population and fertility level are properly balanced than has been previously recognized. These findings have emphasized the critical deficit in the nitrogen economy of southern soils.

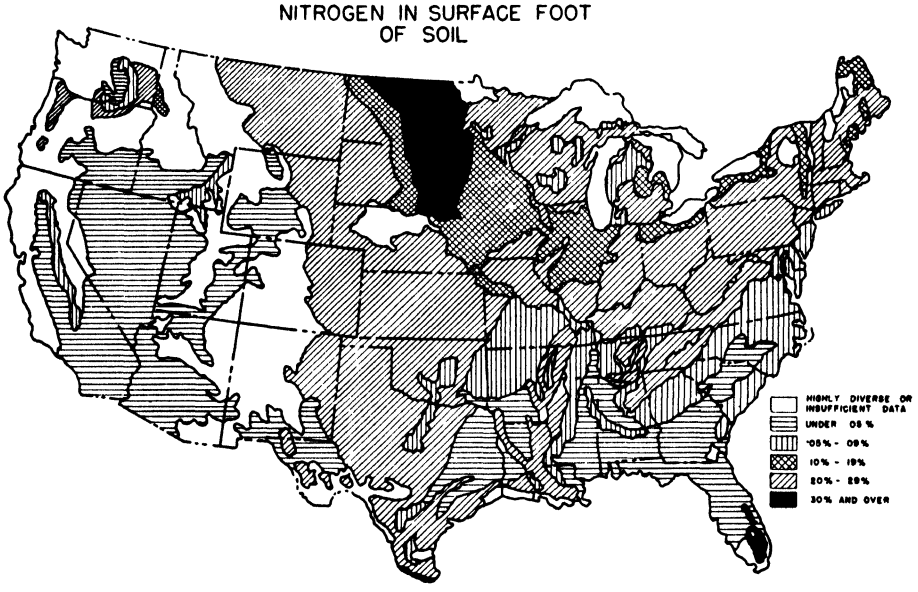


Fig. 1. Soil nitrogen map of the United States. (Mehring, 1945.)

The total nitrogen content of most of the soils of the United States (Fig. 1), exclusive of the Prairie and Chernozem groups, amounts to less than 3,000 lbs. in the surface acre layer. Large areas in the Southeastern and far Western parts of the country contain less than 1,000 lbs. per surface acre. Although present knowledge is inadequate to permit an accurate evaluation of the optimum quantity of soil nitrogen for any specified set of conditions, it is known that less than 4 per cent of the total, depending upon the crop grown and the cultural practices used, generally becomes available for plant use during a season. It is probable that the

amount of soil nitrogen that would have been considered adequate for a particular soil two or three decades ago would no longer be considered sufficient. More nitrogen is necessary now to take advantage of improved crop varieties and better cultural methods. The level at which soil organic matter and nitrogen can be maintained is determined, within limits, by the operator's choice of cropping system and management practices. A sound management program including the judicious selection of crop rotations that include legumes, conservation of crop residues, proper care and utilization of farm manure, and adequate protection against erosion will favor the maintenance of a desirable nitrogen balance and materially decrease the need for additions of nitrogen fertilizer.

II. Factors Affecting Nitrogen Content of Soils

1. Temperate Soils

Under virgin conditions the organic matter and nitrogen content of a soil approaches an equilibrium value the magnitude of which depends primarily upon climate, vegetation, and the physical characteristics of the soil. Jenny (1930) indicated the importance of soil-forming factors in influencing the nitrogen content of medium textured soils in the United States in the following order of decreasing importance: (1) climate, (2) vegetation, (3) topography and parent material, and (4) age. Many soils were originally relatively well supplied with nitrogen, and as a result they produced satisfactory yields during the early years of cultivation. A new set of conditions are established, however, when soils are brought into cultivation, resulting almost invariably in a much lower organic matter and nitrogen level. The decline is a gradual process, being most rapid during the first few years of cultivation. These changes are illustrated by the data presented in Fig. 2. These data from Myers *et al.* (1943) indicate that the equilibrium of soil nitrogen under cultivated conditions occurs at much lower levels but in the same order as in the virgin state.

The great importance of climatic factors in determining the soil organic matter and nitrogen level has been shown by Jenny (1930) who found for grassland soils an inverse relationship between the latter and the mean annual temperature. His data show that in the U. S. soil nitrogen decreases from North to South and that for each fall of 10°C. in mean annual temperature the average nitrogen content increases two- or three-fold. Jenny further found that grassland soils along an annual isotherm increased in nitrogen content with increasing rainfall and humidity. These data emphasize the difference between the operating levels

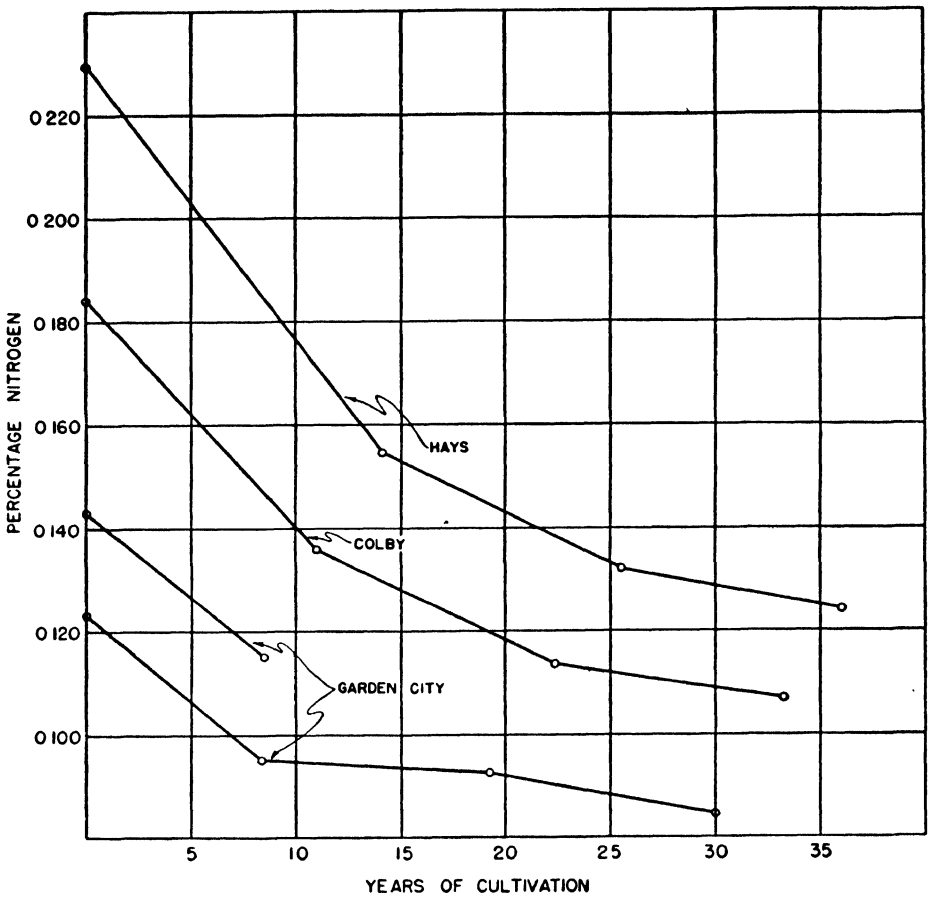


Fig. 2. Effect of cultivation on soil nitrogen content at Hays, Colby, and Garden City, Kansas. (Myers *et al.*, 1943.)

of nitrogen that are practical of attainment in soils of the Northern and those of the Southern part of the United States.

A direct relationship between precipitation and the nitrogen content of Washington soils was reported by Sievers and Holtz (1923). Soils receiving about 8 inches of rainfall annually were found to contain only about 25 per cent as much nitrogen in the surface 6 inches as soils receiving 20 inches per year. This general relationship was confirmed by Fowler and Wheeting (1941), whose data further showed that the increase in organic matter and nitrogen is accompanied by a widening C:N ratio.

Russell and McRuer (1927) examined a series of homogenous types and found the nitrogen to vary with topography as well as with rainfall. The nitrogen content increased with increasing rainfall and, under the same precipitation, level types contained more nitrogen than rolling types. Russell (1927) reported work done on Minnesota, Kansas, and Nebraska

soils showing a close correlation between nitrogen and texture, the finer textured soils being highest in nitrogen. It is generally recognized that it is more difficult to build up or maintain the nitrogen content of coarse textured soils than it is to build up or maintain nitrogen in fine textured soils.

2. Tropical Soils

On the basis of the data presented by Jenny (1930) for the United States, the soils of the tropics should be very low in organic matter and nitrogen. Jenny, Bingham, and Padilla-Saravia (1948) showed that the nitrogen and organic matter contents of the equatorial soils of Colombia, South America, are related to climate. The nitrogen-climate surface of the Colombian soils was found to be very similar in shape to the nitrogen-climate surface for soils of the Great Plains area. A comparison, however, of the Colombian and North American soils with equal annual temperature and moisture values shows the Colombian soils to be much higher in nitrogen and organic matter than the North American soils. They point out that many of the light colored soils from the hot and humid areas are much higher in nitrogen and organic matter than their color indicates.

Dean (1930) found that in an unselected group of Hawaiian soils the mean nitrogen content of the 223 samples examined was 0.31 per cent. The author concluded that the nitrogen content of Hawaiian soils did not agree with the data presented by Jenny for the United States and that to agree the average nitrogen content should be less than 0.1 per cent. In discussing the soils of Cuba, Bennett and Allison (1928) state that the supply of organic matter is higher in well-drained tropical soils than is generally supposed by numerous writers who have assumed that with good porosity and aeration organic matter in tropical soils is soon dissipated. Jenny, Gessel, and Bingham (1950) found that Colombian and Costa Rican soils were rich in nitrogen and organic matter as compared with Californian soils of the Sierra Nevada mountains.

It appears evident that some tropical soils are higher in nitrogen and organic matter than expected on the basis of available data for the soils of North America. On the other hand, a few investigators have emphasized the low nitrogen and organic matter content of certain tropical soils. Mohr (1944) states that in the low, hilly lands of the tropics conditions are optimum for mineralization of plant residues, and, as a result, little organic matter can remain either in the original or transformed state. He points out, however, that at elevations above 1000 meters, with good moisture and aeration, the humus content increases with elevation. He suggested the predominance of molds over bacteria in the soil at the

higher elevations as the reason for greater accumulations of organic matter. Corbet (1935) also emphasized the low nitrogen content of tropical soils in the Dutch East Indies.

There is little information in the literature as to why some tropical soils are abnormally high in nitrogen and humus. It has been suggested by some writers that the tropics are high in humus because of the large amount of vegetative growth produced. Data by Jenny *et al.* (1950) show that tropical forests dropped 8,000 to 11,000 lbs. of leaves and twigs per acre per year, whereas forests of the Nevada Sierra mountains of California produced only 800 to 3,000 lbs. It has also been suggested that organic matter accumulates in tropical soils because of an inactive microbial population. Jenny *et al.* (1950) have calculated the rate of decomposition of forest floors in Colombia to be higher than in California. They also found that alfalfa leaves placed in natural soils decomposed faster in tropical soils than in temperate soils. These findings would lead one to expect low contents of nitrogen and organic matter in tropical soils even though litter fall is large. Jenny (1950) has attempted to bring these two conflicting observations into harmony. His data show that the decomposition of the forest floor, which rests on the mineral soils, proceeds rapidly and that observations indicate a considerable portion of the decomposition products infiltrate into the mineral soil. The rate of decomposition of the infiltrated products appears to be slow and as a result humus accumulates rapidly to a high level. Jenny suggested favorable climatic conditions and high annual rate of nitrogen fixation, largely by leguminous trees, as primary causes of luxuriant growth.

It is difficult to understand why the infiltrated products decompose so slowly. Kelley (1915) has emphasized the inert nature of the uncultivated soils of Hawaii and has suggested the lack of aeration as one of the causes. An examination of British Guiana sugar-cane soils by Hardy and Hewitt (1948) revealed a low nitrifying capacity in these soils. The authors attributed the low nitrifying capacity to absence of proper nitrifying organisms. They were not certain that the absence of nitrosomonas and nitrobacter was the only reason for the low nitrifying capacity since they did not determine the effect of inoculation. They also suggested a shortage of available phosphate as a partial cause of the low nitrifying capacity. It is apparent that organic matter of tropical soils, especially the portion mixed with the mineral soils, decomposes more slowly than one would expect on the basis of climatic conditions. It is evident, therefore, that for some reason soil conditions are unfavorable for active microbial decomposition. It is generally known that many tropical soils are deficient in certain mineral elements such as phosphorus. The avail-

able phosphorus content of these soils may be too low to support an active microbial population.

III. Nature of Organic Nitrogen in the Soil

Although organic matter is a very important part of the soil, little is known about the chemistry of this material. Such information is needed in order to evaluate properly the role of organic matter in soil fertility. The C:N ratio is often used as a means of characterizing organic matter, but we do not know why soils of one area may have a different ratio than soils of another area. Many of the methods of approach have been empirical in nature and as a result have added little to our basic knowledge of soil organic matter.

As plant residues decompose a considerable quantity of microbial cell substance is formed. According to Norman (1942), one-third to one-half of the organic fraction of the soil may be microbially derived if decomposition takes place under aerobic conditions. During the process of decomposition, the more resistant constituents of plant residues accumulate along with microbial substances. It is now generally believed that lignin or lignin-derived material makes up a substantial part of the organic fraction of soils. Gottlieb and Hendricks (1945) have presented evidence to show that plant lignin in the soil is altered considerably by decomposition. Their studies on the hydrogenation of "alkali lignin" indicate that lignin in the soil undergoes a similar type of change as does lignin treated with alkali, but at a much slower rate.

Soil organic matter also contains nitrogenous complexes that are important from the standpoint of fertility. The biological resistance of organic soil nitrogen is indicated by the fact that less than 4 per cent becomes available in any one season. Soil nitrogen is usually considered to be proteinaceous in character, but for some reason it is much less available than the nitrogen in ordinary proteins. Waksman and Iyer (1933) have presented data to support their theory that the availability of the soil protein is reduced through combination with lignin. If protein nitrogen is stabilized by association with lignin this phenomenon may furnish a partial explanation for the lack of build-up of soil nitrogen following continued use of green manure crops.

Another explanation of the unavailability of organic nitrogen has been put forward by Ensminger and Gieseking (1942). They demonstrated that mixtures of proteins with certain clays are more resistant to hydrolysis by proteolytic enzymes than proteins alone. Previous work by them (1939) had shown that proteins are adsorbed within the "001" lattice spacing of montmorillonitic clays. The adsorption of proteins was found to increase with increasing pH, which indicates that the pro-

teins react as bases. Unpublished data by Ensminger show that the addition of montmorillonitic clays to proteins and to Florida peat was effective in rendering these materials less susceptible to microbial decomposition under laboratory conditions as measured by the rate of CO_2 evolution or by the quantity of nitrates formed. Recent work by Allison *et al.* (1949) show that the nature and amount of colloid present in sand-colloid mixtures in which organic materials are decomposing is an important factor in determining the quantity of residual carbon after a year of decomposition. The effect of the colloid was marked where readily decomposable materials were added, but there was no effect where peat, sawdust and cellulose were used. Montmorillonite exerted the greatest effect in holding carbon and kaolin exerted the least. Carrington colloid, which is mainly a mixture of montmorillonite and hydrous mica, gave an intermediate effect. In some cases the addition of 10 per cent bentonite to sand nearly doubled the quantity of residual carbon. It is interesting to note in this regard that work by Goring and Bartholomew (1949) shows bentonite to be effective in decreasing the rate of mineralization of organic phosphorus. They also found the effect of kaolinite to be less marked. As previously stated it is a common observation that it is easier to build up or maintain organic matter in a heavy soil than it is in a sandy soil. On the basis of present knowledge it is not possible to determine if this is due wholly or in part to the protective action of the clay in heavy soils. Poor aeration in heavy textured soils is often given as the reason why they hold more carbon than sandy soils. Allison *et al.* (1950) believe this explanation to be inadequate and point out that, where water logging is not a problem, the oxygen supply in both sand and clay soils is sufficient for rapid and complete aerobic decomposition of plant materials. Even so, evidence presented by Myers (1937), Tyulin (1938), Springer (1940) and others further emphasizes the probable interaction between inorganic and organic colloids in the soil. Springer (1940) believes that the chernozems contain rather stable inorganic-organic complexes. A new field of research is opening up as a result of these studies and basic information about these complexes may add much to our knowledge of the nitrogen economy of soils.

It appears that soil organic matter is not only a mixture of organic constituents ranging from unchanged plant residues to that component designated as humus, but is also so closely united with the inorganic fraction as to be changed in properties as a result of the union. Although environmental conditions affect the nature of soil organic matter, the organic matter of different soils is similar in certain respects. The question is often asked as to what influence cropping systems have on the nature of soil organic matter. This question can not be fully answered

until better methods have been developed for characterizing the organic fraction. It is interesting to note in this connection that Peevy and Norman (1948) conclude from their studies that alkaline hypoiodite may be useful in detecting differences in the nature of soil organic matter.

IV. Nitrogen Transformations

During the course of a year there is a considerable intake and outgo of nitrogen in most soils including a number of complex reactions. These reactions, which are collectively termed the "nitrogen cycle," are largely biological, and closely parallel a similar series of reactions of the organic carbon. Although the nitrogen cycle has been studied intensively for many years and is understood in general, our knowledge of it is still seriously lacking in certain respects. Nitrogen occurs in soils principally in organic complexes of microbial origin. The original source of this combined nitrogen was the elemental nitrogen in the earth's atmosphere which has been tapped through fixation, by lightning discharge, and by certain groups of microorganisms. The micro and macroflora debris which is returned to the soil is the material from which the reserve soil nitrogen supply is derived.

1. Nitrification

As organic residues decompose, there is a narrowing of the C:N ratio until an equilibrium ratio of about 12:1 is reached. During the process of decomposition, the nitrogen in the residues becomes less and less available. Broadbent and Norman (1946) working with the stable isotope of nitrogen, N^{15}, found that the addition of energy supplying material increased the rate of release of nitrogen from the soil organic matter. They state that the unavailability of organic soil nitrogen may be due to the lack of enough energy material to support an active microbial population rather than to the formation of resistant complexes. If the availability of organic soil nitrogen is increased by the addition of such energy materials as plant residues, it is obvious that the carbon in soil organic matter should also be more readily utilized by the microorganisms.

Nitrogen availability is known to be strongly influenced by the decomposition of plant residues in the soil. Parberry and Swaby (1942) studied the release of nitrogen from different organic materials added to soils and found that sufficient nitrogen for crop needs was liberated in one season only from materials containing an initial nitrogen content of greater than 2.5 per cent. No nitrogen was liberated in this period from materials having less than 1.5 per cent nitrogen. Waksman and Tenney (1927) found that 1.7 per cent nitrogen was adequate for microbial needs.

Bledsoe (1937) studied a number of weeds common to Florida in relation to the rate of nitrification, and concluded that the water-soluble nitrogen content appeared to be the most important factor involved in the nitrification of green and dried plants, followed by total nitrogen and degree of hydration or moisture. His data show that if the water-soluble nitrogen content is 0.5 per cent or above, favorable nitrate accumulation occurs, even though the total nitrogen content is less than 1.7 per cent. Whiting (1926) also found that the water-soluble nitrogen content of materials determined to a large extent the rate of nitrification and that there was usually a direct relationship between water-soluble nitrogen and total nitrogen. On the basis of these investigations it is improbable that many materials with a nitrogen content of less than 1.5 per cent would give a positive release of nitrogen in one season. This means that only legumes and certain nonlegumes in the early stages of growth will give a positive release of nitrogen. On the other hand a quick release may be expected from materials with a nitrogen content of more than about 2.5 per cent.

When soil organic matter decomposes, ammonia is liberated and under favorable soil conditions it is converted to nitrate. Nitrification has long been considered to be a biological process, but in recent years Dhar (1933) and others working in India have contended that the process is photochemical, especially in the tropics. Waksman and Madhok (1937) investigated the effect of light and heat on nitrate formation in soils and concluded that biological oxidation must still be considered as the important process in nitrate formation. Fraps and Sterges (1935) repeated some of the experiments of Dhar and concluded that photonitrification was of little or no importance in normal soils.

The total soil organic nitrogen has been regarded as an important factor in determining the amount of available nitrogen that a soil will supply. Work by Waksman (1923), Burgess (1918), Brown (1916), Gowda (1924), Gainey (1936), Fraps (1920, 1921), and Fraps and Sterges (1947) has shown that usually the more fertile soils produce the greatest amounts of nitrate, but they also found many exceptions. Gainey (1936) and Allison and Sterling (1949) found that nitrate formation was directly related to total soil nitrogen. There are a number of other factors, however, that affect the production of nitrates in field soils. One factor is soil treatment, such as the addition of limestone, phosphorus, and potassium. A second factor is tillage operations, such as plowing, cultivation, fallowing, and mulching. Third, such climatic conditions as temperature and moisture are very important.

Sewell and Gainey (1932) and Call (1914) have shown that in Kansas July plowing for wheat, *Triticum vulgare*, has produced approximately

10 bushels per acre more than September plowing. They found that the acre yield of wheat was proportional to the nitrates present at seeding time. Beneficial effects of fallowing in arid regions appears to be due to an increase in nitrates as well as to an increase in moisture. Buckman (1910) working with Montana soils having an annual rainfall of 12 to 17 inches concluded that an increase in moisture meant an increase in nitrates if other factors were favorable. Harper (1945) stated that available nitrogen in the Southern Great Plains area may be low at the time of planting fall crops because of dry weather and unfavorable conditions for tillage during summer months. Smith and Vandecaveye (1946), in a study of the productivity of Palouse silt loam, reported that nitrogen was the principal factor affecting crop yields under a continuous wheat system, but nitrogen was not a factor under a wheat-fallow system. Moisture was also an important factor, since continuous wheat plus nitrogen fertilizers did not yield as high as wheat-fallow plus nitrogen.

It is a generally accepted fact that the greatest accumulation of nitrates takes place during the summer months and the least during winter months. Usually nitrates increase from winter to summer and decrease from summer to winter. These seasonal variations in nitrates are closely associated with such climatic factors as moisture and temperature. Part of the increase from winter to summer may be due to the rather intensive period of cultivation in spring and summer. Lyon and Bizzell (1913) presented evidence to show that freezing and thawing increases the subsequent formation of nitrates.

It is apparent that the rate of nitrification in soils containing a reserve of organic nitrogen can be increased by various treatments and cultural practices. At the same time it is evident that nitrification can occur only at the expense of the total soil nitrogen supply and, therefore, cannot be maintained at a high level unless the reserve supply of nitrogen is maintained or increased.

2. Symbiotic Nitrogen Fixation

Nitrogen fixation has been and will continue to be one of the most important factors in the nitrogen balance of soils. The importance of nitrogen fixation is indicated in the report on the balance sheet of plant nutrients in the United States by Lipman and Conybeare (1936). For the year of 1930, they estimate that of the 16,253,862 short tons of nitrogen added to the agricultural soils of the United States, 9,830,736 tons were added as a result of biological nitrogen fixation. The quantity of nitrogen fixed can be increased considerably by making conditions

more favorable for biological fixation and by increasing the acreage of legumes.

Rhizobia in the nodules of living leguminous plants fix nitrogen. How much nitrogen will be fixed by legume bacteria depends on a number of factors. Such soil conditions as aeration, available nitrogen, moisture, and the amount of active calcium are very important. Also, some strains of the various species of Rhizobium are not effective in fixing nitrogen. This indicates the importance of inoculating with commercial cultures of known effectiveness. Certain legumes fix much more nitrogen than others. The nitrogen content of most inoculated legumes does not vary too widely, so it follows that the quantity of nitrogen fixed is more or less proportional to the total growth of the legume. The amount of vegetative growth obtained will vary with the legume used and of course the growth of any particular legume will depend upon the fertility of the soil.

Bracken and Larson (1947) calculated the nitrogen increase from alfalfa on 20 farms in Cache Valley, Utah. The 20 farms showed an average fixation of 246 lbs. per acre per year. These workers based their calculations on the nitrogen in the hay plus that accumulated in the soil. This means that some of the 246 lbs. of nitrogen resulted from nonsymbiotic fixation. In a 10-year experiment at Ithaca, New York, Lyon and Bizzell (1934) found that continuous alfalfa gave an apparent fixation of 268 lbs. of nitrogen per acre per year. With barley, rye, or oats, annual nonsymbiotic fixation amounted to 17 lbs. Assuming that erosion, leaching, and volatilization losses were the same for the two cropping systems this would leave 251 lbs. acquired symbiotically. Duggar (1899) found that the air dry weight of vines, roots, and stubble of hairy vetch, *Vicia villosa*, Roth, cut April 19 was 3,967 lbs. per acre and contained 137 lbs. of nitrogen. Vetch cut May 9 weighed 6,870 lbs. and contained 202.8 lbs. of nitrogen. Although these figures do not show the amount of nitrogen fixed by vetch since part of the nitrogen was taken from the soil, they do indicate that fixation increases as the plants get older. Lipman and Conybeare (1936) estimated that legumes fixed an average of 87.6 lbs. of nitrogen per acre per year. Gustafson (1948) states that 80 lbs. is a conservative estimate of the average annual fixation of nitrogen by legumes. These are average figures for all legumes under a variety of conditions and are lower than may be expected for certain legumes under favorable conditions. It is evident then that an increase in legume acreage will go a long way in providing the extra nitrogen needed to maintain high yields. Also, an increase in the acreage of legumes would help to prevent excessive losses of soil nitrogen by

erosion and leaching as well as increase the addition of nitrogen to the soil.

3. Nonsymbiotic Nitrogen Fixation

Certain organisms living in the soil obtain nitrogen from the air and use soil organic matter as a source of energy. Since these organisms are not directly associated with higher plants, the transformation of elemental nitrogen to a fixed form is known as nonsymbiotic fixation. The amount of nitrogen fixed by this process depends on such factors as the supply of readily available energy material, supply of available nitrogen, and pH. Soils high in available nitrogen probably fix little or no nitrogen in this manner. The Azotobacter group of bacteria, which is largely responsible for free fixation, is very sensitive to pH. Work by Gainey (1948) shows that pH 6.0 or above is favorable. An available supply of mineral nutrients, especially calcium and phosphorus, favors vigorous fixation.

The data on the quantity of nitrogen fixed nonsymbiotically are rather meager. Lyon and Wilson (1928) report that land kept in grass for 10 years without nitrogen additions gained 415 lbs. of nitrogen. Probably about 6 lbs. was added by rainwater, but the loss by drainage and volatilization was probably greater than the addition in rain. It would appear that the annual gain of 41.5 lbs. of nitrogen would be a conservative figure ascribed to fixation under the conditions of this experiment. Lyon and Buckman (1947) state that at least 25 lbs. of nitrogen is fixed nonsymbiotically in a representative arable soil. It should be pointed out, however, that conditions in many soils are not favorable for this type of fixation. Lipman and Conybeare (1936) reported 6 lbs. per acre per year as the average quantity of nitrogen fixed nonsymbiotically. Although the amount may not be large, it is an important source of soil nitrogen and in any sound soil management program consideration should be given to making conditions as near optimum as possible for this type of fixation.

A comprehensive review of the literature on inoculation of crops by Allison (1947) reveals that Russian workers have reported rather large yield increases from the inoculation of soils with Azotobacter species. Allison *et al.* (1947) studied the effect under greenhouse conditions of inoculating two soils with Azotobacter and "Azotogen." They found no significant effect of inoculation on the growth or nitrogen content of such crops as barley, *Hordenum* sp., Sudangrass, *Sorghum vulgare sudanese,* kale, *Brassica oleracea acephala,* rape, *Brassica* sp., rye, *Secale cereale,* and Swiss chard, *Beta cicla.* Work by Gainey (1949) showed no evi-

dence that the maintenance of Azotobacter in a soil for 20 years had any effect on crop growth or the nitrogen balance of the soil.

V. Effect of Cropping Practices on Nitrogen Level

Under natural conditions there exists an equilibrium between the addition of organic matter by vegetation and its decomposition by microorganisms. As shown previously, the equilibrium level of nitrogen is determined largely by climatic conditions. Cultivation of soils usually results in a decrease in nitrogen content from that in the virgin state by speeding up microbial decomposition and by subjecting the land to greater losses of nitrogen by erosion and leaching.

Numerous studies have been made of the effect of cropping on both rate of decline and final nitrogen content of soils in the wheat-growing regions. Shutt (1910) found that a soil of Indian Head, Saskatchewan, had lost almost one-third of its nitrogen after nearly a quarter of a century of cultivation. Crop removal accounted for 700 lbs. of the loss, leaving unaccounted 1,486 lbs. For Minnesota conditions Snyder (1905) calculated that, out of 7,700 lbs. at the beginning of the experiment, continuous wheat plots had lost 2,039 lbs. of nitrogen per acre foot in 12 years. The crops removed 450 lbs., indicating a loss of about 1,600 lbs. by other means. A rotation consisting of wheat, clover, wheat, oats, and corn with a dressing of farm manure every 5 years showed a loss of nitrogen of about 18 per cent. Harper (1945) reported that 11 Oklahoma Panhandle soils had lost 14.8 per cent of their nitrogen after 15 years of cropping. Brown *et al.* (1942) reported that in Alberta the largest loss of nitrogen occurred with soils originally high in nitrogen. The nitrogen content of the surface 6 inches was 17 to 22 per cent lower after 30 years of cultivation. It appears that these soils lose approximately one per cent of their nitrogen for every year of cultivation. Dodge and Jones (1948) studied the effect of long-time fertility treatments on nitrogen and carbon content of plots at Manhattan, Kansas, and concluded that the fertilizer treatments and cropping systems had only a slight influence on the trend of nitrogen or carbon, but may have an influence on the speed at which equilibrium is reached as well as the ultimate level. This conclusion is supported by the data of Myers *et al.* (1943) for western Kansas, who show that soils cropped to continuous small grain and alternate small grain and fallow tend to reach an equilibrium state quicker and at a higher nitrogen level than do systems that include row crops. The soils at Hays, Colby and Garden City were approaching a state of equilibrium with respect to nitrogen after 30 to 35 years of cultivation (Fig. 2). The approaching equilibrium level was highest at Hays and was lowest at Garden City.

Bracken and Greaves (1941) surveyed the nitrogen losses on farms in two areas of Utah. A study of 9 dry farms in Cache Valley, northern Utah, showed the first foot of virgin land to be 15.9 per cent higher in nitrogen than adjacent wheat land. Twelve farms in Juab Valley, central Utah, were found to be 14.5 per cent lower in nitrogen than virgin soils. They considered the equilibrium levels of Cache Valley and Juab Valley soils to be approximately 0.17 and 0.09 per cent nitrogen, respectively. Severely eroded areas had lost 58.5 per cent of their nitrogen.

Salter and Green (1933) attempted to estimate to what extent various crops have increased or decreased the organic carbon and nitrogen content of soils. They give the following yearly changes in percentage of the total nitrogen present in the soil: corn, −2.97; wheat, −1.56; oats, −1.45; legume-grass hay in a 5-year rotation (predominantly timothy), +2.87. It is evident from these data that rotations containing hay crops, especially legumes, tend to conserve soil nitrogen. White *et al.* (1945) reported that, at the end of 72 years, unfertilized grassland soils had a nitrogen content 68.2 per cent above an unfertilized plot in a 4-year grain rotation, and 40.0 per cent higher than a PK treated plot in the same rotation. These data show that phosphorus and potassium are important in conserving soil nitrogen.

Jenny (1933) investigated the effect of cropping on decline of soil nitrogen in the Middle West. Reduction in soil nitrogen was greater in the earlier years of cultivation, as shown by the following: first 20 years, −25 per cent; second 20 years, −10 per cent; and third 20 years, −7 per cent. Data by Myers *et al.* (1943) show the nitrogen trend of dry land soils to be of the same pattern as is characteristic for the more humid soils of the Middle West. The fact that soils under clean cultivation tend to approach a new nitrogen equilibrium at which point a finite value is maintained points toward nonsymbiotic nitrogen fixation as a contributing factor.

Some of the plots of the Rothamsted Experiment Station in England have been in continuous wheat for more than a century except for fallow every fifth year since 1925. Crowther (1947) gives a summary of the nitrogen changes for the period 1865 to 1945. He concluded that the unmanured plots had reached a substantial equilibrium within the first 20 years. The plots receiving farmyard manure increased annually in nitrogen content for the first 40 years and then leveled off. In 1945 plots that had received farmyard manure annually since 1843 were over twice as high in nitrogen as the untreated plots.

In the Southeast much of the land has been in cultivation for a long period, and humidity and temperature have been favorable for decomposition. As a result of these conditions, many of the soils have attained

a cultivated state of equilibrium with respect to organic matter and nitrogen. Cropping systems that include winter or summer legumes, or both, will usually provide a satisfactory turnover of nitrogen and the total may actually be increased by such systems. Tidmore and Volk (1945) found an increase in soil nitrogen amounting to 30 per cent over a 9-year period by turning under soybeans, *Glycine soja*, every other year. Work by Moser (1942) showed the average organic matter content of the Piedmont section of South Carolina to be about one per cent. It was found, however, that the organic matter level could be raised to 1.5 per cent by using lespedeza, vetch and crimson clover, *Trifolium incarnatum*, in the cropping system. Lespedeza grown continuously raised the organic matter content to 2.7 per cent, indicating that amounts as high as 2.7 per cent would be difficult to maintain under practical farming operations. The results of Holley *et al.* (1948) in Georgia show a slight upward trend in soil nitrogen for rotations with and without legumes. Apparently the commercial nitrogen applied to the crops in the no-legume rotation was sufficient to maintain as much soil nitrogen as the use of legumes. Jones (1942) concluded from a study of various systems of green manure crop management using lysimeters that the nitrogen content of the soils was maintained at a constant level for 4 years when 225 lbs. of sodium nitrate was used. There was a net gain in nitrogen when summer legumes were turned under, but the net gain was highest when vetch was grown as a source of nitrogen.

The decline of soil nitrogen under cultivation is due to several causes. One of the most easily measured losses of soil nitrogen is that by crop removal. The magnitude of this loss will vary with the crop as well as with the yield. Russell (1927) believes some gaseous nitrogen product is formed as a result of cultivation. He referred to one of the Broadbalk wheat plots that received 14 tons of farmyard manure annually, containing 200 lbs. of nitrogen. This plot lost nitrogen amounting to 70 per cent of the quantity added. The no-manure plot alongside, in spite of leaching, showed no apparent loss of nitrogen. The work of Shutt in Saskatchewan (1910), Snyder in Minnesota (1905), and Swanson and Latshaw in Kansas (1919) showed that much of the nitrogen lost by cultivation could not be accounted for by crop removal. In attempting to account for nitrogen losses from dry-land soils in Utah by means other than crop removal, Bracken and Greaves (1941) believed that slight losses occurred through leaching and erosion. They thought that the major loss was due perhaps to chemical and biological changes resulting in volatilization. Lysimeter investigations by Collison *et al.* (1933) showed an unaccounted loss of nitrogen amounting to as much as 118 lbs. per acre per year. The authors conclude that such losses must

be due to volatilization. In the greenhouse at high nitrogen levels, Pinck *et al.* (1945) observed a nitrogen loss amounting to 14 per cent of that added. They suggested that much of the loss may have been due to metabolic processes occurring within the plant.

All studies do not indicate such a high loss of unaccounted for nitrogen. Lysimeter studies by Smith (1944) in Arizona showed that a Mohave clay, which had been double cropped to wheat and hegari, *Sorghum vulgare,* for 12 years increased in nitrogen from 0.052 per cent to 0.067 per cent. A Gila clay under the same conditions showed a decrease in nitrogen from 0.085 per cent to 0.063 per cent. Except for one year all crops were removed from the tanks. All plots had a positive nitrogen balance when crop removal was considered.

The unaccounted-for-loss of nitrogen under field conditions just mentioned may have been high, since losses by leaching and erosion were not known but assumed to be unimportant. These losses, especially by erosion, may have been greater than assumed. Even though only a small amount of runoff occurred, it is possible that considerable nitrogen was lost. Martin (1941), working with Collington sandy loam in New Jersey, showed that the eroded material contained from 3 to 8 times as much organic matter and nitrogen as the soil itself. Rogers (1941) also reported a higher nitrogen content of eroded material than of original soil. The greater concentration of organic matter and nitrogen in the eroded material may be due in part to the floating off of pieces of organic matter not thoroughly incorporated with the inorganic fraction of the soil. Eroded material is usually higher in clay than the parent soil, and Kardos and Bowlsby (1941) showed the percentage of organic matter to be higher and the C:N ratio to be lower in the clay fraction than in the whole soil.

Some of the earliest work dealing with losses of plant nutrients under various cropping systems as a result of sheet erosion was reported by Miller and Krusekopf (1932). Their data show that such cropping systems as continuous corn, continuous wheat, and corn-wheat-clover rotations lost respectively 66, 32, and 26 lbs. of nitrogen per acre annually. A plot in the same experiment plowed 4 inches deep and kept fallow lost 118 lbs. as compared with a loss of 0.6 lb. of nitrogen from a continuous bluegrass, *Poa pratensis,* L., sod. According to Uhland (1947), a Shelby loam at Bethany, Missouri, which had been cropped to corn continuously for 10 years, lost 50.9 tons of soil per acre per year. Land in a 3-year rotation of corn, wheat, and hay lost 7.51 tons of soil. There was only a trace of soil lost from land in continuous alfalfa or bluegrass. At Clarinda, Iowa, continuous corn plots lost 5.32 times as much soil as a 3-year rotation of corn-oats-clover. These data show that soil losses

may be decreased considerably by following the proper cropping system. Rotations including clovers result in less erosion than continuous corn, but the effect cannot be explained entirely by the greater cover provided by the rotation. For example, data presented by Miller and Krusekopf (1932) show that during the 6-month growing period continuous corn plots lost more soil from erosion than the rotation plot in corn. They suggested improved soil granulation as a reason.

These and other data point to the large losses of surface soil accompanying certain cropping practices. Usually loss of surface soil means proportionate losses of nitrogen and organic matter. In this connection Slater and Carleton (1938) examined a Shelby silt loam and a Marshall silt loam and observed a linear function between erosion losses and organic matter depletion. The organic matter content of the soils dropped 0.002 per cent for each ton of soil eroded. They estimated that on a fallowed plot erosion had increased the depletion of organic matter to 18 times that normally lost by oxidation.

There is little doubt as to the influence of erosion on the rate of organic matter and nitrogen depletion. If erosion is kept to a minimum, the job of maintaining a satisfactory level of soil nitrogen will be a much easier one. The detrimental effect of erosion, as measured by crop yields, will obviously appear much quicker on soils with a shallow surface horizon.

VI. Nitrogen Economy of Eroded Soils

Decline in soil nitrogen, whether it be due to increased oxidation as a result of cultivation, crop removal, erosion, or a combination of these, is usually accompanied by a decrease in crop yields, especially of nonlegumes (Fig. 3). Results from Zanesville, Ohio, reported by Borst *et al.* (1945) show a close correlation between erosion, organic matter, and corn yields for continuous corn. Uhland (1947) reported results of a study of corn yields in relation to depth of surface soil for 18 fields near Fowler, Indiana. Yields were in direct proportion to depth of topsoil and varied from 19.8 bushels where no topsoil remained to 69.5 bushels where the topsoil measured 12 inches.

Although all of the decrease in crop yields resulting from erosion is probably not caused by loss of nitrogen, there are data at hand that show nitrogen to be a major factor. Rost (1939) studied the relative yields of oats in pot tests using successive soil layers of 6 profiles and observed a decrease in yields from the surface downward. The addition of a nitrogen fertilizer largely or completely removed any differences in the productivity of various layers. The relative yields of red clover decreased for the second 6-inch, and second and third foot sections, but

rose for the fifth foot. The addition of phosphate or phosphate and potash completely removed any differences in productivity except for one layer of one profile. Hays *et al.* (1948) found that the loss of 3 or 4 inches of the surface from a Fayette silt loam did not permanently

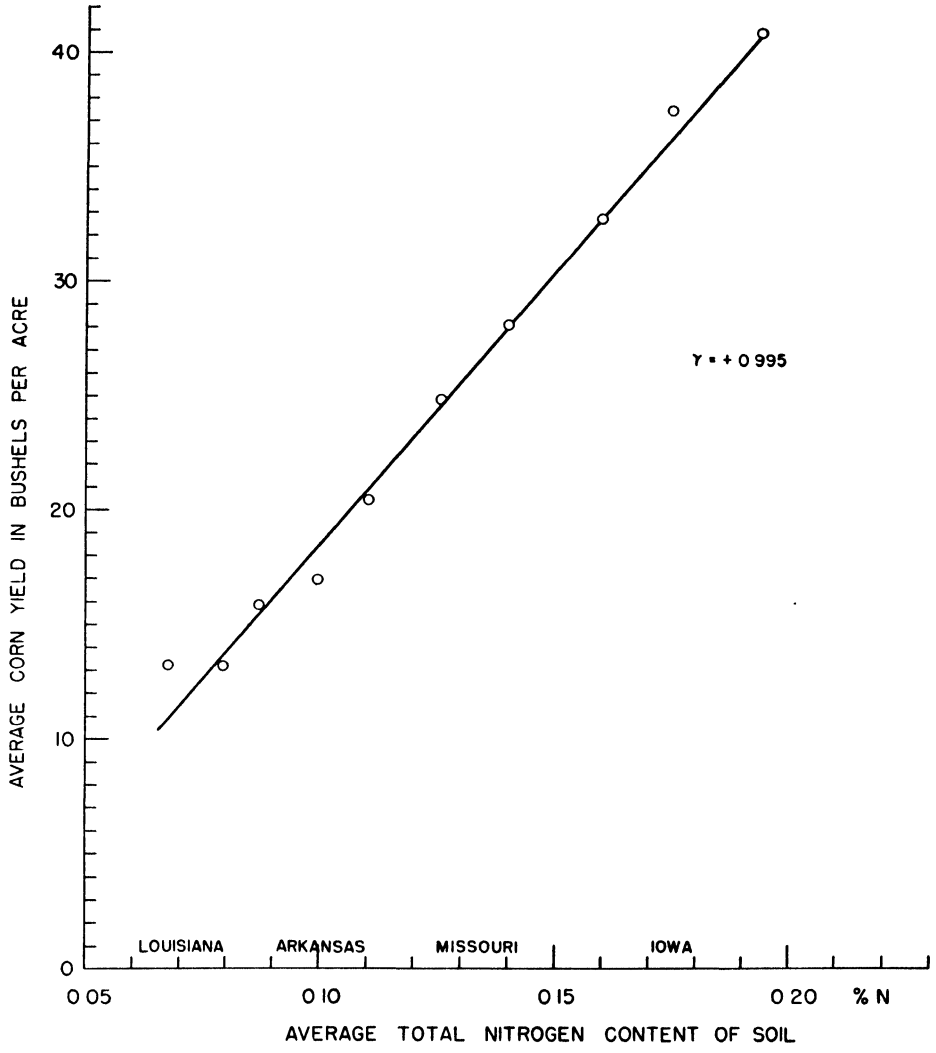


Fig. 3. The average corn yield per acre in relation to the average total nitrogen content of the soil. (Jenny, 1930.)

impair its productivity if managed properly. This means that practices are needed that will build up the organic and nitrogen content, such as long rotations including 3 years or more of alfalfa-grass hay and applications of barnyard manure. Fayette silt loam is a young soil and the main difference between surface and subsoil is in the organic matter

and nitrogen contents. Results of an experiment carried out at Bethany, Missouri, from 1932-1942 and reported by Smith *et al.* (1945) show the effects of cropping systems and treatments on the productivity of an exposed Shelby loam subsoil. Corn was planted on all plots in 1942 to determine the producing capacity of the subsoil as a result of past treatments. The surface soil without treatment produced 43 bushels of corn. A rotation of corn, oats, and sweet clover, *Melilotus* sp., with sweet clover turned under the second year plus an original application of lime and a 4-12-4 fertilizer to oats yielded 44 bushels. The same rotation and lime treatment with superphosphate applied to oats plus 8 tons of barnyard manure plowed under before all previous corn crops yielded 64.6 bushels. Continuous grass-legume meadow for 11 years with an original treatment of lime and 4-12-4 fertilizer yielded 44.2 bushels. A rotation of corn, wheat, and meadow 2 years on limed subsoil with 4-12-4 fertilizer applied to oats produced 34.6 bushels of corn. It appears from these data that in addition to lime and 4-12-4 fertilizer, organic matter and nitrogen are necessary to bring the producing capacity of the subsoil up to that of the untreated surface soil.

VII. Commercial Nitrogen *vs.* Barnyard Manure and Green Manure

The question often arises as to the relative merits of commercial nitrogen and such sources as barnyard manure and green manures for crop production. In fact a group of popular writers have gone so far as to state that manured crops are superior to commercially fertilized crops for human consumption. Although the value of manure and crop residues of various kinds as soil amendments for crop production is generally recognized, it is difficult if not impossible in many instances to obtain enough of these materials for maximum yields. Under ordinary farming conditions, it is often necessary to supply a part of the nitrogen needs of nonlegumes by addition of commercial nitrogen, if maximum yields are to be obtained.

At the Rothamsted Experiment Station wheat has been grown continuously since 1844 and yield records have been kept since 1852. Yield data for a 95-year period are reported by Bear (1949). These data show that plots receiving as much as 1,392 lbs. of fertilizer outyielded a plot receiving 15.7 tons of farmyard manure annually. Data by Thorne (1930) of the Ohio Experiment Station reveal that chemicals, applied in amounts equivalent to the N, P_2O_5, K_2O in manure, were just as effective as manure in increasing crop yields. Thorne wrote the following on the subject of manures: "When manure has been compared with chemical fertilizers the manure usually has been used in such amounts as to carry

far larger quantities of the essential elements of fertility than those given in the chemicals and, without stopping to consider this point, the carbonaceous matter of the manure has been credited with the superior effect produced." As reported by Smith (1942) the 50-year average of continuous wheat plots on Sanborn Field shows that 6 tons of manure produced 18.8 bushels as compared with 20.3 bushels for a complete fertilizer. The complete fertilizer contained nitrogen, phosphorus, and potash equivalent to that contained in a 40-bushel wheat crop.

Green manuring has been practiced from early times with variable results. The efficiency of the practice seems to vary with such circumstances as soil, climate, and crop. It is often stated that green manuring is not effective in regions having less than 20 inches of rainfall. It is generally believed that the main benefit of plowing under green manure crops results from the addition of nitrogen and organic matter in the soil. Other benefits that may result from the green manures are improved physical properties and mobilization of plant nutrients. It is apparent that many of the benefits materialize only when decomposition takes place. Green manures are subject to rapid decomposition, which means that the succeeding crop would receive most of the benefits and that little nitrogen reserve would be built up. Indeed, results of longtime fertility experiments have been disappointing with respect to building up organic matter and nitrogen reserves. In fact, results by Broadbent and Norman (1946), using isotopic nitrogen, show that the addition of Sudangrass accelerated the decomposition of soil organic matter. Thus, not only are green manures rapidly consumed, but they also seem to increase the rate of decomposition of the organic matter already in the soil.

Although the practice of green manuring may not be successful in raising the nitrogen reserve of soils, real proof of the value of the practice will depend on its effect on crop yields. There are numerous publications showing the effect of green manuring on crop yields. There are few publications, however, showing the relative value of legume nitrogen turned under in the form of green manure and a comparable amount of commercial nitrogen. In many of the experiments reported, the quantity of nitrogen turned under by legumes has been much greater than the quantity of commercial nitrogen applied. Unless this point is considered the wrong impression may be obtained as to the relative value of the two forms of nitrogen.

At the Georgia Agricultural Experiment Station on Cecil sandy loam Hale (1936) conducted an 8-year field test in which winter legume green manure and nitrate of soda were compared for production of cotton, *Gossypium hirsutum.* Hairy vetch and Austrian winter peas, *Pisum*

sativum arvense, turned under 2 weeks before planting cotton produced 1,044 lbs. of seed cotton as compared to 951 lbs. where 100 lbs. of nitrate of soda was used. Plots that received 200 lbs. per acre of nitrate of soda produced 1,154 lbs. of seed cotton or approximately 100 lbs. more than the green manure plots. According to the author, at least one ton of air-dry material was turned under, which should have been equivalent to 60 to 80 lbs. of nitrogen. Under conditions of this experiment commercial nitrogen was applied at a rate somewhat lower than that furnished by the winter legumes, but was more efficient pound for pound for production of cotton.

A 12-year average of results in Louisiana reported by Haddon (1941-1942) show that turning under 13,671 lbs. of Oregon vetch, *Vicia sativa,* increased the yield of seed cotton 932 lbs. per acre. In the same test, 500 lbs. per acre of nitrate of soda increased the yield of seed cotton 920 lbs. Although the nitrogen content of the vetch is not given, it would probably be safe to say that more nitrogen was turned under in the form of vetch than was supplied by 500 lbs. of nitrate of soda. The increases were rather large in both cases due to the steady decline of check plots over the 12-year period.

Krantz (1946) studied the effect on corn yields of rate of application of nitrogen with and without cover crops. His data show that Austrian winter peas produced an average of 88.6 bushels of corn at two locations and that 90 lbs. of commercial nitrogen produced 82.7 bushels. Also, there was no significant difference between corn produced by 180 lbs. of commercial nitrogen and that produced by Austrian winter peas plus 90 lbs. of commercial nitrogen.

Blair and Prince (1940) investigated the comparative values of green manures and nitrate of soda for the growth of wheat and rye. Cowpeas, *Vigna sinensis,* the first few years and soybeans thereafter, were sown immediately after grain harvest. The soybean crops contained about 69 lbs. of nitrogen and it was assumed that two-thirds came directly from the air. Certain plots were top-dressed with 160 lbs. per acre of nitrate of soda. Average yields for 14 years show that nitrate of soda produced 22.8 bushels of wheat as compared with 21.2 bushels for green manuring. In the case of rye nitrate of soda produced 24.5 bushels and green manuring 18.6 bushels.

It is a common practice among the vegetable growers of the Atlantic Coast to fertilize small grain cover crops with commercial nitrogen. If the cover crop is utilized as a green manure, the question arises as to the efficiency of the nitrogen thus applied in terms of increased yields of the succeeding crop. Unpublished data by the Alabama Agricultural Experiment Station show a greater efficiency of nitrogen as measured by

corn yields when applied directly to the corn crop. For example, 40 lbs. of nitrogen applied to oats at planting time plus 40 lbs. at time of turning oats produced 32.6 bushels of corn as a 6-year average. Eighty lbs. of nitrogen, applied to corn as a side-dressing produced 44.4 bushels. Also, 40 lbs. of nitrogen applied to oats at planting time and 40 lbs. to corn as a side-dressing produced 37.8 bushels, which is 6.6 bushels less than the same amount of nitrogen applied directly to corn. Results of greenhouse experiments by Pinck *et al.* (1948) show the largest yields and the greatest recovery of added nitrogen where no green manure crop was turned under.

Cover crops seeded for the purpose of turning under are used most extensively in the eastern and southeastern states. Along the Atlantic Coast catch crops are extensively used and in the southern states winter legumes are commonly used. In either case the cover crops do not interfere with regular cash crops. It is doubtful if cover crops can be grown profitably unless they can be grown in off seasons. In the North, legume crops in the regular rotation are in effect green manures.

The extent to which any individual farmer should use green manure crops will depend on a number of factors. Cover crops that are turned under in the late spring present a problem in getting land prepared in time for the crop to follow. Farmers with tractors can usually handle this problem without much difficulty. Land subject to serious erosion should certainly be planted to a cover crop if at all possible in order to lessen the loss of valuable topsoil. The cost of commercial nitrogen is another factor to be considered. When nitrogen prices are high, use of legume cover crops becomes more attractive. Also because of physical properties, certain soils may be more responsive to green manuring than others. On the basis of present data, it would seem wise to grow green manure crops, especially legumes, wherever it is possible to turn them under in time to plant the succeeding crop at its best seeding date, and to use commercial nitrogen where legumes are not grown. Results by Hale (1936) show that winter legumes plus 100 lbs. of sodium nitrate produced 104 lbs. more seed cotton than winter legumes alone. Krantz (1946) obtained an increase in yield of corn by the use of commercial nitrogen with winter legumes over winter legumes alone. Research workers in Illinois (1948) state that the lack of nitrogen is holding down corn yields on many Illinois soils. They believe, however, that where deep-rooting, "stand over" legumes occupy the land one-fourth of the time, applications of commercial nitrogen are not economical. It is apparent that the successful farmer must use considerable skill in combining the best fertilizer and cropping practices to furnish adequate

nitrogen and other nutrients as well as to maintain a good physical condition.

VIII. Nitrogen Trends in Various Parts of The U. S.

1. General Trends

Soil analyses show that many of our soils are lower in nitrogen and organic matter than they were under virgin conditions, and that a state of equilibrium has not been reached. If we are to look ahead with the idea of maintaining the fertility of our soils, we should familiarize ourselves with some general trends. Lipman and Conybeare (1936) have prepared a balance sheet of plant nutrients for the soils of the United States and their estimates for nitrogen are as follows:

	Tons
Losses (harvested crops, grazing, erosion, leaching)	22,899,046
Additions (fertilizer, manures, rainfall, irrigation water, seeds, nitrogen fixation)	16,253,862
Net annual loss	6,645,184

According to their estimates, 25.09, 24.2, and 23.0 lbs. per acre of nitrogen are lost annually by removal in harvested crops, erosion and leaching, respectively. Mehring and Parks (1949) have estimated the amount of nitrogen removed in harvested crops as compared with the amount added in fertilizers and manures for various sections of the country. Their estimates are presented in Fig. 4. Although in some sections more nitrogen is added by fertilizers and manures than is removed in crops, the data for the United States as a whole show that about twice as much nitrogen is removed by crops as is added by fertilizers and manures. Since most crops are grown to be harvested and removed, little can be done about this loss other than to return as much of the plant residue as possible. Erosion losses are being reduced by better soil conservation practices, and leaching losses can be minimized by keeping the land covered as much as possible and by applying commercial nitrogen to crops at the proper time. Such practices can go a long way in decreasing the spread between losses and additions.

A nitrogen balance may also be approached by increasing additions. Additions of nitrogen to the soil may be increased considerably by increasing the acreage of legumes and by increasing the amount fixed per acre. The latter may be accomplished by proper inoculation, liming, and fertilization. Soil treatments that favor symbiotic fixation will in most cases be favorable for nonsymbiotic fixation. Efficient handling

and use of manure would also favor a balance between additions and removal of nitrogen. It is well known that much of the manure produced is never returned to the land. Lyon and Buckman (1947) estimate that only 40 per cent of the nitrogen removed in crops will reach the soil again. Mehring and Parks (private communication) estimate a yearly production of 1,371,059,000 tons of manure in the United States and utilization of only 221,790,000 tons. This amounts to an annual application of manure nitrogen of 1,448,790 tons. It is obvious from

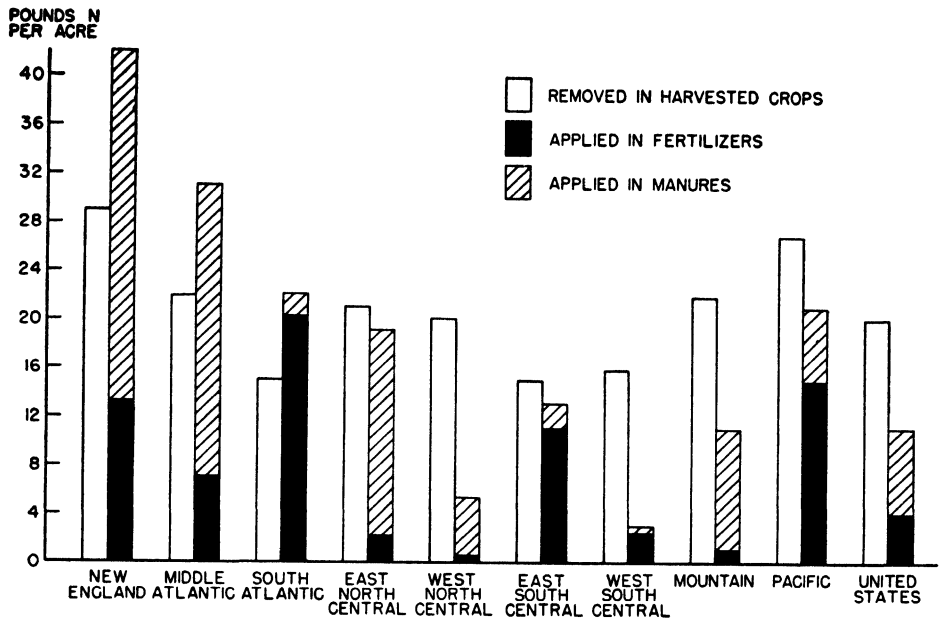


Fig. 4. Average annual removal of nitrogen in harvested crops and the amounts replaced in fertilizers and manures. (Mehring and Parks, 1949.)

these figures that proper use of farmyard manure could materially increase our nitrogen additions to soil. Commercial nitrogen is being used in ever increasing amounts. Figures presented by Scholl and Wallace (1949) show that 824,482 tons of commercial nitrogen were applied to our soils in the year ending June 30, 1948. This discussion of nitrogen balance should not be taken to mean that a balanced nitrogen sheet necessarily means sufficient nitrogen for maximum yields under all conditions. It does indicate, however, the nitrogen trend for the country, and points to the need of establishing a balance if we are to maintain a high productivity for the country as a whole. Improved crop varieties outyield old varieties and as a result remove more nutrients per acre. Unless these nutrients are replaced, yields and perhaps quality of crops will decline. The gradual decrease in protein content of corn grain dur-

ing the past number of years may be due in part to the decline of soil nitrogen.

2. Southeast

Fertility trends with respect to nitrogen vary somewhat from region to region. In the Southeast soils have always been low in nitrogen and organic matter. It is probable that some of the cultivated soils that have been well managed are higher in nitrogen than under virgin conditions. Conditions are favorable for microbial decomposition for a large portion of the year, which makes it difficult to build up a reserve supply of nitrogen. A turnover of nitrogen and organic matter can be maintained by use of crop residues and summer and winter legumes. Even though winter legumes may be grown successfully without interfering with regular cash crops, it is difficult for a farmer to turn more than one-fourth of his crop land late in the spring with mule power. Until more farms are mechanized, this puts a rather definite limit on the extent of winter legume acreage. If Alabama is representative of the Southeast that limit has not been approached. One-fourth of the cultivated land in Alabama would amount to a little over 2,000,000 acres, whereas in 1948 there were approximately 1,000,000 acres planted to winter legumes. It is interesting to note, however, that the winter legume acreage in Alabama is on the increase. In 1918 there were less than 1,000 acres planted as compared with 1,000,000 acres planted in 1948. Assuming an average fixation of 60 lbs. of nitrogen per acre, legumes would furnish 30,000 tons annually. The fixed nitrogen plus slightly more than 40,000 tons of commercial nitrogen gives a total of about 70,000 tons of nitrogen for Alabama crops. Experimental results show that the cotton and corn acreage alone should receive close to 100,000 tons. These figures serve as an indication of the need for nitrogen in this part of the country if crops are to be produced most economically. Studies in the Southeast have revealed rather consistent returns from the application of nitrogen to corn. In this area 2 lbs. of nitrogen can be expected to produce a bushel of corn. The extra bushels from nitrogen are economical bushels, since they are produced at little added cost other than the cost of the nitrogen. The same is true for cotton where a pound of nitrogen will produce about 12 lbs. of seed cotton. Cummings (1949) estimates that an additional 165,000 tons of nitrogen would be required to increase corn yields in nine southern states by 10 bushels per acre.

In the Southeast winter legumes play an important part as far as the nitrogen economy of row crop land is concerned, but other legume crops are becoming prominent in the overall nitrogen economy. Alfalfa and *Lespedeza sericea* are becoming important forage crops, and, when grown

on land suited to row crops, they can be used effectively in cropping systems. This is pointed out by the work of Krantz (1949). He obtained a yield of 127.2 bushels of corn per acre in 1947 following a 4-year stand of alfalfa on a Cecil loam. The plot received in addition 500 lbs. per acre of 4-10-10 fertilizer. Results by Mooers and Hazelwood (1945) show that land in high-yielding sericea for 3 or more years can be expected to produce large yields of corn for several successive years. The acreage of improved permanent pastures is increasing rapidly. These pastures are usually legume-grass mixtures. The legumes serve as forage and supply some nitrogen for the grass.

3. Midwest

Many of the soils of the Midwest were rich in organic matter and nitrogen when first brought under cultivation. Cultivation has caused a decrease in the nitrogen and organic matter content of these soils with a resulting decrease in fertility. Even so the average corn yield in Iowa, for example, increased from 39.3 bushels per acre for the period 1929-1933 to 54.4 bushels for the period 1939-1943. This increase in yield of 15 bushels was brought about in spite of the decline in fertility, primarily by the widespread use of hybrid corn and to some extent by better cultural practices. This increased yield means an additional removal of nutrient elements, which will have to be supplied in order to continue to reap the benefits of hybrid corn. During the past 10 to 15 years there has been an increase in acreage of such soil-depleting row crops as corn and soybeans. This has been accompanied by a decrease in acreage of legume-grass meadows and pastures. Thus, the more rapid decline in soil fertility in recent years has resulted in greater increases in yields from fertilizers, especially nitrogen.

Although the midwestern states are not using large quantities of nitrogen when compared with consumption in some of the southern states, the percentage increase in recent years has been large. For example, nitrogen consumption in the West-North-Central States was 11,392 tons for the year ending June 30, 1946, and was 37,580 tons for the year ending June 30, 1948. Pierre (1949) stated that the North Central states should be using more fertilizer and estimated that amounts used in Iowa at present should be more than trebled.

The extent to which commercial nitrogen consumption will increase in the Midwest will depend on several factors. Many of the soils of this region are still relatively high in nitrogen, and if properly managed, a high nitrogen fertility level may be maintained with little or no commercial nitrogen. The climate of the Midwest favors the use of farm-produced nitrogen. Temperature and rainfall are favorable to production

and use of organic matter as a source of nitrogen for crops. The type of farming carried on in the area is also favorable to farm-produced nitrogen. Large quantities of feed crops are grown and on many farms the production of these crops is accompanied by livestock production. This type of farming not only encourages but necessitates the use of legumes and sod crops in the cropping system and at the same time provides for the fixation of atmospheric nitrogen in the soil. These legume and sod crops not only conserve and add nitrogen, but promote a better physical condition.

4. Great Plains

The average annual rainfall of the Great Plains area varies from slightly less than 13 inches in the western part to 22 inches in eastern North Dakota. While rainfall is higher in the southern part of the region it is relatively less effective in producing crops. Much of the rainfall in the Great Plains occurs during the summer months.

According to Myers *et al.* (1943), moisture is the overall limiting factor in crop production in the dry-land areas of the Great Plains. Such conservation practices as terracing and contour farming can do much to increase yields. Maintaining a high level of organic matter will increase the efficiency of rainfall by increasing the rate of infiltration. Especially in the western part of the region, alternate small grain and fallow is practiced as a means of using the existing moisture to better advantage.

A review of literature by Harper (1945) on the response of crops to nitrogen fertilization showed that in most cases nitrogen increased yields little or not at all. Land that has been summer fallowed will seldom respond to nitrogen fertilization because of the accumulation of nitrate nitrogen brought about by fallowing. Also, plowing as far ahead of wheat sowing time as possible will usually bring about sufficient nitrate accumulation to eliminate the need for commercial nitrogen.

5. Irrigated Regions

Most of the arid and semi-arid lands were low in nitrogen and organic matter when first put under irrigation. It has been surprising that many of these soils with little or no commercial nitrogen have produced profitable yields of grains and vegetable crops in rotation with alfalfa. As a general rule about one-fourth the land is kept in alfalfa. McGeorge (1949) believes that in Arizona crops are getting nitrogen from several natural sources, such as irrigation water, especially pump water, and nonsymbiotic nitrogen fixation. Analyses show 10 to 50 p.p.m. of nitrate in many of the pump waters. It is evident that an acre foot of water

would contain a significant amount of nitrate. Smith (1944) working with a red desert soil of Arizona found strong evidence of considerable nonsymbiotic nitrogen fixation.

Even though these soils have produced good crops without the use of much nitrogen fertilizer, recent work has shown that nitrogen fertilizer may be used to advantage. Work by the Division of Soil Management and Irrigation, U.S. Department of Agriculture (private communication) shows that the lack of nitrogen is limiting yields of nonlegumes in the Columbia River Basin. Nitrogen was found to increase the efficiency of a limited supply of irrigation water. Also, an increased supply of irrigation water was used even more efficiently with increasing amounts of nitrogen. Salter (1949) has revealed that exceptional crop yields may be produced if water as well as other factors are controlled. Such yields as 162 bushels of corn, 174 bushels of grain sorghum and almost 600 bushels of potatoes per acre have been obtained under irrigation.

Where the supply of irrigation water is limited, it is probable that most of the needed nitrogen can be produced on the farm by growing legumes in the rotation. Where a more ample supply of water is available, it is very probable that commercial nitrogen may be used economically.

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Vegetable Production

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I. Introduction

Increase in population and changes in diet have greatly stimulated vegetable growers to increase their acreage. Not only are more acres being planted to vegetables, but the average yield per acre, in the case of a considerable number of crops, has improved fairly steadily during the past decade or more.

Thirty years ago the amount of land planted to crops for processing exceeded that for the fresh market. Since strictly market garden production, however, does not enter into statistical summaries, the difference may not have been as great as the data indicate. From 1926 to 1942, the fresh market acreage exceeded that for processing. This increase was due to the development of large scale vegetable production in areas at great distances from the ultimate markets. Since then the acreages for processing and for fresh market have been about equal, first, because of the increased demand for processing crops during the war years, and second, because of the expansion of the frozen food industry.

Fresh market production of the 25 most important vegetables, omitting potatoes and sweet potatoes from consideration, utilized an average of 1,694,000, 1,677,000, and 1,892,000 acres annually for the three 5-year periods: 1934-38, 1939-43, and 1944-48, inclusive. The 11 important processed crops averaged 1,383,000, 1,633,000 and 1,916,000 acres during the same periods.

The production of vegetables for processing, in the main, represents cash crops in general farm rotations, and is conducted in areas where the climate and soil provide a good yield at low cost. The vegetable crops destined for the fresh market, on the other hand, are grown where the climatic conditions are favorable for high yields and where the produce may be sent to market under optimum price conditions. As indicated above, there was little difference in the acreages of the two types of production during the period 1944 to 1948 inclusive, yet the farm value averaged $590,401,000 annually for the vegetables sold fresh and only $215,569,000 for those processed.

The six most important states in the production of fresh vegetables are California, Texas, Florida, New York, New Jersey, and Arizona. A comparison of the average annual acreages for the periods 1944-48 and 1939-43 shows for California a gain of 13.0 per cent; for Florida, 29.2 per cent; for New York, 9.9 per cent; and for New Jersey a loss of 0.5 per cent. Acreage increase was greatest in Arizona (48.6 per cent) with Texas next (41.8 per cent). During the past 5 years the average annual acreage devoted to fresh vegetable production in Texas was 351,760, compared to 382,290 acres in California. The expanding acreage in the

lower Rio Grande Valley is aided by a favorable freight rate compared to that from California. The upward trend in Texas coupled with the shift from vegetables to field crops in certain districts of California might make Texas the leading fresh vegetable producing state in the near future.

The ranking states in the growing of vegetables for processing are Wisconsin in the lead, followed by California, Indiana, Minnesota, New York, and Illinois. The average annual acreage from 1944 to 1948 was 37.8 per cent greater in Wisconsin than in the previous five years. California and Minnesota showed a 30 per cent gain; Illinois and New York 11.2 per cent and 15.6 per cent, respectively; while Indiana had a 4.4 per cent decrease. Although the total acreage is rather minor compared to that of sweet corn grown for processing in Wisconsin, Minnesota, and Illinois, a recent development in Idaho and Oregon has been the almost three-fold increase, from an average of 4,000 acres each during the period 1937 to 1946 to over 11,500 acres in 1948. Washington had about the same acreage in 1948 as Idaho and Oregon, although the percentage increase was not so great. The processing pea acreages in these three northwestern states has shown a somewhat similar expansion. Climatic conditions in the northwest are such that quality is not rapidly lost as these crops mature. Since a very considerable proportion of the sweet corn and the pea crops there are quick-frozen, this maintenance of quality is very important. The most spectacular acreage change among the processing crops is that of green lima beans in California, this also being due to the climatic adaptation of the area to a crop grown for freezing. In 1948 there were 21,700 acres of green lima beans harvested, compared to an average of only 3,220 acres a year during the period 1937 to 1946.

During the 10 year period 1939 to 1948, the national farm value of all tomatoes for both fresh market and processing averaged annually $139,105,000, while that of lettuce, its nearest rival, was $69,841,000. Snap beans were next with $49,148,000; onion, celery, and peas were closely grouped around the $40,000,000 figure.

The losses in weight and quality of fresh vegetables during the marketing period are great, especially at the retail level. To reduce this waste much research has been conducted; recent developments in consumer packaging may be helpful. Space will not be available in this review to cover these recent trends in marketing. Neither will it be possible to review the voluminous literature concerning the new materials coming to the fore in the control of insects and diseases.

Much has been accomplished in recent years in the improvement of varieties, in the fertilization of vegetables, and in techniques to increase yields or reduce unit costs. All of these are important to the future

expansion of vegetable production and constitute some major advances from recent research.

II. Fertilization

Adequate fertilization is perhaps more important in the culture of vegetables than with most other crops. The development of a high quality product is as great a consideration as is the maintenance of high yields. The intensive production of vegetable crops on high-priced land requires heavy fertilization. For their potentialities to be fully realized, the new hybrids and other high yielding varieties may well require even heavier and more efficient fertilization than has been practiced in the past. The use of new and improved materials for the control of insects and diseases will tend to justify an increased use of fertilizers. Therefore, there is much research under way wherever vegetables are grown to determine for such local conditions the best fertilizer materials, the optimum rates at which they should be supplied, and the most suitable methods of applying them.

1. Liquid and Gas

New products and new methods of fertilizer application are becoming increasingly available for use by many vegetable growers. Important new materials were described by Merz (1940). Probably the most significant change in the fertilizer industry has been the use of liquid and gaseous materials. These may be applied in the irrigation water, injected into the soil, or sprayed directly on the soil, as described by King, Newcomb, and Chenoweth (1943). McCollam and Fullmer (1948) estimated that about 6 per cent of the total tonnage of fertilizer sold in California in 1947 was applied in liquid form.

The material having the greatest increase in use has been anhydrous ammonia (NH_3). Rosenstein (1936) called the method of applying this material in the irrigation water "nitrogation." Cylinders of anhydrous ammonia containing 150 lbs. each are connected by steel tubes. The gas is metered into the irrigation water through calibrated orifices, the orifice size depending upon the temperature of the ammonia and the rate of delivery desired. Sawyer (1948) stated that the concentration of ammonia in the water should be between 50 and 75 p.p.m., with 110 p.p.m. as the upper limit.

Chapman (1944) showed the effect of soil permeability, temperature, and agitation on the losses of ammonia from the irrigation water. He concluded that under most field conditions losses will be less than 10 to 12 per cent but that with high water temperatures and low soil permeability they might be over 26 per cent.

Beaumont and Larsinos (1932), in field and plot tests, found ammonia solution to be only about 70 per cent as effective as equivalent amounts of nitrogen derived from ammonia sulfate or sodium nitrate. Chapman (1944) reported aqueous ammonia to be comparable with other sources of nitrogen. Lorenz and Doneen (unpublished) have found anhydrous ammonia as good a source of nitrogen for potatoes and onions as ammonium sulfate.

Jenny, Ayers, and Hosking (1945) concluded that the adsorption of ammonia from ammonium hydroxide was largely dependent upon soil texture. The fine textured soils adsorbed more nitrogen than coarse textured soils. They found that acid soils tend to adsorb more nitrogen from ammonium hydroxide than from ammonium sulfate, while the reverse was true on alkaline soils.

"Nitrojection," described by Sawyer (1948), refers to the direct injection of anhydrous ammonia into the soil. By this method ammonia under its own pressure is injected into the soil in furrows made by chisels or other furrow openers. Andrews, Edwards, and Hammons (1948) state that in Mississippi there are 200 machines for applying ammonia by this method. Their work showed that anhydrous ammonia and solutions of ammonia have crop-producing values equal to or superior to ammonium nitrate placed in the soil in the conventional manner.

Jackson and Chang (1947) demonstrated the tremendous power of the soil to fix gaseous ammonia and concluded that gaseous loss of NH_3 from the soil is not an important factor in the use of anhydrous ammonia as a fertilizer. They showed that even coarse-textured soils have good efficiency in retaining gaseous ammonia. Finding that the moisture content of the soil had only a slight effect on ammonia retention, they concluded that this factor could probably be neglected in field practice.

Jenny, Ayers, and Hosking (1945) found that NH_3 adsorbed on dry clays was loosely held and could be removed by aeration, indicating that direct injection of NH_3 may not be advisable under certain soil conditions.

2. New Materials

To meet the need for cheaper water-insoluble forms of nitrogen several urea-formaldehyde materials have been produced. By varying the proportion of these ingredients, fertilizers containing practically all degrees of solubility can be prepared. McCool (1941) described one of these, urea-ammonia-liquor-37, which in tests on tomatoes and corn gave yields fairly comparable to those with nitrogen derived from cottonseed meal.

3. Fertilizer Placement

The latest general recommendations on fertilizer placement have been summarized in a report by the National Joint Committee on Fertilizer Placement (1948). These vary somewhat for the different vegetables, but for practically all of those planted on the level, the committee recommends that the fertilizer be applied in bands 2 to 3 inches to the side and 1 to 2 inches below the seed. With large amounts of fertilizer (1,000 lbs. or more per acre) the bands should be placed at the greater distance from the seed. Also, when exceptionally large amounts of fertilizer are used, part or even all of it may be applied broadcast and then plowed or disked under prior to planting.

Vegetables planted on beds and grown with furrow irrigation, as in Arizona and California, should be fertilized by placing bands in the shoulder of the bed, approximately 4 inches deep and 2 inches from the plant row. Lorenz (1949) showed that with bed-grown, transplanted onions, best results were obtained by placing the fertilizer directly under the plant row before setting the plants. A single band in the center of the bed 5 or 6 inches from the plants was inferior to one under each row or in each shoulder of the bed. If applied approximately two months after transplanting, fertilizers in the shoulder of the bed gave much better results than in the center. Such direct-seeded crops as spinach, onions, and peas, which are irrigated before emergence, experienced harmful results when the fertilizer was placed 2 to 3 inches directly under the plant row.

4. Nitrogen Sprays

Hamilton, Palmiter, and Anderson (1943) suggested the use of uramon in foliage sprays as a means of regulating the nitrogen supply of apple trees. This method of application has been applied recently to certain vegetable crops. Results summarized by the Du Pont Company (1948) show that potatoes have responded to midseason sprays containing 20 to 25 lbs. of urea per 100 gallons of water. Plants vary, however, in their susceptibility to injury from nitrogen foliage sprays and for tomatoes it seems safe to use only 5 lbs. of urea per 100 gallons of spray as compared to 4 or 5 times this amount for potatoes. Tests conducted in the greenhouse and in the field in California (Lorenz, unpublished) using rates as high as 60 lbs. of urea for 100 gallons of water have shown very little benefit on lettuce, spinach, and potatoes. If enough urea was applied to give increased foliage color or growth, burning of the foliage usually occurred.

5. Plow Sole Application

"Plowing down" fertilizers has become popular in some of the Eastern states. With that method, Sayre (1942), in New York, reported an increase of approximately 2 tons of tomatoes per acre during dry seasons. Rahn (1943), in Pennsylvania, reported slightly better results from fertilizers plowed down in bands than from broadcast applications.

The benefits from plow sole applications are most frequently attributed to several causes. Since the fertilizers are located 6 to 10 inches below the surface in moist soil, the roots can readily absorb them. The plant nutrients, such as potassium and phosphorus, are in an area where they are less readily fixed by the alternate wetting and drying of the soil. Moreover, the crop is less likely to be injured by fertilizer burning due to high concentration of soluble salts.

There are two common methods of plowing down fertilizers: broadcasting before plowing and applying as a single band in the bottom of each furrow. The latter method appears to be the better, since it should result in less fixation of certain plant nutrients. Inasmuch as the yield-benefits reported from plow sole applications are small, it is doubtful that this method of fertilizer application offers many possibilities. On the other hand, it does present another method of band placement.

6. Starter Solutions

The common term for plant food dissolved in water and used to hasten recovery of transplanted seedlings is starter solution. It is presumed that the application of fertilizer in the immediate area of the root stimulates early root development. This is often reflected in more rapid early growth and possibly in earlier maturity (Natl. Joint Comm. on Fert. Appl., 1948). Sayre (1941) reported that starter solutions gave good results on transplanted tomatoes, cabbage, celery, pepper, eggplant, and muskmelon, and on certain seed-sown crops such as beans, peas, sweet corn, and beets. Rahn (1943), in Pennsylvania, also noted that starter solutions were most effective in increasing the early yield of tomatoes and sweet corn but that somewhat less favorable results were obtained on the early yields of cabbage and snap beans. The total yields of tomatoes, snap beans, and cabbage were increased but the final yield of sweet corn was not.

To prepare starter solutions, fertilizer mixtures of soluble materials and high analysis, such as 25-52-0, 12-52-17, or simple compounds, such as 11-48-0 Ammo-phos, sodium nitrate, or potassium nitrate, are dissolved in water at rates approximating 5 lbs. per 50 gallons of water. One pint to one quart of the starter solution is applied to each plant.

Damage to the young seedlings may result if the fertilizer materials are concentrated much above 5 lbs. per 50 gallons of water.

III. Trace Elements

The need for supplying small quantities of certain trace elements for vegetable production on some soils has long been recognized. Such use has become a part of normal commercial practice wherever the need for these exists. Recently sodium and molybdenum applications to vegetables have been demonstrated as being of importance in some situations.

1. Sodium

Hartwell and Damon (1919) mentioned the possible value of sodium in the growth of certain plants. Recent work by Harmer and Benne (1941), Sayre and Shafer (1944), and Sayre and Vittum (1947) showed distinct value from the use of this element in the production of certain crops. Sayre and his coworkers demonstrated that sodium applications from several sources corrected certain deficiency symptoms and increased the yield of beets grown in New York. They believed that sodium functioned as an independent element and did not partially substitute for potassium. Raleigh (1948), using solution cultures, found that chlorides gave more consistent increases in the growth of table beets than did additions of sodium.

On the basis of field experiments, Harmer and Benne (1941) recommended using 500 to 1,000 lbs. of sodium chloride per acre for celery, table beets, and turnips grown on the muck soils in Michigan. They did not, however, recommend its use for certain other crops such as lettuce, corn, parsley, potatoes, and tomatoes. Similar benefits were obtained with sodium sulfate and sodium chloride, indicating that sodium, and not chloride, was responsible for the yield increase. In fact, they obtained increases in yield only when sodium was applied with potassium.

Holt and Volk (1945), using nutrient solution, found sodium to increase the growth of 7 different crops when potash was omitted. They stated that the beneficial effect of sodium decreased as the potash level of the nutrient media increased but not in direct proportion to it. They concluded that for some plants sodium may be an essential element for maximum growth and that sodium can be substituted for potassium to a variable extent, depending on the kind of plant.

2. Molybdenum

On certain soils in Australia and New Zealand, cauliflower and broccoli plants show a "whiptail" distortion and interveinal chlorosis. Davies

(1945) found that the addition of 3 lbs. per acre of sodium molybdate to the soil eliminated the interveinal chlorosis of cauliflower plants. Mitchell (1945) noted that the whiptail distortion could be corrected by applications of 5 to 20 lbs. of ammonium molybdate per acre. Since then, Waring, Shirlow, and Wilson (1947) and Wilson and Waring (1948) found that even smaller concentrations of molybdenum were effective and suggested using rates of from one-fourth lb. to two lbs. per acre of sodium or ammonium molybdate for the control of this disease. Wilson (1948) obtained a yellowing of the outer leaves, marginal leaf burning, and reduced plant size of lettuce grown on soils that were deficient in molybdenum and where whiptail had been observed on cauliflower. This disorder in lettuce was also corrected by the addition of molybdenum to the soil. Warington (1946) has also shown that molybdenum is essential in the nutrition of lettuce.

Wilson and Waring (1948) found that molybdenum deficiency symptoms were most prominent on plants receiving heavy nitrogen fertilization and suggested that the function of molybdenum in the plant is related to nitrate reduction. Their results agree with the work of Steinberg (1937) on *Aspergillus niger*. This indicated that molybdenum is essential for activation of nitrate reductase in the reduction process, whereby nitrates are reduced to ammonia.

IV. Development of New Vegetable Varieties

It would be impracticable to list all the new vegetable varieties that have appeared in recent years. In some instances they have been short-lived; in others, they will remain in use for many years. Some varieties have very wide adaptation. Many, however, are fairly restricted in their climatic requirements and do well only at certain seasons of the year or in particular places. Thus the widely scattered vegetable industry requires varieties with specific adaptation, and plant breeders have attempted to fill this need.

The GREAT LAKES variety of lettuce (*Lactuca sativa*, L.), developed by Barrons and Whitaker (1943), has caused widespread disruption in the lettuce industry. While it was selected primarily for summer harvest in Michigan, its characteristics of hard heading, slow bolting, and considerable tipburn resistance have enabled it to replace the better quality Imperials formerly planted and have led to the production of head lettuce in areas and at times of the year not previously possible. Various improved strains of GREAT LAKES are now appearing, as well as varieties, such as PENNLAKE (Lewis, 1949), which have GREAT LAKES in their parentage.

Thompson (1948) has released the PROGRESS lettuce variety designed to replace IMPERIAL 44 which, though of high quality, was quite susceptible to tipburn and slime. PROGRESS is the result of a cross between IMPERIAL 44 and an unnamed hybrid. When planted as an early season lettuce, it is quite resistant to tipburn. The color is dark green and the quality is good.

Examples that characterize the multitudinous objectives of modern vegetable improvement are listed below:

The SUMMER PROLIFIC tomato (*Lycopersicon esculentum,* Mill.) described by Denman (1948), which sets well in hot weather in Texas and resists splitting after thunder storms; the high yielding MAGNOLIA PICKLING cucumber (*Cucumis sativus,* L.) for Mississippi (Anderson, 1949); the IOWA YELLOW GLOBE 44 of Peterson and Haber (1949), a high-yielding storage onion (*Allium Cepa,* L.) for peat or muck soils; the very uniform, sure-heading MICHILI, a selection of CHIHILI Chinese cabbage (*Brassica pekinensis,* Rupr.) by Drewes (1948); the TRIUMPH bush lima bean (*Phaseolus lunatus,* L.) developed by Magruder and Wester (1948) for processing; the V-1 cantaloupe (*Cucumis Melo,* L.), produced by John Moran of the Ferry-Morse Seed Co. and discussed by Cuthbertson (1948), which is sulphur resistant and thus may be dusted for the control of powdery mildew (the latest development is SULFUR RESISTANT 91); FLAGSHIP, a F_1 hybrid sweet corn (*Zea Mays,* L.) (Eto, 1948), which has few suckers, the ears borne at a uniform height, and strong roots, all of which adapt it to mechanical harvesting; WISCONSIN GOLDEN 800 (Andrew, 1948), a F_1 hybrid sweet corn with a high degree of cold resistance in the spring; SAN JOAQUIN, an early-maturing, high-yielding, nonbolting onion developed by Davis and Jones (1946) for the Southwest; and EXCEL, a Bermuda type onion for the South, the work of Jones, Perry, and Davis (1947), a variety which produces 35 per cent more marketable onions as much as 14 days earlier than YELLOW BERMUDA, because it is fairly resistant to bolting, doubling, and splitting.

Resistance to Disease

The major portion of the breeding work with vegetables is aimed at the development of resistance to disease, or in some cases, to insects. The only sure avenue of control in combatting some diseases attacking vegetables is inherited resistance, or at least considerable tolerance. Evidence is accumulating that wheel injury to some crops when spray and dust equipment moves through a field may be considerable. The application of fungicides and insecticides by airplane is not entirely satisfactory, because weather conditions may upset what needs to be a carefully timed application. Moreover, resistance is particularly impor-

tant in eliminating virus diseases, because even though insecticides may be applied to control vectors, insects may inoculate the plants before the insecticide kills them. Thus resistance is an advantage even for the control of a disease or insect that may be held in check by the application of some material to the foliage.

Wilt-resistant watermelons (*Citrullus vulgaris,* Schrad.) developed elsewhere have been of little value in southeastern Missouri. Starting with a resistant plant, probably a natural hybrid, in DIXIE QUEEN, Hibbard (1947) produced MISSOURI QUEEN, which is highly resistant to most strains of fusarium wilt. Epps and Sherbakoff (1949) report the release of the MILES watermelon for use on wilt-infested soils of Tennessee. It is the result of a cross between DIXIE QUEEN and the wilt-resistant KLONDIKE R-7 developed in California. MILES is a very productive, high quality melon, showing 12.1 per cent soluble solids in some tests.

The CONGO watermelon described by Andrus (1949) has considerable resistance to anthracnose but not to downy mildew or to fusarium wilt. An African melon was crossed with IOWA BELLE, and an inbred line from this was crossed with GARRISON. The resulting melon has dark green striping and a hard rind. A comprehensive review of watermelon breeding has been prepared by Parris (1949) covering the inheritance of plant and fruit characters and placing particular emphasis on the development of disease resistance.

Many varieties of peas (*Pisum sativum,* L.) have been released for use in the fresh market, cannery, or freezing plant. Each use requires different characteristics as to color and size of berry, and concentration of pod maturity, but all may need resistance to certain diseases. Anderson (1948) reports the release of SHOSHONE for canning, a wilt-resistant pea, resulting from a cross of PRIDE by ROGERS GIANT HAMPER. It has outyielded all other varieties of the PERFECTION type. VICTORY FREEZER with the same parentage is designed for quick freezing.

Zaumeyer (1949) has developed RIVAL, a round-podded green bean (*Phaseolus vulgaris,* L.), resulting from a cross between U. S. NO. 5 REFUGEE and FULL MEASURE. Tests in many locations have shown its wide adaptation for market, canning, and freezing. The pods are borne fairly high on the plant and are quite concentrated in time of maturity. They are stringless and fiberless. RIVAL is resistant to the common bean mosaic and the new strain, New York 15 mosaic. Both these viruses are seed-borne. The average yield of RIVAL in all states where tests were run was 9,080 lbs. of green beans per acre, compared to 5,580 lbs. for TENDERGREEN.

Another Zaumeyer (1950) development is TOPCROP, a sister line of RIVAL, from the U. S. NO. 5 REFUGEE by FULL MEASURE cross. It is immune

to the common bean mosaic and the virus disease "greasy pod." The entirely stringless green pods are round in cross-section, fairly straight, and meaty, and are without fiber. TOPCROP is adapted to most parts of the country for canning, freezing, and fresh market. It has the vigor and hardiness to develop plants of good size under adverse conditions.

The SUPERGREEN snap bean by Anderson (1948) came from a cross between IDAHO REFUGEE and FULL MEASURE. It shows considerable tolerance to both forms of the common bean mosaic and outyields TENDERGREEN and FULL MEASURE. It also has a fairly concentrated pod set. A bean designed for the southern states is LOGAN, from a cross of U. S. NO. 5 REFUGEE and BLACK VALENTINE. This variety described by Wade (1943) is highly resistant to the common bean mosaic and to powdery mildew. It shows tolerance to rust and to bacterial blight. One very favorable characteristic is its ability to set pods during hot weather.

In some sections of the United States, curly top is a problem in bean growing. The PIONEER, developed from a series of crosses of BURTNER and BLUE LAKE (Dana, 1944), has resistance to the curly top virus and that of the common bean mosaic. In the snap bean stage, the pods are of good quality.

Australia inclines to varieties stemming from the old CANADIAN WONDER. Shirlow (1947) has released RICHMOND WONDER from a cross of CLARENDON WONDER by WELLINGTON WONDER. It is a heavy producer of straight pods, 9 to 10 inches in length and oval in shape. These are fleshy but have fairly heavy strings and fibers as they age. The RICHMOND WONDER has comparatively good resistance to halo blight and angular leaf spot.

The greatest hazard to cucumber production in the southern states is downy mildew (*Pseudosperonospora cubensis*). PALMETTO, a dark green slicing variety, developed by Barnes (1948), is highly resistant but not immune to this disease. Immunity to downy mildew (*Peronospora spinaciae*) has been introduced by Smith (1949) into the HOLLANDIA and VIROFLAY varieties of spinach (*Spinacea oleracea*, L.). The immunity was identified as a single dominant gene in a variety of spinach from Iran.

Probably greater effort is being devoted to breeding tomatoes for disease resistance than any other vegetable crop. Young and MacArthur (1947) have cataloged and described 49 characters with gene symbols and more than 60 other characters without gene symbols. This work is an aid in recognizing the good, mediocre, and undesirable characters to be watched for in any developmental program.

The Southern Tomato Exchange Program (STEP) has been established by the workers in the southern states to evaluate critically new

tomato varieties arising from the breeding work in that area. Material from other sections of the country is sometimes included. Yarnell (1948) has discussed the method of operation and the advantages which have accrued from the wide-spread observations on the disease-resistance and productivity of new varieties prior to their official release. Other co-operative vegetable trials are handled in the same general manner.

The steps in the development of WISCONSIN 55 tomato have been described by Walker, Pound, and Kuntz (1948). This variety was designed for canning purposes. Its tolerance of early blight delays defoliation. WISCONSIN 55 is classed as intermediate in its resistance to fusarium wilt.

The SOUTHLAND reported by Andrus (1948) is a general purpose variety. It has resistance to collar rot and early blight. Moreover, it is moderately resistant to phytophthera and alternaria blights, and is almost immune to fusarium wilt. SOUTHLAND is claimed to be relatively resistant to fruit cake, puff, and blossom-end rot.

In addition to wilt resistance, unless a tomato for the South has the ability to set fruit during hot weather, its seasons of production will be limited. One that combines these two factors is the ALL SEASON developed in Louisiana (George, 1949). The pink color of its fruit, however, is a drawback on some markets.

For winter and spring production, where the variety must set fruit under cool temperatures and low light intensity, the LAKELAND described by Skirm (1948) may have a place. It is not as susceptible to fusarium wilt or mosaic as is RUTGERS, which it might replace, but the fruits are free from radial cracking and almost free from circumferential cracks.

The spotted wilt virus is under intensive study in Australia and the United States. So far no highly resistant varieties have appeared. The most ambitious breeding program for spotted wilt resistance in the tomato is in Hawaii. There the multiple objective is for resistance to spotted wilt, gray leaf spot, nematode, tobacco mosaic, and fusarium wilt, along with high-yielding ability, top quality, and high vitamin C content. Frazier, Kikuta, and Hendrix (1947) reported their progress in this program. The first variety to be released from this work by Kikuta, Hendrix, and Frazier (1945) is PEARL HARBOR. This was from a cross between BOUNTY and BC-10 developed by the California Experiment Station. BC-10 was a F_6 selection of 133-6 x *L. pimpinellifolium* backcrossed to 133-6. PEARL HARBOR shows a high degree of resistance to spotted wilt in Hawaii. Since this resistance is transmitted to the F_1 progeny of crosses, the authors suggest that F_1 hybrid seed with PEARL HARBOR as one parent might be useful. This may not prove satisfactory, however, because Hutton and Peak (1949) have shown that the character

for spotted wilt resistance is not only highly recessive but also dependent on multifactorial inheritance. The linkage between the resistance and the *L. pimpinellifolium* growth characters is such that the resistance is lost as succeeding generations approach desirable commercial characteristics.

Smith and Gardner (1950) have pointed out that under severe epidemic conditions, so-called spotted wilt resistant varieties become diseased. When spotted wilt is less epidemic, they make satisfactory growth and set fruit, while susceptible varieties are severely damaged. This confused situation may be due to the existence of several strains of virus. Holmes (1948) accounted for the susceptibility of PEARL HARBOR to spotted wilt in New Jersey by the presence of a strain of the causative virus different from that occurring in Hawaii.

According to Norris (1946), the spotted wilt virus is a complex of 5 distinct strains: the Tip Blight, Necrotic, Ringspot, Mild, and Very Mild. In his studies, *L. peruvianum* appeared to be immune to the last 4 strains of the spotted wilt virus and highly resistant to the Tip Blight form. Therefore, the development of a resistant variety undoubtedly will have to come from the crossing of *L. peruvianum* with *L. esculentum*, a cross which is facilitated by the embryo culture technique of the hybrid embryo as demonstrated by Smith (1944).

Cabbage yellows is an important disease on many soils, particularly in the northern states. Research at the Wisconsin station has shown that resistance is inherited in two ways. One type is a quantitative character controlled by a number of genes and affected by high temperatures and the nutrition of the plant. The other is a qualitative character controlled by a single gene, *R*, completely dominant to the susceptible gene, *r*. The latter type is the better and has been incorporated in each of five early and midseason varieties of cabbage (*Brassica oleracea* var. CAPITATA, L.) by Walker and Jolivette (1948) who compared these with susceptible varieties of the same maturity groups. The resistant varieties are WISCONSIN GOLDEN ACRE, RESISTANT DETROIT, RACINE MARKET, MARION MARKET, and GLOBE. The single factor resistance was also introduced into late-maturing varieties. Walker *et al.* (1948) described the IMPROVED WISCONSIN BALLHEAD and compared its growth characteristics with that of late susceptible varieties. Work on WISCONSIN HOLLANDER to which the single gene for resistance has been added is still in progress.

Resistance to nematode, *H. marioni*, is one of the great needs in vegetable production, especially with warm-season crops planted in the southern and western United States. It is one of the most difficult problems facing the vegetable breeder. More progress has been made with

the tomato than with any other vegetable crop. Watts (1947) obtained cuttings from a F_1 plant developed by Smith (1944) from a cross between MICHIGAN STATE FORCING (*L. esculentum*) and *L. peruvianum*, P. I. 128,-657 through the use of the embryo culture technique. The F_1 clone is self-sterile. Watts succeeded in crossing the F_1 clone with commercial varieties and obtained one strongly resistant plant, which was self-fertile. His results indicate that the nematode resistance is controlled by two dominant factors.

Frazier and Dennett (1950), using Watts' material, note that resistance is not a matter of preventing nematode entrance but of counteracting gall formation. A high degree of resistance was passed on to the F_4 progeny of crosses with commercial varieties. A fruit diameter of 2 inches or more has been obtained, but further back-crossing is necessary to get commercial types. The authors suggest that the high dominance of resistance may make possible the early commercial use of F_1 hybrid material.

In 1938 a new race of *Erysiphe cichoracearum*, D C threatened the Imperial Valley cantaloupe industry. All commercial varieties of cantaloupes, including POWDERY MILDEW RESISTANT NO. 45, were susceptible. Pryor, Whitaker, and Davis (1946) described the steps taken to meet this new race of mildew. Returning to some of the material originally developed in the course of breeding of POWDERY MILDEW RESISTANT NO. 45, they found a gene for resistance to this second race of mildew in the *Cucumis Melo* imported from India. This was incorporated into No. 45 and other commercial varieties so that by successive crossing and back-crossing, three new varieties, No. 5, 6, and 7 have been developed all highly resistant but not immune to both mildew races. Of these, No. 6, is the most popular commercially.

Ivanhoff (1945) outlined the development of TEXAS RESISTANT NO. 1 cantaloupe, which is high-yielding in the absence of pests and shows considerable resistance to downy mildew and aphids.

Resistance to a form of pepper mosaic occurring in Puerto Rico has been introduced into the CALIFORNIA WONDER variety of pepper (*Capsicum frutescens*, L.) by Riollano, Adsuar, and Rodriquez (1948) by crossing it with a Mexican hot pepper, CAIARESMENO. Pungency and disease resistance were found to be inherited as single genetic factors. A number of resistant lines with acceptable market qualities have been developed but are as yet unnamed.

V. Utilization of Heterosis

The potentialities in the use of heterosis appear unlimited, but each vegetable crop presents certain problems in the production of F_1 seed and in the commercial advantages which may be obtained by its use. Ashton (1946) has given a comprehensive review of the research having to do with the exploitation of heterosis with vegetable crops among others.

The widespread employment of F_1 hybrids in sweet corn production and the extensive developmental program with this crop have stimulated interest in the possibility of capitalizing on this genetic phenomenon in the production of other vegetables.

1. Sweet Corn

The F_1 hybrid sweet corns (*Zea Mays*, L.) have almost eliminated the older open-pollinated varieties in the commercial production of sweet corn in the United States. Perhaps the relative ease of producing hybrid seed and its consequent minor cost have supplemented the natural advantages to be derived from its use. New hybrid sweet corns continue to appear yearly. Singleton (1948) has reviewed the historical background, particularly in relation to the program of the Connecticut Agricultural Experiment Station, which has been a leader in this work. He points out that the great need now is a comprehensive study of quality in inbreds. Doty *et al.* (1945) have demonstrated that inbreds differ in their sugar content at harvest time and in the rate at which the sugar is changed into polysaccharides during marketing or holding.

Earliness is an important economic factor in growing sweet corn for market in many parts of the country. This involves both the adaptation of a given variety to planting as early in the spring as possible, even while growth conditions are sub-optimum, and the possession of the ability to make the maximum rate of growth in order to reach market maturity quickly. An approach to this latter problem has been suggested by Haskell and Singleton (1949), who tested 17 lines of sweet corn, mostly inbreds. They compared germination when seed was held in moist soil at 50°F. for 32 days before removal to a warm greenhouse with that of seed planted directly in the field at the earliest possible date. They found a significant correlation. The controlled temperature method, they believe, is more severe than the field conditions but may serve as a means of pretesting for cold resistance and may reduce the number of lines which would need to be planted in the field. There is considerable variation between lines. The ability to germinate at low temperatures

seems to depend more on the genetic constitution of the embryo than on the sugar-starch relationship of the endosperm.

The release of a new sweet corn inbred, Oh55, has been announced by Park (1949). It has been crossed with Connecticut inbred C53 to give the BROOKHAVEN, and with C68 to give the PERSHING varieties. These two F_1 hybrids have shown outstanding resistance to the corn earworm in four years' trials in southern Texas.

2. Tomato

Hybrid vigor in tomatoes has been extensively investigated and the older literature well reviewed. Already there are a number of F_1 hybrids named and available through commercial channels. Several problems remain to be solved, if the use of hybrid tomato seed is to assume importance commercially. The shift toward the use of F_1 hybrids in tomato has not been as spectacular as with sweet corn.

Powers (1945) found in his studies that the greatly increased yield of his best F_1 hybrid over the best yielding variety, DENMARK, was due to an increase in earliness. He concluded that all of the high producing F_1 hybrids had at least one parent derived from crosses between *Lycopersicum esculentum,* Mill. and *L. pimpinellifolium,* (Jusl.) Mill.

Munger (1947) compared for two successive years the yielding ability of F_1 hybrids of EARLIANA X VALIANT and EARLIANA X RUTGERS with the standard early varieties, EARLIANA, VALIANT, and VICTOR. The F_1 of EARLIANA X VALIANT gave significantly greater early yields than any of the others. The other F_1 was better than EARLIANA or VALIANT. There was little difference in the size of marketable fruits (over 3 ounces) between the varieties.

Shifriss (1945b) announced the release of the BURPEE HYBRID tomato. Since then the BURPEE'S BIG BOY, BURPEEANA EARLY HYBRID, FORDHOOK HYBRID, and CLINTON HYBRID, all F_1's, have been introduced and are available commercially. He pointed out that there may be a remarkable increase in the number of fruits set on each plant, compared to the parents. These fruits may be mutually inhibitive, or carbohydrate production may be inadequate. As a consequence smaller sized fruits are produced than would be anticipated in the F_1 progeny, which should have fruits about intermediate in size compared to the two parental forms. The counteraction of this size effect may call for radical changes in fertilizer and other cultural practices. Shifriss (1947) believes that the greater yield of hybrids is due to the greater absorption of nutrients and to the ability to utilize them to advantage. They would therefore have to be well fertilized if their ultimate potential were to be realized.

Spacing influences yields and would be related also to the need for

optimum supplies of nutrients and moisture. Larson and Currence (1944) studied the effect of 2-, 3-, 4-, and 6-foot spacings of plants in *4-foot rows, on the early yield, total* yield, and fruit size of 4 hybrids and the PRITCHARD variety. Not all the strains responded in the same way to a change in spacing, depending apparently on their inherent plant size. Early yield per acre was significantly greater at a 2-foot spacing than at the other spacings. The total yield per acre was significantly less at the 6-foot spacing than at the others. The 2- and 3-foot spacings gave significantly smaller fruit than those at 4 and 6 feet. Hybrids which developed their maximum size at a close spacing failed to increase it at wider spacings.

Not only do cultural practices influence the results with F_1 hybrid tomatoes, but soils are important also, as shown by Larson and Marchant (1944). They compared three F_1 lines on two soil types in locations where the mean temperatures were approximately the same. Since the hybrids did not behave the same on the two soils, the authors concluded that it will probably be necessary to develop F_1 lines for specific soil types. This might make the use of F_1 hybrids as complicated as is the production of the seed itself.

According to Larson (1948), Currence has compiled data on the relationship between the best yielding hybrid and the best yielding standard variety in trials in eight scattered geographical locations in the eastern and central United States. The average increase in yield in all the states was 32 per cent. This increase in yield in F_1 hybrids which usually is accompanied by earliness would well justify the expense of the more costly hybrid seed, provided fruit size is adequate.

It is toward the development of techniques for producing hybrid seed at a minimum cost that considerable recent research has been directed.

The use of complete male sterility in contrast to the semi-sterility suggested by Currence (1944) has been recommended by Rick (1944) as a means of avoiding the necessity for emasculation. In further studies (Rick, 1945), male sterile mutants were found fairly readily, about 5 per cent of all unfruitful plants or 0.005 per cent of all plants; in all varieties investigated Rick (1948) noted that male sterility in each mutant was due to a different single recessive gene. No mutants for female sterility or cytoplasmic male sterility were found. All but one of the mutants so far studied yield 50 per cent male sterile individuals by backcrossing while that one, *ms5*, produces functional pollen and so is reproducible in 100 per cent of the progenies obtained by self-fertilization.

Although the tomato is normally self-pollinated, variations in the rate

of natural cross-pollination might be utilized with male-sterile mutants to avoid hand pollination as well as emasculation. Rick (1947) studied the effect of the planting arrangements of male-sterile and female plants on the seed production in male-sterile plants through the activity of native solitary bees at Davis, California. The highest yield of hybrid seed for vector transmission of pollen was 4 per cent of that from fertile plants. Vector activity in different regions of California measured in the same manner has been reported more recently (Rick, 1949). Rates of natural cross-pollination in different localities fluctuated greatly, the yield of hybrid seed varying from 2 to 47 per cent of that of the fertile-plant yields. Whether or not the natural vectors alone could be relied upon to produce satisfactory crops of hybrid seed on male-sterile plants, it is demonstrated that they can substantially supplement yields produced by hand pollination.

Roever (1948) reported a type of functional sterility in which the anthers fail to dehisce. This was due to a simple recessive gene, which could be easily incorporated in other desirable parent lines. It can be maintained as a pure line by hand pollination for use as a female parent. Larson and Paur (1948) described this recessive mutant in greater detail. It is a gamopetalous type with the extremity of the corolla coalesced, preventing the discharge of the pollen.

With the use of some one of these forms of sterility in lines with good combining ability and the employment of the mechanical pollen collector of Cottrell-Dormer (1945), the time necessary to produce an ounce of seed might well be reduced to 30 or 45 minutes. This would make hybrid seed more reasonable in cost and lead to its extensive use in commercial tomato production.

Larson and Currence (1944) compared the yielding ability of F_1 and F_2 lines of tomatoes with those of the parents. The average increase in yield of the F_1 over the parental average was 39 per cent, while that of the F_2 over the parental average was 23 per cent. The use of F_2 seed would be another way of avoiding the high cost of F_1 seed, provided the F_2 populations are not undesirably variable.

3. Pepper

Martin (1949) reported the discovery of a male-sterile strain of cayenne pepper (*Capsicum frutescens*, L.) which may expedite the production of F_1 hybrid seed. Since the cost of obtaining F_1 hybrid seed by hand pollination is almost prohibitive, he studied the potentialities of F_2 progenies of fertile inbreds the seed of which could be produced at a reasonably low cost. The F_2 seed of certain lines gave larger yields than the inbreds but not equal to that from the F_1 seed. In the most

desirable line, the F_2 gave an increase of 428 lbs. of dried pepper per acre over the inbred, and the F_1 270 lbs. over the F_2.

4. Carrot

Welch and Grimball (1947) found a male-sterile plant in the carrot variety TENDERSWEET (*Daucus Carota*, L.). This has potential use for the easy production of F_1 hybrid seed which should result in uniform sized roots and tops, and uniform color of roots which would be of material advantage in the commercial production of bunched carrots.

5. Onion

The utilization of hybrid vigor in onions (*Allium Cepa*, L.) is developing rapidly. Some F_1 hybrids are available commercially, being produced by the use of male-sterility, which has been described by Jones and Clarke (1943). All the plants with normal cytoplasm, *N*, produce viable pollen. When the sterile type of cytoplasm, *S*, is in combination with the recessive gene for male sterility, *ms*, no viable pollen is produced, but if it is present with the dominant gene, *Ms*, then viable pollen is produced.

In order to maintain the materials for the production of F_1 hybrid seed without emasculation and hand pollination, it is necessary to carry along certain lines: a male-sterile line with the genotype *S ms ms* and a fertile line with the genotype *N ms ms*. All the progeny from crossing these two will be male sterile. The male-sterile line so maintained is then crossed by natural vectors with the particular male-fertile inbred parent showing the best combining ability. It may have the genotype *N Ms Ms*, *N Ms ms* or *N ms ms*.

Jones and Davis (1944) report that the male sterile character has been incorporated in almost all important commercial varieties. Resistance to thrips and various diseases is readily introduced into the F_1 hybrids in some cases. Among the advantages gained by the use of F_1 hybrids can be great size, as in CALIFORNIA HYBRID RED NO. 1, if that is desired. Far more important, however, are uniformity of maturity and size of bulb. These factors are important in the mechanical harvesting of onions and in reducing the grading necessary for market preparation.

6. Eggplant

A beneficial effect on yield from the planting of F_1 hybrids of the eggplant (*Solanum Melongena*, L.) has been demonstrated by Odland and Noll (1948). The size of fruit produced by the F_1 plants was about the same as the mean of the fruit size of the parents. The increase in yield was due, therefore, to the setting of more fruits per plant. They

noted also a greater uniformity in size of fruits of the F_1 plants than on the parental lines. The early yield on the hybrids was greater than on the parents, and this was correlated with the larger total yield. The mean yield of all 16 hybrids used in their studies was 62 per cent greater than the mean yield of all the parents. The highest yielding hybrid produced 17.25 tons more fruit per acre than the highest yielding parent. NEW HAMPSHIRE HYBRID (not a F_1) X FLORIDA HIGHBUSH gave F_1 progeny which outyielded significantly all parent varieties and all hybrids except EARLY LONG PURPLE X NEW HAMPSHIRE HYBRID.

7. *Squash*

Male sterility in squash (*Cucurbita maxima*, Duch.) was reported by Scott and Riner (1946). They found that a single recessive gene conditioned the abortion of the androecium in the bud stage with consequent absence of pollen. This factor is inherited as a single recessive. Thus no pollen is produced. This characteristic should make the production of F_1 hybrid seed a simple process. It may be worthwhile to explore the possibility of hybrid vigor in squash with this male sterile character, as Hutchins and Croston (1941) found in their study of 10 F_1 hybrid lines that increased yield over that of the higher yielding parent occurred in 7 cases, while in the other 3 the yields were not greatly different. This was a combined effect of maturity, weight per fruit, and number of fruit per plant. It appeared that this heterosis effect was more pronounced when the parents differed considerably in their readily observable characteristics than when the parents were closely related.

Curtis (1942) described the YANKEE HYBRID, a yellow straightneck summer squash (*Cucurbita Pepo*, L.), which is a F_1 resulting from a cross between EARLY PROLIFIC STRAIGHTNECK and an inbred, CONNECTICUT NO. 10. The very early production of female blossoms leads to a profitable large early yield, although the total yield through the whole growing season may not differ much from that of the EARLY PROLIFIC. Curtis recommended that the 2 inbred parental lines be planted in alternate rows, isolated at least 2 miles from other squash plantings. All male blossoms should be removed from the plants in the row which is to be the female parent.

Shifriss (1945c) discussed a form of male sterility in *C. Pepo*, similar to that reported later in *C. Maxima* by Scott and Riner (1946). To get the hybrid seed, all the male fertile plants in a backcross population are removed in one roguing. Since the staminate blossoms appear 7 to 14 days ahead of the female blossoms, it is simple to take one male blossom from each plant and determine by quick examination whether the androecium is shrivelled. If this form of male sterility were introduced into

the horticultural varieties of *C. Pepo,* it would facilitate the production of F_1 hybrid seed at low cost.

8. Cantaloupe

Hybrid vigor in the cantaloupe or muskmelon (*Cucumis Melo,* L.) was studied by Munger (1942). Three F_1 hybrids between a fusarium resistant selection No. 13 and BENDER, HONEY ROCK, WEAVER SPECIAL, or QUEEN OF COLORADO were included in 4 field experiments in New York. Considering his experiments as a whole, the hybrids as a group yielded more fruit than their parents. The yield of fruits from the hybrids was about the same or a little less than that of BENDER, the popular variety of the area. When yield of flesh and sugar were used as the criteria, the hybrids produced a higher proportion of flesh and much more sugar than BENDER. The hybrids usually led in the production of early fruit although in most cases the differences were not great. Munger suggested that where disease resistance is dominant, hybrids may provide stop-gap control until true breeding varieties are developed. For example, a F_1 between No. 13 and POWDERY MILDEW RESISTANT NO. 45 carried resistance to both fusarium wilt and powdery mildew. It was of good quality and appearance. As with other crops, however, the cost of F_1 hybrid seed may be a deterent to its use.

A recent development in this field was the discovery by Bohn and Whitaker (1949) of a simple recessive gene for male sterility in the muskmelon. Meiosis is apparently normal, but the development of the mother pollen cells seems to end at the tetrad stage. This male sterile mutant could be useful in breeding work as well as simplifying the production of F_1 hybrid seed for commercial plantings.

9. Cucumber

Shifriss (1945a) developed the BURPEE HYBRID cucumber (*Cucumis sativus,* L.) from an inbred line of a temperate zone cucumber crossed with that of one from the tropics. While not immune to disease, it shows considerable resistance to downy mildew, mosaic and wilt.

10. Cabbage

In a comparison of 7 standard varieties of cabbage (*Brassica oleracea* var. *capitata,* L.) with an equal number of F_1 hybrids, Odland and Noll (1950) found that the yield of the hybrids was 31 per cent greater than that of the standards. To take advantage of this hybrid vigor, they have outlined a six-step procedure for the production of F_1 seed without the necessity for hand pollination.

Four inbred lines, two each of two varieties, all homozygous for self-

incompatibile genes are combined in a manner similar to that used in the production of double-crossed corn. The inbred lines and the F_1 hybrid in each variety constitute lines which are completely self-incompatible, yet entirely cross-compatible in both directions. This plan should make practical the commercial growing of hybrid seed, once the proper inbreds with good combining ability are developed.

11. Asparagus

The dioecious condition in *Asparagus officinalis*, L. might be utilized to circumvent hand emasculation and hand pollination in the production of F_1 hybrids. Randall and Rick (1945) suggested a method in which homozygous pistillate lines could be developed from haploids that occur naturally in twin seedlings and inbred staminate lines from the occasional seeds produced by self-pollination in certain staminate plants, described by Rick and Hanna (1943).

VI. Growth Control Techniques

There is always an interest on the part of those concerned with vegetable production in any procedure that will simplify operations or make more certain that the ultimate goals of maturity date, quality and yield are attained.

1. Plant Production and Handling

In southern areas, where the season is earlier, the vegetable industry has made an extensive practice of growing and shipping plants for transplanting into fields in the North. This is very common on the East coast and to a lesser extent in the western states. Problems exist in the transportation and handling of such plants and in the employment of techniques which will aid them in resuming growth when put in their final position.

More than 10,000 acres were devoted to tomato plant beds in Georgia alone during 1946, according to Miller *et al.* (1949), who studied various methods of shipping the plants to northern growers by rail and air. They concluded that enough bunker ice should be used in the refrigerator cars to reduce plant temperatures to the range of 50° to 70°F.; higher or lower temperatures were found injurious to subsequent growth. This cooling would require 5,000 lbs. of ice per car if outside temperatures were between 70° and 80°F., and 6,000 lbs. if they ranged between 80° and 90°F. Diagonally opposite vents should remain open. Fan cars iced in the same way are preferred if available and should move with vents closed. Shipment by airplane cuts the time in transit to about

one-sixth of that required for rail movement. The plants for air shipment should be placed on wet peat moss in crates.

How the plants should be held if unfavorable weather conditions faced a grower when he received his shipment was another aspect of this problem that has been studied by Thomas and Moore (1947). Plants were sent from Tifton, Georgia, to Lafayette, Indiana. Three shipments arrived with lapses of 2 days, and the fourth after 3 days en route. All were put in the field when the last one arrived. The other three had been held 3, 5, or 7 days in a dry room at 70°F. There were 8 bundles of 25 plants, each packed with peat moss in a ⅝ bushel hamper. One hamper of each shipment was moistened by standing in 3 inches of water for 5 to 10 minutes daily. A significant decrease in stand and in the average number of leaves left on each plant was evident at the end of 7 days in the field, when the plants were held longer than 3 days in storage. After 16 days in the field, the plants in both lots held 7 days and in that held 5 days without moistening had fewer leaves than the other lots. Early yield, but not total yield, of fruit was significantly greater in the plants set immediately or held for only 3 days than in those held 5 or 7 days.

One explanation for the results of Thomas and Moore may have been the exhaustion of the carbohydrate reserves during the period in transit and storage. Went and Carter (1948) experimented with the application of solutions containing 10 per cent sucrose and 0.025 per cent sulfanilamide with a little drene as a wetting agent. When this mixture was sprayed on leaves of tomato plants held in the dark, apical growth measurements showed that the sugar was absorbed more readily through the lower epidermis than through the upper one. Growth, even in the latter case, was almost twice that of the unsprayed controls. As a result of this and other experiments, Went and Carter suggested that if tomato plants were sprayed with a sugar solution just before shipping, they would not suffer the setback so commonly observed.

These authors noted also beneficial effects of sugar applications to the foliage of tomato plants growing at high temperatures and low light intensities. Smith (unpublished) utilized this technique in California on tomato plants at the time they were transplanted from the plant bed to the field. It very definitely reduced the number of plants lost where field setting was done at high temperatures. No beneficial effect was noted under moderate temperatures.

Another possible means of avoiding this loss of plants is suggested by the work of Burgis (1948). He reported that spraying the tops of tomato plants with a 10 per cent aqueous solution of Geon 31 X, a synthetic latex, before they were pulled from the plantbed, or dipping them

in such a solution as they were pulled, caused the plants to be stiff and easy to handle in the transplanting operation. The treated plants showed much less wilting the day after being transplanted to the field than did those not given the latex treatment.

In his desire to place his crop on the market at the earliest possible moment under his local climatic conditions, the grower usually starts his plants under some sort of protection. Even though they suffer a check when transplanted to the field, a gain in earliness of maturity is still usually obtained. Cauliflower is one of the most difficult crops to handle in this way because of its tendency to "button," or apparently to develop a curd too soon, with accompanying restricted leaf growth. Carew and Thompson (1948) studied the factors responsible for this development. They concluded that the curds in the so-called prematurely heading plants are no further advanced than in those hidden by normally developed foliage. "Buttoning," however, was increased if the plants were held in flats beyond the best stage of development for transplanting to the field and if the soil in the field had a low level of available nitrogen thus preventing vigorous vegetative growth. Contrary to common belief, checking the growth of the young plants by exposure for about 3 weeks to a temperature range of 40° to 50°F., or keeping the soil moisture low in the plant bed effected a decrease in later "buttoning."

2. Fruit Set

It has long been known that tomato blossoms fail to pollinate themselves when temperatures are too low or too high, when there is no wind to agitate them, or when certain physiological processes are at a minimum. Went (1944) made extensive studies of thermoperiodicity, that is, diurnal fluctuations in temperature, in relation to the growth and fruiting of tomatoes. He placed particular importance on the night temperature. Fruit set failed to occur, or was reduced, if the night temperatures were below 59°F. or above 68°F. Varieties differed somewhat in their critical minimum night temperature.

Inasmuch as temperature is important in the setting of vegetable fruits and little can be done about it aside from making some adjustments in planting dates, investigators have sought artificial means of aiding fruit set under field conditions. A delayed planting date might give the grower a yield of tomato fruits, but would likely cause him to miss the high premium usually obtained for the first fruit to reach the market early in the season. Mitchell (1947) stated that growth-regulating substances have proved valuable in setting tomato fruits under greenhouse conditions, but no consistent effect has been obtained out-

of-doors. No improvement in yield of MARGLOBE tomatoes grown in the field was noted by Murneek (1947) in Missouri. He used β-naphthoxyacetic acid at 20 to 100 p.p.m. and *p*-chlorophenoxyacetic acid at 10 and 20 p.p.m., applied at weekly intervals from mid-June to late September, some concentrations on whole plants and others on the flowers only. The only effect observed was a maximum increase of 15 per cent in fruit size by application of the most concentrated solutions of the two growth substances. He concluded that hormone sprays are of no value for field-grown tomatoes except possibly where sunlight is subnormal.

On the other hand, Wittwer, Stallworth, and Howell (1948) found that the minimum night temperatures during June in Michigan are below the optimum range of 59° to 68°F. suggested by Went (1944). Under these conditions, a 25 p.p.m. *p*-chlorophenoxyacetic acid spray applied to the first flower clusters of VICTOR and RUTGERS varieties planted for early market gave a significant increase in number and size of early fruits. Even with RUTGERS, grown for canning from southern-grown plants and not commencing to bloom until July 9, spraying the first, second, and third flower clusters increased the early and total yields and the fruit size by about a half ounce over the controls.

During 1945 to 1947, Mann and Minges (1949) conducted 29 experiments in widely scattered areas in California where market tomatoes flower under cool temperatures. They used β-naphthoxyacetic acid, *p*-chlorophenoxyacetic acid and its sodium salt, and 2, 4-dichlorophenoxyacetic acid, all applied as aerosols, water sprays, or in dust carriers to the flower clusters as a whole. Each growth substance was used through a range of concentrations, which were not necessarily the same for all four materials. In all tests the treated blossoms produced larger fruits than those of the check plants but size varied with the chemical used, its concentration, and the carrier. This greater fruit size was considered in part the reason, at least in some of the experiments, for the increased early yields on treated plants. The growth-substance treatment seemed to shift the yield of fruit to an earlier part of the season rather than to increase the total yielding capacity of the plants. All combinations of growth substances and carriers were effective in setting fruit. A single spraying of a solution of 50 p.p.m. of 4-chlorophenoxyacetic acid gave the most consistent results.

That the application of growth-regulator sprays may be effective when night temperatures fail to drop below the 77°F. maximum noted by Went (1944) is evident from the work of Mullison and Mullison (1948). In Caracao where the minimum night temperature was above 78°F. and the minimum day temperature 83°F., rising to 90°F. or above, flower abscission is a frequent cause of poor fruit set. They grew by the gravel-

culture technique 3 nondeterminate varieties, INDIANA BALTIMORE, MICHIGAN STATE FORCING, and PAN AMERICA, with 3 determinates, PEARSON, VICTOR, and PRITCHARD. Of the growth stimulants used, *p*-chlorophenoxyacetic acid at 75 mg./l. gave the best fruit set and fruit size, with a very considerable increase over the controls.

Some growth stimulants have failed to give beneficial results, as was the case in the experiments of Paddock (1948). He made 3 applications to tomato plants in Texas during the month of April. The growth substances were either atomized on the inflorescences or applied to the whole plant in the pest control spray containing Copper Hydro and lead arsenate. Alpha-2, 4, 5-trichlorophenoxypropionic acid was used at 10 mg./l. while α 2-chlorophenoxypropionic acid was given at a 25 mg. rate. Yields were reduced markedly by applying either hormone with the copper and lead spray to the whole plants. Alpha-2, 4, 5-trichlorophenoxypropionic acid applied in this way caused considerable deformity of the plants. The yields from the plants receiving the atomized treatment of either of these two materials were not significantly different from those of the plants having the pest control spray without a growth substance.

An explanation for the sometimes conflicting results obtained by different investigators has been offered by Hemphill (1949). He found that the growth-regulating substances applied to young flower buds may delay their opening and also stimulate the development of rough, puffy fruits. Successful results can be obtained if the spray containing the growth substance is directed away from the terminal portion of the plant which bears young buds. Hemphill thought that the application should be delayed until 3 or 4 flowers in each of the several lower clusters have opened.

The effect on their composition by the hormone setting of tomatoes was studied by Holmes *et al.* (1948). They used PRITCHARD tomatoes set by the use of β-naphthoxyacetic acid at 50 p.p.m. There was no significant difference in the mineral or vitamin constituents between fruits set with the growth substance, with or without prior emasculation of the blossoms, and the fruits from untreated plants.

A warning as to a possible detrimental effect on the tomato fruits set by the use of growth substances has been given by Howlett (1949). Such fruits produced in greenhouses have a tendency toward premature softening 1 or 2 days after picking. Whether this softening will be a factor in field-grown tomatoes set with growth substances is not yet known.

Blossom and pod drop in pole, bush, and lima beans are sometimes a result of unfavorable conditions, especially of hot dry weather or of

insect activity. The results in the use of growth substances as correctives have been conflicting.

Wester and Marth (1947) obtained no significant effect in Maryland on the yield of pods of 13 varieties of bush lima beans from α-naphthaleneacetic acid applied in various concentrations in dusts and in sprays. The number of applications and their timing had no influence nor did the inclusion of boron. The natural setting of pods was good at the time they made their tests. Plants of the HENDERSON, PEERLESS, and FORDHOOK 242 bush lima varieties were treated by Clore (1948), in the State of Washington, with water sprays containing 0.5 per cent Carbowax 4000 and 5, 50, 100 or 1,000 p.p.m. of α-naphthaleneacetic acid. The yield from the 5 p.p.m. rate was not better than that of the untreated plot but as the concentration was increased above this, the yields were reduced very strikingly.

In Missouri, Wittwer and Murneek (1946) sprayed or dusted snap bean plants of several varieties 3 to 5 days after the appearance of the first flowers. In their experiments the treatments were given 1 to 5 times at weekly intervals. Para-chlorophenoxypropionic acid was more promising than α-*o*-chlorophenoxypropionic acid, β-naphthoxyacetic acid, or 2, 4-dichlorophenoxyacetic acid. The best concentrations of this material was 2 p.p.m. in a water spray, or 25 p.p.m. in a dust if 50 lbs. of dust were used per acre. Large benefits in yield were obtained when flowering occurred in hot weather. Even when conditions were favorable for fruit setting, there was a gain by the use of the growth regulator. The authors expressed the belief that growth regulators are not likely to be effective where seed formation and development are important, as in peas, lima beans, and dry shell beans.

Fisher, Riker, and Allen (1946) in Wisconsin used IDAHO REFUGEE and ROUND POD KIDNEY WAX beans. Their most effective growth stimulant was α-naphthaleneacetic acid applied in dust form to the wax beans; it was not helpful, however, on the green beans. Sprays were usually detrimental. Dusting twice with 70 p.p.m. and 140 p.p.m. gave a slight increase in yield in their first year's tests. This yield might have been better had not rain followed each dusting. The next year, without rain interference, a 24 per cent increase in yield was obtained by the use of 40 p.p.m. and 12 per cent from 80 p.p.m.; 160 p.p.m. decreased it. The authors concluded that the increase in yield from the treated plants was due to an increase in the number of beans produced rather than to any effect on size.

Para-chlorophenoxyacetic acid at 2 p.p.m., sprayed on TENDERGREEN BEAN plants twice a week during August, in New York, by Randhawa and Thompson (1948) for a total of 5 applications, increased the total

yield. Beta-naphthoxyacetic acid and α-*o*-chlorophenoxypropionic acid gave no significant increases, while 2, 4, 5-trichlorophenoxyacetic acid depressed the yields. The second year of the experiments, when the beans flowered in July, the early yields were increased but not the total yields by 3 sprayings at weekly intervals in the case of all the materials. Not all of the concentrations used gave increases in yield. The beneficial effect seemed to be the darker green color, uniformity, and increased length of pods compared with those of the untreated plots. There was no difference in the number of seeds. No significant difference in the ascorbic acid content of the beans from the sprayed and check plants was found.

3. Growth Inhibition

Growth substances have been used also to retard the metabolic activities of vegetables. In an attempt to extend the marketing period of cauliflower, Carolus, Lee, and Vandermark (1947) used the methyl ester of α-naphthaleneacetic acid to check the formation of an abscission layer in the leaf petioles around the curd to delay the yellowing of the petioles; and to reduce loss in weight of the head. When the cauliflower heads were held at 32°F. and 80 to 90 per cent relative humidity, 100 mg. of the chemical sprayed on the leaves, or placed on shredded paper in a paper bag enclosing the head, was markedly effective in retarding the undesirable changes.

Isbell (1948) studied the effect of dusts containing 2.2 per cent of the methyl ester of naphthaleneacetic acid or of methyl 1-naphthaleneacetate on kohlrabi, turnips, potatoes, and sweet potatoes, using one lb. of dust to 8 to 10 bushels of the vegetable. The sprouting of potatoes was delayed by the treatment. While sprouting of sweet potatoes appeared to be delayed, there was some evidence of internal injury. Untreated lots of kohlrabi and turnips had more usable individuals at the end of the storage period than did the treated lots.

On the other hand, Smith (1946) reported the successful retardation of root and shoot growth of carrots, beets, rutabagas, and turnips during storage by the use of the methyl ester of naphthaleneacetic acid, applied by either the dust or the impregnated shredded paper techniques.

VII. Labor Saving Devices

In addition to planting varieties that will yield well in spite of the presence of pests, and to fertilizing and irrigating the plants so that the maximum yield can be obtained, the grower is able also to cut his unit

cost of production by the utilization of mechanical aids and cultural techniques.

Hand labor is usually expensive, either because of the hourly wage or because of inefficiency. Thus any technique that will increase the hourly output per worker helps the grower.

1. Direct Field Seeding

Certain vegetable crops have been started customarily in some form of plantbed where they could be provided with close supervision while awaiting suitable seasonal conditions in the field. This has been true particularly in the case of tomato and celery. Transplanting does check the growth of the plants and may reduce the yield.

Recently there has been a decided swing to the direct-field seeding of these crops. Half the acreage of cannery tomatoes in certain of the midwestern states is currently so planted and much of that in California both for canning and for the fresh market in the fall and winter months. More than half of the celery for late fall harvest in the central coastal district of California has in recent years been seeded directly in the field where the crop is to mature.

Several problems arise in direct-field seedings. One is the matter of weed competition with the small seedlings. The pre-emergence spraying of the planted field with a material which does not have a deleterious influence on the germination of the crop seed has greatly reduced the weed problem. Furthermore, selective oil sprays can be used to eliminate weeds from among the young celery plants.

Providing a proper moisture supply under field conditions is sometimes difficult. Doneen and MacGillivray (1943) have classified vegetable seeds into 4 groups, depending on their ability to extract moisture from the soil in the process of germination. Tomato seed was able to absorb water fairly well when the soil moisture was close to the permanent wilting percentage, although germination would occur sooner if the soil moisture were higher than that. Of the 21 vegetables studied celery seed, on the other hand, was the least able to extract moisture from the soil. The moisture content had to be well above the permanent wilting percentage of the soil in order to get any germination at all, and close to the field capacity if satisfactory germination was to be obtained. Thus with celery seed great care must be exercised in direct-field seedings to see that the soil moisture content is held at a high level.

Another characteristic of celery seed is its slow rate of germination compared to many other vegetable seeds. Efforts have been made by Taylor (1949) to overcome this delay. He developed a technique for

prespouting hypochlorite-treated celery seed at an alternating temperature of 48°F. for 16 hours and 70°F. for 8 hours. After 8½ days, about 10 per cent of the seeds showed sprouts. When planted in the field, such seed began to emerge in 3½ days. This was approximately 2 weeks earlier than would have been expected from unsprouted seed.

Thinning of vegetable plants from seed planted directly in the field is an expense. Moreover, if the plants in the seeded row are too thick, or if thinning is delayed too long, there is likely to be damage to the root systems of the plants left after thinning. This may produce a check in growth that would be of some economic importance where speed of maturation from seeding to harvest is critical. The accurate spacing of each seed in the row does much to alleviate this condition and to make thinning easier, or to eliminate it altogether. This can be accomplished either by the use of drills which meter quite well those seeds that are naturally more or less spherical in shape, or by adding a material to the seeds which will make them spherical for subsequent use in a precision planter. The precision planter is the more important of the two. There is no point in making each seed into a spherical ball, if these are then to be planted at random in the row by the dispersion system.

Pelleted onion and carrot seeds can be sown where the plants are to mature. With crops such as lettuce, tomato, and others in which each plant should finally be 10 to 24 inches from its neighbors in the row, the job of cutting out the extra plants with a hoe is greatly simplified if a pelleted seed is dropped every 2 to 3 inches than if unpelleted seed were drilled at random. Moreover, the finger work to remove one of two plants standing very closely adjacent is eliminated.

Bainer (1947) described a number of precision planters, both of commercial and of modified types used in his tests: Cobbley, Rassmann, Milton, International No. 40, and John Deere Nos. 55 and 66. The planters were equipped with horizontal or vertical plates with a given size of cell for the size of seed to be planted, a cutoff to prevent more than one seed staying in each cell, and a knockout or ejector to make the seed leave the cell at the proper time. An important characteristic of a precision planter must be a smooth small tube (½ to ¾″) through which the seed falls from the metering device to the furrow. Any roughness in this tube will retard the fall and the seed will not be evenly spaced.

The Ventura bean planter with vertical rotors has been modified recently for precision planting of pelleted seed. Since no cutoff is needed, there is no cracking or injury of the built up coating of the seeds. A plexiglass tunnel or guide over the top of the cups enables the operator to see that the machine is feeding properly. As the plate passes the apex

of its rotation, the seed falls out of the cup against the back of the preceding cup. It is then ready to drop free at the proper moment. The plexiglass tunnel holds the seed from dropping sideways off the plate.

Some confusion exists in the use of the terms coating and pelleting. Some writers take the view that coating is building up one seed in size, while pelleting involves putting several seeds into a ball as for range reseeding.

The term coating might be more appropriate in cases such as that recommended by Newhall (1945), in which onion seed received a light treatment with methyl cellulose and then equal weights of seed and a dust containing Arasan or Thiosan were mixed together to give the seed protection from the soil-borne onion smut organism. The seed size was not increased greatly.

Pelleting, on the other hand, more aptly describes the procedure in which materials are added to a seed regardless of its original shape until it becomes more or less spherical. Two general processes have been used. By the method described by Vogelsang, Schupp, and Reeve (1947) the seed is alternately wet with a methyl cellulose solution as it revolves in a pan, and dusted with feldspar or preferably 65 per cent feldspar and 35 per cent flyash. The methocel binds the material to the seed, and the whole is built into a pellet. The other method, Burgesser (1949), involves the use of a special montmorillonite which is adhesive when damp, forming a hard pellet as it dries.

The increase in weight of each individual seed depends on the original shape. An onion seed can be built into a pellet 8 to 10/64 of an inch in diameter, with an increase of about 8 times its weight. On the other hand, the weight of each carrot seed is increased about 22 times to get a pellet the same size as that of the onion, and a lettuce seed 60 times for a pellet 10 to 12/64 of an inch in diameter. This increase in bulk makes for more expense in handling. Inasmuch as pelleted seeds should be accurately spaced, however, this means that far less seed is planted to the acre. The saving in seed may just about offset the cost of pelleting and the extra handling charges.

Linn and Newhall (1948) have compared onion seed coated with methyl cellulose plus a fungicide with pellets made by use of methyl cellulose plus feldspar and a fungicide. The latter were very hard balls, while the former were more or less mealy. It required plate hole 20 in a Planet Jr. No. 300 seed drill to plant about the same number of seeds per foot of the feldspar pellets, as were distributed by plate hole 10 for the coated seed, and plate hole 8 for the untreated seed. This was not precision planting. The authors noted that when this conventional type of seed drill was used, there was considerable cracking, splitting, and

crushing of the pellets. The two types of covering of the seed plus either Arasan or Tersan were about equally effective in the control of onion smut. Leach (1948) found that when a quantity of Arasan equivalent to 75 per cent of the seed weight was included in the coating of onion seed, emergence was delayed by 50 per cent. Coating onion seed with Arasan at 5 per cent of the seed weight, or without it, had no effect on germination or rate of emergence. In his studies, the coating of tomato seeds resulted in a slight delay in emergence but did not affect the percentage of germination. The addition of Arasan or Phygon to the coating material increased the protection, but organic mercury retarded and reduced emergence.

Vogelsang, Schupp, and Reeve (1947) experimented with additions to the pelleting material of superphosphate or of a 2-5-5 fertilizer at the rate of 5 to 10 per cent of the weight of the seed. The 10 per cent addition of superphosphate had the least injurious effect on emergence. They stated that fungicides would have to be applied to the seed greatly in excess of the recommendations of the fungicide manufacturers, if preemergence and post-emergence damping-off were to be controlled. In contrast, Burgesser (1949) stated that the results with the inclusion of fertilizing materials in the pellets have not been encouraging, largely because the quantity which could be incorporated without being toxic is but a few ounces per acre. He remarked also that growth-promoting substances, such as hormones and vitamins, have shown no consistent value.

Other problems have been pointed out by Carew (1949). Sometimes as much as 30 per cent of the pellets were "dummies," *i.e.*, contained no seed; the pellet had been formed around a bit of dirt or chaff by the methocel process. In other instances each pellet contained 2 or 3 seeds. These manufacturing details should be possible of correction since this condition has not been the general experience elsewhere. Carew cited the fact that there were sometimes 2 or 3 days delay in emergence of lettuce seedlings from pelleted seed, and as emergence was uneven, it tended to prolong the harvest period.

Bishop (1948) studied the effect of pelleting by the montmorillonite method on the seed and its germination. Lettuce, tomato, and onion seed were used. The pellets were crushed to remove the seed, or the clay was washed off with a stream of water. The freed seed was then compared with uncoated seed of the same lot, which was washed in an equivalent quantity of water. There was no difference in the germination behavior of the 3 lots, thus indicating that the pelleting process in itself had not harmed the seed. In uncovered cold frames and in field tests, the pelleted seeds germinated just as well, but at a slightly slower rate

than the uncoated seeds. The author believed this delay was of no commercial importance. The standard laboratory germination tests of naked and pelleted seed showed some reduction in germination due to pelleting. Vogelsang, Schupp, and Reeve (1947) have indicated that, under normal temperature conditions, the rate of emergence is the same, but when it is cool the pelleting may delay emergence by several days.

Plantings made with pelleted seeds fit well with the use of pre-emergence sprays and selective herbicides. If the pelleting delays emergence a few days, it may simplify the timing of a pre-emergence spray. The systems used by carrot growers have been described by Taylor (1949). Precision planting of seed and spraying with an oil spray after emergence means that the rows can be placed close together without danger of crowding the developing carrots and without the necessity of having a wide uncropped area between every two broad-banded rows. The practice of chiseling or deep loosening of the soil between the rows, which is so ingrained in the minds of many growers, can be eliminated. The tops are less leggy when the seed is pelleted and planted with precision machinery, because crowding is avoided. Even then, however, growers of carrots for bunching cannot count on having all their plants produce good, smooth roots of marketable size. Mann and MacGillivray (1949) noted that some carrot plants having plenty of space in the row, as would be the case if pelleted seed were planted, still developed roots too small for marketing. This small size was due in part to hereditary factors. The most important reason, however, was delayed germination. The percentage of carrot seeds with small or weak embryos ran high in some samples, even though the seed size was satisfactory. Slowly germinating seedlings suffered in competition with the foliage or roots of the more vigorous plants.

Carew (1949) suggested that wider use of chemical weed killers might be possible if pelleted seeds were planted. Activated carbon placed in the material surrounding the seed might protect it from the harmful effects of 2,4-D (2,4-dichlorophenoxyacetic acid), applied to the soil as a pre-emergence spray.

2. Use of Herbicides

Since it has been demonstrated that the principal benefit from the cultivation of the soil around growing plants is the control of weeds, methods have been sought to reduce the labor involved. Chemical weed control cannot completely replace, but should supplement, usual tillage operations. Crafts and Harvey (1949b) have reviewed the literature relating to the new weed control techniques.

This means of weed control has reached the stage of development

where it is possible for research institutions to publish specific recommendations for the use of herbicides on vegetables—for example, those of Carew (1949), Dunham, Crim and Heggeness (1949), and Crafts and Harvey (1949a). There are 2 main methods employed in chemical weed control in crops—pre-emergence and post-emergence applications. In the latter, selectivity must be considered, lest the vegetable plants as well as the weeds be killed. With some crops, so-called "stem sprays" can be employed. Here the spray is directed at the weeds and the very base of the plants, thus avoiding the foliage of the crop. Much work is in progress adapting the methods to species and varieties and evaluating the potentialities of the new materials, such as maleic hydrazide and others that are becoming available.

Research has shown that 2,4-D has varying effects on vegetable plants and seeds, depending on environmental conditions, especially temperature and moisture, and on the time of applications in relation to planting. Under moist soil conditions, the 2,4-D gives an effective control of weeds with a rapid disappearance of toxicity, whereas in dry soil the toxicity remains for a long period, according to Warren and Hernandez (1948) and Crafts (1949). That heavy rains following the application of 2,4-D made above germinating seed may cause injury to the developing seedlings is apparent from the studies of Dearborn, Sweet, and Havis (1948). Danielson (1948) obtained good control of the weeds in an over-wintered crop of spinach in Virginia by the preplanting use of 1.4 lbs. of the sodium salt of 2,4-D in 100 to 500 gallons of water per acre. When the spinach was planted 4 days after treatment of the soil in early November, the stand was poor; when seeding was delayed until 12 days after treatment, there was no injurious effect on the stand.

Sweet corn varieties differ in their susceptibility to 2,4-D injury. Dearborn, Sweet, and Havis (1948) applied one lb. of the ammonium salt of 2,4-D to small sweet corn plants of 8 varieties 14 days after planting. The foliage of LINCOLN and IOANA showed the least injury, while that of SENECA DAWN and NORTH STAR was most severely affected. The resistance of 18 varieties of sweet corn to 2,4-D was studied by Ellis and Bullard (1948). They used 0.7 lb. of the acid per acre as a sodium salt when the plants were 15 to 18 inches tall. The spray was directed toward the base of the plants, thus avoiding the leaves. The corn had received two prior cultivations. No significant difference was observed between the check and treated plots as to stand, yield of ears, or time of maturity. The 2,4-D had apparently caused brittleness in some varieties for a wind storm which occurred a week after the spraying, snapped off more plants of COUNTRY GENTLEMAN, WHITE HYBRID 3321, and HURON than of other varieties. Zink (1949b) gave 1, 2, and 3 lbs. per

acre applications of the sodium salt of 2,4-D to 12-inch high plants of 12 hybrid sweet corn varieties. The sprays were applied at the base of the plant. He thought that the more advanced physiological age of the quicker maturing varieties or the fact that not all varieties normally produce brace roots to the same extent would be responsible for varietal differences in resistance to development of collar effect about the stalk and of abnormal brace roots. Brace roots would provide for easy access of the 2,4-D. SENECA 60, MARCROSS, CARMEL CROSS, LINCOLN, and SENECA CHIEF were least injured.

The butyl ester of 2,4-D was used by Alban and Keirns (1948) for pre-emergence experiments with 25 different vegetable crops. An application of 0.66 lb. per acre held weeds in check for about 3 weeks; less than that amount failed to give good weed control. Moreover, 2, 3, or 4 times the 0.66 lb. rate eliminated or controlled all weeds for at least 6 weeks. Only sweet corn, snap bean, mung bean, potato, and asparagus developed satisfactorily following a pre-emergence application of 1.33 lbs. of the butyl ester per acre. These crops, plus tomato, peas, cucumber, and lima bean, grew well where 0.66 lb. of the ester were applied per acre. The other 16 crops did not tolerate a concentration which would control weeds.

Great reliance has been placed on oils as herbicides. Quite specific recommendations are being made for their use as pre-emergence sprays or as selective sprays. For pre-emergence work, it appears important that the crop seed be planted deep enough to allow maximum germination of the weeds to be killed off before the crop seedlings emerge. This has been stressed by Nixon and Smith (1949) for the elimination of weeds in tomato plant beds and would hold true, of course, for any planting where a pre-emergence herbicide treatment is to be made.

Havis (1948) studied the effects of 31 pure hydrocarbons of the aromatic, olefin, and paraffin series on peas, lettuce, spinach, carrot, onion, and timothy. These hydrocarbons had boiling ranges from 80° to 300°C. Those with a boiling range between 150 and 275°C. were in general more toxic than those with a higher or a lower boiling range. Stoddard Solvent, 4 aromatic distillates, and dinitro ortho secondary butyl phenol (Dow Contact) were compared by Sweet and Havis (1948). Application was made 2 days after planting beet and radish seed. The tar distillates with high boiling ranges were not effective weed killers. These authors also tested various nonselective herbicides applied about the bases of tomato, cabbage, and broccoli plants 3 weeks after they had been transplanted to the field. Even though no spray hit the foliage, the ammonium salt of 2,4-D was injurious to the plants. Neither it nor the methyl ester of naphthaleneacetic acid gave good control of the weeds.

Dow contact, Stoddard Solvent, a heavy aromatic naphtha, and an aromatic distillate all gave good weed control. As machinery is developed to make possible the directive application of herbicides—as was done in this work—a whole new field of use for some of the oil fractions seems probable.

Other materials are finding a place. Lachman (1948) has shown that isopropyl *n*-phenyl carbamate as a pre-emergence spray at 5 or 10 lbs. per acre killed grasses with little harm to the germination of the seed of broadleaved plants. Snap bean, beet, spinach, and onions from sets appeared especially resistant.

One of the newer materials is potassium cyanate. Hedlin (1948) used 0.5 per cent and one per cent sprayed on seedling onions at a rate of 80 gallons per acre. Weeds were effectively controlled, especially if small. When the onions were larger, he used 1, 2, 3, and 4 per cent solutions. Observations on weed kill indicated that a 2 per cent spray was strong enough to control the weeds, if small, without injury to the onion tops or the resultant yield. Zink (1949a) found that the degree of control of weeds with potassium cyanate decreased rapidly as the weeds became older. Effective control necessitated that the weeds be dry when the herbicide was applied and have several hours of dry weather following the application. A 0.9 per cent solution at 80 gallons per acre applied under low pressure (25 to 50 lbs. per square inch) to onions 2 to 3 inches high did not injure the onions and controlled broadleaved weeds. Concentrations of 1.8, 2.4, or 3.6 per cent caused burning of the foliage of seedling onions when used with or without a wetting agent and applied at a rate of 60 gallons per acre. He found that garlic was more tolerant of the stronger concentrations than was the onion.

Observations by growers and research workers indicate that when weeds develop under dry conditions they may be hard to kill with potassium cyanate even though they are small. Warren and Ellis (1950) believed that the rate of application may have to be determined by the succulence of the onion plant rather than by its size or stage of development. In their studies, potassium cyanate did not injure onion plants, if there had been considerable dry weather previous to the treatment. On the other hand, if the plants were succulent, the same rate of application used without injury on the somewhat hardened plants could prove harmful.

3. Harvesting Machinery

Much of the developmental work on equipment for expediting the harvesting of vegetable crops is done by the manufacturers of farm machinery. Portable viners, which will cut the vines and depod peas

and lima beans as they operate through a field, and machines for lifting and topping carrots and beets to be stored or used in processing, are pieces of equipment which are coming into general use.

Attempts to adapt for sweet corn harvesting the regular field corn picker which snaps or pulls the ear from the stalk have proved only moderately successful. Often there is too much bruising and husking of the sweet corn ears. In addition, up to 25 per cent of the ears may be left in the field. The use of pickers also breaks down the stalks, preventing their use as silage. Burr (1949) surveyed the use of 131 mechanical sweet corn harvesters of 5 different types used in Wisconsin and Minnesota in 1948. There was a wide range in the degree of success obtained with them, depending in part on the tonnage of green matter to be put through the machine. Twist (1949) described one type of improved sweet corn harvester which harvests 2 rows of corn at a time. The knives cut the stalks into segments as these are drawn down through the picker heads. As the shank of the ear is cut, the ear falls to one side.

Not all sweet corn varieties are successfully harvested by machine, according to Huelsen (1948). The COUNTRY GENTLEMAN hybrids are fairly well adapted, EVERGREEN hybrids less well, and practically all of the yellow hybrids poorly adapted. Both Huelsen and Twist (1949) have indicated some of the characteristics which must be incorporated into a sweet corn variety before it can be considered well adapted for mechanical harvesting. These are: relatively few leaves, a stiff strong stalk and root system, few suckers, tight heavy husks, ears borne at least 18 to 24 inches above the ground surface, and a medium shank to the ear. Huelsen thought that an ear with a shank which will snap off readily at a weak node just below the ear, as in the case of Country Gentleman, would be best. Thus a machine which gave the stalk a vigorous shake might work.

The method of planting has a bearing also on the success in the use of mechanical harvesters. Drilled corn seems to be handled more readily by the machine than check-rowed corn.

The harvesting of snap beans is an expensive hand operation and one that presents difficulties if it is to be done mechanically. A variety with a concentrated pod set would be best adapted for machine harvesting. Yeager (1949) described a picking machine, developed by J. W. Ward of Vernon, N. Y., which effectively harvests the pods from 2 rows of beans with very little bruising. The leaves are removed automatically. Then even the very small beans are taken from the vines by the teeth on the revolving drums and deposited in bags.

Various types of machines have been designed to lift and top onions. The elevating mechanism of most of these operates much the same as

that of a potato digger. A different principle is incorporated in a machine designed and built by Lorenzen (1950). A narrow, wedge-shaped blade cuts the roots, thus loosening the bulbs. The onion plants are carried upward and to the rear by a pair of round rubber belts, which grasp them by their necks. Disc knives cut off the tops, allowing the bulbs to be conveyed to the sacks. This apparatus will harvest 2 acres in a 10-hour day. Between 87 and 99 per cent recovery of the bulbs has been obtained, depending on the weed population in the field. This harvesting machine can be used readily on early onions, which in many cases are harvested before many of the tops have commenced to ripen at the neck, or in fields where 50 to 60 per cent of the tops are down. A planting made with F_1 hybrid onion seed would be likely to reach the maturity stage for harvesting more uniformly than would ordinary stocks, a factor which would be an advantage for mechanical harvesting.

Thus with all 3 of these crops, sweet corn, snap bean, and onion, it is obvious that a breeding program is desirable in order to develop varieties with those particular characteristics which will fit them for mechanical harvesting. This same procedure will have to be followed in the mechanical harvesting of asparagus and tomatoes, which is already in the testing stage. Modifications in spacing and other cultural techniques must accompany the development of adaptive varieties, if hand labor is to be eliminated in the harvesting of these two crops.

VIII. Possible Future Developments

One may expect that the trends indicated in the preceding discussion will continue in much the same directions in the near future. There is likely to be constant emphasis on the development of methods and techniques to reduce production costs per unit of the harvested crop. Herbicidal sprays may change our whole conception of the spacings that should be given to vegetable plants. Closer spacing than is now common may permit a greater return per unit area for the usually high-priced land on which vegetables are so often grown. Such a change will necessitate a re-evaluation of fertilizer and irrigation practices.

The future appears bright for the development of new vegetable varieties of high quality. Many of these will have improved resistance to some of the diseases difficult to control otherwise.

The vegetable industry as a whole can benefit materially from the development of new uses for vegetables. Furthermore, the distribution system by which vegetables are marketed needs to be studied critically, both from the economic aspect and from that of maintaining quality.

It may be that consumer-size packaging, now being widely discussed, will play an important part in altering the distribution of fresh vegetables.

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Prairie Soils of the Upper Mississippi Valley

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I. Introduction

In "Soils and Men," the 1938 Yearbook of the U.S. Department of Agriculture, prairie soils were defined as "the zonal group of soils having a very dark brown or grayish brown surface horizon, grading through brown soil to the lighter colored parent material at 2 to 5 feet, developed under tall grasses, in a temperate, relatively humid climate. The term has a restricted meaning in soil science and is not applied to all dark-colored soils of the treeless plains but only to those in which carbonates have not been concentrated in any part of the profile by the soil-forming

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processes." The purpose of this paper is to review the characteristics, concepts of genesis and the geography of the Prairie soils of the upper Mississippi Valley and to reexamine the concepts of Prairie soils in relation to the present system of soil classification.

The concept of Prairie soils was introduced by Marbut (1927) as a dark-colored soil in whose maturely developed profile no higher percentage of lime carbonate is found than in the parent material beneath and in which either a shifting or an accumulation of sesquioxide or both has taken place. Marbut grouped the Prairie soils with the Pedalfers, and in a later publication (1935) described the Prairie soil in more detail.

He said, "the typical Prairie soil profile has a very dark brown or black surface horizon, or layer, the blackness being caused by the presence of a high percentage of organic matter. . . . This layer is underlain by a brown horizon which is little if any heavier in texture than the surface horizon but differs from the surface layer in the much lower percentage of organic matter and in the brown color. . . . This layer, in turn, is underlain by parent materials ranging widely in character."

"The profile just described is the ideal and somewhat theoretical profile. The soil over most of the area is less dark than the typical soil, is slightly acid at the surface, the colloids in the surface are slightly deflocculated, and very slight eluviation has taken place. The soil is in the earliest stages of podzolic development. In soil survey work a soil in the prairies is accepted as a member of the prairie group if the surface horizon has a well-defined dark color and is 8 or more inches thick. Most of the Prairie soils are slightly degraded."

Barshad (1946) concluded that the Prairie soils can be defined more precisely by basing the definition on soil properties which show small variations between profiles.

He stated, "These are, besides dark brown to black surface color, granular structure, and absence of lime accumulation in the profile, the predominance of Ca and Mg ions among the exchangeable bases, the presence of exchangeable H^+ throughout the profile, the three-layer type of crystal lattice of the clay minerals, the nature of the correlation with depth—a diffusion pattern—of the pH, of the percentage unsaturation, of the C, of the N, and of the C-N ratio, and also the nature of the variation with depth in the composition of the clay. The common feature with respect to the clay distribution with depth is that the pattern of the distribution is the result of extensive clay migration."

The experience of many people working in soil survey over the years has indicated that Marbut's and Barshad's concepts of Prairie soils require some modification. Barshad's requirement that there be a diffusion type of relation between depth and such properties as pH and the percentage unsaturation would eliminate from the Prairie soils a number of the soils of the midwestern United States which are much more closely related to that group than to any other. Profile data which show that the lower part of the A horizon may have a lower base saturation and

that the B_2 may have a lower pH than either the horizon above or below are common. Likewise, Barshad's requirement that the clay minerals of Prairie soils have a three layer type of crystal lattice may prove unwise. Soils develop from kaolinitic shales or from other parent materials which cannot form significant quantities of clays with a three layer crystal lattice. Under a humid climate and a grass vegetation such soils might develop all of the other physical and chemical characteristics of the Prairie soils.

The authors believe in the light of their present knowledge that the only characteristics common to all the Prairie soils of the United States are as follows:

1. A dark colored surface horizon, 6 inches or more in thickness in virgin soils with Munsell color values in the immediate vicinity of 10YR 3/1, 3/2, or 2/2 when moist. The content of organic carbon in available analyses of uncultivated samples ranges from about 0.5 per cent to 6 per cent. Organic carbon contents decrease gradually with depth. Carbon-nitrogen ratios of the surface horizons are approximately 11 ± 2 and decrease gradually with depth to about 7 ± 2 in the lower B horizon.
2. Subsoil colors of brown, yellowish brown or greyish brown predominate, frequently with mottles or incipient gleying.
3. The exchange complex contains H^+ but usually in smaller amounts than the combined Ca^{++} and Mg^{++}. No horizon has yet been found where the H^+ exceeded the combined amounts of the bases. Although such soils might exist, it is doubtful that a soil should be considered a Prairie soil if the H^+ greatly exceeds the total Ca^{++}, Mg^{++} and K^+. The pH measurements of Prairie soils show a range of 4.5 to 7.0 in the surface.
4. Horizons are not sharply separated but have diffuse boundaries. The transitional horizons are usually several inches thick.

Further experience may show this list to be too inclusive.

No general statement concerning the structure, clay distribution, type of clay mineral present, or presence or absence of a zone of lime accumulation in the Prairie soils can be safely made at the present time. The reasons why generalizations regarding these properties cannot be made will be discussed later.

II. Characteristics of a Modal Prairie Soil

In presenting the current concept of the Prairie soils it seems desirable to select some example which may typify the "modal" or "ideal" Prairie soil and consider the deviations of other Prairie soils from this soil as functions of the various soil forming factors. For this example the authors have selected the Tama silt loam as found in central and eastern Iowa.

However, before entering a detailed description of the Tama series

it is desirable to mention the overall range of the Prairie soils so that the Tama soils will be seen in proper perspective. The parent materials of Prairie soils range from sands on one hand to clays on the other. The thickness of the A_1 [1] horizon ranges from about 6 to over 20 inches,

[1] Letter designations for horizons used in this paper have the following meanings as applied to Prairie soils: A. A major surface horizon which is the horizon of eluviation of clay and/or the horizon of maximum organic matter accumulation. The A_1 horizon is dark in color. The A_3 horizon is transitional to B, but more like A than B; B. The horizon of illuviation of clay and/or an intermediate horizon between the A and C differing from them in color and structure. The B_1 is transitional to the A, but more like B than A. The B_2 is that part of the B having the greatest illuviation of clay and may be absent. The B_3 is transitional to C, but more like B than C; C. The parent material which underlies the solum, as distinguished from accidental substrata. It may be either oxidized and leached or oxidized and unleached in Prairie soils.

and the thickness of the solum ranges from about 25 to as much as 100 inches. The pH of the A_1 horizon ranges from about 4.5 to 7. Where the distribution of clay is the result of genetic processes, the ratio of the clay contents of the A_1 and B_2 horizons ranges from about 1.1 to about 0.5. The mode is sometimes, but not always, at the center of the ranges. The modal texture of the parent material is medium textured, a silt loam or loam, because of the extensive loess deposits and extensive till deposits of loam texture. The thickness of the A_1 horizon is about 14 inches and of the solum is about 36 inches. The pH is in the neighborhood of 5 to 6. The modal ratio of clay content of the A_1 to the B_2 horizons is about 0.9. While the location of the mode is a geologic accident, the Tama profile was selected because it lies near the mode of many properties.

Of the properties listed above the degree of development of the texture profile, that is the ratio of the percent of clay in the A_1 and B_2 horizons is considered of outstanding importance from the point of view of classifying the Prairie soils. As will be pointed out later, this ratio is believed to be a reflection of the degree of weathering of the soil, and the variations in a considerable number of other properties are correlated with variations in the degree of development of the textural profile.

The suggestion of Thorp and Smith (1949) that minimal, medial, and maximal subgroups be established for the various great soil groups, based on the relative degree of horizon differentiation, has been adopted in this paper. In the Prairie soils the development of textural profile is considered of more significance on the average than any other property which might be chosen as the basis for subdivision into minimal, medial, and maximal subgroups. While the subgroups will be discussed in more

detail later it may be said in general that the minimal Prairie soils show no textural difference between A and B horizons, the medial Prairie soils have a B horizon which is slightly heavier in texture than the A, and the maximal Prairie soils have a B horizon which is considerably heavier than the A horizon. From this point of view the Tama profile is a medial Prairie soil. As was pointed out by Riecken (1945), however, the distribution of soils with different degrees of genetic textural horizon develop-

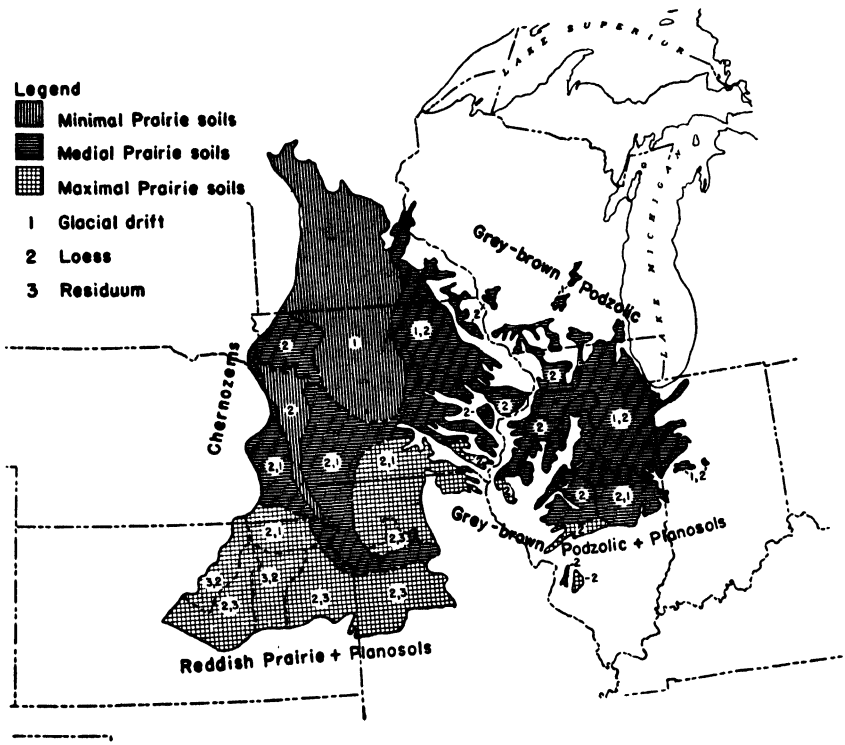


Fig. 1. Distribution of minimal, medial and maximal Prairie soils and dominant parent materials in upper Mississippi Valley.

ment is quite largely a matter of geologic accident. If no additional glacial deposits had been made following the Kansan glacial age and if no catastrophic erosion had occurred, the Prairie series chosen as a middle-of-the-range representative of the group would probably have been what is now considered a maximal Prairie soil. On the other hand if the Prairie soils were coextensive with the late Wisconsin glacial deposits there would probably have been no maximal Prairie soils. The general distribution of the minimal, medial, and maximal Prairie soils is shown in Fig. 1.

The selection of the Tama soil to represent the "modal" Prairie soil

has therefore been governed by several factors. In most of its characteristics, and especially its physical properties, it is modal. Furthermore, in the mapping history of the Tama soil, it has been somewhat more specifically defined than has been the case for some other prominent Prairie soil series, such as Marshall, Carrington or Grundy, which might have been used. The choice was also favored by the fact that a considerable body of quantitative information concerning the Tama soils was available to the authors.

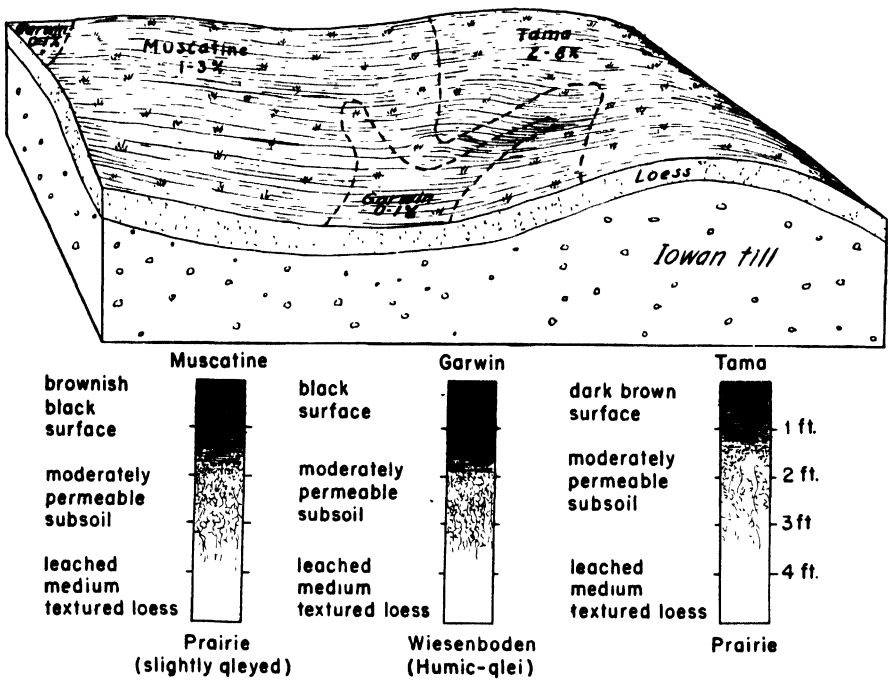


Fig. 2. Relationship of soil characteristics to topography in Tama and Grundy Counties, Iowa.

In central and eastern Iowa the Tama soils are developed from loess on gently undulating to rolling upland sites (Fig. 2). The loess is believed to have been deposited during or following the retreat of the Iowan ice sheet. In the Tama soils area this loess deposit has a maximum thickness of 125 inches or more. The native vegetation on the Tama soils was tall grass prairie (chiefly *Andropogan furcatus*). According to Kincer *et al.* (1941) the area has an annual rainfall of about 34 inches of which about 24 inches comes during the warm season. Average monthly temperatures range from about 18°F. in January to 74°F. in July with a frost free period of about 160 days.

The morphological characteristics of a Tama silt loam profile sampled near Gladbrook, Iowa by R. W. Simonson are as follows:

$A_{1—1}$	0-6″	The furrow slice, a mellow, very dark grayish brown (Munsell color value 10YR 3/2 moist) heavy silt loam with indistinct medium and fine crumb structure. (Nomenclature for soil structure after Templin *et al.* 1945). The soil mass is permeated by pinholes, and occasional worm holes (1 mm. in diameter). Plant roots abundant.
$A_{1—2}$	6-12″	Very dark grayish brown (10YR 3/2 moist) friable light silty clay loam with well-developed medium granular and fine crumb structure. Plant roots and pinholes are abundant, and worm holes (2-3 mm.) are common. Horizon boundaries are diffuse.
A_3 & B_1	12-18″	Variegated dark brown (10YR 4/3 moist) and very dark grayish brown (10YR 3/2 moist) friable light silty clay loam having fairly distinct medium granular and fine crumb structure. Individual aggregates are largely one color or the other, but crushed mass is very dark greyish brown. Plant roots are common and pinholes abundant. Worm holes passing vertically through the horizon are common (20-60 per sq. ft.). Horizon boundaries are diffuse.
$B_{2—1}$	18-27″	Dark brown (10YR 4/3 moist) silty clay loam having occasional distinct nut-like aggregates (2-4 cm.) and many indistinct fragments. Aggregates crush to fine granules if broken down carefully. Plant roots and worm holes are common, and pinholes abundant. Horizon boundaries are diffuse.
$B_{2—2}$	27-36″	Dark yellowish brown (10YR 4/4 moist) grading into yellowish brown (10YR 5/4 moist) silty clay loam that digs out in coarse irregular blocks which break readily to medium granular and blocky structure. The crushed color is yellowish brown. Plant roots are present but not common. Pinholes are common and worm holes less common than horizon above. Horizon boundaries are diffuse.
B_3	36-48″	Yellowish brown (10YR 5/4 moist) light silty clay loam which crushes to light yellowish brown (10YR 6/4 moist). Numerous mottles of reddish yellow (5YR 6/5 moist) and small black iron concretions are present. Structure is indistinct in places but soil mass breaks down readily into medium blocky structure when removed. The faces of the blocks are commonly coated with dark yellowish brown. Plant roots and worm holes are scarce, but pinholes are common. Horizon boundaries are diffuse.
C	48″ +	Very pale brown (10YR 7/3 to 7/4 moist) silt loam with numerous reddish yellow mottles, and occasional small iron concretions. Structure is similar to horizon above but aggregates are larger. A few dark yellowish brown coatings are present on surface of aggregates. Plant roots and worm holes are scarce, but pinholes are common. Grades into calcareous loess between 60 and 100 inches.

The profile described above was situated in a cultivated field on a slope of about 4 to 5 per cent on the side of a low ridge.

Some of the chemical and physical properties of samples from this same profile are shown in Table I.

The mechanical analysis of this Tama profile shows a slight accumulation of clay in the B horizon. The zone of clay enrichment is rather broad and no semblance of an abrupt claypan is evidenced. The sand fraction as determined in this analysis consists of some concretionary material.

The carbon and nitrogen contents are highest in the surface and decrease gradually with depth. In no case does a layer have a higher content of carbon or nitrogen than the layer above it in the profile.

Calcium is the dominant replaceable cation. The surface layer showed the lowest replaceable calcium content of any horizon in the profile. The amount of replaceable magnesium is about one-third of the replaceable calcium in layers near the surface, and increases to about one-half the replaceable calcium in the lower layers. In contrast to calcium and magnesium, the content of replaceable potassium is highest in the surface layers. The replaceable hydrogen content decreases gradually from the surface downwards.

Replaceable sodium was not determined in this profile, but results from similar soils indicate that the replaceable sodium content of the Tama soils would probably not be greater than 0.2 or 0.3 milli equivalents per 100 g. in any horizon.

The pH value of the surface layer is the lowest in the profile, with the samples from the middle of the B horizon being slightly more acid than those from the A_3 or B_1. The least acid samples were those from the C horizon.

The phosphorus content is highest in the C horizons and is at a minimum in the upper B horizon. If the parent material is assumed to have had a uniform phosphorus content, the present distribution of phosphorus would indicate some downward movement of phosphorus. The acid soluble phosphorus in this profile has been studied by Pearson, Spry and Pierre (1940). They found that the percentage of the total phosphorus that is soluble in dilute acid is very low in the surface soil and in the upper B horizon, but increases markedly in the lower B and in the C horizons. The nature of the phosphate compounds in the C horizon of this profile has been studied by Stelly and Pierre (1942), who concluded that a mixture of apatite and aluminum or ferrous phosphates, with the apatite form predominant, was present in this horizon.

The Tama silt loam profile, for which the description and analysis are reported above, has not been subjected to total chemical analysis by fusion procedures. However, Marbut (1935) has reported the total analysis of a Tama silt loam profile taken just north of Newton, Iowa.

TABLE I

Physical and Chemical Properties of Different Horizons of Tama Silt Loam (P-27, Tama County, Iowa)[a]

No.	Depth, inches	>50μ Sand, per cent	<2μ Clay, per cent	Carbon, per cent	Nitrogen, per cent	C/N ratio	Total phosphorus p.p.m.	Replaceable cations meq./100g. Ca	Mg	K	H	pH	Base saturation, per cent
1	0-6	4.4	27.5	2.86	0.249	11.5	585	11.3	4.1	0.85	8.0	5.1	67
2	6-9			2.44	0.210	11.6	596	13.3	4.6	0.66	6.8	5.3	73
3	9-12	4.3	31.7	1.98	0.178	11.1		13.1	4.8	0.53	5.2		78
4	12-15			1.74	0.156	11.1	470	13.4	4.4	0.47	4.4	5.5	81
5	15-18	4.2	32.4	1.46	0.132	11.0		12.6	5.6	0.46	4.2		82
6	18-21			1.12	0.104	10.8	386	12.9	6.1	0.47	4.1	5.4	83
7	21-24	4.8	34.0	0.91	0.088	10.3							
8	24-27			0.71	0.072	9.9	465	15.0	6.5	0.55	3.3	5.2	87
9	27-30	6.0	34.2	0.59	0.062	9.5							
10	30-33			0.47			622	14.8	7.8	0.56	3.1	5.3	88
11	33-36	7.9	31.8	0.41									
12	36-39			0.34	0.040	8.5	620	15.1	7.6		2.4	5.5	91
13	39-42	7.9	27.9	0.31				13.8	7.2	0.40			
14	42-45			0.29			699				1.8	5.8	
15	45-48			0.25									
16	48-54			0.18	0.031	5.8	750	13.4		0.28	1.0	5.8	

[a] All results expressed on oven dry basis.

TABLE II

Chemical Composition of Tama Silt Loam, Newton, Iowa[a, b]

Horizon	Depth, inches	SiO_2, per cent	TiO_2, per cent	Fe_2O_3, per cent	Al_2O_3, per cent	MnO, per cent	CaO, per cent	MgO, per cent	K_2O, per cent	Na_2O, per cent	P_2O_5, per cent	SO_3, per cent	Ignition loss, per cent	Total, per cent	N, per cent
A_3	6-12	70.80	0.69	3.82	11.48	0.13	0.98	0.92	2.05	0.93	0.18	0.15	8.39	100.52	0.24
A_3	14-24	70.56	0.67	3.91	12.15	0.14	0.79	0.88	2.01	0.91	0.14	0.15	7.90	100.21	0.21
B	24-50	69.90	0.72	5.09	14.30	0.12	0.86	1.33	2.01	0.91	0.10	0.09	5.07	100.50	0.07
C_1	50-70	70.21	0.69	4.78	13.63	0.13	0.76	1.14	1.97	0.88	0.10	0.09	5.85	100.23	0.11
C_2	90 +	71.10	0.65	5.03	13.90	0.14	0.93	1.36	2.00	0.95	0.15	0.10	4.16	100.47	0.05

[a] Whole soil, oven dry basis. [b] Marbut (1935).

The Tama soils of this Newton area are very similar to the Tama soil described here. The analyses reported by Marbut are shown in Table II. The samples used in this analysis represent rather broad layers in the profile and consequently may not reveal certain trends that would become evident if thinner layers were analyzed individually. Nevertheless, there is apparently a downward movement of iron and aluminum either as free oxides or as a part of the clay. The alkaline earth and alkali bases were present in rather high amounts. The lower layers were generally higher in magnesium than the upper layers. The contents of Ca, K, and Na did not show any pronounced trends in vertical distribution. The analysis reported by Marbut shows a somewhat higher percentage of nitrogen than the analysis shown in Table I. This suggests that the Tama profile used for Marbut's study may have come from a more gentle slope than the one used in Table I. The surface layer was omitted in Marbut's report.

The minerals in the clay fraction of the surface layer of the Tama profile from Tama County have been studied by Russell and Haddock (1940). On the basis of differential thermal studies, chemical analysis, and cation exchange capacity, these workers concluded that the clay fraction of this sample was dominated by minerals of the montmorillonite and illite groups, with very minor amounts of kaolinite. Peterson (1944) has also reported thermal studies of certain horizons of a Tama profile from the same locality. Peterson's work indicates that kaolinite is probably not a major constituent of the samples (6 to 7 inches and 26 to 36 inches) which he studied. Although the clay mineral data for this soil profile are quite incomplete it seems likely that the colloids in this Tama soil are predominantly 2:1 lattice type clay minerals. This is in accord with the criteria of Barshad (1946) on the types of clay minerals in Prairie soils. Ross and Hendricks (1945) have also pointed out that the soils derived from loess and glacial till in this region contain largely 2:1 lattice type clays.

From studies of soil development on loess (Smith, 1942) it appears likely that at least half of the clay ($<2\mu$) in the Tama soil has been formed from coarser material subsequent to the deposition of the loess.

III. Variability of Prairie Soils as Functions of Soil-Forming Factors

The Tama profile described in the preceding pages was selected as an example of the modal or middle-of-the-range Prairie soils. To describe the Prairie soils it is also necessary to describe the ways in which other Prairie soils differ from the Tama profile. Since any profile variations

are due to variations of one or more of the soil forming factors, the current concepts of the roles of the individual soil forming factors in the genesis of Prairie soils are presented.

1. Biotic Factors

Throughout most of the prairie region of the Middle West the native prairies and forests existed side by side in an intricate but orderly pattern controlled in large part by slope. The forests occupied belts of strongly sloping lands along the streams and were spreading slowly over

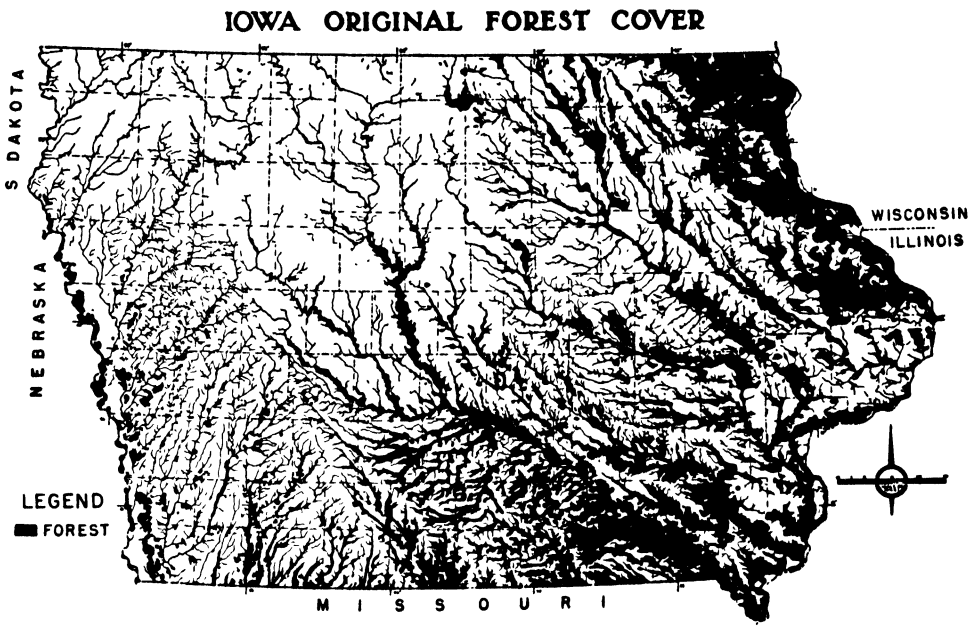


Fig. 3. Original forest cover of Iowa.

the more gently sloping portions of the uplands. They occupied gentler slopes in the eastern part of the region than in the western part. In the eastern part of the Prairie region (western Indiana and eastern Illinois) most slopes in excess of six to eight per cent were forested, and many gentler slopes on narrow and broad ridges were forested. In the central part (eastern Iowa), slopes steeper than 8 to 10 per cent were usually forested as well as some of the gentler slopes on narrow ridges. In western Iowa slopes in excess of twenty per cent were generally forested only if they faced north or east or were in protected coves. A similar relationship of slope and vegetation in northern Missouri has been described by Shrader (1946). The belts of forest were wider in general to the east of the streams than to the west even though slopes

were comparable. The intricate pattern of prairie and forest for Iowa is shown in Fig. 3. The heavily forested areas in northeastern and southeastern Iowa are hilly, and the level or gently sloping broad ridges commonly had a grass vegetation. Equally hilly areas in western Iowa along Missouri River were largely prairie, although the forests have spread rapidly since settlement in any uncultivated fields.

There has been much speculation as to why the grass persisted in a climate humid enough to support a mixed hardwood forest vegetation. Prairie fires, grazing by buffalo, soil and moisture conditions, drought cycles, and the competitive ability of the tall grasses have all been suggested as reasons for the presence of the prairie (McComb and Loomis, 1944). The original prairie consisted chiefly of big bluestem (*Andropogan furcatus*) with an admixture of a considerable number of other grasses, legumes, and various other forbs. The grasses commonly reached a height of 6 to 8 feet, and formed a very tough sod. With the sod to keep tree seeds from reaching the soil, and the intense competition for moisture and light between the tall grasses and the tiny seedlings of the trees, the competitive ability of the grasses must have been very great. Nevertheless, the soil conditions indicate that in many areas the trees were slowly invading the prairie prior to settlement. A few sites still remain where a dense mature forest, chiefly elm, oak and hickory, is growing on soils which are indistinguishable in the field from the adjacent Prairie soils. Starting in such an area and studying the morphological changes in the soil with distance toward the nearest area of Gray-brown Podzolic soil, it is often found that the changes are more or less continuous over a distance of one-sixteenth to one-quarter mile. The first perceptible morphologic change from the Prairie to the Grey-brown Podzolic soil is either an increase in the degree of development of the structural aggregates in the B horizon in the well-drained soils or the appearance of light and then heavy grey coatings in the lower part of the A horizon of moderately well-drained soils. The most rapid decrease in organic matter seems to occur in the lower part of the A horizon where the normal differences between Prairie and Gray-brown Podzolic soils are greatest. The next stage is the development of the Gray-brown Podzolic A_1 and A_2 horizons overlying a B horizon which has nearly the normal color for the Prairie soils. Following this the organic content decreases in the upper part of the B horizon. The most persistent evidence of a former prairie vegetation is the presence of organic coatings on the structural aggregates in the lower part of the B horizon. This transition is shown schematically in Fig. 4. The chemical and invisible physical changes which occur during the change of a Prairie soil into a Gray-brown Podzolic soil have not been studied in any detail, nor can

any good estimate be made of the time required for the complete transformation, other than that it is at least several hundred and probably well over a thousand years. The reverse process, the regradation of a Gray-brown Podzolic soil into a Prairie soil, is theoretically possible so long as chemical weathering has not been so severe that the primary calcium bearing minerals have been destroyed. There are extensive areas of Prairie soils in eastern Iowa and northwestern Illinois which are now correlated with the Tama series. In these the B horizon has

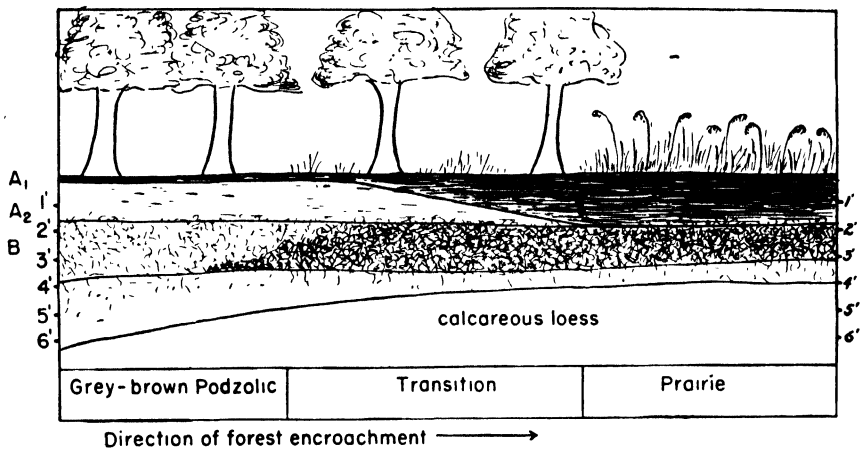


Fig. 4. Schematic diagram of transition from Gray-brown Podzolic to Prairie soil.

both the structure and the moderate-to-heavy coating of light grey silt on the structural aggregates which are normally considered characteristic of Gray-brown Podzolic soils. No better explanation has been advanced for these grey coatings than that they are relict characteristics of a former Gray-brown Podzolic soil which has been converted into a Prairie soil by the encroachment of grass on the forest. The reasons for a shift from forest to grass vegetation are not clear unless the change was associated with the so-called "climatic optimum" discussed by Flint (1947), a period about 6000 to 4000 years ago when the climate was thought to have been warmer and drier than that of today.

It is possible to form an opinion as to which of the properties of the Prairie soils are due to the grass vegetation by comparing adjacent Prairie and Gray-brown Podzolic soils developed on comparable slopes from the same parent materials. For this purpose the Tama profile (Prairie), Table I, may be compared with a profile of Fayette silt loam (Gray-brown Podzolic) taken in the same county. The data for the Fayette profile are given in Table III.

TABLE III

Physical and Chemical Properties of Different Horizons of Fayette Silt Loam (P-32, Tama County, Iowa)[a]

No.	Depth, inches	Horizon	>50μ Sand, per cent	<2μ Clay, per cent	Carbon, per cent	Nitrogen, per cent	C/N Ratio	Replaceable cations—meq./100g. Ca	Mg	K	H	Cation ex. cap. meq./100g.	Base saturation per cent
1	0-1½	A_1	6.0	23.6	4.11	0.338	12.1	18.3	3.7	0.29	5.9	20.1	79
2	1½-4	A_{21}			2.11	0.184	11.5	5.4	2.3	0.48	11.0	16.5	42
3	4-7	A_{22}	5.0	20.6	1.56	0.133	11.7				11.2		
4	7-10	A_{23}			0.92	0.089	10.3	2.4	2.3	0.32	7.5	11.2	40
5	10-13	B_1	5.2	20.5	0.60	0.078	7.7				4.8		
6	13-16	B_1			0.53	0.062	8.6	6.9	3.9	0.42	4.6	14.3	71
7	16-19	B_{21}	4.8	29.7	0.44	0.057	7.7				4.3		
8	19-22	B_{22}			0.41	0.052	7.9	11.2	6.1	0.54	4.5	20.9	80
9	22-25	B_{23}	5.2	35.5	0.41	0.050	8.2				5.2		
10	25-28	B_{22}			0.46	0.048	9.6	12.8	6.8	0.62	5.6	22.7	78
11	28-31	B_{23}	5.8	35.3	0.36						5.7		
12	31-34	B_3			0.37			12.7	6.9	0.55	5.6	23.1	78
13	34-37	B_3	7.1	32.3	0.33						5.4		
14	37-40	B_3			0.35			12.3	6.8	0.59		22.9	79
15	40-43	B_3	6.2	31.5	0.38	0.039	9.8				5.0		
16	43-46	B_3			0.27			12.7	6.8	0.57		22.1	81
17	46-49	C_1	6.5	29.4	0.25						4.5		
18	49-54	C_1			0.23	0.031	7.4	12.6	6.7	0.49		21.6	81
											4.4		

[a] All results expressed on oven dry basis.

Study of the two sets of data would indicate that the differences are ones of degree as much as of kind. The organic carbon content of the Tama profile is approximately twice that of the Fayette profile. There is evidence of stronger leaching in the Fayette, for the A_2 horizon has a much higher percentage of exchangeable H. There is also evidence of either greater clay movement or a more rapid rate of formation and destruction of clay under forest vegetation, for the Fayette A horizon is lower in clay and the B higher in clay than the Tama. The ratios of exchange capacity and clay contents of the two B horizons are very similar, indicating a similarity in the kind of clay minerals present. Peterson (1946), using x-ray diffraction, thermal analysis and exchange capacities was unable to find significant differences between the clay minerals in the Prairie and Gray-brown Podzolic soils formed from loess in Iowa.

The differences in amounts and distribution of organic matter have been explained by Marbut (1928) and others as being the resultant differences of organic matter additions on and in the soil. The theory has been that forest leaf litter decomposes on the surface, while the fibrous grass roots decompose in the soil. This theory is strengthened by Cline's (1949) observation that where leaf litter is carried into a nearly neutral soil by earthworms to decompose in the soil, a thick A_1 horizon comparable to that of the Prairie soils has been formed. Accurate measurements of the comparative return of organic matter by grasses and trees have not yet been made. While leaf return can be measured, the numbers of roots which die and decompose each year have not yet been satisfactorily measured. The best comparative estimates available are given in Table IV.

TABLE IV

Estimates of Annual Organic Matter Production by Grass and Trees

	Roots, lbs. per acre 0-6 inches	Tops, lbs. per acre	Total, lbs. per acre
Grass	312-540 [a]	1600-4400 [c]	1912-4940
Trees	375-625 [b]	4000-6000 [d]	4375-6625

[a] Thorp (1948) for big bluestem (*Andropogan furcatus*).

[b] Scholtes (1940) for shortleaf and loblolly pine.

[c] Jenny (1941) for tall grass Prairie.

[d] Chandler (1941) estimates of leaf litter from deciduous hardwood forest, multiplied by two to allow for woody growth.

The annual additions of organic matter to Prairie and Gray-brown Podzolic soils are apparently of the same order of magnitude, and the

differences in organic matter content cannot be ascribed to different rates of organic matter addition. This was the conclusion reached by Jenny (1941).

Differences in acidity between the Prairie and Gray-brown Podzolic soils have been advanced as an explanation for the differences in organic matter. This explanation seems untenable. The vegetation and organic matter differences of the Chernozem and Gray-wooded soils of Alberta and Saskatchewan and western Minnesota parallel the relationships between the Prairie and Gray-brown Podzolic soils of the corn belt. Yet the Grey-wooded soils have the same reaction profile as the Chernozems, according to the data of Newton, Ward and Bentley (1948). If reaction is the controlling factor it would seem that the Gray-wooded soils should resemble the Chernozems rather than the Gray-brown Podzolic soils.

Without additional data it is not safe to draw conclusions as to the reasons for the differences in organic matter contents between the Prairie and Gray-brown Podzolic soils except that they are related in some way to the native vegetations.

The differences in the degree of saturation of the Tama and Fayette profiles are characteristic of the differences found between Prairie and Gray-brown Podzolic soils where all soil forming factors other than vegetation are held constant. The lower saturation of the Fayette profile reflects the greater leaching of the Gray-brown Podzolic soils. Smith (1942) showed that 50 per cent more carbonates had been leached from Gray-brown Podzolic soils than from comparable Prairie soils in Illinois. The greater proportion of exchangeable hydrogen and the greater loss of carbonates under forest conditions probably represent a combination of a lower return of bases in plant residues, a higher acidity of the water entering the soil after passing through the leaf litter, and interception of water for transpiration of greater depths by the trees. Quantitative data are not available to permit comparison of the grass and forest vegetations on these points.

Since volume weight measurements were not made on the Tama and Fayette profiles, it is only possible to make a rough comparison of the total clay contents. From the data available on volume weights in similar soils, it would appear that the total amount of clay in the two soils is almost identical. The significant difference is in the distribution of the clay, the Tama having more clay in the A and less in the B horizon than the Fayette. The differences are thought to represent differences in eluviation under grass and forest, but the reasons for the differences are unknown.

There are undoubtedly faunal differences among the various Prairie

soils, but no studies have been reported. Changes in the Prairie soils induced by man are discussed later.

2. Climate

In considering variations in the properties of Prairie soils that have been brought about as a result of climate, certain characteristics of the climate of the upper Mississippi Valley are of prime importance. For one thing the area shows no regions of rapid change in any of the ordinarily measured components of climate. The climate of the region as a whole is controlled by factors effective over long distances rather than by local features such as topography or bodies of water.

The climatic range over the area of Prairie soils in the upper Mississippi valley is wide. Some of the more significant climatic features of weather stations around the periphery of the Prairie soil area are shown in Table V. Along with this situation of very gradual changes in climate within the prairie region the parent materials of the area are variable, with no single uniform parent material covering a broad expanse.

In spite of these difficulties Jenny (1930) has been able to establish certain relationships between climate and the content of soil organic matter and nitrogen in this region. These relationships became evident when large numbers of samples were considered in relation to gradients in climate. In Jenny's work the organic matter and nitrogen in a wide variety of soils was found to decrease exponentially with mean annual temperature, and to increase logarithmically with the humidity factor (N. S. Q.).

It should be noted in connection with the work done by Jenny on the effect of temperature upon soil organic matter, that differences in the age of the parent materials tend to parallel differences in temperature in most of the regions studied. Through central United States where the temperature increases from north to south, the northern part of the area is covered by late Pleistocene deposits, the central part is dominated by early Pleistocene materials and the soils of south central United States are predominantly formed from deposits of pre-Pleistocene origin.

A compilation of data available from several sources provides certain comparisons of the effect of rainfall on the properties of soils developed from loess under grass vegetation. In Fig. 5 the pH values of two Chernozem soils and three Prairie soils, developed under varying amount of annual rainfall from loess of reasonably similar texture are shown. While the age and mineralogical composition of the loess from which these soils formed is undoubtedly subject to some variation, it is felt that it is more nearly uniform than any other parent material covering a similar range of climatic conditions in the upper Mississippi valley.

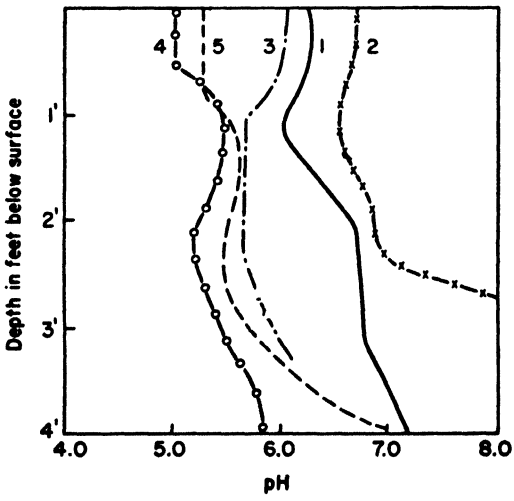
TABLE V

Climatic Features of Weather Stations on the Periphery of the Midwestern Prairie Soil Area [a]

Station and location in prairie area	January av. temp., ° F.	July av. temp., ° F.	Growing season, days	Precipitation—inches November through March	Precipitation—inches April through Oct.	Precipitation—inches Annual
Columbus, Nebraska (western limit)	22.3	76.4	160	4.42	23.37	26.79
Alexandria, Minnesota (northern limit)	7.5	69.7	140	3.06	19.06	22.12
Sedalia, Missouri (southern limit)	29.7	76.9	179	10.55	29.42	39.97
Lafayette, Indiana (eastern limit)	27.5	76.2	168	13.12	24.88	38.00

[a] Kincer *et al.* (1941).

The topography was also fairly similar for all types, the sites being on gently rolling upland divides. Since these profiles fall almost on an east-west line mean temperatures do not differ greatly. The pH values indicate that the two soils developed under the highest rainfall levels are the most acid, and the two soils developed under the lowest rainfall are the least acid of the 5 profiles considered. The loess from which the Tama profile from Illinois developed is apparently higher in calcium carbonate than the loess from which any of the other profiles were formed. There-



1. Hastings, (Chernozem), Sherman Co. Nebr., Ann. Rainfall 23.7"
2. Holdrege, (Chernozem), Phelps Co. Nebr., Ann. Rainfall 23.2"
3. Marshall, (Prairie), Shelby Co. Iowa, Ann. Rainfall 29.3"
4. Tama, (Prairie), Tama Co. Iowa, Ann. Rainfall 33.8"
5. Tama, (Prairie), Menard Co. Illinois, Ann. Rainfall 34.6"

Fig. 5. pH values of selected soils developed from loess under tall grass vegetation with varying rainfall.

fore, the differences in parent material may have tended to minimize, rather than accentuate the differences in pH due to rainfall. Since the differences are not extreme, the limitations of pH values as criteria for characterizing soil types must be kept in mind in appraising their significance.

Although climatic conditions over the north central prairie area of United States are relatively uniform, it appears that soils with very similar profile characteristics can be formed under other combinations of climatic factors. For example, Barshad (1946) has shown that the Prairie soils of California are very similar to the Prairie soils of the Midwest, even though climatic conditions vary. The California Prairie soils are formed under a lower annual rainfall differing in seasonal distribution from that of the Midwest prairie area. Winter temperatures tend to be higher and summer temperatures lower in the California Prairie soil area than in the Midwest prairie area. Since the major part of the rainfall in the California Prairie soil area comes in the cool, but frost free, winter months, the effect of this rainfall on soil weathering is greater than that of the summer rainfall of the Midwest.

3. Parent Materials

a. Physical Characteristics. One of the early important Prairie soil series was the Marshall series, developed from glacial materials which included both loess and till materials. This broad series was soon subdivided into many other series, at first the division into "loess" and "drift" soils being expressed. Later the physical character of the loess or drift was recognized as being very important in influencing the kind of soil formed. In Illinois, Stauffer (1935) and Wascher and Winters (1938), on the basis of laboratory and field studies, concluded that the Prairie soil derived from Wisconsin drift and earlier classified as "Brown Silt Loam" could be subdivided into the following series on the basis of the mechanical composition of the till: the Clarence series, derived from a clayey till, the matrix of which has a high content of Maquoketa shale whose principal clay mineral is illite; the Saybrook series, derived from a till much lower in clay; and the Swygert and Elliott series, derived from tills of intermediate clay contents. As pointed out by Odell (1947) these series, under similar management, vary in productivity.

According to studies of Walker and Brown (1936) the sandy-textured Prairie soils accumulate less organic matter than similar soils with silt loam or silty clay loam surface and subsoil textures. Their analyses of the surface horizons of 6 soils formerly considered types within a series are given in Table VI. Presumably the soils in this study had adequate surface drainage. Therefore it is likely that the differences in organic

matter content were a resultant of better fertility and moisture holding status of the finer textured soils.

TABLE VI

Average Phosphorus, Nitrogen and Carbon Content of Surface Layers of Some Prairie Soil Types [a]

Surface texture	Lbs. per acre (2,000,000 lbs. of soil)		
	Phosphorus	Nitrogen	Carbon
Sand	800	550	8,000
Fine sand	750	850	11,500
Sandy loam	864	2,000	25,000
Fine sandy loam	895	2,133	26,380
Loam	1,147	3,756	44,300
Silt loam	1,288	4,606	53,580

[a] Based on data for soils formerly mapped as types of the Carrington series.

While mechanical composition has been considered important in classifying Prairie soils into series, other physical properties such as porosity and compaction must be considered. For example, the Clarion and Monona soils are minimal Prairie soils without textural profiles. The Monona soils are developed from nearly sand-free loess having a volume weight (apparent specific gravity) of 1.3. The Clarion soils have developed from Wisconsin till having about the same clay content as the loess but 30 to 50 per cent sand and a volume weight of 1.5. The difference in volume weight, or compaction, results in a lower aeration porosity and a lower permeability in the till below the Clarion solum than in the loess below the Monona solum. The substratum porosity is important in the design of terrace systems for runoff control. Level terraces can be used with safety on Monona soils because of the high permeability of the substratum, but it is doubtful if conventional level terraces can be safely used on Clarion soils because of the greater compaction and lower permeability of the till substratum. Thus, it is necessary to distinguish between the Clarion and Monona series on the basis of the substratum porosity even though there are other differences of importance.

b. Mineralogical and Chemical Characteristics. Since the vast majority of Prairie soils are developed in loess or glacial drift with a very similar and very highly mixed mineralogical composition, the importance of mineral composition on soil character is difficult to assess, except in a few outstanding instances. Although Graham (1943) and Springer

(1948) have shown that Prairie soils series vary in minerals important in plant nutrition, these differences are more likely a result of weathering intensities than of original differences in the mineral composition.

The principal mineralogical differences are found in soils developed from water-sorted materials, where high percentages of clay minerals have been segregated or removed. In such cases covarying factors such as porosity and permeability are associated with the mineralogy.

The mineralogical composition of the loess and tills of Iowa are essentially the same except for size distribution of the particles according to Kay and Graham (1941). Nevertheless, according to available data by Hutton (1948) and Riecken, Allaway, and Smith (1947) the Monona series developed from loess has a larger amount and probably a higher supplying power of available K than does the Clarion series developed from till. This is thought to be due to the larger content of silt sized minerals in the Monona series than in the Clarion series. In the Monona profile there is almost no sand size fraction, but over 70 per cent silt size fraction. In the Clarion profile about 30 to 50 per cent of medium sized sand is usually present.

c. Stratified Materials. It has long been the practice in the classification of soils into series to give considerable emphasis to the geological origin of the material in the lower horizons. This has been and is the practice in the Prairie region. In Table VII there are listed several

TABLE VII

Examples of Prairie Soil Series Derived from Mixed (Stratified) Parent Materials

Series	Nature of parent material	Main agricultural significance of substratum
Sac	Thin well-sorted loess over medium plastic calcareous glacial till.	Water storage capacity too low for use of level terraces.
Dodgeville	Thin loess over jointed limestone.	Soil is droughty and rate of soil-loss by erosion should be kept at minimum.
Lacona	Thin loess over kaolinitic shale.	Permeability and fertility of shale is low.
O'Neill	Thin loess over gravel.	Soil is droughty.

Prairie soil series derived from stratified materials. There are many other such series where the parent material of the upper layers is of distinctly different character than in the lower horizons. As discussed by Riecken and Smith (1949a) the solum, including what is commonly

referred to as the A and B horizons, may be formed from one kind of material, while the substratum is of an entirely different lithology and/or physical character. In many of these instances, a sample of the parent material from which the solum has been formed is no longer present. From the agricultural point of view, it is sometimes quite important to identify the nature of the material in the substratum below the solum.

As pointed out by Riecken and Smith (1949a), the solums of such series as the Sac and Galva series is derived from similar material, while the most significant differences occur below the solum. In most of the series used for illustration in Table VII, the solums are usually different in one or more properties, but the differences, such as degree of acidity or small differences in texture, may not be as important as the character of the substratum material. It is the intention here to stress the fact that in practice the character of the substratum material below the solum is given important weight in classifying the Prairie soils in series when the substratum lies within the range of roots of common crops and its characteristics influence the choice of crops, soil management practices, or the productivity of the soil.

d. Progressively Changing Materials. Where the parent material is changed progressively by slow deposition, the thickness and nature of the various horizons are usually somewhat different from those in soils the parent material of which was deposited at one time. In Fig. 6, there is illustrated the common occurrence of soils derived from very thick loess in western Iowa. The Napier and Castana series are derived from colluvial and/or talus deposited materials. Where rapid recent or modern deposition has taken place the Hornick series, an Alluvial soil, is found. In Table VIII, the thickness and relative organic matter content of the Napier, Hornick and Monona series is compared. The Monona series, developed on slopes which had slow geologic erosion, has a moder-

TABLE VIII

Comparison of Horizon Thickness and Organic Content of Napier, Monona and Hornick Series

Series	Thickness of organic layer, inches	Relative organic matter content	Parent material changes
Napier (Prairie)	15-35	high	Slow deposition
Hornick (Alluvial)	absent [a]	low	Rapid deposition
Monona (Prairie)	9-12	medium high	Slow erosion

[a] Organic content low and horizon of its accumulation not apparent.

ately thick organic layer. The Napier series, developed on slopes which had slow geologic deposition, has a much thicker organic layer with a higher organic matter content throughout. The higher organic matter content is considered due in part to the somewhat less well-aerated but more favorable moisture conditions. The thicker organic layer is considered to be due to slow deposition of new parent material on the A horizon of the soil, with the organic matter accumulating again in the new material. In the Napier series, the texture profile is no more de-

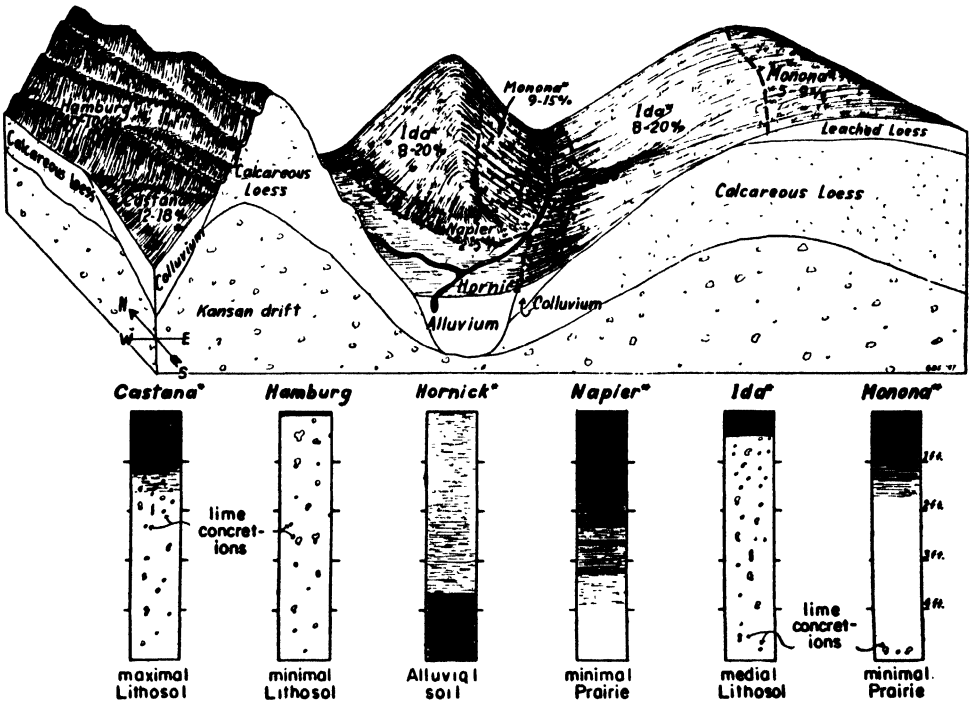


Fig. 6. Relationship of soil characteristics to topography and parent material in western Iowa.

veloped than in the Monona profile, and Hutton (1948) has shown that the latter has no textural B horizon. It would seem that new parent material in the Napier series is added at a more rapid rate than the clay can form or accumulate to develop a textural B horizon.

Where truncation occurs after soil formation has been initiated, the soil profile often acquires some characteristics not common to soils where truncation has not occurred. Iron oxide mottlings of various hues of yellow and strong brown are present in the middle solum of the Shelby series, as recently defined in the Livingston County, Missouri, Soil Survey. The Shelby is one of the Prairie soils derived from Kansan and/or

Nebraskan glacial till. Such mottlings in soils often are interpreted as being caused by poor internal aeration. In the Shelby series, however, these mottlings are more probably a relict mottling from a former profile of weathering. In certain areas of southeastern Iowa and western Illinois where loess-mantled Illinoisan glacial deposits occur, post-loess dissection of the landscape may be the cause of the presence of mottlings in the solum of some Prairie series developed in the loess. Through truncation iron oxide mottlings developed in deeply buried materials are brought close to the surface and tend to persist in any newly developed solum.

e. Thickness of Solum. In Fig. 7, the thickness of the solums of 4 representative Prairie soil series are shown graphically. The thickness of the solum increases with increasing coarseness of texture and/or permeability of the parent material. The thickness of the solums of the 4 series is 25, 30, 48 and 90 inches. Stauffer (1935) studied the Clarence, Elliott and Saybrook series in some detail. He found that the $CaCO_3$ equivalent of the unleached till from which each of these soils was derived is about 20 per cent. The till from which the Clarence soil was derived contains about 50 per cent 5 micron clay, and the till from which the Elliott soil was derived contains about 40 per cent 5 micron clay. The thickness of the solum of the Clarence is about 25 inches at which depth primary carbonates were found. The solum of the Elliott is about 30 inches thick, with primary carbonates at 30 inches. The solum of the Saybrook series is about 36 inches thick. It was formed from loam-textured till of about 16 per cent 5 micron clay content, with $CaCO_3$ equivalent of about 20 per cent. The till of these three series is of the same geological age, occurring intermixed on the same ground moraines in the Tazewell drift area in northeastern and east central Illinois. Therefore, the thickness of the solum of the Clarence, Elliott and Saybrook series is related to the texture and the permeability of the till.

In Fig. 7, the Muscatine series, with a solum of about 48 inches, is derived from a calcareous loess containing about 80 per cent silt, and the Thurman series, with a solum of about 90 inches, is formed from calcareous medium-to-fine eolian sand.

These examples indicate that the thickness of the solum of Prairie soils depends in part upon the character of the parent material. Of the many properties of parent material affecting solum thickness, perhaps the most important is the porosity of the material, although other factors such as lime content, height of ground water, slope characteristics and time of weathering are also important. For the series represented in

Fig. 7, the porosity of the parent materials has been the most important factor in causing differences in thickness of solum.

For the Thurman series, illustrated by the thickest solum in Fig. 7, the B horizon is considered to be truly genetic. Studies of the colloid extracted from the so-called B horizon of the Thurman soil indicate that it is made up of 2:1 lattice clays with about 8 per cent free iron oxide. The fine clay (<0.2μ) has an exchange capacity of 64 meq. per 100 g. Except for the fact that this colloid is higher in free iron oxide it seems

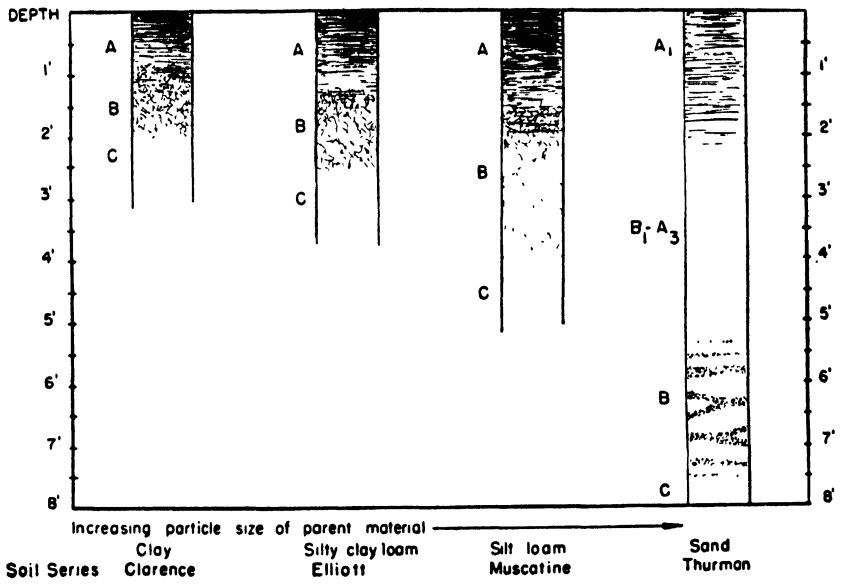


Fig. 7. Relation of particle size to solum thickness.

to be very similar to the colloid extracted from B horizons of other Prairie soils. The clay layers found at about 72 inches depth tend to parallel the surface, cut across bedding planes, and are unrelated to the water table level. The clay is therefore considered by the authors to have formed in the solum and accumulated in layers as illustrated in Fig. 7.

It is of interest to speculate on the factors causing accumulation of the clay in thin layers at depths of 60 to 80 inches in the solum of the Thurman series. This clay is chiefly less than 0.2μ in size, and because the water table is low and the pores large it would likely have migrated still deeper in the absence of a flocculating agent. The clay contains about 8 per cent free iron oxides as determined by the method of Jeffries (1946), while the clay in the B_2 layers of other Prairie soils such as the Monona and Seymour series contains from 2.5 to 6 per cent free

iron oxides, according to Hutton (1948). The authors consider that the clay in the Thurman is probably flocculated by the iron oxides. It is likely that the concentration of iron oxides above 60 or 70 inches is too low to cause flocculation at shallower depths, and that sufficient concentration of iron oxides is reached only at depths of 60 to 80 inches.

4. Time

In considering the variations in Prairie soils that have resulted from differences in the time during which soil development has taken place, it must be emphasized that the majority of the Prairie soils are developed from relatively young parent materials. The vast majority if not all of the Prairie soils of the upper Mississippi Valley have been formed since the Wisconsin glaciations, which occurred late in the Pleistocene period. This fact was pointed out by Norton (1933) when he attributed the existence of most of the Prairie soils to the youth and unweathered condition of the parent material. Because of this it is difficult to find groups of Prairie soils which form a chrono-sequence, in Jenny's (1946) terminology, covering an extended time interval.

Perhaps the best example of chrono-sequences in the Prairie great soil group are found in soils formed from loess of varying thickness, but deposited at the same time and from the same source. The difference in the "effective age" of such sequences of soils has been pointed out by Smith (1942) as being due to the differences in the age of that portion of the loess from which the solum has developed. Smith compared two "end members" of such a sequence, the Jasper silt loam (now called Richview) and the Tama silt loam, both of which had developed under grass vegetation on sites with good surface drainage. The Jasper soil, representing the older member of the sequence, showed a more highly developed textural B horizon, had a lower percentage base saturation, and was lower in organic carbon than was the Tama soil, the young member of the sequence. It was concluded from these observations that the Prairie soils are not in equilibrium with their environment and that the direction of their development is toward the Planosols.

Another study of such a sequence of Prairie soils developed from varying thicknesses of loess has been reported by Hutton (1947). The tendency toward increased differentiation of textural horizons, accompanied by an increase in replaceable hydrogen was also evident in this work.

These trends in the development of Prairie soils had been recognized by Marbut (1928) who pointed out that saturation with bases decreases with age in the Prairie soils. He also indicated that an increase in the

degree of eluviation and illuviation should coincide with this decrease in percentage base saturation.

A detailed study of the formation and movement of clay in one Prairie soil, the Grundy silt loam of Missouri, has been reported by Haseman and Marshall (1945). They used the zircon in the soil as an inert and immobile reference material for the calculation of changes in other constituents. By this criterion the Grundy soil was developed from loess which was essentially uniform to a depth of 69 inches. The clay content of the whole profile was found to have been increased about 20 per cent by the processes of soil formation. Definite evidence of movement of clay in the profile was obtained. The A horizon (0-17 inches) had lost 66 per cent of the clay it contained originally. This represents a minimum amount of translocation since some clay was formed in this horizon during the development of the profile. On the other hand, the clay content of certain layers in the B horizon had approximately doubled during the development of the profile. Along with the formation and movement of clay the various layers in the profile had changed in volume. The A horizon had shrunk but the B horizon showed marked swelling, for a net increase in volume in the entire profile of about 8 per cent. An increase in weight of about 6 per cent for the whole profile was attributed to oxidation and hydration of the minerals and accumulation of organic matter.

Investigations of the actual mechanism by which differentiation of textural horizons takes place in Prairie soils are rather limited. However, this same process as it occurs in the level soils associated with the Prairie soils of Illinois has been investigated in detail by Bray (1934, 1935). It is highly probably that the mechanism involved in the formation of claypans in these soils is nearly the same as that occurring in the Prairie soils developed on sites with somewhat better surface drainage. The process as outlined by Bray is essentially a formation of 2:1 lattice type clay in both A and B horizons and the translocation of a part of the clay formed in the surface layer to the B horizon. The formation of clay from coarser materials is inaugurated before the profile section is leached free of calcium carbonate, and, in the Illinois soils studied, the total amount of fine clay in the profile reached a maximum while the soil was only slightly acid. The movement of clay from the surface was attributed to transport by drainage waters moving through channels in the soil mass in turbulent flow. Deposition of clay in the B horizon was attributed to a decrease in the rate of flow of the percolating water.

In a laboratory study of claypan formation, Smith (1934) found evidence that deposition of clays in the B horizon may be brought about

by the flocculation of the clay by electrolytes in the ground water or by iron oxide colloids carrying a charge opposite that of the clay. It seems likely that this second effect, namely the flocculation of clays by iron oxides, may tend to stabilize the colloids in the surface layers of well drained soils, and contributes to the fact that claypans form more slowly in soils with good surface drainage than in soils developed on level sites.

In Hutton's (1947) work it was found that among the older soils the heaviest layer in the B horizon tended to occur closer to the surface as the soils became more highly weathered. The amount of 2 μ clay in the heaviest layer increased regularly as the soils became more highly weathered. These observations might be interpreted as indicating that the B horizon develops by a sieve action, with mobile clay from the A horizon being stopped by the impenetrable B horizon. Or, it might be interpreted as representing the influence of a finer textured parent material which was discussed earlier.

Bray (1937) concluded that the clay formed in the Illinois soils he studied was largely "superfine" clay, that is clay with particles having equivalent diameter less than 0.06 μ. One process proposed for the formation of the material consisted of "flaking off" of particles from the edge of weathering mica, along with a loss of K from the particles to form a beidellite-nontronite type of mineral. As weathering progressed the SiO_2 percentage in the coarse clay increased through loss of other constituents. Decomposition of the fine clay was apparently not significant until the soils had reached stages of profile development which would exceed those included in the Prairie great soil group.

Most of the mineralogical investigations of Prairie soil colloids, such as those by Hendricks and Fry (1930), Russell and Haddock (1940), Peterson (1944), Hutton (1948), and Barshad (1946) have shown that 2:1 lattice type minerals dominate the clay fractions of these soils. Minor amounts of quartz and iron oxides are usually present. Barshad concluded from his studies and from a consideration of other work that the dominance of 2:1 lattice type clays in Prairie soils could be used as a criterion for defining this great soil group. Exceptions to this rule, although rare, merit some consideration. For example, Alexander, Hendricks, and Nelson (1939) estimated that kaolinite comprised almost one-half of the material finer than 0.3 μ in the B_3 horizon of a Prairie soil (Carrington) from Iowa. Subsequent investigations by the authors indicate that kaolinitic clays are an important constituent of the coarse 2.0—0.2 μ clay in several Carrington profiles. However, since kaolinite is present in the relatively unweathered till at the base of these profiles it appears that it is not a product of soil-forming processes. Nevertheless, it may be preferable in defining the Prairie soils to require that only the

clay formed during soil development be dominantly 2:1 lattice clay minerals, and to exclude from the definition any clay inherited from the parent material.

A weathering sequence of clay sized minerals has recently been proposed by Jackson *et al.* (1948). A consideration of available information on the clays in Prairie soils indicates that stages 6 through 9 (quartz, illite, mica intermediates, montmorillonite) are most common. The absence of major amounts of stage 5 minerals (albite and other feldspars) is indicated by the low amounts of nonreplaceable Na and Ca ordinarily found in Prairie soil colloids (Marbut, 1935, and Hutton, 1948). Aside from instances in which the parent material contained kaolinite, such as mentioned above, there is little information pointing to kaolinite in Prairie soils. In fact, several studies (Whiteside and Marshall, 1944, and Larson *et al.*, 1946) of Planosols which may be considered post-Prairie soils have failed to indicate that major amounts of stage 10 minerals (1:1 lattice clays) have been formed even at these advanced stages of profile development. In accord with the ideas of Jackson *et al.* (1948) concerning the effect of particle size upon rate of weathering, the coarse clay (2 to 0.2 μ) of Prairie soils tends to be largely the quartz and illite minerals of stages 6 and 7 in their weathering sequence, whereas, the fine clay tends to be dominated by mica-intermediates and montmorillonites of stages 8 and 9. An apparent deviation from the weathering sequence has been found to occur in the coarse clay fractions of surface horizons of older Prairie soils and Planosols by several investigators (Whiteside and Marshall, 1944; Bray, 1934; Larson *et al.*, 1946). In these instances quartz seems to become dominant in the coarse clay (2-0.2 μ) of such soils. This may be due to the fact that since the rate of solution of quartz is a function of its particle size, quartz in the coarse clay fraction is more resistant, relative to other minerals, than is quartz in the fine clay fraction. Another factor that must be kept in mind is that under some conditions certain minerals may break down to finer particle sizes and be eluviated from the surface horizons at an early stage of weathering, whereas under conditions where no clay movement was possible these minerals might persist in the surface horizons for a greater period of time. In instances where redistribution of clay is possible the entire profile must be considered in evaluating the stage of weathering.

To summarize the effects of time and the course of weathering in Prairie soils, some of the principal processes may be listed as follows:

1. The removal of free carbonates from the profile is inaugurated before the soil has reached a stage of development that would entitle it to be considered as a Prairie soil, and this process is completed while the profile is still in the minimal or medial stage of Prairie soil development.

2. The removal of bases from the profile is inaugurated in very young Prairie soils and continues throughout all stages of Prairie soil development.

3. The amount of organic matter in the profile of a Prairie soil increases during the early stages of profile development, reaches a maximum, and then declines at advanced stages of profile development.

4. The formation of 2:1 lattice type clays is started in young Prairie soils and may in some cases continue through most of the stages of profile development within the ranges of Prairie soils. In cases where a maximum clay content within the profile is reached at an earlier stage of profile development, this maximum may be due to a balance between clay formation and clay decomposition.

5. The redistribution of clay within the profile starts in the medial Prairie soils and continues through and beyond the maximal Prairie soils.

6. The decomposition of primary minerals, especially the feldspars, takes place throughout all stages of Prairie soil development.

5. Topography

The early concepts of Prairie soils implied that these soils should be found on gently undulating upland sites. In such sites the removal of soil by erosion under natural conditions was supposed to balance the effects of weathering and leaching and result in a "steady state" which was considered to be a normal soil in equilibrium with its environment. In light of the discussion of the effects of time on the genesis of Prairie soils as given in earlier sections of this paper it appears that only a few Prairie soils are actually found in such a steady state; most of them seem to be tending to develop into Planosols. The effect of topography on the Prairie soils is most evident as it regulates the relative rate at which different segments of the landscape advance through the Prairie stage of soil development. Variations in the amount of water entering and moving through the soil profile account for much of the effect of topography upon the rate of soil weathering.

The role of topography on the development of the various portions of a Prairie soil landscape developed from a single parent material is affected by a number of factors. Among these are, degree of slope gradient, length of slope, direction of slope, curvature of slope, nature of parent material, age of soil, and position of permanent free water table.

While the effects of topography are evident in nearly all soil characteristics, the distribution of organic matter and clay in the profile can be used to typify many of the changes taking place as a result of topographic variations.

A detailed study of the accumulation of nitrogen in the profiles of some minimal Prairie soils and Lithosols as affected by the direction, length and percentage of slope has been reported by Aandahl (1948). A series of profiles arranged on traverses across hills in a virgin prairie area in western Iowa was investigated. The parent material was deep,

silty loess, containing about 5 per cent calcium carbonate equivalent and being quite permeable to water. The permanent water table was not a factor in limiting the downward movement of water. The general findings of this study are shown in Fig. 8. The effects of length and direction of slope upon accumulation of nitrogen and leaching of $CaCO_3$ are evident from this figure. Profiles from the lower parts of west facing slopes were higher in nitrogen and more deeply leached than were soils near the top of these slopes. In fact, profiles on the crest of such slopes

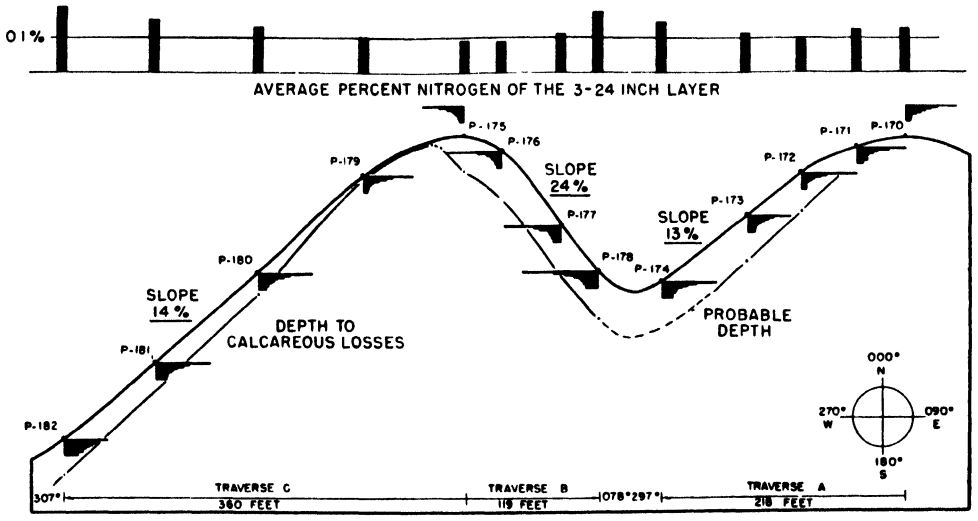


Fig. 8. Per cent nitrogen profiles and average per cent nitrogen of the 3-24 inch layer of virgin soil profiles on different slope positions of the Ida-Monona soil area of Ida County, Iowa.

showed essentially no leaching of $CaCO_3$. On east facing slopes the $CaCO_3$ was leached to greater depths even though the slope gradient was greater. This general relationship is shown in Fig. 6. Observations of the vegetation on virgin areas in this region indicate that east slopes are universally more densely covered by grasses or brush than are west and south facing slopes. This may be due to the protection from hot winds and to partial shading afforded by east facing slopes.

The relation of topography to the distribution of soil types in a prairie area having somewhat different geomorphological features is also shown in Fig. 2. This figure shows the distribution of the Tama, Muscatine and Garwin soils developed from a relatively thin deposit of silty loess over Iowan till in Tama County, Iowa. Slopes in the area are longer and not as steep as in the Monona-Ida area considered by Aandahl (1948). The Tama soils described earlier in this paper are found on undulating topog-

raphy, especially near the convex crests of long slopes. The Muscatine soils, which have thicker A horizons and somewhat more mottled subsoils are found on very gently sloping divides and near the base of long slopes. The Garwin soils, which are deep black soils with highly mottled subsoils (Wiesenboden or Humic-glei soils) usually occupy flats, depressional areas and drainageways. The differences in organic matter and clay distribution between Tama and Muscatine are shown in Table IX.

TABLE IX

Comparison of Organic Carbon and Clay Contents of Tama and Muscatine Soils [a]

	Tama P-27, 4 per cent slope		Muscatine P-32,[b] 1 per cent slope	
Depth, inches	Organic carbon, per cent	Clay, per cent	Organic carbon, per cent	Clay, per cent
0-6	2.86	27.5	3.38	28.2
6-9	2.44		3.29	
9-12	1.98	31.7	2.67	34.2
12-15	1.74		2.35	
15-18	1.46	32.4	2.04	33.9
18-21	1.12		1.84	
21-24	0.91	34.0	1.76	36.7
24-27	0.71		1.36	
27-30	0.59	34.2	0.82	38.9

[a] Samples collected and determinations made under the supervision of Roy W. Simonson.

[b] Muscatine profile sampled is a borderline profile transitional to Garwin.

With increased weathering a different effect of slope is seen. In southeastern Iowa where maximal Prairie soils are extensive, the slopes of 1 per cent are occupied by the Edina series, a Planosol developed under grass, while slopes of 4 per cent are occupied by the Seymour series, a maximal Prairie soil. Data on these soils show that the Seymour soils have a higher content of organic carbon than do the gentler sloping Edina soils. The clay content of the Edina subsoil is higher than is that of the Seymour.

Smith (1941) pointed out the changing relationships between Prairie and Wiesenboden soils on the one hand and Planosols on the other hand as the soils are subjected to increased weathering. These relationships are shown in Fig. 9. In young parent materials, minimal Prairie soils are likely to occupy level areas, gentle slopes, the base of long slopes and protected coves, while steeper and more exposed areas are occupied by Lithosols. Planosols are very rare and are found only in distinct depressions over a low water table. At somewhat more advanced stages the

level areas are occupied by very deep Prairie soils or Wiesenboden soils. The more sloping sites, which in more youthful situations were occupied by Lithosols, are now occupied by Prairie soils. The subsoils of these Prairie soils are only slightly mottled. Planosols are found in slight depressions and are more common than in the young area (Muscatine

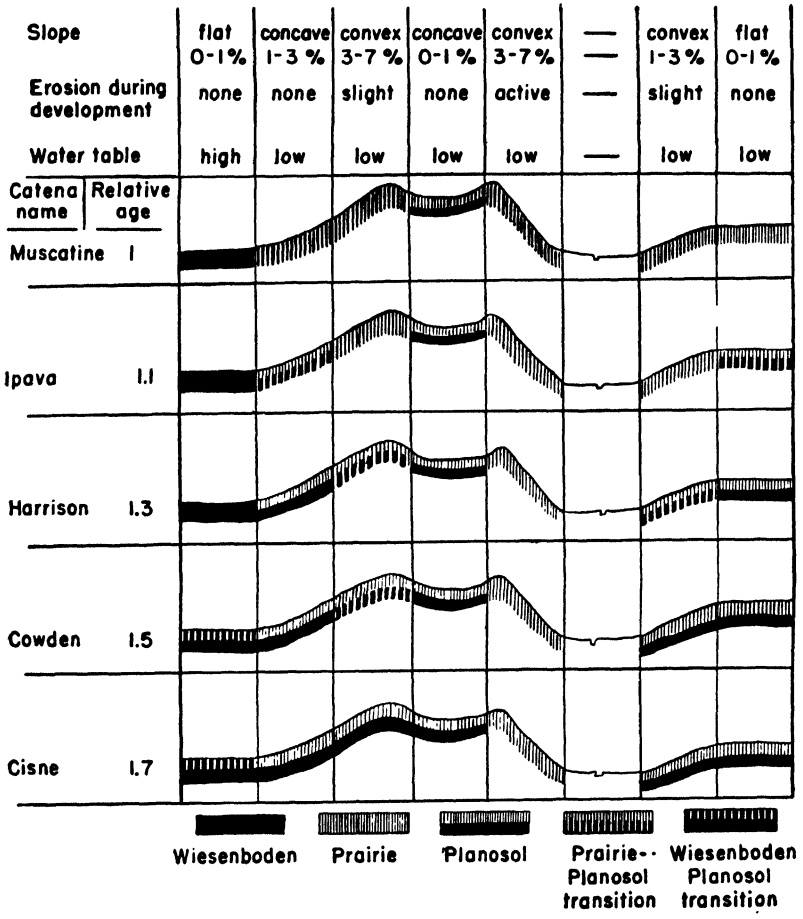


Fig. 9. Relationship between topography and soil character in southwest central Illinois: Menard, Sangamon, Christian, and Fayette Counties.

and Ipava catenas, Fig. 9). In areas where the soils are still older and more highly developed, the Prairie soils on the more sloping sites are found to have mottled subsoils and to show marked accumulation of clay in the B horizons. Planosols occupy level areas as well as depressions, and may even be found on gentle slopes (Harrison catena, Fig. 9). Thus it appears that as the soils grow older, the percentage of the landscape covered by Planosols shows a steady increase at the expense of

Prairie and Wiesenboden soils. With continued weathering the Planosols tend to occupy all areas which have not been rejuvenated by geologic erosion, or where a high water table has not inhibited the translocation of clay (Cowden and Cisne catenas, Fig. 9). In general, geologic erosion has rarely been a factor on slopes of less than about 7 per cent. In the eastern part of the Prairie region slopes of much over 7 per cent have usually been forested. In the western part of the Prairie region slopes from about 7 to 15 per cent are usually occupied by Prairie soils, but slopes much in excess of 15 per cent have suffered such rapid geologic erosion that the areas are occupied by Lithosols rather than Prairie soils.

The effects of topography upon soil development are also dependent upon the nature of the parent material and the position of the water table. In general wherever the water table is low, porous parent materials tend to minimize the effects of slope gradients upon the soil profiles, whereas impervious parent materials accentuate the effects of topography.

6. Summary of Concepts of Prairie Soil Genesis

Since the soil is the resultant product of the interaction of all the various soil forming factors, it is not possible to isolate and study the influence of any one factor except in a frame of reference of all the other factors. Given one set of conditions a particular soil forming factor may produce effects in one direction, while under a slightly different set of conditions it may produce effects in the opposite direction. For example, it was shown that the relations between slope and organic matter are sometimes reversed as the soil becomes more weathered.

The Prairie soils of the upper Mississippi Valley can be considered to have developed under relatively uniform climatic and biotic influences. They have developed from a variety of parent materials ranging from an occasional sand deposit high in quartz through the dominant calcareous alluvial and glacial sediments of highly mixed mineralogical composition to the occasional residuum from illitic and kaolinitic shales. Before they became Prairie soils they were Lithosols or Alluvial soils, and possibly some may have been young Gray-brown Podzolic soils. In most years some water moved down through the soil on its way to underground outlets. Further, before they could become Prairie soils some organic matter had to accumulate, and carbonates had to be removed from the surface horizons. By this time the formation of 2:1 lattice clay minerals had begun. With increased time the carbonate zone moved downward and the A_1 horizon thickened until it attained the normal thickness for the A_1 of a Prairie soil. This is now considered the maximal stage of the Lithosol although there is some reason to classify this as the pre-minimal stage of the Prairie soils. With still more time the carbonate

zone is separated from the zone of organic matter accumulation and the soil enters the minimal stage of the Prairie soil. The time required to reach this stage will vary with the slope factors, the parent material and the climate.

In the minimal stage the clay content of the soil is nearly uniform with depth. It is thought that this means that the clay has been largely formed in place during and shortly after the removal of the carbonates. The primary feldspars have not been strongly weathered, and appreciable amounts of calcium and sodium are being released. The micas and illites are releasing potash rapidly. Nevertheless, exchangeable hydrogen is present in small amounts in the exchange complex.

With additional weathering evidence of actual clay movement can be found, and the soil enters the medial stage. In general only the fine clay ($<0.2\ \mu$) appears to move in the soil. Movement is believed to start as a result of turbulent flow of water. Movement of the clay stops either when the downward movement of the water is stopped when a fine pore is reached, or when the clay particles are flocculated by electrolytes or by positively charged hydrated iron oxide particles. In fine textured materials the clay accumulates at shallow depths (18 to 24 inches or less). In coarse textured materials (sands) the clay moves to depths of five or more feet very commonly, and is believed to stop as a result of the flocculating effect of hydrated iron oxides.

During the medial stage the organic matter content appears to reach a maximum. Weathering of the silt size calcium feldspars in the A horizon is largely but not entirely completed. Sodium and potassium feldspars are the least weathered of the feldspars. With continued leaching and reduced release of bases, base saturation of the surface horizon drops to the neighborhood of 50 to 70 per cent, but saturation in the lower horizons remains high. While there is little positive evidence, it seems probable that clay formation continues in both A and B horizons, possibly at a reduced rate, and that decomposition of some of the clays begins.

From a geological point of view, the time required to pass through the medial stage into the maximal stage is often short, not much more than the time since the Iowan glacial age. In the western part of the Prairie region there seems to be a narrow range of slopes where slow but continuous erosion will prolong the medial stage. This range seems to lie in the neighborhood of 7 to 15 per cent slopes. In the eastern part of the Prairie region slopes steep enough for erosion to be active under grass sod have usually been invaded by forests.

With continued leaching, and accompanying formation and movement of clay in medium and fine textured materials, a sharp textural

contrast is developed between the A and B horizons, and the transitional horizons (A_3 and B_1) are narrowed to an inch or two. The pores in the B horizon are clogged with clay and conditions are favorable for occasional waterlogging and gleying. There is considerable doubt that this stage will be reached if the matrix is coarse textured or if the solum is underlain at shallow depths with coarse textured materials. Under these conditions it appears that there may actually be a complete removal of a considerable portion of the clay either as clay or as decomposition products.

At this stage in the finer materials, when gleying occurs, the soils are grading into Planosols and are considered maximal Prairie soils. They are considered to become Planosols when the B horizon becomes so slowly permeable that an intermittent water table develops above the B horizon and produces a distinct bleached A_2 horizon with base saturation well below 50 per cent.

In the coarse materials, where the solum remains too permeable for gleying, the direction of development has not been studied. However, the reddish colored B horizons of such soils suggest that they may become Reddish Prairie soils. The classification of such borderline soils will have to await more precise definition of the Reddish Prairie soils.

The Prairie soils of the upper Mississippi Valley are relatively young, with few exceptions either being formed in materials deposited during the Wisconsin glacial age or formed from older deposits exposed by erosion during or since Wisconsin time. The Prairie soils would have only minor extent in the Mississippi Valley were it not for the extensive recent glacial deposits.

IV. Classification of Prairie Soils

1. In Higher Categories

Marbut's (1927) classification of all soils into Pedalfers and Pedocals centered attention on the presence or absence of a zone of $CaCO_3$ accumulation as the differentiating criterion between Prairie soils and Chernozems. The analytical data available to Marbut indicated that this was a valid criterion. Jenny and Leonard (1934) studied the depth to the layer of carbonate concretions along a transect extending from Colorado through Kansas to Missouri. They noted an increase in the depth to the zone of lime accumulation with increase in rainfall but reported the presence of zones of lime accumulation in the Prairie zone under rainfall between 35 and 40 inches. In general with the higher rainfall the zone of lime accumulation lay somewhere between 60 and 120 inches.

Factors other than rainfall also appear to influence the presence or absence of a zone of lime accumulation as well as the depth to the concretionary zone. The lime content of the original parent material is, within limits, as important as is rainfall. Soils developed in noncalcareous materials or in materials having very low lime contents are apt to lack a zone of $CaCO_3$ accumulation. Very sandy soils such as the Thurman which straddles the Chernozem-Prairie zone lack a horizon of lime accumulation according to present information. On the other hand the Clarion soils found in central Iowa and the Clarence soils found in eastern Illinois have carbonates at depths as shallow as 25 to 35 inches. In a Clarion profile sampled near Ames, Iowa, the upper few inches of the carbonate zone were white and had a calcium carbonate equivalent of approximately 39 per cent. The till directly below this had a calcium carbonate equivalent of only 19 per cent. A Clarence profile reported by Stauffer (1935) from eastern Illinois showed some evidence of a zone of calcium carbonate accumulation. The Saybrook and Elliott soils from eastern Illinois reported by Stauffer showed definite evidence of having a zone of lime accumulation at a depth of about 4 to 5 feet, having both a maximum of secondary and of total carbonates, followed by a decrease with depth.

The age of the soil is another factor which can influence the presence or absence of a zone of $CaCO_3$ accumulation or its depth. Because of cyclical or seasonal fluctuations there are years when the rainfall is more than 50 per cent above average. For example, the mean annual rainfall for Nebraska is given as 22.3 inches but in 1905 the rainfall was 31.5 inches and in 1915, 35.6 inches, according to the 1941 Yearbook of the U. S. Department of Agriculture. Given enough of such seasons of above average rainfall the soils will tend to take on some of the characteristics associated with the most humid periods. Most of the Chernozem soils of northern United States and Canada, such as the Prairie soils, have developed since the start of Wisconsin time and are relatively young soils.

Viewed as a whole the soils of the Chernozem region more commonly have a zone of $CaCO_3$ accumulation than do the soils of the Prairie region, and the depth to the zone is shallower. Nevertheless, because of the lack of a zone of lime accumulation in some of the soils in the Chernozem zone and the presence of the zone of lime accumulation in some of the Prairie soils at the eastern or most humid limit of the Prairie region, there appears to be reason to question the validity of the separation of Prairie and Chernozem soils as different zonal great soil groups if the zone of $CaCO_3$ accumulation is the differentiating criterion. No other criterion has been suggested which would be more valid.

When Baldwin *et al.* (1938) established great soil groups for the

intra-zonal soils associated with the Prairie soils it became important to develop criteria for distinguishing between the Prairie soils and the other great soil groups. Riecken (1945) pointed out the necessity for considering borderline series in defining a great soil group. If the Prairie great soil group is too narrowly defined either new great soil groups must be established for the borderline series or they will be left outside any group. He pointed out that incipient gleying must be permitted in those Prairie series which constitute intergrades with Wiesenboden (Humic-glei) soils. He also pointed out the Prairie group must accommodate intergrades with the Planosols which have mottled heavy textured genetic B horizons. The Muscatine and Seymour series were selected as examples of Prairie soils which are intergrades with the Wiesenboden (Humic-glei) and Planosols respectively.

Riecken (1945) also pointed out that it is difficult to establish hard and fast rules for drawing the boundaries between different great soil groups and that different men are apt to draw the boundaries in different places. However, once the criteria are agreed upon all series having similar features should be grouped readily into the same great soil group. For example, if it is decided that the Muscatine series is to be classed as a Prairie soil it follows that the Floyd, Mahaska, Ipava and Lisbon series must also be classed as Prairie soils. The problems involved in determining the borderline between the Prairie soils on the one hand and the Chernozem, Wiesenboden (Humic-glei), Planosol, Lithosol, Alluvial soil, Reddish Prairie, and Gray-brown Podzolic soils on the other hand cannot be discussed in detail in this paper, but will be discussed elsewhere.

2. In Lower Categories

a. Into Series. In classifying the Prairie soils into different series, the 10 fundamental features of the soil profile listed by Marbut (1927) are taken into consideration.

In a recent review of the concept of the series, Riecken and Smith (1949a) have emphasized that at times the character of the substratum material is important in classifying soils into series. This was discussed earlier. Perhaps, therefore, the thickness of soil profile significant to agriculture should be added to the list of fundamental soil features. It is also possible that certain physical properties such as porosity and permeability should also be added to the list.

For the Midwest, more than 120 different Prairie soil series have been recognized up to the present. Some of these series, such as the Clarion, occupy an extensive area, whereas others, such as the Minden may be

quite minor in extent. No attempt will be made here to list all the Prairie series recognized.

Phases of soil types, as discussed by Riecken and Smith (1949a), have properties of the profile within the defined range of the soil type and series. For Prairie soils, the most common phases mapped are those indicating slope and accelerated erosion. Generally, the number of phases mapped is dependent on the degree of detail needed for the objective in mind.

b. Into Families. The concept of family accepted here is essentially that outlined by Baldwin, Kellogg and Thorp (1938), namely, that a family is a category in soil classification between series and great soil group and composed of one or more distinct series having similar profiles. As indicated by Riecken and Smith (1949a), little published information is available for guidance in grouping of series into families.

As the family category is intermediate in generalization between the Great Soil Group and series, it is obvious that not all of the fundamental soil features can be used if a large number of families is to be avoided. Some of the features which seem to be important enough to warrant consideration as family criteria are: thickness of the A horizon and of the solum, degree of gleying, texture and mineralogy of the solum, and degree of horizon development. Examples of possible families with the major morphologic criteria are given in Table X.

TABLE X

Examples of Families, with Major Morphologic Criteria

Family	Major morphologic criteria
Napier	A_1 thick, 20 inches or more; slight B development; silty; not gleyed.
Gravity	A_1 thick, 20 inches or more; slight B development; silty; slightly gleyed.
Tama	Average A_1; medium B development; silty; not gleyed.
Muscatine	Average A_1; medium B development; silty; slightly gleyed.
Grundy	Average A_1; strong B development; silty clay; slightly gleyed.
Monona	Average A_1; slight B development; silty; not gleyed.
Thurman	Average A_1; thick A_3-B_1; slight B development; sand; not gleyed.
Clarence	Average A_1; medium B development; clay; slightly gleyed.

In classifying Prairie soils at categorical levels between the great soil group and the series, there are two other considerations. One is whether the nomenclature should be connotative or abstract, and the other is the number of categories needed between the great soil group and series to express the various features. If the soil family is to be

used for making statements about the agriculture, the tendency would be to have a rather large number of families. However, if the family category is to be used chiefly to express fundamental soil characteristics, few families would be needed. After further study it might be decided that two categories would be more useful, so that agricultural predictions could be made at the lower level.

V. Distribution of the Prairie Soils

Because of limitations of scale, it is not possible to give here the details of the current nomenclature of the Prairie Soil Series in map form. Soil association maps showing the general distribution of Prairie Series have been published for Indiana by Bushnell (1944), for Illinois by the University of Illinois Agricultural Experiment Station (1949), for Wisconsin by Muckenhirn and Dahlstrand (1947), for Minnesota by McMiller (1947), for Iowa by Riecken and Smith (1949b), for northern Missouri by Shrader (1946), and for Kansas and Nebraska by Thorp *et al.* (1948). A revised association map for the United States is in preparation by the Division of Soil Survey, Bureau of Plant Industry, Soils, and Agricultural Engineering.

Fig. 1 is a generalized map showing the major areas of occurrence of Prairie soils in the Middle West compiled from the sources listed above. The boundaries of the Prairie soils and the original prairies were not the same. There were large areas of prairie in northeastern Missouri and southern Illinois, where the soils are considered Planosols because they have a low base saturation, a distinctly bleached A_2 horizon, and an abrupt boundary between the A horizon and the claypan.

While Fig. 1 cannot show detailed soil association areas, it is possible to show in a general way the main groups of parent materials according to origin, and the regional distribution of the minimal, medial and maximal Prairie soils. The dominance of loess and glacial drift will be noted. Where more than one kind of parent material is important, the most extensive is listed first.

The classification into minimal, medial and maximal Prairie soils is based on the profile characteristics of the upland Prairie soils having slopes from about 3 to 8 per cent. Obviously in the region of maximal Prairie soils, there are younger and less developed soils on some of the low terraces and some of the steeper slopes. The map therefore shows only the degree of horizon differentiation for the most extensive upland soils on slopes ranging from 3 to 8 per cent. There is some question yet about the proper classification of some of the areas called maximal in central Kansas.

The boundaries on the north and east between the Prairie and Gray-brown Podzolic soils, while highly generalized, are sharp, and the transitions are usually not more than one-quarter mile in width. The boundaries between the Prairie soils, Reddish Prairie soils and Planosols on the south are gradational, and the transition takes place over a distance of 10 to 20 miles or more. The boundary to the west between the Chernozem and Prairie soils has been discussed elsewhere. The boundary as drawn represents the common presence or absence of a distinct zone of lime accumulation in soils developed since Late Wisconsin time from permeable highly calcareous parent materials having slope gradients of two to seven per cent with a low water table. With these restrictions the transition still occupies a very broad zone, perhaps more than 200 miles in width, and may possibly be a separation of little or no validity.

VI. Crop Yields from Prairie Soils

The outstanding agricultural characteristic of the Prairie soils has been the high yields of grain crops produced without use of fertilizers although the use of fertilizers has been increasing rapidly in recent years. The period of exploitive agriculture of the Prairie soils appears to be drawing to a close. While continued cultivation will in time produce mineral nutrient deficiencies which could cause declines in yields, the first hundred years of cultivation have not witnessed any appreciable decline in average yields. Declines in the amount of available nitrogen released through decomposition of the soil organic matter have been compensated for by increased growth of legumes, improved varieties, and improved cultural methods. For the period 1940-1944, census data shows that average acre yields of corn (maize) for some whole townships (36 square miles) have been as high as 70 bushels on some of the best Prairie soils. These yields were reported in Tama and Grundy Counties, Iowa, where Tama and Muscatine soils are dominant. During the same period, corn yields in comparable townships in Lyon County, Iowa, on the border between Prairie and Chernozems soils (Moody soils) were 50 bushels per acre, or 20 bushels less. In these townships, areas of Intrazonal and Azonal soils are minor in extent and probably have had little influence on the average yields.

Yields from specific soils have been reported by Odell (1947). He reports that individual farmers on Tama-Muscatine soils have obtained acre corn yields as high as 85 to 90 bushels for the whole period 1937-1944. These are probably about the top farm yields obtained over a period of years in the corn belt. They were secured by farmers using essentially a corn-corn-oats-clover or corn-corn-oats-clover-clover rota-

tion with applications of barnyard manure and limestone, but without significant amounts of commercial fertilizers. While the highest farm yields exceed these values in favorable years, no farm is known to the authors where harvested yields for the entire planted acreage have averaged as much as 100 bushels of corn per acre over a 5-year period. Corn yields from the best Wiesenboden (Humic-glei) and Alluvial soils may approach those of the most productive Prairie soils, but probably do not exceed them.

While the most productive Prairie soils under the best of the prevailing systems of management have been producing the corn yields mentioned above, average yields on the other Prairie soils have been considerably lower. Odell (1947) reported farm yields of only 33 bushels of corn from Hagener loamy sand, a Prairie soil developed from eolian sand, and 29 bushels from Clarence silt loam and Rowe silty clay, Prairie and Wiesenboden (Humic-glei) soils respectively developed from till having a clay texture. These yields were secured by farmers who had only one-eighth of their land in legumes each year. Obviously corn yields are still lower if the Prairie soils are truncated by erosion and no provision is made for supplying nitrogen to the corn.

The range in average farm yields for the 1937-1944 period for crops other than corn reported by Odell (1947) from farms on Prairie soils are as follows: soybeans, 11 to 24 bushels per acre; winter wheat, 16 to 28 bushels; oats, 19 to 49 bushels; spring barley, 27 to 39 bushels; alfalfa hay, 2.0 to 2.8 tons. These figures cover the range between the poorer soils under about average management to the better soils under better than average management. Each figure is an average of the yields obtained by a number of farmers so the extreme range is somewhat greater than the figures given.

With respect to productivity, the Tama series, cited earlier as a modal Prairie soil, lies well above the middle of the range of the Prairie soils and probably is somewhat higher in productivity than modal because of its higher rainfall.

Changes under Cultivation

A few studies have been made of the changes which have occurred in the Prairie soils during cultivation. In most cases the virgin site was represented by a field which had never been plowed, but which had been used for meadow or pasture. Samples from this field were compared with samples from an adjacent cultivated field.

In reviewing the literature it is often difficult if not impossible to be sure exactly what has happened. Not only is there always the possibility of original differences in the soils compared, but erosion may have re-

moved layers of unknown thickness from the cultivated soils. In that case different layers are compared when the surface 6 inches are studied. Organic matter may be lost through decomposition in the cultivated fields or through erosion, and the effects should be separated if possible.

Whiteside and Smith (1941) compared virgin and cultivated samples of Flanagan silt loam, a moderately well drained medial Prairie soil developed from thin loess over Wisconsin till of Tazewell age. The cultivated field was first plowed in the late 1850's. No fertilizers were ever added. The cultivated field showed a loss of 32 per cent of the original 3.66 per cent of organic carbon in the surface 5 inches, and 15 per cent loss in the 5 to 12-inch layer. No differences were observed below 12 inches. About 30 per cent of the exchangeable bases in the upper foot were lost, but there was little change in the percentage of saturation, apparently because the loss of organic matter reduced the exchange capacity. No change was found in mechanical composition.

Ulrich (1949) compared the surfaces of virgin and cultivated samples of Minden silt loam, a medial Prairie soil developed from thick loess in western Iowa. He found reductions of 33 per cent in the original 3.34 per cent carbon, and 31 per cent in nitrogen in the surface 6 inches. The volume weight of the surface had increased from 0.96 to 1.19 and aeration porosity had been reduced by about one-third.

There was no evidence of erosion from either the Flanagan or Minden soils nor was there much opportunity because they were nearly level. The loss of one-third of the original organic matter in these studies must have been primarily by decomposition and oxidation. The loss represents a movement toward a new equilibrium where the level of organic carbon will be determined largely by the rotation, the amount and quality of crop residues returned, and the amount of manure added.

Anderson (1949) showed nitrogen decreases of 31 and 36 per cent in the surface 6 inches of Marshall and Grundy soils, medial and maximal Prairie soils, developed from loess in southwestern Iowa. In the 6- to 12-inch layers of these soils he found nitrogen decreases of 21 and 35 per cent, respectively. However, the mechanical analysis of the Grundy soil indicates that some erosion had occurred on the cultivated soil.

Anderson found no consistent change in pH, but there was a consistent decrease in exchangeable potassium in the surface 6 inches of the cultivated soils and in the percentage of large (greater than 0.25 mm.) aggregates. He found decreases in aeration porosity in the Prairie soils, the decrease ranging from 4 per cent of the original aeration porosity in a soil developed from glacial drift to 58 per cent in the Marshall samples.

Rost and Rowles (1940) in Minnesota have reported comparisons of

6 cultivated Carrington silt loam and 6 Tama silt loam surfaces with an equal number of samples from pastures which were presumed to have been uncultivated. They showed a 12 per cent loss of the original 2.66 per cent organic carbon in the upper surface of Carrington silt loam and a 5 per cent loss of the organic carbon in the lower A. In Tama silt loam they found that 13 per cent of the original 2.84 per cent organic carbon had been lost from the upper A (0 to 4 or 0 to 6 inches) but that no change had occurred below 4 or 6 inches. The mechanical analyses of the samples suggest that some slight erosion of the cultivated fields had taken place.

Hide and Metzger (1939) studied the effects of cultivation on some of the Prairie soils of Kansas. Twenty sites were selected where comparisons could be made between virgin soils, and soils which had been cultivated for 30 years or more across the slope and up and down the slope. The differences represent the combined effects of loss of organic matter by erosion and by accelerated decomposition. On the average they found a loss of 37 per cent of the carbon and 32 per cent of the nitrogen in the surface layer where cultivation was across the slope. Where cultivation was up and down the slope, 44 per cent of the carbon and 37 per cent of the nitrogen had been lost from the surface. Of the soils studied, 4 were on slopes of 10 per cent or more, 7 were on slopes of 5 to 10 per cent and 9 were on slopes of 4 per cent or less. The greatest total loss occurred on soils having the greatest total amount of organic carbon, but the percentage losses were not related to total amounts.

Several studies have been made of long time experiments to determine the effects of rotations and soil treatments on the Prairie soils. From these studies it is evident that the organic matter content of cultivated Prairie soils must still be declining. The level at which the organic matter will be eventually stabilized appears to depend upon the rotations used, the applications of crop residues and manure, the degree to which erosion is controlled and to a less extent the application of fertilizers.

The Morrow plots in Illinois, established in 1876, appear to offer the best opportunity to measure long time changes in organic matter as influenced by rotations and soil treatment. On these plots it is possible to compare the effects of continuous corn since 1876 with rotations of corn and oats since 1876, and of corn, oats and clover since 1901. The corn, oats and clover plots from 1876 to 1901 were in a rotation of corn, corn, oats, meadow (3 years).

Each of the 3 plots has been split into a north and south half. The north half has had no soil treatment and all crop residues have been removed. The south half of each plot has received animal manure applications ahead of the corn equal in weight to the dry weight of all

crops produced. In addition the south half of each plot has received applications of lime and phosphate.

The organic carbon was reported by DeTurk *et al.* (1927) for samples collected in 1913 and 1923. Stauffer *et al.* (1940) reported data for samples collected in 1938. These data are given in Table XI.

TABLE XI

Organic Carbon Content of Surface Layer of Morrow Plots as Influenced by Crop Rotation [a]

Year sampled	Continuous corn		Corn-oats		Corn-oats-clover	
	O North	MLP [b] South	O North	MLP [b] South	O North	MLP [b] South
1913	2.11	2.48	2.37	2.64	2.63	2.92
1923	1.94	2.35	2.21	2.68	2.57	2.88
1938	1.74	2.09	2.14	2.44	2.28	3.35

[a] 1913 and 1923 samples were 6⅔ inches; 1938 sample was 6 inches.

[b] Barnyard manure, lime and phosphate.

The soil type on the Morrow plots has not been determined by the Illinois Experiment Station because it does not exactly fit any established type, but it is a very close relative of the Flanagan series studied by Whiteside and Smith (1941). The organic carbon content of the virgin Flanagan silt loam was 3.66 per cent for the surface 5 inches. The Morrow plots could not have been greatly different from this value. By the time the first samples were collected in 1913 the experiment had been under way for 36 years and the effects of the different rotations and treatments were already apparent. The next 25 years of the experiment showed a further decline in the organic carbon for every rotation without treatment. With treatment, only the corn-oats-clover rotation failed to show a decline. However, in every case the decline during the 25 year period was less than it must have been in the preceding period. The low carbon value of the continuous corn plots, according to Stauffer *et al.* (1940), has been influenced in part by erosion despite the gentle slope of one to two per cent. They also point out that the sod borders of the plots which have been in Kentucky bluegrass (*Poa pratensis*) sod since 1904 have an organic carbon content of 3.2 per cent for the surface 6 inches. It would appear that a rotation of corn, oats and clover plus manure, lime and phosphate is at least as effective in maintaining the organic carbon content of the Prairie soils as is bluegrass.

Peevy, Smith, and Brown (1940) report similar general conclusions from the study of long time rotation and manurial treatments in Iowa

on Clarion loam, a minimal Prairie soil. Dodge and Jones (1948) also drew similar conclusions from a study of rotation and manurial experiments on a Prairie soil, Geary silty clay loam in Kansas.

The effect of erosion induced by cultivation of the Prairie soils is to remove organic matter. Thus, when erosion is active the Prairie soils tend to lose their principal distinguishing characteristic and the farmers lose one of their principal assets. While it is possible in some instances to determine with reasonable accuracy the thickness of the layer removed by erosion, in other instances it is not now possible to make even a reasonable estimate. Until the relation of the slope factors to organic matter content is known no valid estimates of the effect of erosion can be made. Figure 8 taken from Aandahl (1948) illustrates conditions in a virgin Prairie area. It was pointed out earlier that slope gradient is not the only factor affecting the topsoil thickness. The curvature, length and direction of the slope at times appear more important than gradient. Estimates of erosion based on the assumption that the original topsoil thickness was uniform or varied only with slope gradient have little validity over areas of much extent. Such estimates have a pronounced tendency to overestimate the amount of erosion which has taken place.

The influence of erosion on yields of crops, principally corn, has received some attention, but again the conclusions are clouded by the difficulties of determining the amount of loss, and in controlling such factors as shape of slope, slope gradient, and soil management, all of which may have independent effects on yields.

Where erosion does not bring to the surface material with greatly different physical and chemical properties the principal effect of sheet erosion is to reduce the nitrogen supplying power of the soil. Experiments with desurfaced plots on Tama silt loam at Dixon, Illinois, according to Bauer *et al.* (1945), have shown that a rotation including legumes plus fertilizers enabled the Tama subsoil to produce as much corn as the soil with its original A_1 horizon but without fertilizers. Yields of alfalfa hay were not greatly affected by desurfacing. Oat yields were reduced but no nitrogen was reported to have been applied to the oats. It seems probable that the effects of erosion on minimal and medial Prairie soils developed in medium textured parent materials can be largely overcome by use of fertilizers. The main damage therefore lies in increased costs of production, or in reduced yields if proper rotations and fertilizers are not used.

The maximal Prairie soils, and the minimal or medial Prairie soils developed in heavy textured parent materials, present a different picture. The physical properties of the B horizons of such soils make cultivation difficult. Seedbeds are difficult to prepare, and aeration is poor. Con-

sequently the loss of the A_1 horizon of such soils would seriously reduce future crop yields even though fertilizers are used. Future study may show methods of overcoming these handicaps but no methods are known now. The areas of maximal Prairie soils shown in Fig. 1 are therefore the principal areas where erosion probably will permanently reduce the productive capacity. Areas of soils developed from heavy textured parent materials can also be permanently damaged by erosion. Except for northeastern Illinois such areas are usually of only local importance.

Subsequent to the completion of this manuscript, and the setting of the type, the authors agreed to propose the name "Brunigra" as a substitute for "Prairie soils." The need for changing the name of Prairie soils has been apparent for many years because of the confusion between the meaning of "Prairie soils," a great soil group, and "prairie soils," referring to all soils developed under grass vegetation. The long established usage of the latter term gives it precedence. Delay in coining a new name seemed wise until it could be established that there were distinct enough differences between Prairie soils and Chernozems to warrant two great soil groups. The relation between the Brunigra soils and Chernozems will be discussed in more detail in a subsequent paper.

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Ladino Clover

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I. History and Distribution

Seed of ladino clover was first planted in the United States in the spring of 1891 at the North Carolina Experiment Station at Raleigh. McCarthy and Emery (1894) described it as follows: "This is an improved variety of the common white clover. Our seed came from Fratelli Ingegnoli, Milan, Italy. The plant is much more robust and has larger leaves than the common species, but produces very little seed. If it seeded more freely it would undoubtedly supersede the common white clover, as it gives more than twice as much herbage and seems as hardy as the other." In 1950 the seed problem has been largely solved and the prediction that ladino would supersede common white clover has come to pass.

1. History

The name "ladino" appears to have been derived from Lodi, a town in the Province of Lombardy in northern Italy. There in the upper valley of the Po it is thought to have developed by natural selection from the common white clover.

According to Madson and Coke (1937), seed was obtained for experimental purposes by the United States Department of Agriculture in 1903. Trials made in the Northeastern states were failures, but new tests were made in Idaho in 1911 where initial success with both forage and seed production was obtained. The first field planting for commercial seed production was undertaken in southern Idaho in 1918. According to Badley (1930), Jones (1931), Medeck (1929), Pickett (1933), Storgaard (1930), and Tesche (1929), ladino readily became accepted in California and Oregon and was soon widely and enthusiastically grown in those states.

Although immediate acceptance of ladino as a valuable crop was not forthcoming, the Pacific Coast states recognized its merits and it became established there in the period from 1920 to 1930. During the following decade, experiments and field performance tests proved its adaptation to the Northeastern United States, and trials from 1940 to 1950 have shown its value in the Great Lake States and in many of the Southeastern states. Now it is grown to some extent in every state except

North Dakota, and national estimates indicate about 4 million acres planted to ladino and ladino-grass mixtures.

This rapid acceptance of ladino under different climatic and soil conditions indicates that it is widely adapted if modifications in local environment are made to meet its requirements. It means, further, that the crop is productive, nutritious and economically practical to grow over large areas of the United States. In 1942 Hollowell said, "Ladino is rapidly becoming the foundation of an intensive grassland agriculture in the Northeastern states." His statement has since proved true and it might now be applied to areas of the Great Lake States, some of the Southeastern states, and to irrigated ladino valleys in the West.

2. Distribution

Ladino alone and in mixed plantings is grown most intensively in California and Oregon, where about 800 thousand acres are produced under irrigation. The crop is generally planted in the Northeastern states. Ohio and New York each grow about one-half million acres in mixed plantings primarily for pasture. Already 300 thousand acres are indicated in Wisconsin and such Southeastern states as Virginia, North Carolina, and Tennessee are growing well over 150,000 acres each. The crop is increasing in acreage and significance in all except one or two states. Table I gives the acreage of ladino clover by states as estimated for 1949.

Acceptance of ladino in the cornbelt states has been indicated by Hollowell (1946) and in the Southeastern states by Lovvorn (1947, 1949). That it is more extensively grown than is generally supposed is shown in Table I.

II. Characteristics and Adaptation

1. Description

Ladino clover, *Trifolium repens* L., is a large form of common white clover. The variety name LATUM has been added to it by several writers, as, for example, Madson and Coke (1937), and Schoth (1936, 1944), but this is believed to be incorrect.

According to a study by Ahlgren and Sprague (1940) ladino compared to common white clover is several times larger in all plant organs but otherwise similar in appearance. It possesses thick, fleshy stolons which root readily at the nodes and under favorable conditions spread vigorously, since plants may cover an area of 9 to more than 16 square feet. The stolons are the most stable feature of the plant and are most useful in distinguishing it from common forms of white clover (Fig. 1).

The petioles may range in height from 6 to 30 inches, depending on growth conditions, and each petiole bears a single leaf composed of three leaflets. The plant does not usually flower so profusely as white clover. The seed cannot be distinguished from white clover, being similar in size, color, and shape. The root system is shallower than that associated with red clover, *Trifolium pratense,* or alsike clover, *Trifolium hybridum.*



Fig. 1. A typical ladino clover plant showing general growth habit. (By permission of McGraw-Hill Book Co.)

2. Adaptation

This clover has a wide climatic tolerance, yet its spread is limited by extreme cold, drought, or heat. Its broad climatic adaptation was predicted by Hegnauer as early as 1931.

a. Cold Resistance. Ahlgren and Burcalow (1949) have reported that "ladino appears to be as winter hardy as medium red clover but it is less hardy than common white clover." Under Connecticut condi-

TABLE I

Estimated Ladino Clover Acreage in the United States, 1949

State	Acreage	State	Acreage
Alabama	2,000	Nebraska	100
Arizona	1,000	Nevada	2,000
Arkansas	5,000	New Hampshire	30,000
California	587,000	New Jersey	80,000
Colorado	1,500	New Mexico	10,000
Connecticut	75,000	New York	500,000
Delaware	10,000	North Carolina	175,000
Florida	400	North Dakota	0
Georgia	63,000	Ohio	500,000
Idaho	33,000	Oklahoma	7,500
Illinois	135,000	Oregon	111,000
Iowa	5,000	Pennsylvania	87,500
Indiana	15,000	Rhode Island	500
Kansas	7,500	South Carolina	50,000
Kentucky	50,000	South Dakota	500
Louisiana	7,500	Tennessee	375,000
Maine	45,000	Texas	1,000
Maryland	50,000	Utah	2,000
Massachusetts	9,000	Vermont	100,000
Michigan	10,000	Virginia	167,500
Minnesota	500	Washington	7,000
Mississippi	20,000	West Virginia	1,000
Missouri	1,000	Wisconsin	300,000
Montana	5,000	Wyoming	50

Total in United States 3,646,050 acres

tions, Brown (1937) found that ladino was about as hardy as alfalfa. Investigations by Fuelleman (1948) on reported failures due to winterkilling in Illinois have shown these failures to be related to improper fall management. It was a common impression, as indicated by Bruins (1930), that ladino was not so hardy as red clover or alfalfa and, therefore, it could not be grown in the colder northern latitudes. Its Italian origin is also partly responsible for this early conclusion. Adequate hardiness to withstand the severe winters of Maine has been indicated by Fink (1943). Pure stands of ladino are subject to winterkilling by heaving, according to Brown and Munsell (1941), but this difficulty is largely eliminated when ladino is grown in association with a grass. This conclusion was also reached by Schoth (1944).

Smith (1949) has shown that ladino has less ability to survive encased in ice than does common white clover. Presumably this means that

survival under ice sheets during severe winter weather is also less certain.

b. Summer Temperatures and Moisture. In the Southeast the high temperatures and shorter day periods result in reduced blooming. According to Hollowell (1948), some ladino dies in summer and fails to reseed. In parts of the Southeast this species frequently behaves as an annual. Madson and Coke (1933) have also noted that excessive high temperatures restrict its growth and injure the crop.

Ladino requires a good supply of moisture for normal growth. Thus on the grazing lands of the West it makes its best growth under irrigation, as indicated by Hegnauer (1931), Jones (1930), Jones and Brandt (1930), Miller and Booher (1949), and Whitney (1939). Cool and moist weather stimulates vegetative growth in the humid regions. Bright, warm, and dry weather increases flowering and seed set, and under very dry conditions the crop becomes almost dormant or the stand may be injured. The difficulties experienced in growing the crop west of the Mississippi River, except under irrigation, are for the most part related to lack of available moisture and high temperatures.

c. Soil Conditions. Most investigators agree that ladino is best adapted to moist well-drained soils and not to dry, sandy, or very wet soils. This has been indicated by Ahlgren (1946), Donaldson (1939), Haddock (1943), Johnstone (1947), Phillips (1943), Rumler (1945), Snyder (1949), Van Alstine (1943), and many others. No evidence has been presented to indicate adaptation on dry or light soils. It will grow fairly well on droughty and sandy soils in seasons of abundant rainfall, but under these conditions it is not reliable.

Ladino appears to be more tolerant of wet soils than is alfalfa or red clover but slightly less so than alsike clover. Madson and Coke (1937) indicated that it is rather intolerant of alkali.

3. Breeding and Genetics

No specific investigations on the breeding or genetics of ladino clover have been reported, although considerable work on common white clover may be found. It is probable that ladino is similar to white clover in most phases of breeding and genetic behavior.

Some important characteristics of white clover that may be applicable are the presence or absence of glucosides and enzymes, as indicated by Williams (1939), Milville and Doak (1940), and Corkill (1940); the presence of a high degree of sterility, as shown by Williams (1931); and the almost complete self-compatability, as described by Atwood (1942).

Natural crossing by bees is undoubtedly the primary means of pollination for ladino clover.

4. Diseases and Insects

Only a few diseases are known to attack ladino. A leafspot disease, *Cercospora zebrina,* has been reported by Garber and others (1946). An inherited disease similar to a virus has been described by Atwood and Kreitlow (1946). *Sclerotinia trifoliorum* or common root rot was reported by Kreitlow (1949) and has been found extensively in the Atlantic coastal states. A virus referred to as "yellow patch" and given the trinomial *Marmon medicaginis H.* var. *Ladino* n. var. has been described by Kreitlow and Price (1949).

Such insects as the potato leafhopper, *Empoasca fabae* (Harv.), the lygus bug, *Lygus* sp., the alfalfa plant bug, *Adelphocoris lineolatus* (Goeze), and grasshoppers injure ladino in Wisconsin according to Ahlgren and Burcalow (1946). The lygus and alfalfa plant bugs cause the flowers to blast, thus reducing seed yields. Leafhoppers and grasshoppers consume and injure the leaves. Hollowell (1942) has reported the flea beetle, *Halticus citvi* (Ashm.) as very destructive in the Northeast. It makes small whitish spots scattered over most of the leaf surface. Thatcher, Dodd, and Willard (1948) have indicated that the clover leaf weevil, *Hypera punctate* (Fab.) often damages ladino by feeding on the leaves in May.

III. Establishment and Management

1. Effect of Lime and Soil pH

Best response from ladino is usually found on soils in which the pH ranges between 6.0 and 6.5. In North Carolina Lovvorn and Dobson (1947) suggested the use of 1 to 1½ tons of lime per acre for land not recently limed. In Connecticut Brown and Munsell (1941) have studied the effect of lime and soil pH on ladino. On a soil of pH 5.64 the ladino yield was 2,290 lbs. per acre; at 5.77 it was 2,624; at 5.82 it was 2,953, and at 5.96 it was 3,160 lbs. per acre. There was thus a difference of about 40 per cent in yield in favor of the highest pH value. It is apparent that ladino, like other legumes, is favorably affected by addition of adequate quantities of lime to the soil. Although it does respond to lime, it has been said by Brown and Munsell (1941) to be more tolerant of acid soils than is alfalfa. Hollowell (1942) has indicated that it "will grow well on medium to slightly acid soils." Fink (1943) said that it "will grow on acid soils provided the soil contains a minimum of 1500 pounds of available calcium per acre."

2. Fertilizing New Seedings

For making new seedings of ladino various fertilizer treatments are suggested. Thus Eby (1941) has suggested broadcasting 400 lbs. of a 5-10-10 fertilizer per acre for a ladino-grass seeding or 800 lbs. of an 0-12-12 material for a ladino-alfalfa mixture. Thatcher, Dodd, and Willard (1948) suggested 500 lbs. per acre of 0-20-0 or 0-12-12. Liberal applications of phosphate and potash fertilizer have been advocated by Owens (1945) but no nitrogen, since this is said to stimulate grass companions to the detriment of the ladino. In Maryland, Kemp, Kuhn, and Magruder (1943) suggested 300 to 800 lbs. per acre of 0-14-6 or 0-12-12, depending on the natural fertility of the soil. In Maine (1943) plowing under 10-15 tons of manure fortified with superphosphate has been suggested. The use of 300 lbs. of 4-12-4 or its equivalent is a practice indicated in Virginia by Hutcheson (1942). Prince (1945a) wrote that the most successful ladino growers in New Hampshire are using a complete fertilizer for seeding down. Light applications of nitrogen fertilizer or manure together with phosphate and potash have been suggested by Kenney, Fergus, and Henson (1949). Ahlgren and Burcalow (1949) have reported that 200 to 400 lbs. of commercial fertilizers such as 0-20-10, 0-20-20, 0-10-20, 0-14-7, and 0-9-27 per acre are commonly used in the Midwest. In North Carolina, Lovvorn and Dobson (1947) advocated from 700 to 1000 lbs. of a 2-12-12 fertilizer per acre. In Oregon (1944) about 300 lbs. of superphosphate has been suggested per acre and if the soils are poor the addition of nitrogen and potash is said to be advisable.

In seeding down to ladino and ladino-grass mixtures many workers suggest plowing under 5 to 10 tons of manure per acre. Supplemental mineral fertilizers, especially phosphates, are also added. In the Northeast and the Southeast complete fertilizer mixtures containing moderate amounts of nitrogen are suggested. In the Midwest straight mineral fertilizers are generally supplied. Under irrigated Western conditions if fertilizer is supplied it is usually superphosphate with smaller quantities of nitrogen and potash.

3. Fertilizer Tests

The most extensive fertilizer tests on ladino have been conducted by Brown and Munsell (1941). Their work shows that mineral fertilizers used in conjunction with lime will double and treble the ladino yields under Connecticut conditions. The application of lime alone or phosphate fertilizer alone was unsatisfactory. Similarly plots to which a combination of phosphate and potash was applied gave inferior re-

sponses to similar plots to which lime was also added. Addition of nitrogen resulted in reduced yield from the ladino. This is in agreement with recent results reported by Garber *et al.* (1946). Further studies by Brown and Munsell (1941) showed that the spring addition of 100 lbs. of potash per acre stimulated ladino so that, by October, it occupied 61 per cent of the treated area as compared to only 29 per cent on untreated plots. Furthermore, the second cutting of ladino was increased 60 per cent by the potash treatment. The use of lime together with phosphate and potash fertilizers invariably maintained better stands of ladino than did any of these treatments used singly.

Brown and Munsell pointed out that a good ladino-grass crop will remove 40 lbs. of phosphoric acid per acre and that a basic application of 200 to 300 lbs. of 20 per cent superphosphate or its equivalent must be added to replace this loss. Also, that 70 to 100 lbs. of potash are contained in a good crop, and that an annual acre treatment of 150 to 200 lbs. of 50 per cent muriate of potash is needed to offset this. They conclude that there is no justification for using nitrogen fertilizers on fields having 30 per cent or more of their areas occupied by ladino.

Fink (1943) indicated that 8 tons of manure fortified with superphosphate (80 lbs. N, 80 lbs. P_2O_5, and 80 lbs. of K_2O per acre) will maintain satisfactory stands of a ladino-timothy mixture in Maine. He also suggested that the annual application of 80 lbs. of phosphoric acid and 80 lbs. of potash will provide satisfactory yield and survival of this mixture. Further nitrogen is not needed to maintain ladino-timothy stands and its use for this mixture will depend on economic conditions. According to Fink, about 35 lbs. of phosphoric acid and 169 lbs. of potash are removed per acre by a good crop of ladino. This larger quantity of potash, compared with that indicated by Brown and Munsell, can mean only that more was available under the conditions of these Maine experiments.

Under Vermont conditions Midgley (1938) increased ladino yields by lime and fertilizer treatments. The use of 1½ tons of lime per acre on Woodbridge loam resulted in a 3-year average yield of ladino of 3,326 lbs. dry matter per acre. Lime plus 80 lbs. of phosphoric acid and 100 lbs. of potash produced 5,670 lbs.; lime and double the amount of phosphoric acid and potash yielded 7,323 lbs. per acre. Adding the equivalent of 300 lbs. of ammonium sulfate per acre to the last treatment increased the yield to 8,097 lbs. Substituting 8 tons of barnyard manure for the potash and nitrogen gave 6,046 lbs. Midgley concluded that lime in conjunction with heavy mineral fertilizer treatment was most satisfactory for ladino.

In New York, Blaser and McAuliffe (1949) showed that phosphate

applications gave increased yields of ladino and grass and that drilling this fertilizer was superior to broadcasting it. Work reported from Wisconsin by Ahlgren and Burcalow (1949) showed an average 2-year increase in ladino yields of 4.2 to 6.7 tons per acre from an annual application of 300 lbs. of 0-20-20 fertilizer per acre.

At the U.S. Regional Pasture Laboratory, workers (1946) concluded that the use of nitrogen fertilizer on an orchard grass-ladino association reduced the amount of clover in the mixtures because of increased stimulation of the grass and subsequent competition from it.

Several investigators have emphasized the value of potash in relation to productiveness and persistence of ladino. Thus Ahlgren (1941) has shown that yields increase with increasing amounts of potassium from 1 to 256 p.p.m. supplied in nutrient solution. Sprague and Eby (1948) reported 6 years' results on ladino maintenance with varying potash treatments. Beginning with a good stand of ladino their annual potash treatments gave the following results: (a) no treatment, 20.6 per cent ladino, (b) 50 lbs. K_2O per acre, 37.3 per cent, (c) 100 lbs. K_2O, 47.8 per cent, and (d) 200 lbs. K_2O, 60.0 per cent ladino. The 200 lbs. of muriate of potash per acre treatment thus resulted in a ground coverage of 40 per cent more clover at the end of 6 years than the plot receiving no potash.

For ladino in New Jersey, Sprague and Eby (1948) have suggested 10 to 20 lbs. borax per acre in a few soils too low in boron. Use of boron has also been suggested for certain soils in Georgia by Brooks and Buice (1947).

4. Topdressing Established Stands

Most authorities agree that mineral fertilizer treatments are best for maintaining productive stands of ladino. Sprague and Eby (1948) suggested the use of 300 to 400 lbs. of 0-19-19 or 0-20-20 fertilizer per acre as an annual treatment in New Jersey. Small annual applications of phosphoric acid and potash in Georgia have been recommended by Brooks and Buice (1947). In Rhode Island, Shaw (1944) recommended light topdressings of manure in fall followed by the equivalent of 600 lbs. of 0-14-14 in spring. He suggested spring topdressings of 800 lbs. of 5-10-10 per acre if manure is not added. In Pennsylvania Grau (1944b) recommended 8 to 10 loads of superphosphated manure or 300 lbs. of 0-14-7 or 0-12-12 per acre, applied annually. About 500 lbs. per acre of 0-20-0 or 0-12-12 was suggested by Thatcher, Dodd, and Willard (1948) in Ohio. Ahlgren and Burcalow (1949) reported that moderate applications of barnyard manure fortified with phosphate fertilizers, or 200 to 250 lbs. of a phosphate and potash mixture per acre, are ap-

plied in early spring every 2 or 3 years in the Midwest. In New York Van Alstine (1943) suggested 500 lbs. of 0-20-10 or 0-20-20 per acre annually. For North Carolina the recommendation made by Lovvorn and Dobson (1947) is 400 to 600 lbs. of 0-10-20, 0-12-12, or 0-9-27 per acre.

Thus on established ladino stands most workers suggest the use of a light manure topdressing in early fall followed by a mineral fertilizer treatment in spring. The application of such complete mineral fertilizers as 0-14-14 or 0-10-20 is most common at rates of 200 to 500 lbs. per acre per year.

5. Suitable Grass Companions

The question of whether to grow ladino clover alone or with a grass or grasses was first propounded by Brown and Munsell (1941). From their research on this question, begun about 1932, they concluded that suitable grasses tend to increase total yield and to protect ladino against winterkilling. Other points favoring the inclusion of a grass are: (a) reduction of laxative effect of ladino on cattle; (b) decreased danger from bloat when ladino is pastured; (c) increased ease of mowing and curing; and (d) enhancement of the chances of obtaining a satisfactory crop.

a. The Northeast. The choice of satisfactory plant associations depends on the use to be made of the crop, and on regional conditions affecting the adaptation of various grasses and legumes. Thus Fink (1943) reported that "none appear so widely adapted to Maine conditions as is timothy." A similar suggestion was made by Talbot and Miner (1946). Brown and Munsell (1941) and Owens (1945) expressed the belief that, in Connecticut, orchard grass, *Dactylis glomerata,* is most satisfactory in ladino mixtures used primarily for pasture, and timothy, *Phleum pratense,* for those seeded chiefly for hay. The addition of ladino to red clover-timothy hay mixtures has also been suggested. Haddock (1943) in New Hampshire advocated mixtures with red clover, alsike clover, alfalfa, *Medicago sativa,* or timothy for hay and with timothy, orchard grass, or smooth bromegrass, *Bromus inermis,* for pasture. Smith (1949) in Vermont has propounded similar pasture mixtures except that orchard grass is not recommended for either hay or pasture. For New Jersey, Sprague and Eby (1948) suggested at least 1 lb. of ladino in all pasture mixtures that include such species as alfalfa, red clover, alsike clover, orchard grass, bromegrass, reed canary grass, and timothy (Fig. 2). Hollowell (1942) indicated that ladino-timothy mixtures are especially valuable in the Northeast on productive soils and where sum-

mer temperatures permit the continuous growth of timothy. Mixtures of ladino with bromegrass, meadow fescue, *Festuca elatior,* and reed canary grass, *Phalaris arundinacea,* are said to be valuable. In Pennsylvania Grau (1944) suggested orchard grass, bromegrass, Alta fescue, *Festuca elatior* var. ARUNDINACEA, tall oatgrass, *Arrheratherum elatuis,* reed canary grass, or perennial ryegrass, *Lolium perenne.*



Fig. 2. A mixture of ladino clover and bromegrass is a favorite for pasture purposes. (Photograph by New Jersey Agricultural Experiment Station.)

b. The Southeast. In the Southeastern states the choice of grass companions is somewhat different from those in the Northeast. Thus Lovvorn and Dobson (1947) indicated orchard grass for well-drained soils and dallis grass, *Paspalum dilatatum,* for poorly drained areas. Redtop, *Agrostis alba,* is also valuable and tall fescue promising. Brooks growth of timothy.

c. The Midwest. In the Midwest the most popular combinations, according to Ahlgren and Burcalow (1946), are alfalfa, red clover, alsike clover, and timothy or bromegrass. For Ohio, Thatcher, Dodd, and Willard (1948) suggested simple mixtures with timothy, smooth bromegrass, or orchard grass. They also felt that ladino adds to the value of Kentucky bluegrass, *Poa pratensis*, pastures although they recognized that it is difficult to maintain a good stand of ladino in a bluegrass sod. Fuelleman (1948), in Illinois, listed alfalfa, red clover, timothy, orchard grass, bromegrass, or meadow fescue as suitable companions.

d. The West. In the West for irrigated pastures Miller and Booher of California (1949) suggested mixtures containing domestic ryegrass, *Lolium multiflorum*, perennial ryegrass, tall fescue, orchard grass, or dallis grass. They indicated that occasionally some alfalfa, bur clover, *Medicago* sp., birdsfoot trefoil, *Lotus corniculatus*, or Harding grass, *Phalaris stanoptera* may be added. Schoth (1944) believed that the best associations in western Oregon are redtop, domestic ryegrass, perennial ryegrass, timothy, orchard grass and Alta fescue. In Washington (1946) such grasses as Alta fescue, domestic ryegrass, perennial ryegrass, Kentucky bluegrass, meadow foxtail, *Alopecurus pratensis*, orchard grass, and creeping red fescue, *Festuca rubra*, are said to be most satisfactory. Alsike and red clover are also mixed.

A study of the grass and legume associations suggested for ladino, as given above, indicates that the erect hay types of crops are recommended as companions. Few authorities advocate growing ladino with such sod formers and shorter growing species as Kentucky bluegrass, redtop, colonial bentgrass, red fescue, or Bermuda grass. The mixtures suggested in the Midwest are similar to those of the Northeastern states. The Southeast is most interested in tall fescue, orchard grass, and dallis grass, and under irrigated Western conditions species common to both the Southeast and Northeast are useful. In addition, domestic and perennial ryegrass and meadow foxtail are considered valuable. Sod type grasses are evidently less valuable than those giving an open type growth or possessing a bunch habit.

Unfortunately, few findings are available concerning the merits of one mixture compared to another. This entire phase of grass-legume companions best suited for growth with ladino clover remains to be clarified. Ladino is seldom sown alone except for seed or for poultry and bee pastures.

6. Seeding Practices

This crop is seeded at the rate of one-half lb. per acre with mixtures used primarily for hay; one lb. if the mixture is for pasture; and 2 to 4 lbs. per acre for straight ladino stands. A single pound of ladino contains about 750,000 seeds or enough for 15 seeds per square foot in an acre of land. Brooks and Buice (1947) studied rates of seeding planting from 2 to 15 lbs. per acre and concluded that 2 to 3 lbs. was as satisfactory as larger rates.

a. Shallow Planting. Most authorities agree that seed must be planted very shallow for best success. Thus Owens (1945) and Smith (1949) suggested from one-half to one inch. Haddock (1943) indicated that the seeds should be barely covered. Sprague and Eby (1948) recommended planting no deeper than one-quarter to one-half inch, and Lovvorn and Dobson (1947) said that the seed should be covered lightly. Less than one-half inch was suggested by Miller and Booher (1949) and by Schoth (1944). A firm compact seedbed obtained by early preparation, harrowing, rolling, or cultipacking is advocated by all authorities. Planting at a depth of one inch or more would appear to be too deep, and a light covering of one-quarter to one-half inch most generally advisable.

b. Inoculation. It is believed that few growers inoculate seed of ladino clover, but several authorities suggest that this procedure be considered. This legume belongs to the same cross-inoculation group as do common white clover, red clover and alsike clover. Thatcher, Dodd, and Willard (1948) have expressed the belief that even though ladino be planted on fields that have previously grown successful crops of these clovers the seed should always be inoculated, especially in view of the recent discovery of superior strains of symbiotic bacteria. Fuelleman (1948) also advocated seed inoculation for fields that have not grown successful crops of clover recently and also if ladino is seeded on infertile and acid soils. Brooks and Buice (1947) reported that "inoculation is very necessary." Hollowell has said that "inoculation is unnecessary, but to insure a crop, it may be advisable, particularly at the first seeding." According to Sprague and Eby (1948), inoculation is advisable on most soils unless successful clover crops have been grown recently. Haddock (1943) indicated no need to inoculate on many soils, but suggested that other soils require inoculation and when ladino is grown on a field for the first time it should always be inoculated. Other workers make no mention of the need for inoculation. It would seem safest to

inoculate the seed until ladino is successfully grown on the area in question.

c. Seeding Dates and Companion Crops. Owens (1945), in Connecticut, suggested seeding in spring with oats or on top of fall-sown rye and pasturing of the companion crops. He indicated that seedings may also be made in early spring alone and in late summer until about August 10. In Maine, Fink (1943) has indicated that seeding with spring oats is most common but planting with canning peas is also practiced. Good stands are also obtained by planting with sudan grass or millet in late spring or early summer. Haddock (1943) has said that, in New Hampshire, early spring seedings on top of land seeded to grass the previous fall or plantings in late July or early August without a companion crop are suggested. Seeding in early spring or late summer has been recommended in New Jersey by Sprague and Eby (1948). The early spring seedings are made on top of a winter grain or with spring oats. It is suggested that the companion crop be mowed for hay or silage or pastured. If oats are to be used for grain, the seeding rate should be reduced to two-thirds the normal rate.

Lovvorn and Dobson (1947) expressed the belief that in North Carolina seeding from September 1 to 15 is best, except in the mountains, where August or April seedings appear more practical. Brooks and Buice reported (1947) late August or early September seedings to be best in Georgia except in the mountains, where good stands are obtained from March or April seedings.

In Wisconsin, according to Ahlgren and Burcalow (1946), spring seedings in oats are considered superior and August or early September seedings somewhat hazardous. Pasturing the companion grain crop or making it into hay is desirable to reduce danger from shading or lodging. Fuelleman (1948) has suggested early planting in March or April in Illinois. Early spring seedings in Ohio are recommended by Thatcher, Dodd, and Willard (1948), who have indicated that midsummer seedings often fail because of unfavorable high temperatures.

Miller and Booher (1949) have indicated that seedings are made in California from October 1 to early March because fall and winter temperatures are more favorable than those of spring and summer. Seedings in Oregon are most successful from May to July, according to Schoth (1944). Fall seedings are not generally recommended because of winterkilling and damage from slugs. Spring seedings from April to May are preferred by Law and Ingham (1944) in Washington, but some early fall seedings are also made.

In northern and central latitudes the most satisfactory time to plant

ladino appears to be in early spring with oats as the companion crop or on top of fall-sown winter grains or grasses. Most authorities suggest that the rate of planting the companion oat crop be reduced or used for silage, hay, or pasture. In southern latitudes early autumn seedings without a companion crop are preferred except at high latitudes, where early spring appears best.

d. Seeding Methods. Throughout the Northeast and the Southeast, seeding is accomplished primarily by means of cyclone and wheelbarrow seeders or the grass-seeding attachments on grain drills. Most workers, as, for example, Ahlgren and Burcalow (1946), Cox (1940), Dickey (1946), Lovvorn (1949) and Serviss (1945a), recommend firming the soil by cultipacking either before or after seeding. Some suggest cultipacking both before and after as extra insurance of a stand. Dilution of the seed with corn meal or other suitable carriers helps to ensure uniform distribution.

Law and Ingham (1944) have found that the best stands of ladino in Washington are obtained by planting with an alfalfa or grass seed drill. Rolling with a corrugated roller prior to seeding is advocated if such drills are not available. This operation is then followed with a light harrowing or another rolling to cover the broadcast seed. Most seedings made in Oregon, according to Schoth (1944), are broadcast and covered by a light harrowing. Miller and Booher (1949) have described several methods used in California, namely, (a) endgate broadcast seeders, (b) seeder and roller combined, and (c) airplanes with special seeding attachments for such tiny seeds as those of ladino.

e. Seed Characteristics. Seed of ladino is indistinguishable from common white clover seed. To derive the greatest benefit pure ladino seed must be used in planting. Most purchasers are cautioned to buy certified seed or seed of known origin from reliable seed dealers.

Some seeds of ladino, according to Thatcher, Dodd, and Willard (1948), are considered "hard" because they are fairly impermeable to absorption of water. This results in delayed germination from as little as a few days to more than a year. Hollowell (1942) has expressed the belief that the presence of 10 to 40 per cent hard seeds in ladino is not objectionable. The delayed germination of such seed may ensure a stand if part of the early seedlings are killed by unfavorable weather conditions.

Hard clover seeds pass through the digestive tracts of animals on ladino pastures or of those consuming ladino hay. As the manure is spread it becomes a source of volunteer ladino plants.

7. *Use in Renovation*

Unproductive pastures may often be improved by adding lime and fertilizer, disking and harrowing, and seeding with ladino alone or with suitable grass partners. Fink (1943) indicated that many low, moist soils, high in organic matter and available calcium, in Maine, can be converted to ladino by simply fertilizing and seeding on top of the old sod in early spring.

Thatcher, Dodd, and Willard (1948) conducted 50 establishment trials with ladino. Analysis of their findings at the close of the 1944 pasture season led to the following conclusions: (1) Where no soil preparation was made and neither lime nor fertilizer applied, only 10 per cent of the trials were successful. (2) Application of lime and fertilizer but no soil preparation gave 23 per cent good stands. (3) Addition of lime and fertilizer together with disking resulted in 41 per cent successes. Of 26 tests conducted in 1945 and 1946, only 8 were failures on land that had been limed, fertilized, and disked. These were explained by late seeding, too little seedbed preparation, overgrazing, or unfavorable weather. In contrast to other legumes tried, ladino was outstanding, as shown in Table II. These results indicate that ladino is readily established by common renovation practices in rundown pastures. Under such conditions, a stand of ladino is as easily obtained as one of red or alsike clover.

TABLE II

A Comparison of the Establishment of Legumes in 18 Renovation Tests on Ohio Farms[a]

Crops	Per cent of perfect stand	Per cent showing good or excellent growth at the end of the first season
Ladino clover	86	78
Alfalfa	67	61
Sweet clover	65	63
Birdsfoot trefoil	51	33
Lespedeza sericea	35	none

[a] *Ohio Agr. Expt. Sta. Bull.* **684** (1948).

8. *Management*

The popularity of ladino clover has increased rapidly with increased knowledge of the techniques of managing the crop. The yield and persistence are closely related to the techniques applied in growing the crop.

a. Care of the New Seeding. The seedling stage is said to be the most critical in the life of the plant. It is common belief that excessive shading may reduce seedling vigor and even destroy the plants and also that early and too close grazing will limit the growth and development of the young plants.

Ladino spreads very little during the first 6 or more weeks of its growth, most of its development being in the form of root and primary top growth. After this initial period, growth of creeping stems becomes rapid if conditions are favorable. To encourage such spread the removal of companion grain crops by grazing or as hay is especially valuable, according to Sprague and Eby (1948). Removal of a companion crop of oats by Brown and Munsell (1941) at various dates, however, did not affect the final stand. The oats were removed on June 13, June 29, and July 6, and the respective ladino stands on October 16 were 97, 98, and 96 per cent.

It has been shown by Thatcher, Dodd, and Willard (1948) that straw from grain crops, if left on the field after combining, may smother ladino.

b. Rotational Grazing. Brown and Munsell (1941) were the first to demonstrate that ladino clover stands were injured under close, continuous clipping and also that frequent and close clipping reduced the yields. Their best management treatment over a period of years was cutting at a 10-inch height back to 4 inches. They concluded that "continuous or close grazing, especially in late fall, are not practices conducive to the well-being of ladino."

Thatcher, Dodd, and Willard (1948) reported that "too close grazing and regrazing before the new growth is well started will quickly thin the stand." They suggested that ladino should not be grazed continuously closer than 3 to 5 inches. Sprague and Eby (1948) have recommended rotation grazing, permitting the clover to be consumed until 3 or 4 inches of top growth remains.

Four years' results by Ahlgren and Burcalow (1949) comparing moderately to closely grazed ladino-bromegrass pastures showed that average yields of dry forage were 1.3 tons per acre greater under moderate grazing. They expressed the belief that the crop ought not to be grazed until it is 8 to 10 inches high and that the grazing should then be down to 4 or 5 inches only. Rotational grazing is the only method suggested for utilizing ladino clover pastures.

It has been pointed out by Thatcher, Dodd, and Willard (1948) and by Sprague and Eby (1948) that the feeding value of ladino changes very little from the young to the bloom stage of growth, and this is an-

other reason why grazing can easily be deferred. The protein content over the entire range of maturity, however, is said to vary from 12 to 30 per cent.

c. Ladino Pasture Yields. Ladino yields reported by Brown and Munsell (1941) indicate a range from 2,500 to 5,500 lbs. of dry matter per acre. In comparisons of ladino-grass mixtures, Sprague and Eby (1948) obtained the following results: ladino-orchard grass, 7,629 lbs.; bromegrass-ladino, 6,555 lbs.; Kentucky bluegrass and white clover, 2,594 lbs. Thus the ladino-grass mixtures were shown to be several times more productive than white clover-bluegrass pastures. According to Ahlgren and Burcalow (1946), ladino-bromegrass yields have been as high as 6,800 lbs. per acre. Fuelleman (1948) reported yields ranging from 3,200 to 7,577 lbs. per acre. In comparative tests in mixtures, the following results were obtained: ladino alone, 4,110; ladino-bromegrass, 5,195; ladino-timothy, 4,426; and ladino-Alta fescue, 4,286. According to Lovvorn and Dobson (1947), ladino pastures produce 3,500 to 5,000 lbs. of dry matter per acre in North Carolina.

d. Carrying Capacity of Ladino Pastures. Brown and Munsell (1941) have indicated that one acre of good ladino is sufficient to provide 200 cow pasture days. Ahlgren and Burcalow (1949) reported that "one acre will provide pasturage for one cow, or 10 to 12 hogs, or 12 to 14 sheep, or 125 turkeys, or 400 to 600 growing chickens or 300 to 350 laying hens." According to Sprague and Eby (1948), ladino will support 500 to 600 young birds per acre. Owens (1945) suggested one acre per cow. Fink (1943) expressed the belief that about two acres of ladino-timothy are needed per cow for hay, silage, and pasture. Fuelleman's (1948) experiments indicated a carrying capacity of one to one and a half animal units per acre.

e. Fall Grazing. All authorities agree that close pasturing in the fall will damage the stand of ladino. According to Schoth (1944), this is more nearly true of ladino alone than when it is grown in grass mixtures. Haddock (1943) expressed the belief that ladino ought not to be grazed in New Hampshire after September 20. Sprague and Eby (1948) suggested leaving 4 to 6 inches of top growth in the field for winter protection, and a similar recommendation was made by Ahlgren and Burcalow (1949).

IV. Utilization

Ladino is used in many so-called "multiple" or "triple" purpose mixtures. It is considered valuable for pasture, hay, and silage and for seed production.

1. Pasture

The primary use for ladino clover is as a constituent of pasture mixtures. All kinds of livestock, including dairy and beef cattle, sheep, hogs, and poultry, relish the tender succulent leaves and their high palatability.

There is some danger that cattle and sheep may bloat on ladino pasture. This hazard may be reduced by growing ladino with one or more grass companions. In this regard, Miller and Booher (1949) have said that 40 to 50 per cent legume has been found to meet the grazing preferences of cattle and sheep with a minimum hazard of bloat. Feeding dry hay or allowing easy access to dry hay, straw, or other grass pastures is an additional safeguard. Withholding cattle and sheep from ladino pastures when the leaves are wet or covered with dew is further protection against bloat.

Studies by Ewalt and Jones (1939) have shown that 65 per cent of the nutrient requirements of high-producing dairy cows could be provided by irrigated ladino pastures.

According to Snyder (1946), ladino is especially valuable for sheep, since a high-yielding, high-protein, nutritious feed is needed. This crop is said to help reduce labor in growing sheep and to permit maximum use of pasture as a source of feed.

In Pennsylvania (1946) ladino pastures were shown to be particularly valuable for growing pigs. Feeding hogs for a 70-day period on ladino pasture with a standard concentrate ration resulted in an average daily gain of 1.33 lbs. per animal. The group fed for the same period in drylot only averaged 1.24 lbs. daily. The investigators concluded that an acre of ladino grazed for 70 days was worth $29.92 in terms of gain made by the pigs.

Reduction in feed costs for growing birds on ladino pasture is usually indicated as 15 to 20 per cent. Furthermore, the mortality rate of birds on clover range is often lower than that of birds raised in confinement. Pullets are said to prefer ladino to any other pasture crop. Flock (1946) expressed the belief that a 20 per cent saving on feed can be made by use of ladino range. Sprague and Eby (1948) showed a 14 per cent saving of feed costs on pullets raised on range compared to those grown in confinement. Kennard, Thatcher, and Chamberlin (1947) have

shown feed cost reductions in raising pullets for egg or meat purposes on ladino range. They also reported better egg production by pullets raised on ladino range than by those in confinement.

2. Hay and Silage

Ladino is considered valuable for hay or silage especially when it is grown in mixtures and carefully managed. If mixed seedings are used continuously for hay, the ladino will soon be lost, because it cannot withstand excessive shading.

Maximum yields are obtained by cutting when ladino is in full bloom. If properly cured, the hay will be of high quality, rich in minerals, vitamins, and protein.

Because of its tangled mass of leaves, the crop is difficult to mow and to cure. Its moisture content (80 to 85 per cent) adds to the curing problem. The tendency for mowed ladino to pack tightly in the windrow also increases the problem of drying. Even when ladino is apparently adequately cured for the mow, spoilage frequently occurs in storage. The use of grasses for companions makes both mowing and curing easier.

Tests conducted by Thatcher, Dodd, and Willard (1948) on ladino for hay have shown that three cuttings a year, averaging 18 to 20 per cent protein and 3 tons of dry matter an acre, may be obtained. Such yields are usually less, however, than comparative hay yields from alfalfa, red or alsike clover mixtures.

A good quality ladino clover-grass silage may be obtained if partial wilting after mowing is permitted and if the proper amount of preservatives is used. Good ladino-timothy silage has been produced by Fink (1943).

3. Seed Production

Until recently, the production of ladino seed has not been adequate to meet the high demands. Heavy demands compared to supplies have resulted in high prices per pound. Though most of the ladino seed is produced in California and Oregon, there is an increasing interest in seed production elsewhere, especially in the North Central states.

In 1944 the high prices for ladino seed led Grau (1944) to suggest use of a dandelion rake in the harvest of the seed from poultry ranges. Suggestions for the growing and harvesting of ladino seed in the humid East have been made by Kenny, Fergus, and Henson (1949), by Sheldon and Dexter (1948), and by Burcalow, Ahlgren, and Smith (1948). The advice given by these men includes (a) the use of certified ladino seed for planting, (b) seeding on a weed-free firm seedbed, and (c) special techniques for harvesting and threshing the seed crop.

In the East the first crop is commonly pastured, or it may be removed for silage and the second growth used for seed production. Pasturing or mowing is best completed by early June so that the seed crop may develop during the hot, dry weather of July and August. The crop is mowed for seed when most of the seedheads are brown. It may be left in the swath, placed in windrows, or allowed to dry and then placed in stacks. Ladino is often combined directly from the windrow or swath, but large losses of seed result from this practice and yields of as low as 10 to 50 lbs. per acre result.

Recently Sheldon and Dexter (1948) developed a vacuum type harvester containing a rotating beater and a suction nozzle. This machine is outstandingly successful in preventing seed losses, as may be noted in Table III. It was more effective than combining directly from windrows

TABLE III

Comparison of Methods of Harvesting Ladino Clover Seed [a]

Methods of harvest	Pounds per acre of seed recovered
Combining from windrows	100
Combining from swaths	60
Vacuum harvests from swaths	160

[a] *Michigan Agr. Expt. Sta. Quart. Bull.* **31** (1948).

and far superior to combining from the swaths (1943). Use of the vacuum type harvester is recommended in Michigan and Wisconsin.

In California, Oregon, and other Western states nearly all the seed is raised under irrigation. The period of greatest blooming is during late June. Early spring growth is grazed as in the East, and mowing is preferred because it gives greater uniformity of growth of the seed crop. In all areas if pasturing is not practiced, the first cutting is usually removed as hay, since it often contains many grasses and weeds. The seed crop is ready for harvest in late August or early September when nearly all the seedheads are brown. A period of two to two and a half months after mowing a hay crop or grazing is required for the ladino seed to reach maturity.

In the West the common practice is to mow, windrow, and shock the ladino in the field for a few days prior to threshing. The seed is threshed by means of a stationary threshing machine with clover-hulling attachments. Seed yields range from 50 to 300 lbs. per acre with average yields about 100 lbs.

Three problems common to ladino seed production in both the East

and West are (a) ensuring adequate pollination, (b) elimination of weed seeds, and (c) maintenance of seed purity. To set seed, the flowers must be pollinated by bees. Ford (1948) has indicated that ladino produces plenty of nectar and is attractive to bees. Newell and Mead (1945) have expressed the belief that it is far superior to red clover but probably not so good as alsike in its attractiveness for bees. According to Wood (1944), it is a valuable honey plant and attractive to bees. In the ladino seed-growing areas, common recommendations include provision of one to two hives of bees per acre of ladino raised for seed.

Madson (1945) was one of the first to point out the problems in producing ladino seed. He recognized that the buyer wanted seed free from undesirable weed seeds and also of the pure ladino type. Such weed seeds as buckhorn, *Plantago lanceolata,* and dock, *Rumex crispus,* are particularly troublesome. Yellow trefoil, *Medicago lupulina,* birdsfoot trefoil, sorrel, *Rumex acetosella,* cinquefoil, *Potentilla* sp., witchgrass, *Panicum capillare,* and alsike clover are other common contaminants.

According to Madson (1945), white Dutch clover and Louisiana white clover have probably been sold occasionally as ladino. This practice is recognized as unfair and it will eventually be corrected through certification or other means. The need to seed ladino on fields free of white clover is also apparent, since the latter cross-pollinates readily with ladino. It is also evident that adequate isolation of ladino seed fields from white clover is necessary to prevent cross-pollination.

The production of ladino seed is increasing steadily according to Edler (1947). In 1936 only 1,220 acres were raised for seed, from which came 106,000 lbs. More recent statistics are as follows: 1940: 7,000 acres and 560,000 lbs. of seed; 1945: 16,800 acres and 990,000 lbs. of seed; 1949: 25,000 acres and 2,400,000 lbs. of seed. Fairly large imports were also made from Italy, so that probably nearly three and three quarter million lbs. of seed were raised in or imported into the United States in 1949. Thus at last the seed supply seems to have caught up with demand.

4. Other Uses

Ladino is being used successfully as a cover crop in orchards according to Haddock (1943), Sprague and Eby (1948) and Thatcher, Dodd, and Willard (1948). The dense mat of low-growing, nitrogenous materials protects the soil and helps conserve moisture. Because it is a perennial and seeds freely, ladino is easy to maintain in orchards. For orchard cover and improvement it is grown alone or with grass companions such as timothy or bluegrass.

It is also useful for growing as orchard mulch and can stand some cultivation. As a competitor with the trees for moisture during dry periods it is much less severe than is alfalfa or sweet clover.

V. Summary

Ladino clover is undoubtedly one of the most important pasture legumes in the United States. The characteristics of this plant which have led to its rapid rise and acceptance by livestock farmers are numerous. A brief recapitulation here appears in order.

As a species, ladino is widely adapted to different soil and climatic conditions. A temperate climate and moist fertile soils favor its growth and development. It will also grow well on poorly drained and mildly acid soils, but it is not adapted to poor droughty soils or extremely wet soils.

It possesses a perennial habit of growth and often establishes itself by natural reseeding. As a companion for the hay type grasses and legumes, it is reasonably satisfactory and far superior to common white clover. It is nutritious and palatable, begins growth early in spring, and recovers rapidly after grazing or mowing. As a pasture crop, it is highly productive.

Among the disadvantages of ladino are its inability to withstand close or continuous grazing and its tendency to winterkill or summerkill. It is difficult to mow for hay and also to cure, and hay yields are usually not comparable to those from alfalfa or red clover.

From a national standpoint there is increasing interest in ladino, primarily as a pasture crop and secondly for hay or silage. The acreage of ladino alone or with grass companions is already around four million, and increases are evident wherever the crop can be grown successfully.

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The Control of Soil Water

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I. The Scope of the Review

A review of work in the field of soil moisture in all its aspects would cover practically the whole subject of soil physics, and it is necessary in the first place to define for the reader the scope of this survey. The decision to control soil water, whether by drainage or by irrigation, or both, is ultimately made upon economic considerations. Control works will only be entered upon by the practising farmer if he has reason to suppose that, as a consequence, the increase in the annual agricultural income will exceed the equivalent annual cost of the measures. The costs of works are in the main determined by purely physical matters such as the design of the drainage or irrigation system. Purely physical matters, such as the effect of the system upon the water table on the one hand or on the distribution of irrigation water on the other, will enter into the first stage of the estimation of returns. We propose to deal with such physical aspects in detail, since the bulk of recent research on drainage and irrigation has been in this field.

Biological questions are raised when we have to consider the effect upon crops, and hence upon income, of the water control measures adopted. We shall find rather little to say upon such topics; one can but present as facts the little information which is available. In any case it must not be forgotten that the advantages experienced may not be biological at all; for example, benefits of drainage may be felt through improvement of farm transport or facilitation of cultivation, both primarily physical matters.

Finally, the farmer is concerned with economic matters such as the market for his increased production. Under the economic heading must also be considered such questions as whether the improved land will attract farmers good enough to exploit the improvements to the full. It is not everybody, for example, who will choose to farm fen peat (muck), fertile as it may be when reclaimed. These economic-cum-psychological, imponderable questions fall quite outside our province; they are mentioned only in order to place the review in its proper agricultural perspective.

II. Research Methods

The approach to problems may commonly be one of two quite different kinds. We may need to know urgently, for practical purposes, the effect of particular treatments applied to soils and crops. In such straits it is enough to have ready at hand the results of field experiments in which just such treatments have been applied. This is the method commonly adopted by the extension or advisory service. It has the

evident advantage of giving the limited amount of information which is specifically sought, and this information can be obtained by any enlightened agronomist who knows what he wants. It has serious disadvantages. Insight into the fundamental processes at work is rarely obtained, so that the information gained is relevant solely to the particular conditions of the experiment and may be applied to other conditions only with more or less risk. In relation to the area benefited, the costs of the investigation may therefore be high, and this is especially the case with engineering projects such as are associated with water control measures.

The alternative method is to make a fundamental analysis of the processes involved in terms both of precisely defined and measurable soil and plant properties and of equally precisely specified conditions. Among the former, for example, we might include the permeability and moisture characteristics of the soil profile and among the latter the rate at which water is being sprayed on the surface or the design of the drainage system which has been installed. Measurement of the circumstances and fundamental properties in any particular case would then enable us to forecast events with accuracy. The advantages of this method are, firstly, its capacity for wide application and, secondly and consequentially, its ultimate economy of effort and, therefore, its cheapness. The disadvantages are that it is slow; it cannot progress at command but must rely on individuals having from time to time flashes of inspiration; it is not necessarily able to answer any practical question on demand; and it requires the services of scientists who are specialists in their own fields.

A third method, in some respects to be regarded as lying between those already described, consists in seeking arbitrarily defined soil and plant properties capable of ready measurement and empirical correlation with field properties of importance which themselves defy precise definition. This concept will be made clearer when it is dealt with in its proper place. All methods have their proper places. We shall present basic ideas as a logically developed skeleton upon which to build a body of observed fact.

III. The Basic Approach

1. The Soil Moisture Characteristic

a. The Concept. All forms of control of soil water content rely upon the control of water movement in soil. This movement is caused by a hydraulic potential gradient, and is limited by a soil property known as permeability. The latter will be defined under III-2.a., while of the

former it is enough to say at the moment that the total potential, which is usually written ϕ, is the sum of two components. If a body of water is high up, it tends to fall to a lower level; height is a measure of the gravitational component of potential. Again, in a system where water is at different pressures at different places, the water tends to move from the higher pressure to the lower pressure zones; pressure is a component of potential. The total potential is obtained simply by adding the components algebraically (*i.e.*, taking their signs into account), a feature which makes potential a more amenable factor to deal with than is the force on soil water, since force components have to be added by geometrical constructions proper to vectors.

For water to move in soil, there must be differing potentials, and in general this implies separately differing gravitational and pressure components. Since the pressure of the water affects the moisture content of the soil, a varying pressure implies a soil of varying properties. It is basic to the study of the movement of water to reach an understanding of the relation between soil water pressure and soil water content. Here we must observe that the pressure is commonly measured relative to atmospheric pressure as zero. A "head" of water in excess of atmospheric pressure is called a hydrostatic pressure, and a diminution of pressure below atmospheric is called sometimes a suction and sometimes a pressure deficiency. The word "suction" is open to some academic objections, but it has the advantage of brevity and of conveying a well understood meaning to the general agronomist, and we shall therefore adopt it here.

Methods of measuring the soil moisture content at a chosen value of water pressure or suction are described under III-1.b.; if we have the results of such measurements and plot them as a curve, as in Fig. 1, this curve describes the whole course of the pressure-moisture content relationship, and has been called the "moisture characteristic" by Childs (1940). Often it appears that the moisture characteristic can have different forms for the same soil, one form when the experiment begins with wet soil and the suction is steadily increased, the other when the soil has initially little water and the suction is steadily relaxed. There has been some difference of opinion as to how far this hysteresis, as it is called, is a real effect, and the matter will be further discussed under III-1.c.

b. Experimental Methods. To determine the moisture content of soil presents no difficulty, but to measure the pressure, and particularly the suction, is another matter. A direct method uses a water manometer in contact with the soil sample via a permeable membrane. Suppose, in

Fig. 2 (a), we have a funnel with a floor in it pierced with holes, in each of which is sealed a fine capillary tube T, of circular cross-section (radius r), the neck of the funnel being connected by a U-tube of rubber to a burette B. Let us fill the apparatus with water and adjust the height of the burette until the level of water in it is the same as that of the floor

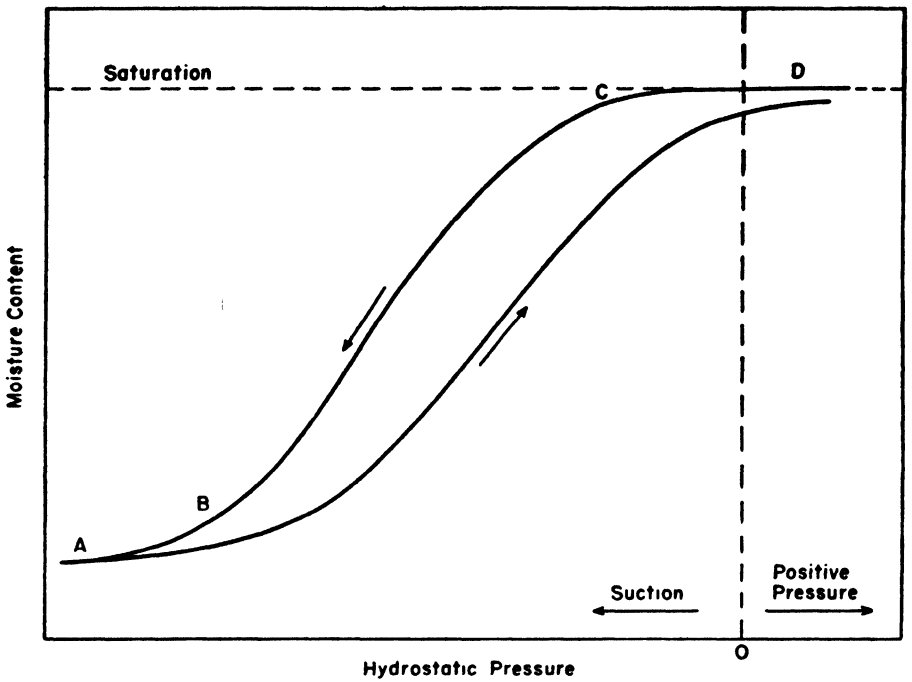


Fig. 1. A hypothetical moisture characteristic. The arrows indicate whether the experiment was carried out with increasing or decreasing moisture content.

of the funnel. Then we know that the capillary tubes will suck water to a height H above the free level in the burette, where

$$H = 2S/g\rho r \qquad \text{(III.1)}$$

S being the surface tension and ρ the density of water. If now we lower the burette, the water level in the capillaries will also fall, until, when it is level with the floor of the funnel, the water level in the burette will be H below the floor, (Fig. 2, b). We could now cut off the capillaries flush with the floor, leaving mere holes (Fig. 2, c), so that these holes are in effect supporting the water beneath them which is subjected to the suction H, (the free water level in the burette being at zero hydrostatic pressure). A further lowering of the burette would, of course, be an attempt to lower the capillary water level below the floor of the funnel, *i.e.*, out of the tubes altogether, when air would rush through the holes

and allow the level of water in the funnel to fall to that in the burette. A filter paper or sintered glass filter is, in effect, just such an array of very fine capillary holes, and provided we do not exceed the suction which the *largest* hole can support, water is held up to the underside of the filter and is therefore in contact with the water in any soil sample which we may place on top. Such a soil sample is thus subjected to the

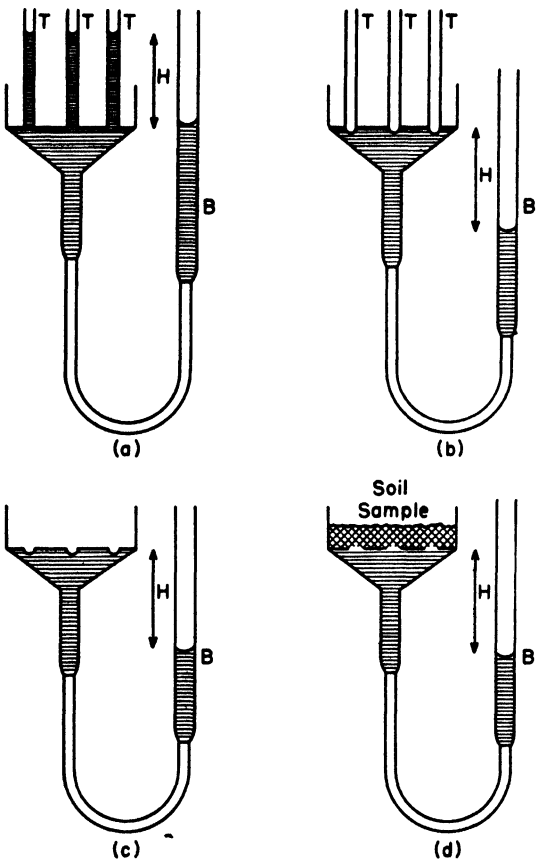


Fig. 2. This explains the action of a membrane in the simple manometer apparatus for measuring moisture characteristics. The capillary meniscus supports the suction H, which is transmitted to the soil sample in (d).

suction indicated by the level of the burette water below the sample (Fig. 2, d).

Filter papers and sintered glass filters are vulnerable, since a single accidental large hole will let air through at low suctions. Recent developments have been directed to the choice of membranes such as cellophane and sausage skin, which will withstand large suctions. A second disadvantage is that, even with adequate membranes, this simple ap-

paratus is limited to suctions less than the height of the water barometer, since at this suction the water in the funnel would fall away from the under side of the "floor" even though no air entered. This limitation has been removed by making the funnel of steel and brass, providing it with an airtight sealed lid, and applying pressure to the space above the "floor" instead of suction to the space below it. In effect this increases the atmospheric pressure suffered by the soil sample, so that the room air pressure on the under side represents a corresponding relative suction; provided the pressure difference on the two sides of the membrane is maintained, it does not matter whether there is pressure on the upper side or suction on the lower. These developments are the work of L. A. Richards and his collaborators, and the very complete list of references which he has given in his recent paper (1949) enables us to avoid quoting them separately. "Pressure plates," as they have been called, have been built to work at pressures up to 180 atmospheres.

The centrifuge has been used to apply high suctions to soil samples. It will be more convenient to discuss the basis of such uses of the centrifuge later (III-1.e), but it may be said here that Russell and Richards (1938) have obtained moisture characteristics in this way.

Various indirect methods have in the past been devised to measure high suctions, and they will be described here only in such measure as is necessary to the understanding of recent criticisms. The best known indirect methods utilize the fact that suction exerted upon water has an effect upon its freezing point and upon the pressure of its vapor in contact with it. Dissolved salts also have just such an effect, so that suction is not uniquely determined unless the other contributory factors are known. The freezing point method cannot be interpreted without certain assumptions, such as that the ice formed is free of the soil water suction (Schofield and Botelho da Costa, 1938). These authors find that suctions measured in this way agreed usually with those measured by a rough direct method, a result confirmed by Richards and Campbell (1948) using thermistors as thermometers. However, Schofield and Botelho da Costa themselves found one soil where agreement was not obtained. More recently Davidson and Schofield (1942) described a soil for which agreement was obtained between the freezing point and vapor pressure methods. Day (1942), on the other hand, finds the freezing point method technically unsatisfactory. Anderson and Edlefson (1942c) use a method of progressive freezing of an initially saturated soil in a dilatometer, and Edlefson and Anderson (1943) interpret these results on the assumption that the strong attractive force which solid surfaces exert on water molecules in their immediate neighborhood introduces a positive pressure. Alexander *et al.* (1936) describe an electrical method

of detecting the freezing point which seems capable of great precision.

We have mentioned that allowance must be made for osmotic pressure when calculating suction from the freezing point or the vapor pressure of soil water. Edlefson and Anderson (1943) require the same correction to be made in the direct membrane method, while Schofield categorically states the contrary, when he says that a "suitable membrane" gives the suction directly (1948). In our opinion it is a mistake to suppose that mechanical potential is only a term in the more general free energy of the water, and that, in consequence, an osmotic pressure difference must always be associated with a hydrostatic pressure difference even in the absence of a semi-permeable membrane. If there should be a momentary mechanical equilibrium between the water on one side of a permeable membrane and the soil solution on the other, with a difference of salt concentration, this is not a true state of thermodynamic equilibrium, which will subsequently be slowly achieved by a process of diffusion, as Edlefson and Anderson themselves recognize. Thermodynamic arguments are based upon states of thermodynamic equilibrium, and it is only where such equilibrium is maintained, for example, by a truly semipermeable membrane that the osmotic pressure in the soil solution must be compensated by a suction on the water in the funnel, giving an indicated suction which is not related to the hydrostatic suction experienced by the soil water. With a truly permeable membrane the suction is obtained without error. To be sure there is no certainty whether a membrane is permeable or semipermeable, since absence of diffused solute in the manometer may mean either that such solute is absent in the soil (no osmotic pressure) or that it is present but excluded by the membrane, when there would be an osmotic component of suction. In a private communication, Schofield suggests very reasonably that a filter coarse enough to break down at suctions of less than 20 atmospheres (capillary radius 750 Å) must be permeable to particles small enough to contribute sensibly to osmotic pressure. Such a membrane would therefore measure suction correctly, but error might arise with the use of membranes such as cellophane and sausage skin (Reitemeier and Richards, 1943).

c. Interpretation of Moisture Characteristics. Soil may lose water by one or both of two different mechanisms. If loss of water is not attended by shrinkage, air must enter. If loss of water is attended by exactly equivalent shrinkage, no air enters, but the particles are drawn more closely together. The interpretation of the moisture characteristic will be different in the two cases.

The entry of air into a "cell" in the voids amounts to an air-water

interface being drawn through the channel of entry. Since water wets the solid surfaces of the channel, the interface must be curved, and will, therefore, support a pressure difference on the two sides given by the well known expression, really just another form of equation III.1.,

$$p = 2S/r \qquad \text{(III.2)}$$

where r is the radius of the cylindrical channel and the pressure on the convex or water side of the interface is less by the amount p than that on the other or air side; *i.e.*, p is the suction on the water. If the channel is not cylindrical no simple expression can be used, but we can calculate a value r from a knowledge of p and refer to it as the effective channel radius, in much the same way as one sometimes calculates the effective radius of a solid particle from a knowledge of the velocity of its fall in water, using Stokes law, even though it be known that the particle is not spherical.

If we increase the suction on a nonshrinking soil from p_1 to p_2 and find that a volume V of water is released in the process, we can say that this volume is contained in channels of size less than r_1 (since otherwise the water would have been released at a suction lower than p_1) but greater than r_2 (since otherwise the water would not have been released at a suction as low as p_2). The moisture characteristic of a nonshrinking soil can therefore be interpreted as reflecting the pore size distribution. That this interpretation is essentially correct has been directly demonstrated by Swanson and Peterson (1942), who compared a direct measurement of pore size distribution under the microscope with that inferred from the moisture characteristic.

This interpretation has provided us with a powerful tool for soil structure investigation, comparable in importance with and complementary to mechanical and aggregate analysis. Donat (1937) has in this way followed the course of tilth formation by frost, while Childs (1940; 1942) has used the method to assess the stability of clay soils to wetting from the dry state and to show the dominant role of organic matter in determining this stability. Feng and Browning (1946) have found this a useful tool for the study of the degree of instability of some soils in Iowa. It may be of interest here to remark that Russell's use of the soil moisture characteristic (1945) to estimate the amount of water required to raise a water table by a given amount is an example of the direct utility of the moisture characteristic without reference to interpretation. The same author's study of soil structure (1941) relies upon the interpretation in terms of pore size distribution. We may cite Bradfield and Jamieson (1938) and Leamer and Lutz (1940) as others who have examined soil structure in this way.

When loss of water is accompanied by an exactly compensating shrinkage of the soil, there is clearly no air entry. In this case we have to deal with colloidal or surface active soil particles, and the increasing suctions which are required for the progressive extraction of water are, in fact, required to draw the solid particles more closely together against the "cushioning" of the Gouy diffuse layers of ions which surround the particles. The distance to which such a layer extends from the solid surface when it is quite free to develop in an infinite amount of external solution has long been known (Gouy, 1910), but the calculation of the equilibrium conditions when the layer development is restricted by the presence of a neighboring particle has but recently been carried out (Langmuir, 1938; Verwey and Overbeek, 1948; and Schofield, 1946). In effect the increased concentration of the dissociated ions in a layer which is thinner than that which would develop freely introduces an osmotic pressure component which, for equilibrium, must be balanced by a suction; release the suction and water will be drawn in to allow the particles to repel each other, *i.e.*, to permit the mass of soil to swell. The further development of this interpretation of the moisture characteristic of a swelling soil is an important field of future research.

A satisfactory interpretation of the moisture characteristic should account for observed hysteresis. In fact observers are not agreed that hysteresis is always demonstrable. Haines (1930), Schofield (1935), S. J. Richards (1938), and Richards and Fireman (1943) are among those who have reported hysteresis, while Christensen (1944) has inferred it from the variations of the permeability of soil at constant suction. On the other hand, among authors who have not been able to satisfy themselves that the phenomenon was demonstrable are Rogers (1935a) and Edlefson and Smith (1943). On theoretical grounds it seems probable that a nonshrinking soil of irregular pore size should exhibit hysteresis. Without necessarily subscribing to Haines's quantitative exposition, we may recognize that if an air-water interface is drawn into a larger cell via a narrower neck, it will require a greater suction to draw it through the neck than is required to prevent it climbing back to the neck through the cell when the suction is released by stages; *i.e.*, the suction required to empty the cell is greater than that which will just permit the cell to refill. Such cells and necks are a feature of loosely packed sands, which typically exhibit hysteresis. Structural cracks of more or less uniform calibre might not show such an effect markedly. When we turn to shrinking soils, we might not expect hysteresis, since the thickness of a restricted Gouy layer is determined uniquely by the suction. However, it might well be that one effect of suction would be to orientate the particles irreversibly into positions of closer

packing. It may be that Schofield referred to such a mechanism when he ascribed hysteresis to "micro-plastic forces" (1935); he shows the similarity in this respect between the moisture characteristic and the pressure volume curves for clays in a later paper (1938).

However one may account for hysteresis, the fact remains that if it occurs, there is a possibility of a drying soil remaining in contact with a wetting soil of lower moisture content yet at equal suction, and being in equilibrium. Schofield (1935) has sought to account for the phenomenon of "field capacity" on these grounds alone.

d. Soil Moisture Constants. In general, soil moisture characteristics are smooth curves, and present no evidence that water is present in sharply defined groups, bound with forces of quite different kinds. At very high suctions, of course, such sharply defined groups may exist and are, in fact, used for diagnosis of clay mineral types. The so-called moisture constants, *e.g.*, hygroscopic moisture, capillary and noncapillary moisture, can only be defined arbitrarily either by specifying a suction pressure or, as in Baver's definition of capillary and noncapillary water (1938), by arbitrarily specifying a feature of the moisture characteristic such as the point of inflexion, where it exists.

e. The Equivalence between the Moisture Characteristic and the Static Moisture Profile. A column of soil with its lower end in a reservoir of water at zero hydrostatic pressure will draw water upwards or, if saturated to begin with, will hold some of the water back and not let it drain wholly out. At a height H cm. above the free water in the reservoir the suction is H cm. of water. Thus at equilibrium, which may possibly be attained only after a long time, the moisture content at height H cm. is that appropriate to a suction of H cm. of water. The plot of moisture content against height (the moisture profile) is, therefore, in such circumstances a repetition of the plot of moisture content against suction (the moisture characteristic), as Buckingham pointed out long ago (1907). If, in the field, water is found to settle out into a borehole to give a free water surface at a definite depth, this free surface is clearly at zero hydrostatic pressure; it is known as the water table. Soil water below this is under pressure and above it is under suction. It is the nature of most moisture characteristics that little water is lost until a certain minimum suction is applied, since even the largest pores are commonly not very large and require a suction of a few centimeters of water to empty them. Hence the zone immediately above the water table experiences increasing suction with height but remains sensibly saturated up to such a height that suction is effective

in dewatering. This zone of saturation is known as the capillary fringe. It is, from its nature, incapable of precise definition; indeed, it may sometimes be incapable of precise location, since if the moisture characteristic does not exhibit a sudden onset of dewatering at a more or less well-defined suction, the soil will not exhibit a more or less well-defined capillary fringe (Childs, 1945a.).

If we imagine the force of gravity to be very much increased (say a thousandfold), the suction of a given column of water of height H is increased in proportion, namely a thousandfold. In absolute units the suction is $g\rho H$ for a column of height H above the water table, where g is the appropriate gravitational acceleration and ρ the density of water. Hence the moisture profile which extended over a height H under gravity would be telescoped into a height of only $H/1000$ in a field of 1000 g. Such very strong fields may be achieved in the centrifuge, where centrifugal force takes the place of gravity and is quite under control up to the limits of the instrument. Russell and Richards' method of obtaining the moisture characteristic (1938) is a method of sampling such a condensed profile at a constant height above the water table and with increasing field strengths. The moisture equivalent (see IV-2.d) is the average moisture content in such a condensed profile with a standardized height (1·6 cm.) of soil column and a standardized field strength of 1000 times gravity. For a critical and detailed examination of the centrifuge method see Schaffer *et al.* (1937).

f. The Soil Moisture Characteristic as a Tool for Measuring Soil Moisture Content. For many practical purposes it is desirable to know the soil moisture content rather than the pressure or suction. The simplest method other than the extraction and drying of a sample is to measure the soil water suction and to infer the moisture content by reference to the moisture characteristic of the soil. The apparatus now customarily called a tensiometer is a permeable membrane and manometer similar in principle to that described under III-1.b. The membrane is usually a tubular or conical probe of unglazed ceramic ware, strong enough to be pushed into a hole prepared for it. When the water in the manometer is in equilibrium with the soil water it reads the prevailing suction. It is usual to calibrate the apparatus directly by measuring the suction recorded at known moisture contents, using the soil from the site where the probe will be buried. Among workers who have developed such apparatus are Rogers (1935a), Richards (1942), Kenworthy (1945), Colman *et al.* (1946), and Hunter and Kelley (1946).

A less direct method relies upon the moisture characteristic of an absorbent body buried in contact with the soil. Such absorbers have com-

monly been plaster blocks and more recently fiberglass or nylon cells. The soil will have a suction appropriate to its moisture content and will transmit this suction to an absorber with which it is in equilibrium. The plaster block will then have a moisture content appropriate to this suction, in accordance with its own moisture characteristic. The moisture content of the block may then be obtained by raising it to the surface for weighing, afterwards replacing it (Davis and Slater, 1942), or by measuring the electrical resistance or capacitance between electrodes buried in the block, as recommended by Fletcher (1939), Anderson and Edlefson (1942a, 1942b), Bouyoucos and Mick (1940, 1947, 1948), Edlefson *et al.* (1942), Bouyoucos (1947, 1949), and Colman and Hendrix (1949). These measured quantities are interpreted in terms of soil moisture content by the aid of an initial direct calibration. Slater and Bryant (1946) have compared some of these methods with direct sampling, and report that each indirect method has its useful range, tensiometers being useful for high moisture contents, weighed plugs being accurate over a fairly wide range, while the resistance blocks as developed at that time had a use for large surveys, where accuracy was not a prime consideration. Thorne and Russell (1947) have found electrical capacitance a most unreliable criterion of soil moisture content, while Childs (1943) has offered objections to this method which do not appear to have been adequately answered by those who proposed them (Anderson, 1943).

The general conditions affecting the accuracy of all soil moisture measurements which depend upon the moisture characteristic are outlined below. Moisture content cannot be inferred with accuracy from a measurement of suction pressure when considerable changes of the latter have but little effect on the former, such as in the regions AB and CD of the hypothetical curves of Fig. 1. This is a limitation imposed by the soil and cannot be circumvented. In addition, if the absorbent block is working in a region where its moisture content is not much affected by changes of suction, insensitivity is imposed by the block. The solution is, of course, to choose a material, whether plaster of paris, fiberglass, nylon or what you will, suited to the range of suctions likely to be encountered.

It may be mentioned here that other indirect methods of soil moisture measurements have been proposed which do not involve the moisture characteristic. Thus Shaw and Baver (1939) use thermal conductance and Anderson (1943) and Wallihan (1945) the electrical conductance of the soil itself to indicate moisture content. Haise and Kelley (1946) and Cummings and Chandler (1940) have assessed the value of the thermal method in comparison with plaster blocks, and agree in regarding

it as being somewhat insensitive and limited to suctions of less than four atmospheres.

2. Soil Permeability

a. Definition. If, in a column of soil of unit cross section, (*e.g.*, one square centimeter) water is flowing at a rate of Q ml. per sec., it may be said to have an effective velocity of Q cm. per sec. If the column occupies only a part of the length of a tube in which it is contained, Q is the actual velocity with which the water travels in the approach section before it enters the soil. The true velocity in the soil is not amenable to discussion; we can never learn much about it and refer always to the measurable effective velocity, v.

It requires a difference of potential between two points in such a column to drive water from one to the other. It is known from experiment that the effective velocity of flow in the column is usually proportional to the potential difference, $\Delta\phi$, between two cross-sectional planes, and inversely proportional to the distance, l, separating those planes. These relationships may be written

$$v = -K\Delta\phi/l \qquad \text{(III.3)}$$

The negative sign indicates that the flow is in the direction opposite to that in which ϕ increases. The quantity $\Delta\phi/l$ is the potential gradient, or the amount by which ϕ changes per unit distance along the column. This law is called Darcy's law after its discoverer (1856). The constant K gives the flow velocity for unit potential gradient, *i.e.*, is a measure of the readiness with which the soil permits the flow of water. It is called the permeability of the soil to water.

Water flow is not always restricted to a single direction by confining tubes, and for that reason a more general definition of permeability is often desirable, of which equation III.3 is a particular case. In an unconfined body of ground water we may connect together in imagination all points which have the same selected potential, and we shall find that we have drawn a surface in the soil body; such a surface is called an equipotential surface. A cross section of the column described above is a case of such a surface. If we choose a slightly different potential we shall draw another surface slightly separated from the first. Thus we may choose intervals of potential and draw a series of separated surfaces rather like the layers of an onion; these surfaces will be closer together at some places than at others. These surfaces being at different potentials, water will flow from one to another, and just as water flowing down sloping ground will take the direction of steepest slope, so in the ground water body it will take the direction of steepest potential gradient.

This is naturally the direction in which it will reach the next equipotential surface in the shortest distance, namely at right angles to the surfaces. The potential gradient at a point is the potential difference between successive equipotentials divided by the shortest distance between those equipotentials at that point, in the direction of that nearest distance. That is what is meant by the vector notation $grad\phi$. The generalised expression for Darcy's law then becomes

$$v = -K \text{ grad } \phi \qquad \text{(III.4)}$$

It is necessary to point out that Darcy's law is a result of experiment and is not universally true. If, for example, the potential gradient is very high, the water may have a turbulent motion in the pores instead of a laminar or streamline motion. Then, just as in a crowd that is jostling instead of orderly, the flow velocity is less than it ought to be according to Darcy's law. Soil water movements are rarely likely to be the result of such excessive potential gradients. Then again, some soils may have structural features which encourage flow in one direction at the expense of others. Such soils are called anisotropic, and in these the average direction of flow may be in a direction other than that of the mean potential gradient. Such properties are fortunately no bar to the solution of problems although they present complications. For an exhaustive treatment of permeability the reader may be referred to Muskat's book (1937).

b. The Measurement of the Permeability of Saturated Soil Samples. Permeability is simply and precisely defined, and would, at first sight, appear to be capable of simple and precise measurement. We have but to pack the soil into a tube of known cross section, clamp it in position, as in Fig. 3, and connect the ends to a source of water and a sink respectively. To maintain saturation the pressure must be positive everywhere, and to maintain flow we must have a higher potential at the inflow end than at the outflow. In Fig. 3, the input potential is the sum of p_1 (equals $g\rho h_1$) and the height component $g\rho H_1$, while the outflow potential is similarly the sum of $g\rho h_2$ and $g\rho H_2$. The difference between these potentials divided by the length of the column, l, is the potential gradient; while the rate of collection of water at the sink in the steady state, divided by the cross section of the tube, gives us v, and we require nothing more for the calculation of K. Engineers, indeed, report permeability measurements in this way as a matter of routine. In fact, many difficulties arise, and considerable literature is devoted to the interpretation of measurements of this kind.

In the first place the material, if it is unconsolidated, must usually

be retained between permeable diaphragms (gauzes, filters and the like) and these absorb a part of the measured potential difference. The junction between the sample and the diaphragm may develop a quite anomalous resistance to flow. This difficulty may be surmounted by inserting manometers at points within the soil column, defining a new length of path over which we know the potential gradient. In our experience such manometers are insensitive and sluggish on the one hand, and capricious on the other. Then the measured flow rate for an un-

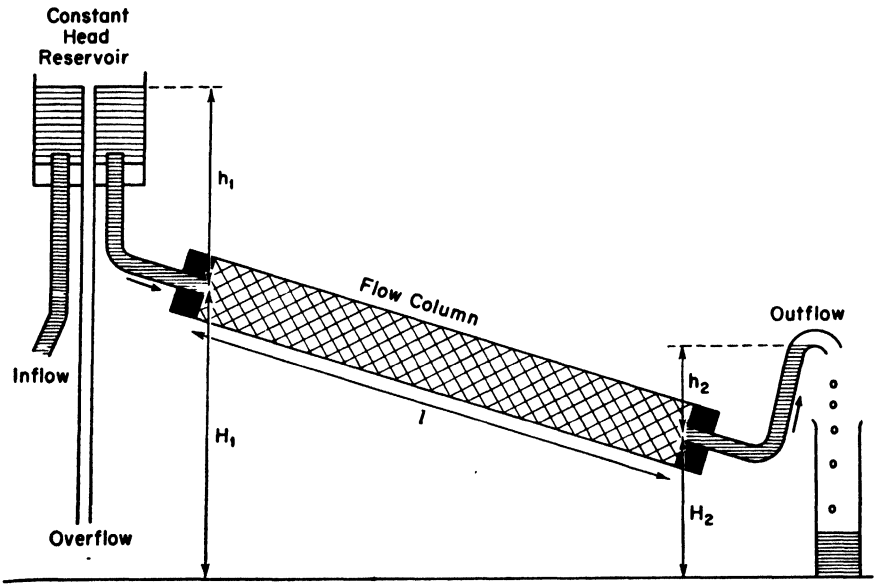


Fig. 3. Diagrammatic representation of an apparatus for measuring the permeability of a porous material, which is packed in the flow tube.

changing potential gradient shows a tendency to change. Smith *et al.* (1944), for example, report a steady decrease of permeability due to fungal growth in the voids, which they reduced by introducing toluene into the flow system. Christiansen (1944), after a review of the literature, comments upon the errors introduced if care is not taken to eliminate trapped air. This air, it is claimed, is not swept out bodily by the flowing water, and gives rise not only to false values of permeability but also to changing values as the trapped air subsequently dissolves. Later, Christiansen *et al.* (1946), used CO_2 to displace air before the wetting of the soil, and while in this way they eliminated a rise of permeability to a peak value after a run of a few days, they did not eliminate a steady fall of permeability. Such a fall may reduce the permeability to one thousandth of its initial value, as Christensen found

(1944). This author also lists some factors which might be expected to cause such a change. Fireman (1944) found that permeability is so dependent upon soil structure and, therefore, upon changes during flow which affect structure, that he regards permeability as among the best criteria of soil structure. He includes trapped air, arbitrary packing, the washing out of electrolytes and consequent modification of colloidal properties, transport of the clay fraction and the growth of micro-organisms as being among important causes of variation of permeability during the course of its measurement. Pillsbury and Appleman (1945) and Smith and Browning (1946) endorse the general opinion as to the errors due to entrapped air and its consequent solution in the flowing water. George (1948), on the other hand, emphasizes the errors due to water releasing dissolved air and thus steadily unsaturating an initially saturated soil sample.

A difficulty of quite another kind is that the preparation of a soil column for a permeability measurement inevitably disturbs a structured soil, so that the results may have little relation to permeability in the field. Various implements have been described purporting to extract undisturbed samples. It will be enough to refer here to that of Goode and Christiansen (1945) and to the elaborate device of Donnan *et al.* (1943). At best one is quite at the mercy of the soil type; a very few stones are sufficient to invalidate the use of such tools. This difficulty can be overcome in one way only, namely by the development of methods of measuring permeability in the field, thereby eliminating the necessity of collecting samples. Such methods might properly be discussed next, but for the fact that the one most recent and least open to objection cannot be described before we have dealt with the theory of drainage. (See IV-3.c.)

c. The Measurement of the Permeability of Unsaturated Soil. The permeability of saturated soil is relevant only to the flow of ground water, *i.e.,* the water at positive pressure below the water table together with that small amount in the capillary fringe which is at small suctions. Such conditions are paramount in drainage problems. When we have to discuss the infiltration of water in conditions of suction, such as accompany most phases of irrigation and even some phases of drainage, then in general we have to deal with the passage of water through soil which is only partially saturated.

Since water can only pass through pores which are full of water, an unsaturated soil necessarily offers greater resistance to flow than a saturated soil. This statement sometimes seems to surprise those who know from experience that a dry soil usually soaks up water more readily

than a wet one, but we have to remember that the wetting of an initially dry soil involves the passage of water along a moisture profile, which may create its own steep potential gradient. The permeability, which may be low, is the velocity of flow per unit potential gradient, and the high velocity of infiltration into a dry soil is due to the high potential gradient, not to a high permeability. Confusion between overall infiltration rate and permeability is far too common. We may refer to a paper by Horton (1940) for a discussion of the relationship between the two concepts.

One may attempt to measure the permeability of unsaturated soils by a steady flow method similar to that described under III-2.b, but certain special difficulties present themselves. Since it is necessary to have suction everywhere to ensure unsaturation, the inflow and outflow must be designed for the supply and withdrawal of water under suction. This may necessitate the enclosure of the soil sample between membranes of the type described under III-1.b, which will maintain the sample in contact with water even under suction; such a solution of the problem was adopted by Richards in his pioneering work (1931). Then, since a potential gradient is necessary to produce flow, and since such a gradient may involve a pressure gradient (in this case a suction gradient), it would appear that a moisture content gradient is unavoidable, moisture content being determined by suction in accordance with the moisture characteristic. We then have difficulty in determining the moisture content at the particular spot where permeability is being investigated, since one cannot sample the column without upsetting the state of flow. Then too, one must be able to measure the potential gradient over short lengths at reasonably uniform moisture content, since otherwise the observed permeability cannot be related to moisture content. Richards (1931) used short soil columns at sensibly constant uniform moisture content and measured the potential gradient with two tensiometers inserted at fairly close spacing.

Moore's method (1939) was to achieve a steady flow state in an upward direction; the soil column standing in free water at constant pressure and losing water by evaporation from the upper end into a room with controlled temperature and air circulation. Apertures were provided in the cans containing the soil, both for the insertion of tensiometers at frequent height intervals and for sampling for moisture content. The rate of flow was necessarily slow, so that sampling did not cause a serious disturbance of the flow state. Flow was permitted to proceed until the steady state was reached, as indicated by constant readings of the tensiometers, a proceeding which lasted several days for the heavier soils used. At the steady state the following quantities

were measured: (a) the rate of supply of water to the base, (b) the suctions recorded by the tensiometers and (c) the soil moisture contents of samples extracted from known heights. Thus at any height of the column, information was obtained both as to moisture content and permeability.

Childs and George (1948, 1950) used a steady state method with downward flow, and with fair control over the rate of flow, the moisture content and the potential gradient. They made use of the fact, pointed out

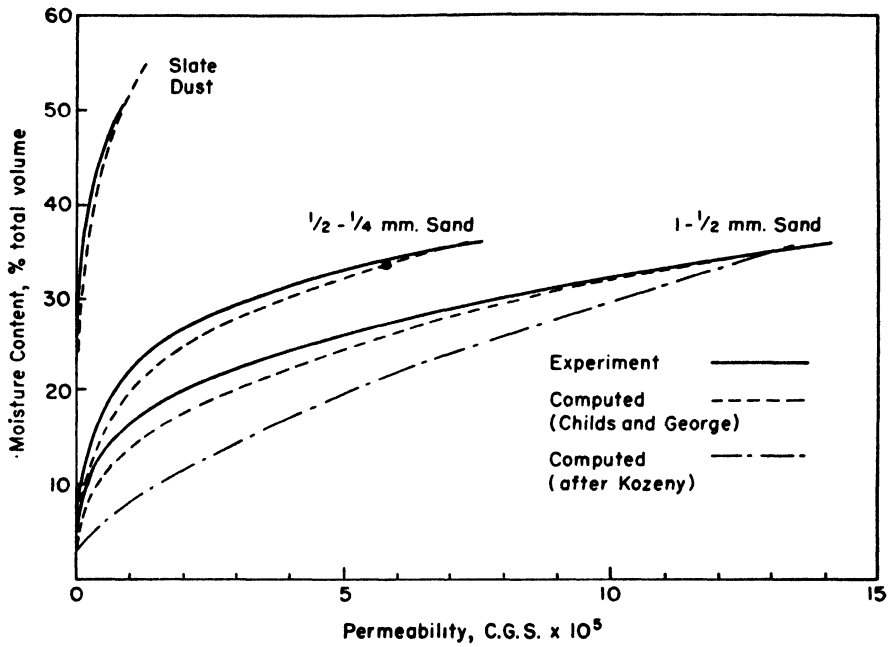


Fig. 4. Experimental and computed curves of the variation of permeability of a porous material with its moisture content.

by Childs (1945a), that, provided the soil column is long enough, a considerable part of it is at uniform moisture content and suction, and is therefore subjected only to the uniform gravitational potential gradient. The uniformity of moisture content permits the use of simple means for indicating it electrically, using the change of apparent capacitance of a condenser of which the soil forms the dielectric. Water was supplied at the upper surface at a controlled rate, this rate determining the moisture content of the column at the steady state. By slanting the column away from the vertical various potential gradients were obtained, down to one half the gravitational gradient. As an example of the dependence of permeability upon moisture content, found in this way, we present Fig. 4. The chief feature of all such curves is the rapid fall of

permeability with quite small degrees of unsaturation; permeability is sensibly zero while there is still an appreciable moisture content.

The difficulties of steady state methods have resulted in attempts to interpret the stages of transience, when the advance of water into dry soil is introducing changes of moisture content everywhere. Bodman and Colman (1943) have developed such a method, elaborated later by Colman and Bodman (1944). They used a soil column contained in a tube built up of short sections and provided with thin sliding diaphragms. Water was supplied at the top and percolated downwards. At any desired stage of penetration the diaphragms, which were intially withdrawn to leave the column continuous, were quickly pushed in, and in this way divided the column into a series of isolated sections. The moisture conditions were thus "frozen" and could be determined at leisure, the moisture content being determined directly and the suction being inferred from a knowledge of the moisture characteristic. In the silty and sandy loams studied water was found to move in such a way as to produce an ever increasing depth of soil, wetted to an almost constant percentage of saturation, separated by a well-marked water front from soil not yet wetted. Thus the mean rate of application of water represented the mean rate of flow through this "transmission" zone, since, once wetted, this zone had no further effective storage capacity. From the nature of the experiment it was possible to find the permeability only at the one degree of unsaturation (70 or 80 per cent of saturation) which the transmission zone happened to present. However, if these authors had calculated the rate of flow at a given section by computing the rate of storage beyond it, they could have measured permeability over the whole range of moisture contents in the flow column. They report that the permeability of the sandy loam at 70 per cent saturation was only one-fifth of that at saturation, but that the silt loam was very little affected down to 80 per cent of saturation.

Bradfield and Jamieson (1938) and Bendixen and Slater (1946) have used as flow columns the samples placed in sintered glass Buchner funnels for moisture characteristic determinations. Noting that each stage of moisture removal requires an appreciable time for attainment of equilibrium, and that the time increases with each stage of dewatering, they have related the permeability of the sample to the moisture content at the stage under consideration. The method does not seem to lend itself to precision, but indicates the general trend of the permeability-moisture content relationship in a convenient way.

Christensen (1944) has compared Richards' and Moore's methods with a radial flow method which he devised, using three Prairie soils as

his materials, but perhaps the chief interest of this paper lies in its discussion of inconstancy and hysteresis exhibited by permeability.

d. The Permeability of Soil to Air. Certain causes of the change of permeability of soil during the course of experiments may be avoided by employing air as the flowing fluid, the relationship between the permeability to water and to air for the same flow path being expounded in the standard texts. Richards (1940) has criticized such methods on the valid grounds that the effects of water on soil are essential factors affecting the flow of water in soil, and not just bothersome complications of technique to be avoided. Smith and Browning (1947) make the same point. In any case we must point out that experiments of this sort must be carried out with precisely the same flow paths; if we are concerned with the flow of water in saturated soil, we must measure the permeability of quite dry soil to air (*i.e.*, air saturated), and it may well be quite impossible to maintain the internal geometry of the wet soil when it is dried.

The measurement of the air permeability of field soils is a different matter; such permeability has importance for plant growth. It is complementary to water permeability, air flowing in air-filled pores concurrently with water flow in water-filled pores. Such measurements hardly fall within the scope of this review, but we may refer to recent advances reported in a paper by Kirkham (1946).

e. The Relationship between the Permeability and the Physical Constitution of Soil. The permeability of soil is a property conferred upon it by a certain geometrical configuration of its solid, liquid and air components; if these are completely specified then the permeability is determined as a consequence. It therefore becomes important to be able to relate permeability to more elementary soil properties, not only because in this way we can be assured that we understand flow processes but also because it might well happen that to infer the permeability from a knowledge of the physical composition is an easier matter than an experimental determination of permeability. It is certainly to be admitted that engineers prefer the converse proposition, namely that it is simpler to measure the permeability and to infer, say, the specific surface of the sand bed concerned, than to measure the specific surface directly (Carman, 1938, 1939; Carman and Arnell, 1948; Arnell and Hennebury, 1948). Such an approach is, however, fundamentally unsound (Childs and George, 1948, 1950), since one can conceive different models of different specific surface having the same permeability; permeability is one of the consequences of a specified physical makeup, not *vice versa*. Insofar

as this converse thesis may give satisfaction in practice, it does so because of the somewhat limited range of porous bed types encountered, these being usually structureless loose sands. As we shall see, the proposition breaks down utterly when we have to deal with structured materials such as soil.

We shall have little to say about the classical formulae relating permeability to physical constitution; these are in the textbooks. It is common experience that permeability is related to soil texture, and that soil texture may often by satisfactorily indicated by the mechanical analysis or a related parameter, such as the specific surface U. Various authors have produced related expressions for the dependence of permeability on these particle characteristics; among those best known are Kozeny (1927), Zunker (1933), Terzaghi (1925), and Fair and Hatch (1933). Engineers have given considerable attention in recent years to elaborating formulae of this type, taking into account such factors as slip of the fluid at the solid surfaces, and we may refer readers to papers by Carman (1947), Rigden (1943, 1947) and Lea and Nurse (1939) without describing them in greater detail here. The inadequacy of them all to account for the properties of soils, as distinct from structureless sands, may be demonstrated by reference to a single example. Fair and Hatch's formula is

$$K = A\{f^3/(1-f)^2\}\{(1/U)^2\} \qquad \text{(III.5)}$$

In this expression f is the porosity (volume of voids per unit apparent volume of porous material), U is the specific surface (surface developed by unit true volume of solids due to fineness of division) and A is a constant of proportionality. The porosity f does not depend upon the fineness of division of the solids, but only upon the closeness of packing, and since close packing is resisted more by small particles than by large, particularly if the smaller particles are surface active (*i.e.*, colloidal), the porosity of clay soils is usually rather higher, but not very much higher, than that of sands. The specific surface depends very much upon the size of the particle, since subdivision of a unit volume of solids clearly increases the exposed surface. Hence, according to equation III.5 the permeability of a clay should be negligible in comparison with a sand. If now we compare two clay soils, one with well developed structural fissures and the other a structureless mass, the structural fissures of the former will increase the porosity but slightly and the specific surface not at all. There should therefore be but little difference between the two permeabilities according to equation III.5. In fact, however, the fissures are dominant in conferring permeability and that of the struc-

tured clay may be many hundreds or thousands of times that of the puddled mass.

The failings of these early formulae are due to a misplaced emphasis on the solid phase of the porous medium. Soil scientists, from the nature of their material, have been much more aware of the dominant role played by the voids, and since we have means of studying the voids which are at least as simple as mechanical analysis, progress in relating permeability to the configuration of the voids has been relatively rapid. Baver (1938) made rough measurements of the permeabilities of a variety of sands and soils with known moisture characteristics. He attaches great significance to the point of inflection of the moisture characteristic; in his view it divides the capillary (higher suction) from the noncapillary (lower suction) water. The larger pores holding noncapillary water are significant for permeability, whilst the suction at the point of inflection indicates whether the soil is characterized by large or small pores. Thus an appreciable proportion of relatively larger pores favors permeability, other things being equal, while a high suction at the flex point inhibits permeability. He therefore defines the porosity factor as the radio of noncapillary water to the logarithm of the suction at the point of inflection, and shows experimentally that the permeability of his samples was a function of this factor. Nelson and Baver (1940) later elaborated this work, confirming earlier results and, in addition, finding a correlation between permeability and the volume of pores drained at a suction of 40 cm. of water, these, of course, being rather large pores. Further empirical relations of this kind were proposed by Smith *et al.* (1944), who sought to assess the contribution to permeability of the various groups of pores present in a soil, instead of seeking to find a particularly significant group. They divided the voids into pores emptied at suctions of less than 10 cm. of water (porosity contribution f_1), those emptied at suctions between 10 and 40 cm. of water (porosity contribution f_2), those emptied at suctions between 40 and 100 cm. of water (porosity contribution f_3), and finally all smaller pores, which had no contribution to make to permeability. Their porosity factor, in the Baver sense, is given as $f_1 + f_2/4 + f_3/10$, the several terms indicating the various weights to be assigned to the given pore groups. Bendixen and Slater (1946) return to the idea of a correlation between permeability and the volume of water drained at a single suction, introducing a time factor. Thus they obtain a correlation with the water drained at a suction of 60 cm. of water in a period of one hour.

The most recent development is due to Childs and George (1948, 1950). They used the whole range of the moisture characteristic to obtain the pore size distribution, and from this calculated the probability of

occurrence of sequences of pore pairs of all the possible combinations of sizes. Making an application of Poiseuille's equation which is perhaps overbold, but is certainly customary in such circumstances, they calculated the contribution to permeability of each group of sequences, and the overall permeability by summing up these contributions. This treatment permitted the calculation of the permeability at any chosen moisture content, since for this purpose one has only to omit from the summation all those contributions involving pores larger than the upper limit of those filled with water at the selected moisture content. The variation of permeability with moisture content which they computed agreed reasonably with the results of their experiments, a test of their theory which is rather rigorous since the type of pore size distribution changes drastically with progressive unsaturation. The comparison of theory with experiment which they present is reproduced in Fig. 4, and includes also a comparison with a Kozeny type of expression as developed for the purpose. These authors also discuss the ability of their treatment to deal with structural and anisotropic permeability, but leave this field for future study.

Recently, Brinkman (1947, 1948) calculated the permeability of porous material on quite novel premises. He calculates the viscous force exerted upon a particle embedded in a porous and permeable material consisting of a packed mass of similar particles. The expression for permeability derived in this way is claimed to be satisfactory over a wide range of porosities, and to cover the case where the particles themselves have a finite permeability. The pore geometry is not explicitly involved.

3. The Diffusion of Water in Soil

When observing water movements the agronomist is usually more conscious of a moisture gradient than of the potential gradient, which is the fundamental cause of movement. To express the rate of water movement in terms of the gradient of the moisture profile is to use the language of diffusion; the rate of movement per unit gradient of moisture content is the coefficient of diffusion.

The coefficient of diffusion may be expressed in terms of concepts which have already been established. The moisture profile gives information about the moisture content and the moisture gradient at any point. The moisture content determines the permeability of the particular soil (see III-2.c and III-2.e) insofar as that is a function of moisture content, and also the suction component of potential; thus the moisture gradient settles the suction potential gradient. The permeability and potential gradient uniquely determine the rate of water movement, which is therefore determined in terms of the moisture gradient at the point.

Hence the coefficient of diffusion may be calculated and expressed by a curve as a function of moisture content. Fig. 5 shows curves for a sand fraction and for a slate dust fraction (Childs and George, 1948, 1950). For light soils the diffusion coefficient varies from high values for wet soils, (implying a ready admission of water by the necessarily wetted surface soil) to very low values for dry soils. As a consequence, the soil can sustain steep moisture gradients for a long time when dry but can maintain only slight moisture gradients when wet. This is one of the reasons

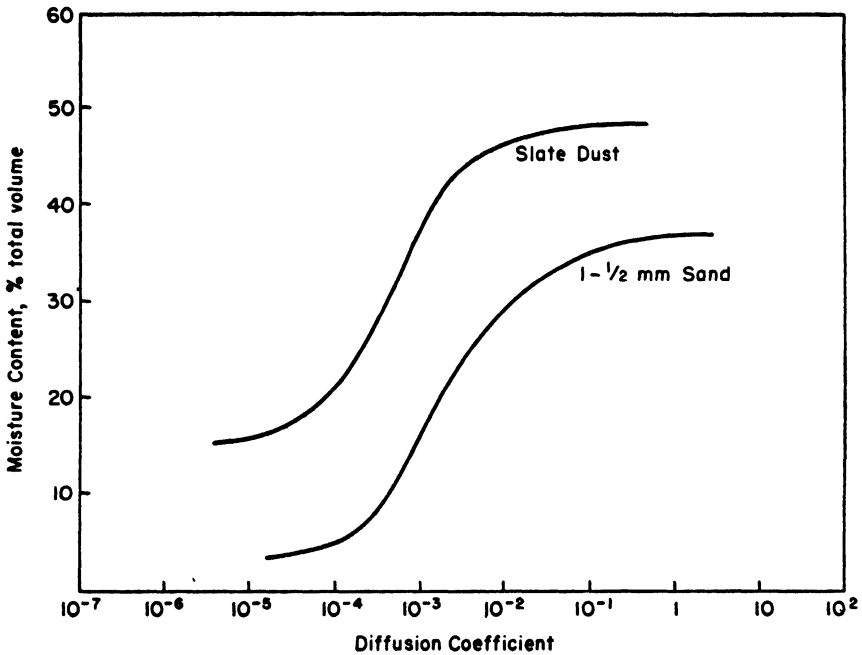


Fig. 5. Curves showing how the diffusion coefficients of porous materials vary with moisture content.

why a deep soil settles down quickly after watering to a state of very slow movement (an apparent equilibrium), characterized by a layer of wet surface soil with a slight moisture gradient separated by a steepening moisture gradient (water front) from the lower dry soil; the moisture content of the wet layer is a characteristic of the soil type and is only slightly affected by other factors. The agronomist recognizes this moisture content as the field capacity; hysteresis may also play a part in this phenomenon (Schofield, 1935).

The coefficient of diffusion of water in heavy soils, complicated by considerations of structure, has not been studied yet, but is low in all circumstances of moisture content. For this reason, such soils even

when wet can maintain steep moisture gradients for a long time, implying a very slow penetration of water applied at the surface. One should certainly use caution in making assumptions as to the constancy of the diffusion coefficient. Childs (1936, 1938) made such an assumption for soils of silty loam and clay texture, based on some small experimental evidence, and was able in this way to account for the main features of the slow redistribution of water in a profile. Recently Kirkham and Feng (1949) have shown that water penetration in lighter soils cannot be accounted for by assuming a uniform diffusion coefficient, which, in view of the above discussion, need occasion no surprise.

IV. Drainage and Irrigation

1. The Soil Water Balance Sheet

Water incident on the soil surface, whether in the form of rain, irrigation water or melting snow, penetrates in the appropriate circumstances described under III-3 to moisten a certain depth to the field capacity. The nature and condition of the soil set a limit to the maximum possible rate of infiltration, and if the rate of application exceeds this limit the excess will remain on the surface and flow either to natural surface drainage channels or to local depressions. If this natural drainage is adequate, such excess will be lost to the soil.

In the intervals between the arrival of water there will be evaporation from the surface. This will dry the surface and thereby bring it to the condition in which it can maintain a steep moisture gradient without much water movement (see III-3), so that the rate of evaporation will soon be reduced to small proportions. Thus water which may have entered readily, leaves by direct evaporation only reluctantly even without considerations of gravity. The remainder of soil water will be used by vegetation. If the whole of the stored water is thus used before the next subsequent watering, the soil starts again in its original dry condition; and if such a state of affairs persists, the region tends to aridity, supporting only the vegetation for which the prevalent water supply suffices. If vegetation with a greater water requirement is desired, then there is a need for irrigation.

If, on the other hand, the water stored from one rainfall is not entirely used before the arrival of the next, water will penetrate to greater and greater depths. In such circumstances there is commonly at some depth or other an impeding layer upon which a body of ground water builds, bounded at its upper limit by the water table and capillary fringe (see III-1.e). This ground water will tend to drain via natural channels just as will surface water, but if, in spite of this tendency,

the water table rises sufficiently near the surface to waterlog the root zone of growing crops, then there is a need for drainage. It is also possible for persistent surface water to produce a drainage need because of inadequate powers of infiltration even though the ground water be at a safe depth. An area which presents a drainage problem one season may well need irrigation at another, and both needs must be considered on their merits. It is no solution to neglect drainage on the grounds that there may be drought later.

In areas of marginally deficient rainfall, use may be made of the nonreturn nature of soil water, *i.e.*, of the relative readiness to accept and reluctance to evaporate. By fallowing for a year to prevent water use by growing vegetation, it is possible to store nearly the whole of that year's rainfall and thus use 2 years' rainfall for one crop. This is the dry farming system.

2. Irrigation

a. Statement of the Problem. Insofar as one may generalize about any agricultural matter, the irrigation problem may be stated in simple terms. One has a limited range of crops in mind, and water resources which are not under complete control but are apportioned in accordance with a policy. One must so use the soil properties as to temper the resources to the crop. The crop is characterized by a certain water requirement and a certain root range, which is to some extent under control by choice of variety. At best, therefore, the depth of soil in which water may usefully be stored is limited by the crop itself; at worst it might be additionally limited by the presence of impeding soil horizons or by a general soil impermeability which prevents adequate penetration of water. The question that arises is, will the storable water suffice to tide the crop over the waterless interval?

b. The Fundamental Solution. The progress outlined under III enables us to explain the occurrence of a recognizable moisture content known as the field capacity, but until the diffusion problem has been completely solved we shall not be able to calculate what this moisture content is, nor in what time a given depth of soil will attain it. Nor, indeed, are we able to report any attempt to account on fundamental lines for a lower limit of useful moisture content, the wilting point. Nevertheless it is in this direction that the fundamental solution must lie. When the solution is complete we shall be able to forecast, from a knowledge of the moisture characteristic profile alone, the whole course of penetration and redistribution of irrigation water in given circumstances, since the moisture characteristic reflects the pore size distri-

bution, which in turn determines the permeability and diffusion coefficient. Given also a knowledge of the wilting point, we shall be able to forecast the storable water content. This concept of usable or available water has been introduced by Haynes (1948).

c. The ad hoc *solution.* The complete fundamental solution is not yet to hand. The alternative is to carry out experimental irrigations on plots in the problem areas, and it was on these lines that the earlier experiments such as those of Israelson (1918), Harris and Turpin (1917) and Greene (1928) were carried out. Such experiments clearly presuppose the existence of a water supply; the expense of bringing water to the area must be undertaken before the benefits can be assessed. The method is therefore more suited to the expansion of an existing irrigation scheme than to the inception of quite new schemes.

d. The Arbitrary Solution. The basic approach explains the phenomenon of the field capacity. The lower limit, the so-called wilting point, is not so explained, but its existence is recognized in a general way by agronomists. While we cannot yet accurately deduce the field capacity on fundamental grounds, considerable attention has been paid to the search for arbitrary treatments which can be shown empirically to reduce the soil to the field capacity. This approach to the problem is quite analogous to the chemists' arbitrary nutrient extraction methods (water, citric acid, buffered acetic acid, neutral salt solutions, etc.) for estimating the nutrient status of a soil; there is no suggestion that plants really do extract their nutrients by employing such reagents, but only a claim, based on experience, that the amounts of nutrient extracted by these reagents can be correlated with crop welfare. In just the same way there is no suggestion that arbitrary imposed conditions such as controlled centrifuging or controlled suctions have any fundamental connection with the phenomenon of field capacity; we have seen that the matter is not so simple. But there is a suggestion that we may be able to hit upon a treatment which will in fact bring the soil to a moisture content which is near enough to the field capacity for the method to be diagnostically useful.

The first of the arbitrary treatments was the well-known centrifugation of Briggs and McLane (1907), which defined the moisture equivalent, a state which Veihmeyer and Hendrickson (1931) identified with the field capacity. Later Veihmeyer and Hendrickson (1949) recognized that the field capacity is not an equilibrium state. For that matter the moisture equivalent is not an equilibrium moisture content but a moisture profile (see III-1.e), with an average moisture content appropriate to a

mean suction of 0.8 atmosphere. Veihmeyer admits that the field capacities of sandy soils are not well represented by the moisture equivalent; but it must be remarked that neither very sandy soils nor the heaviest clays are well suited to irrigation in any case.

Among those who use controlled suctions to achieve the field capacity, Richards and Weaver (1943) recommend a suction of ½ atmosphere if the moisture equivalent exceeds 22 per cent and ⅓ atmosphere for soils of lower moisture equivalent. Colman (1947) has studied the field capacities and moisture characteristics of a wide range of soils, and shows that there is no universally applicable suction which will achieve field capacity. Browning (1941) shows how the ratio of field capacity/moisture equivalent varies with the moisture equivalent. More serious than the variability of the correlation according to soil texture is the fact that the field capacity of a soil of given texture varies according to the circumstances; if the soil is uniform to great depth the field capacity is lower than if a shallow surface layer is underlain by, say, coarse sand or gravel (Moore, 1939). The reason is clear. Water movement slows as soon as the lower material reaches its field capacity, which being coarse, it does at relatively low suctions. The upper layer, in equilibrium with this low suction, has a higher moisture content than it would have had if it could have reached its own characteristic field capacity corresponding to a higher suction. The layer of coarse material acts as an impediment to penetration which may be almost as effective as an inherently impermeable layer. This effect is present to an extreme degree in lysimeters as commonly designed. Colman (1946) has pointed out that, unless the base is in the form of a large tensiometer, it may impose a condition of zero suction and consequent saturation not existing in the field. Furthermore the field capacity seems also to depend upon the moisture content ruling before irrigation (Kraebel and Sinclair, 1940) and upon the depth of penetration of water (Colman, 1944).

The question of the very existence of a definite wilting point seems a vexed one. On the one hand Veihmeyer and his school regard the plant as being able to extract water with undiminished ease right down to a well-defined soil moisture content, at which permanent wilting sets in (Veihmeyer *et al.*, 1943) while Rogers (1935b), growing precisely the same variety of strawberry, observes distress for lack of water at quite low suctions, a result which is allied to earlier work of Powers (1922). One can only say that there is here a contradiction of evidence which indicates some undiscovered difference of technique, and such contradictions must be resolved before discussion can serve a useful purpose. Breazedale and McGeorge (1949) have recently eliminated much ambiguity from wilting point determinations. Then again Wadleigh

et al. (1947) show that a plant may be "trained" to withstand high soil suctions without wilting by growing it in a saline solution at controlled osmotic pressure. Magistad and Reitemeier (1943) have also studied the effect of varying salt concentration at the wilting point. The accepted belief is that the uptake of water by plants becomes increasingly difficult as the soil suction increases, that wilting sets in as soon as transpiration at the leaves exceeds the rate of water intake at the roots, and that the range of suctions over which wilting becomes evident or serious, corresponds to a soil moisture content range which is narrow, the slope of the moisture characteristic being gradual for most soils at large suctions. Thus wilting may set in gradually in terms of suction, but suddenly in terms of decreasing moisture content, so that a more or less well-defined moisture content may be recognized as a "wilting point." It is in this sense that Botelho da Costa (1938) defined a wilting point in terms of suction. It is with the moisture content at the wilting point that the irrigation farmer is concerned. The difference between his soil moisture content and the wilting point moisture content is his "available water" (Allyn and Work, 1941). Reimann *et al.* (1945) have also investigated the "availability" of soil water throughout crop life. Arbitrary suctions for achieving the wilting point have been put at about 16 atmospheres by Botelho da Costa (1938) and at 15 atmospheres by Richards and Weaver (1943).

It may be mentioned here that infiltration of water into soil supporting crops is not the only problem which may confront the irrigation engineer. In some areas, as in parts of California, irrigation water is drawn from wells sunk in alluvial fans, the ground water being replenished by diverting hill streams into water-spreading areas. The paper by Allison (1947) describes some problems presented by the decreasing permeability of such spreading grounds.

3. Drainage

a. The Nature of the Problem. In its physical basis, the drainage problem is simpler than the irrigation problem, since it is concerned with the flow of ground water, *i.e.*, in saturated soil with sensibly uniform permeability. The sorts of problem that arise are presented in a general way in Fig. 6, which indicates diagrammatically a layer of permeable material underlain by an impermeable bed. The ground water body described under IV.1 is built up in the permeable layer, the water table being indicated by the line *AB*. The pressure built up under the water table, together with gravity, forms a potential field which directs flow to an exit *BC* where water emerges at zero hydrostatic pressure; positive pressures cannot be built up since there is free flow over this surface, while

there can be no suction or water would not emerge. Such a surface is called a surface of seepage, and the rate at which water emerges at such a "spring line" is determined by the configuration of the ground water body and by the permeability of the layer. If rainfall exceeds this rate of emergence the water table rises, while if the opposite is the case the water table falls.

If the natural drainage is deficient, the water table may rise dangerously high everywhere, and this is particularly likely if the permeable

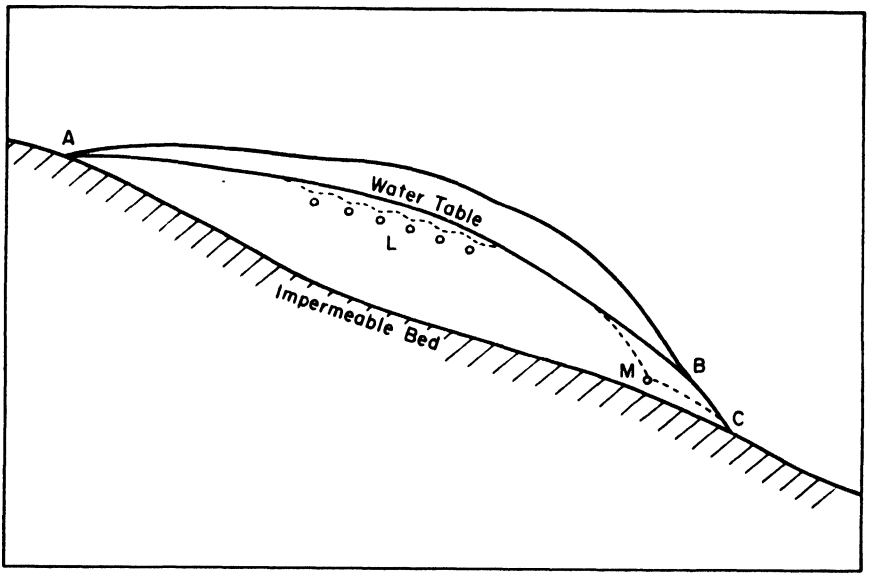


Fig. 6. A hypothetical drainage situation, a body of permeable material resting on an impermeable bed. Rainfall produces groundwater bounded by the water table *AB* and surface of seepage *BC*. A drainage system at *L* controls local water and that at *M* controls foreign water. The dotted line shows the controlled water table.

layer is thin. In such a case drains are laid in positions such as *L* to control the rise of the water table in spite of local rainfall, and one may describe such systems as local systems. On the other hand the water table may only be embarrassing near the natural spring lines, where water is inevitably near the surface, in which case one is more concerned with cutting off the arrival of water from a distance than with guarding against local rainfall; one lays a line or two of drain, in a position such as *M*. Such systems are often called interceptor drains, a poor description since all drains function by intercepting unwelcome water. We prefer to call them foreign water drains. The problem is to determine, for given soil and weather conditions and for a given drainage design, the position and state of movement of the water table and the flow of

water to the drains. The case of heavy clay land, which is characterized commonly by a thin layer of structurally permeable topsoil over an impermeable bed at a depth of perhaps only a few inches, may be regarded as a particular case of the more general circumstances described.

b. The Fundamental Solution. Darcy's law prescribes the flow condition for a given distribution of potential, while it is a consequence of the incompressible nature of water that it cannot be further stored in a region which is already saturated; in any case it is not being stored if the flow has reached a steady state. These two circumstances combined result in a differential equation which the potential must obey. This is the well-known Laplace's equation, about which we need only say here that it cannot be solved at will for any particular problem, but that certain well-known solutions of specific problems occur in all the textbooks. Further, while a solution is in general impossible by routine analysis, it is simple to test whether a supposed solution is really valid. The solution of a particular problem must provide us with a potential distribution which satisfies Laplace's equation and which agrees with the known distribution of potential or streaming conditions imposed at certain boundaries by the particular circumstances of the problem. For example, the water flux across the water table may be known and certainly the pressure here is zero; the potential at the drain may conveniently be the arbitrary datum. It is also known that the pressure at a surface of seepage is zero, and that an impermeable bed coincides with a streamline. These are all boundary conditions which a particular problem might have to account for. When the potential distribution is known, the streamlines may be known to provide a family of curves which intersect the equipotentials at right angles, and may be drawn in to complete the "flow net," whence, from a knowledge of the permeability, the actual rates of flow everywhere may be computed.

c. Some Typical Problems. In Figure 7, we see an idealized case of local drainage, and since an understanding of this case is a prerequisite to understanding more complicated cases, it has been much studied. The idealization lies in supposing the depth and permeability of soil to be uniform, the depth, size and separation of drains to be similarly uniform, and that the steady flow state has been achieved. Furthermore at this stage it is necessary to make the unwarranted assumption that a uniformly distributed rainfall implies a uniformly distributed water flux at the water table. The drastic assumptions made prior to 1934 have been summarized in a paper by Russell (1934). We need only say that they

amounted to assuming the final result, (the elliptical water table), which, not surprisingly, failed to survive even the most casual scrutiny.

It is clear from the symmetry of the case that the section *ABCDEF* in Fig. 7 is representative of the whole cross section. The shape of the water table *AF* is unknown, but the rate of arrival of water there is known; *DCBA* is known to be a streamline and EF is another. This case is certainly not one with a recognized solution, but it is at least possible to transform it into one with less unsettled boundaries. One way

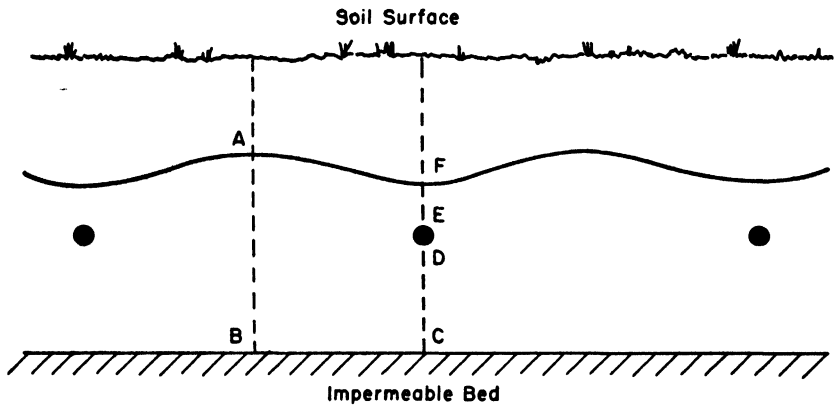


Fig. 7. Diagram showing control of local water, such as at *L* in Fig. 6. In this section three drains are shown of which *ED* is one. *ABCD* and *FE* are boundary streamlines of the section *ABCDEF*, and the problem is to locate the water table *AF* in any given circumstances.

to do this is by drawing the boundaries in a diagram which has for its coordinates the flow velocity components in the x and y directions instead of the position components x and y themselves, the result of being a "hodograph" with boundaries of settled shape. Further transformations result in a problem which is recognizable as a textbook solution provided certain limitations are imposed. This is the method of Gustafsson (1946). Childs (1947b) pointed out that the solution was less general than was supposed. This, and other transformation solutions both for drains and for open ditches, have been described by Wedernikov (1936, 1937, 1939) and by van Deemter (1949). Complete general solutions have yet to be proposed.

One may apply a method of "images" provided the soil is taken as being waterlogged to the surface (the only case in which the position of the water table is known *ab initio*). The flow is then the same as would be obtained if a second similar and similarly drained layer were placed upside down on that shown in Fig. 7, water being fed in at the upper drains and removed at the lower. This is a textbook case, and was pre-

sented as a solution for artesian drainage by Kirkham (1940), and for mixed rainfall and artesian water (Kirkham, 1945a). The latter result confirmed sand model work by Harding and Wood (1941). Kirkham (1947a) also discusses the effect of proximity of drains to the impermeable bed again with a waterlogged soil. Hooghoudt (1940) used the treatment for the case of a water table not at the surface, which is hardly justifiable.

For the complete solution of more general problems one may use analytical methods to elucidate the boundary conditions and then proceed by guided or inspired guessing, approaching a final true solution by trial and error. Childs, in a series of papers (1943c, 1945a, 1945b, 1946, 1947a, 1948), proceeded in this way, using the fact that Darcy's law is formally identical with Ohm's law as a basis for the construction of electrical analogues of the drainage problems, these analogues being made to satisfy the boundary conditions by trial and error. Such problems included cases of foreign water drainage, nonsteady states, and mixed fresh and salt groundwater zones, taking into account both the capillary fringe and the flow through the upper unsaturated soil. The papers should be referred to for further information, since it is stressed that no general formula can be presented; each problem must be studied on its merits. Van Deemter (1949) has used Southwell's method of relaxation to achieve a similar result by purely numerical methods, without appeal to experimental techniques, and has taken into account the possible stratification of the permeable layer. McClelland and Gregg (1944) use the graphical reiteration method.

One may also proceed by building drained sand sections in boxes, and examining the potential distribution by manometers. Hooghoudt (1937b) presented some results of this kind, but appears to have identified the pressure at a point with the height of the water table above. Insofar as such pressure readings reflect the water table position, his results are in agreement with the nonsteady state described by Childs (1947a). Somewhat similar experiments have been described by Donnan (1946) and by Donnan *et al.* (1947), and, in connection with road subgrade drainage, by McClelland (1943).

d. Field Experiments. For descriptions of *ad hoc* experimental drainage fields the reader may be referred to the Transactions of the Sixth Commission of the International Society of Soil Science (1933,*B* and 1937,*B*) and to a paper by Weir (1928). Such experiments sought to trace the variations of water table with weather, in plots with different designs of drainage system. The water table observations were commonly made by the use of vertical perforated tubes forming well bores

of small diameter. Childs (1945a) has shown that the insertion of such tubes tends to upset the preexisting potential distribution and to impose a local draw down on the water table, giving false results. The modern practice is to insert several tubes to different depths, each being open only at the bottom, and in this way to plot a potential distribution. The complete flow net may thus be constructed, and the position of the water table inferred, since it is the surface at which hydrostatic pressure is just zero. Groundwater surveys of this type have been described by Christiansen (1943), by Donnan and Christiansen (1944) and by Kirkham (1947b). The latter studied the natural drainage of a hillside in Iowa by such means. Such natural drainage surveys are likely to be an important development of the future, since artificial drainage systems can hardly be designed with certainty in the absence of information about the water to be intercepted.

An increase of rainfall rate causes the water table to begin to rise, and this rise constitutes a storage of ground water. The drainage rate, which is determined by the ground water configuration, therefore increases but slowly. Similarly, when the rainfall rate decreases, the drainage rate follows the decrease but sluggishly. Ground water drainage is therefore characterized by a stability which is a consequence of the reservoir action of the body of ground water. In very thin soils the reservoir capacity is limited; in clay soils, which may be regarded as a few inches of permeable soil over impermeable clay (see IV.3a), there may be practically no stabilizing action and Childs (1943b) has described an experimental drainage field with mole drains in clay, the outfall performance having the characteristics of surface or storm water.

e. Field Measurements of Permeability. Again it is convenient to refer to Russell's paper (1934) for an account of early work, much of which was descriptive or, at best, semiquantitative. Modern methods seem to be variations of one of these earlier methods, namely that which makes use of the effect of pumped wells on the ground water. A pumped well is essentially a drain, and the flow of soil water to it is a drainage problem similar to those described above. Hooghoudt (1936, 1937a) has been active in relating the rate of rise of water in the well after cessation of pumping to the permeability of the soil in which it is sunk. The treatment is rather an approximate one, but recently Kirkham (1945b) and Luthin and Kirkham (1949) have studied the flow of ground water from a tube open only at the end, giving a solution of Laplace's equation for a spherical cavity, and discussing methods for solving other forms of cavity. From this Kirkham gives formulae which are good approximations to the relationship between soil permeability and the rate of flow of water

from the tube to the ground water. The solutions are equally applicable if the tube is first pumped dry and ground water then allowed to flow to it. The method is thus analogous to the pumped well technique rather than to surface infiltration techniques such as those of Freckman and Janert and of Flodkvist, described by Russell (1934), in that one is studying flow in the zone of ground water and not in the overlying unsaturated soil with unspecifiable conditions.

4. Engineering Aspects

This review would not be complete without a brief reference to some of the problems which the flow of soil water presents to the engineer. The fluctuations of the water table and of the volume of ground water constitute a reservoir action. Where drainage consists of controlling the ground water, drain performance is characterized by considerable stability. Surface or storm water is, on the other hand, violently fluctuating, and a sudden storm may throw loads on the rivers out of all proportion to the total volume of water involved. Flood control and soil conservation are therefore deeply concerned with infiltration, which contributes to ground water at the expense of surface water. The soil conservation stations of the problem areas of the United States, together with Experiment Stations of the State Colleges and Universities, have been much occupied with infiltration studies. The literature is so voluminous that abstraction can be but arbitrary. We may refer to publications of the Tennessee Valley Authority and to progress reports of the regional stations (see, for example, the report for the North-West Appalachian Station, Zanesville, 1939). The general opinion is that surface water is usually a result of an excessive rate of rainfall, there being ample pore space for its accommodation in time. Infiltration rate is suppressed by a variety of factors, some of which we have not previously mentioned; for example, some soils are not easily wetted (Jamieson, 1945). Then again, unstable soil may suffer surface sealing due to lack of organic matter, the sealing being due to the impact of rain on unprotected bare soil. We refer to papers by Musgrave and Free (1936), Ellison and Slater (1945), Duley and Domingo (1943), Kidder *et al.* (1943), Lewis and Powers (1938), McCalla (1944, 1945), and to Parker and Jenny (1945), without any pretence of doing more than pick at random. Sometimes infiltration cannot be expected to cope with rainfall, in spite of the most favorable soil conditions. Wilson *et al.* (1946) have described well designed terraces where such circumstances prevailed. Provision must be made for watercourses protected against erosion; such protection may commonly be afforded by vegetation, and a comprehensive description of such means has been given by, among others, Ree and Palmer

(1949). To deal more thoroughly with this aspect of the study of soil moisture would be to invade the vast field of soil conservation.

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Preservation and Storage of Forage Crops

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I. Introduction

Forage plants are more widely distributed than any other group of crops. They are grown almost exclusively in extensive areas where other crops either cannot be grown because of climatic conditions or are not grown because of transportation costs and other economic factors. They are grown elsewhere in competition with grain and other cash crops to supply forage for needed livestock production. They are also grown to maintain the yields of cash crops by reducing erosion, by increasing organic matter and nitrogen, by improving soil structure, and by aiding in the control of weeds, diseases, and insects.

Regardless of the reason why forage crops are grown, usually one or more harvests per year must be removed and placed in storage if these crops are to be a part of an economic system of farming. Storage is necessary in order to provide winter feed and also because rapid deterioration takes place in the field if crops are not harvested and preserved at the proper stage. In processing crops for storage, and during the storage period, appreciable losses of feeding value usually occur. The magnitude of these losses is usually much larger than the increased production resulting from genetical improvement and the adoption of better management practices; but more emphasis has been placed on research leading to increases in the yield and quality of forage than to decreasing preservation and storage losses.

It is the purpose of this paper to point out the relative importance of the constituents of quality which must be examined in determining the magnitude of losses incurred during preservation and storage. The aim is also to describe the various methods of preservation and to evaluate the degree to which each preserves the original quality.

II. Measurements of Changes in Quality

1. Energy and Protein

Feeding standards for livestock are based on two groups of nutrients, energy-supplying and protein-supplying. An energy source is required for all animal body functions leading to maintenance, growth and production. Therefore, it is needed in much greater quantities than is protein. Ferguson (1949) and Lewis and Eden (1949), discussing dairy rations for Britain, point out that the prime need in quality roughage is a high content of energy sources.

The concentration of energy sources in hay or silage is important because high producing animals require larger quantities of energy supplying constituents, or total digestible nutrients, than are contained in the quantity of good roughage they are able to consume. Therefore, hay or silage must be supplemented with grain. Any decrease in the energy value of the roughage must be compensated by feeding even more grain. Energy in grain is more than twice as expensive as energy in hay, and the cost of the grain necessary to replace a decrease in energy content of the roughage must be used to evaluate the economic loss occurring during preservation and storage.

Protein concentration and its production per acre have been used much more frequently than has energy content in attempting to evaluate the feeding value of roughages. Protein-rich concentrates frequently are more expensive per unit weight than high energy feeds. Because larger quantities of energy sources must be fed than protein, farmers paid on the average more than six times as much for energy sources as for protein in the United States during the 12-year period of 1937-1948. This statement is based on the formula derived by Watson (1939) for determining the relative value of protein and starch equivalents in two feeds, and on U. S. prices as reported in Crops and Markets (1949). During the preceding 12-year period this ratio was even greater. On the English market Watson (1939) found the starch equivalents, the European measure of energy-bearing foodstuffs, to be fully equal in cost to protein equivalents.

Protein, as feeding standards indicate, is a necessary nutrient in the ration of roughage-consuming ruminants and should be supplied in definite ratios with energy-bearing foodstuffs, the exact ratios depending on the kind, age, and production level of the animal. Farm-produced feeds are often too low in protein to meet ration specifications. However, this deficiency usually can be corrected at less net expense than can a deficiency in total digestible nutrients.

When forage crops are harvested at an early stage, both energy constituents and protein content are high. The protein content may be high

enough to eliminate the need for supplemental feeding of this nutrient, but grain still is required to meet the energy needs of high-producing animals. Hence, in determining the value of losses during preservation, comparisons in energy content must be given more weight than protein comparisons.

2. Factors Governing the Content of Energy Sources in Harvested Forages

a. Stage of Growth. Forages which carry the highest percentage of energy constituents come only from immature crops which are highly digestible. Sotola (1941) found that the dry matter in bromegrass, *Bromus inermis,* Leyss, contained 80 per cent of total digestible nutrients when harvested at the 6- and 12-inch stages. This value was only 55 per cent when the crop had matured to the late flowering stage. From growth curve data (MacDonald, unpublished) and the appropriate digestible nutrient content, it can be calculated that the amount of total digestible nutrients per acre increases rapidly to just before heading. The rate of increase then starts declining and no increase occurs in the amount of total digestible nutrients during or after flowering. This indicates that the general practice of harvesting forage crops at the flowering stage secures the maximum yield of total digestible nutrients.

If the values of the acre yields at the various growth stages are determined in a dairy ration, however, it is found that when the crop is harvested just prior to heading its acre value is more than 50 per cent higher than when harvested at the flowering stage. Since a 1,000-lb. cow producing over 12 or 15 lbs. of milk daily requires some grain (Woodward, 1939) and the energy in grain is about 2.5 times more expensive than the energy in hay, the value of the higher energy content of early cut hay which replaces the grain in the ration more than offsets the higher total energy production obtained by later cutting.

Woodman and Evans (1935) have also shown that there is a great decrease in digestibility of alfalfa, *Medicago sativa* L., as it matures. The fact is inescapable that high quality roughage must come from an immature crop. The acre yield of such forage may be lower but its feeding value in a dairy ration is higher than that cut later if one considers the amount of supplemental grain feeding required.

b. *Respiration.* Hay and silage may decrease in energy value in several other ways besides being allowed to mature beyond the vegetative stage. Respiratory activity present in the plant continues after it is cut. The respiration of leaves from detached wheat, *Triticum vulgare* Vill. during a 6-day starvation period, has been measured by Duff and

Forward (1949). Expressing their data on the rate of carbon dioxide evolution in terms of pounds of dry matter respired per ton of 14 per cent moisture hay per day, the rate of loss during the first hour of starvation at 22.2°C. was 130 lbs., but this dropped to about 30 lbs. at the end of the first day. Thereafter, the rate rose slowly to the fifth day when the dry matter loss was 50 lbs. per day. The rate again fell to 30 lbs. at the end of the sixth day when observations ceased. This experiment was performed with green tissue maintained at its original high moisture content in a darkened moist chamber during the starvation period. The time curve of dry matter losses from detached leaves described above is very similar in shape and magnitude to those reported by Yemm (1935) for several other plant species. It is also similar to loss curves obtained when hay plants were dried rapidly to 20 per cent moisture and held at that level for 5 or 6 days. Rehydrating artificially dried hay to 20 per cent permits respiration losses similar in quantity to those upon dehydration to 20 per cent but the curve starts out at near zero rate and builds up slowly, (very slowly if the mold spore population is low) to a 30-60 lb. peak (Musgrave and Dawson, unpublished data). While the above losses were all observed under aerobic conditions, Phillips *et al.* (1935) observed this type of loss curve when they subjected moistened alfalfa to anaerobic conditions.

The respirational loss upon rehydration to 13.5-25 per cent moisture is due to a microbial population composed chiefly of only 3 or 4 fungus species (Galloway, 1935; Wright, 1941). The major loss in the case of dehydration to 20 per cent moisture is very likely from the same source but Duff and Forward (1949) attributed the losses from starving leaves held at high moisture content entirely to the respiratory activities of the plant cells. Although there is a remarkable similarity in the rates and amounts of respiration from plant materials under the three different moisture conditions, these workers have shown that the greatest deterioration will be found in the plants with the highest percentage of growing tissue and the highest content of simple carbohydrates.

According to Yemm (1937) there is a steady transformation of insoluble nitrogen compounds to soluble compounds during the early stages of the starvation of a leaf. When the carbohydrate supply becomes limiting for respiration there is a rapid accumulation of ammonia. Fleischmann (1912) observed these same changes when whole plants were slowly cured into hay, and measured high losses of nitrogen especially when leaching followed slow curing.

c. Leaching of Nutrients. The leaching loss from hay has been measured under very few conditions where it could be separated from

other losses. Guilbert *et al.* (1931) working with field-cured hays found leaching losses of nitrogen-free extract to range from 6 to 35 per cent, but organic matter losses were small. These losses were created by laboratory methods approximating complete water extraction. Such leaching has not been related to that from rainfall of various types and intensities. Elliott (1947) found that one inch of simulated rain over a one-hour period leached 1.9, 0.3, and 4.7 per cent of the dry matter from rapidly-dried hay of timothy, *Phleum pratense* L., red clover, *Trifolium pratense* L., and alfalfa, respectively. Although the timothy samples showed no significant loss of dry matter, its digestibility as measured by rabbits did drop 20.2 per cent due to leaching and subsequent artificial drying at 70°C.

Wiegner (1925) found that the dry matter lost during field weathering was practically 100 per cent digestible. These losses included leaching, leaf and respiration losses. Sotola (1933) has shown that leaves from slowly cured alfalfa are about 66 per cent digestible. Putting Wiegner's conclusions and Sotola's findings together would indicate that leaching may have harmful effects in addition to nutrient removal as is also suggested by Elliott's data (1947).

Kellner (1915) and others have shown that as digestible nutrients become less concentrated in a feed due to any cause the energy required for digestion increases. In hay, according to Wiegner (1925), this loss will amount to about one-third of the total of energy losses from all field and stack sources.

3. Correlations of Energy Sources with Protein, Fiber, and Carotene

Although the energy derivable is the basis of determining the value of feed it is not an easy determination to make. Expensive feeding trials requiring considerable time are necessary. Therefore, many attempts have been made to find a chemical determination which could be correlated with feeding value (Crampton and Jackson, 1944). The use of protein content as a measure of feeding value was found unsatisfactory for naturally occurring hays (Watson and Ferguson, 1937). On the other hand it is still used as an indicator of quality in artificially dried grass in Britain (Ferguson, 1949). Crampton and Jackson (1944) working with green and dried pasture clippings found that protein content was of no value in predicting the seasonal variation in digestibility of pasture grasses. Fiber was equally poor as an index of nutritive value. Yet for 167 European and Indian hays Watson and Ferguson (1937) report fair inverse agreement between nutritive value and a figure obtained by adding to the protein content twice the fiber content. A

straight line negative relationship exists but no statistical proof of the significance of the regression coefficient is offered. Crampton and Jackson (1944) and others could not predict digestibility of forage from its lignin content as determined by the Crampton and Maynard method (1938). Ellis *et al.* (1946), however, improved the method for lignin determination and suggested the possibility of using lignin content as a means of estimating the digestibility of forages. Using this improved method Forbes *et al.* (1946), Swift *et al.* (1947), and Kane *et al.* (1949) have found lignin to be indigestible and have had success in determining the digestibility of forages from the ratio of lignin in the feces to that in the forage consumed. Saltonstall (1948) found a close relationship between digestibility of pasture herbage and its lignin content but the recovery of the lignin in the feces was not complete. Since lignin as determined by existing methods may be partially digestible, and since a given level of lignin does not result in the same digestibility of different forage crops or of the same forage crop grown under different environmental conditions, its content is not an accurate index of the nutritive value of forages.

Carotene has been tried as an indicator of nutritive value undoubtedly because it has been found to be destroyed by the same agents as are the energy-yielding constituents, namely, maturity, leafiness, weathering and oxidation. One of these causes alone, however, such as oxidation in storage, can reduce the carotene content to near zero while only a very slight change in energy content takes place (Camburn *et al.*, 1944). Ferguson (1949) concludes that although a high carotene content in dairy hay will maintain the vitamin A content of dairy products through the winter, the farmer is paid no premium for this practice at the present time. Therefore, little value is placed on carotene content above that needed for the health of the stock. This amount can be as low as 2 p.p.m. and yet meet minimum requirements for milk cows building up a store of vitamin A each year while on pasture.

III. Silage

1. Problems of Silage Making

The making of silage is a possible method of preserving excess pasture and the first cutting from meadow crops when climatic conditions are unfavorable for field curing of hay. It also is the most satisfactory method of storing weedy crops and plants with coarse stalks, such as corn or sorghums, which may result in considerable waste if fed as hay or fodder.

a. Characteristics of Silage. Silage is a high quality succulent feed with a clean acid odor and taste. It is firm in texture and green to brown in color. Morrison (1948) states that good silage is a very palatable feed and animals will generally eat more roughage dry matter if fed a mixture of silage and hay than if fed hay alone. This feeding practice not only increases animal production but may result in a considerable saving in the amount of concentrates required for good production. Shepherd *et al.* (1948) listed the following standards upon which silage can be judged. These were set up by the American Dairy Science Association Committee on silage methods in 1942.

> *Very good:* clean, acid odor and taste, no butyric acid, no mold, sliminess or proteolysis, acid pH of 3.5 to 4.2, ammonia nitrogen less than 10 per cent of total nitrogen. *Good:* acid odor and taste, trace only of butyric acid, acid pH of 4.2 to 4.5, ammonia nitrogen 10 to 15 per cent of total nitrogen. *Fair:* some butyric acid, slight proteolysis or some mold, acid pH 4.5 to 4.8, ammonia nitrogen 15 to 20 per cent of total nitrogen. *Poor:* high butyric acid, high proteolysis, sliminess or mold, acid pH above 4.8, ammonia nitrogen about 20 per cent of total nitrogen.

b. Principles of Silage Making. The principles of silage making consist of handling the material so that aerobic activity will be small and undesirable anaerobic activity will be prevented. In order to decrease aerobic losses the green fodder is placed in a suitable enclosure or stack and compressed, thereby limiting the amount of entrapped oxygen and excluding the entrance of oxygen into the interior of the silage. Greater compression and exclusion of air is accomplished by fine chopping, careful packing and the addition of more succulent material or water. Settling and further compaction occurs with the death of the cells and as the plant tissue loses its tugor and becomes flaccid. Wherever there is an exposed surface, mold growth results. Within a few weeks the mold growth permeates 6 to 12 inches into the silage before the shortage of oxygen inhibits further fungal activity (Miller and Golding, 1949). The molds on the surface of compact silage have such a high requirement for oxygen that any inward movement of oxygen by diffusion is prevented by the seal set up by the molds (Watson, 1939).

If the entrance of air is not prevented, the aerobic organisms, especially molds, grow very rapidly and may result in such severe heating that the hay will actually char, with tremendous losses in feeding value (Amos and Woodman, 1922).

To prevent undesirable anaerobic respiration resulting in putrefaction, butyric acid formation and other undesirable fermentations, the pH of

the silage generally is lowered. This is accomplished by means of lactic acid fermentation or the addition of inorganic acids (Watson, 1948).

c. Comparison of Carbohydrate and Protein Crops for Silage. Corn, *Zea mays* L. and sorghum, *Sorghum vulgare* Pers., cut in the glazed to early dent or similar stage of maturity usually produce a very good silage. This has been attributed to the good supply of carbohydrates and to a dry matter content (28–30 per cent) sufficiently high to result in little or no excess moisture. By the nature of the material it normally packs loosely enough for drainage of any excess liquid from the mass, which prevents the silage from becoming excessively wet. These factors encourage the formation of lactic acid which effectively lowers the pH and inhibits the undesirable fermentations. Probably the chief problem in large stalk carbohydrate-rich crops is having dry, light, and fluffy material which packs poorly and becomes moldy (Watson, 1939).

If corn and sorghums are cut when immature they are lower in carbohydrate and dry matter content. When the crop is ensiled it packs tightly. Free water is released from the plant material by compression during the ensiling process and by the subsequent settling. Silage from immature corn frequently is high in pH and butyric acid content, and putrefaction may result. The probability of this occurring is increased if the excess liquid is not drained from the silage. The problem of controlling these undesirable fermentations is even more acute in silage made from protein-rich, immature hay and pasture forage crops in which the carbohydrate content is low, the moisture content is frequently high, and the fine stems facilitate tighter packing than in the case of corn.

d. Detrimental Effects of Poor Quality Silage. A moldy condition in silage indicates that large losses of nutrients have occurred (Amos and Woodman, 1922). Reed and Barber (1917) report that although most of the molds in silage are nonpathogenic, some are pathogenic to animals. Morrison (1948) points out that slightly moldy silage may not affect cattle, but sheep and especially horses are more apt to be affected. Moldiness may cause unpalatability in silage and stock usually refuse to eat normal quantities of it.

The undesirable fermentations so difficult to control in protein-rich crops usually result in a silage with an offensive odor. It is unpleasant to handle and causes several feeding problems. It may be unpalatable and the animals will not consume enough to constitute the normal quantity of roughage. This must be compensated for by feeding more grain or a decrease in production will result. If putrefaction has occurred, according to Russell (1908), the proteins and amino acids are broken

down into ammonia, amines and amides, some of which may be toxic to animals and may cause digestive disorders when fed. van Beynum and Pette (1940) state that when butyric acid silage is fed to animals it is impossible to prevent contamination of the milk with butyric organisms. Such milk may have an off-flavor and is unsuited for the making of certain cheeses in which gas-producing organisms are objectionable.

Thus not only does moldy or undesirably fermented silage probably result in greater amounts having to be discarded as inedible, but the remaining silage is less palatable, and is consumed in smaller quantities which results in decreased production, increases the problem of producing high quality milk and cheese, and may be toxic if fed to animals. Considerable research has been devoted to determining methods of preventing undesirable fermentation especially in the protein-rich crops.

2. The Ensilage Process

a. Chemical Changes. When a green crop is ensiled the plant cells and aerobic microorganisms rapidly exhaust the oxygen in the entrapped air and release carbon dioxide, water and heat. In a period of a few hours, if the material is properly stored, aerobic respiration ceases, but the enzyme systems still function under anaerobic conditions (Peterson *et al.*, 1925).

Babcock and Russell (1900), Sherman and Bechdel (1918), LeClerc (1939) and others have stated that protoplasmic respiration and enzyme activity are the chief factors involved in preservation of silage. To prove this theory Russell (1908) ensiled crops with no treatment, with toluene to prevent microbial activity, and with heat to prevent both microbial and enzymatic activity. Because the toluene treated material was well preserved, even though it did not have a typical silage aroma and appearance, he concluded that the bacterial action was of secondary importance and merely complicated the process. Esten and Mason (1912), Hunter and Bushnell (1916), and others took the opposite view that the activity of microorganisms was the more important phase of the process since the acidity developed by the organisms helped to prevent undesirable fermentations. Peterson *et al.* (1925) showed that sterilized corn inoculated with lactic acid organisms was preserved as good quality silage. The activity of the plant cells is important but unless there is complete sterilization of the mass, the action of the microorganisms cannot be overlooked because the types which develop determine the quality of the silage.

The major changes in the carbohydrate fraction of the ensiled crop from anaerobic processes and the resulting losses in energy are due to the

formation of organic acids. The organic acids consist of the nonvolatile acids, chiefly lactic, and the volatile acids, determined as acetic acid although butyric acid is reported separately. The relative and total amounts of these acids are so important in determining the quality of silage that Kirsch and Hildebrandt (1930) established 5 classes of silage on the basis of their organic acid content. The American Dairy Science Association also considered acid content in their classification (Shepherd *et al.*, 1948).

Of the nonvolatile acids, lactic is present in the largest amounts with formic, propionic, malic, succinic and other acids also reported as present (Russell, 1908; Neidig, 1918; Peterson *et al.*, 1925). Lactic acid usually comprises over 50 per cent of the organic acids in silage classified as very good, and generally amounts to 1 to 2 per cent of the fresh silage (Kirsch and Hildebrandt, 1930). Since lactic acid has a much higher dissociation constant ($K = 1.38 \times 10^{-4}$) than either acetic acid ($K = 1.75 \times 10^{-5}$) or butyric acid ($K = 1.48 \times 10^{-5}$) the pH of 3.5 to 4.2 which high quality silage attains is largely determined by lactic acid.

Heineman and Hixson (1921) found that the bacteriological changes in corn silage consisted of 3 phases, but in the final phase the lactic acid bacteria dominate the fermentation. The hexoses and pentoses in corn silage make an excellent medium for these organisms. Butyric acid organisms attack more complex carbohydrates than lactic acid organisms, and according to Archibald (1946), butyric acid formation may be high in excessively wet silage. Acetic acid is a byproduct of the lactic and butyric acid organisms, and may be formed in large quantities if the lactic acid organisms lack an adequate supply of fermentable carbohydrates (Stone *et al.*, 1943). While alcohols and aldehydes have been isolated from silage they do not appear to play an important role in its making (Hart and Willaman, 1912).

The degree of protein breakdown has been determined by comparing the soluble nitrogen and ammonia nitrogen in the silage with that present in the fresh crop. In all types of silage a portion of the protein undergoes a breakdown to amino acids as a result of a tryptic enzyme present in plants (Russell, 1908; Lamb, 1917; Hunter, 1921). Further changes beyond the amino acids may be caused by other enzymes, but probably the proteolytic bacteria of the Clostridium group play an important role (Allen and Harrison, 1937; Rosenberg and Nisman, 1949). Several species of soil bacilli are frequently found in silage and have the ability to digest proteins and even the lactobacilli organisms may attack proteins in the absence of carbohydrates (Hunter, 1917, 1918). The organisms break down protein compounds to organic acids, especially butyric

acid and ammonia, amides, and amines (Russell, 1908; Schieblich, 1930, 1931). If growth of these organisms is not suppressed, undesirable characteristics may develop in the silage and feeding problems may result.

Formation of nitric dioxide from fermenting silage has been reported recently (Anon., 1949). The gas probably is released as nitric oxide which is oxidized to the dioxide when it comes in contact with atmospheric oxygen. The conditions which bring about this loss of nitrogen are not understood, but it is due probably to the reduction of nitrates by the anaerobic organisms (Wilson, 1943).

The mineral portion of the plant may undergo changes in combination but will not be lost unless leached from the silage in the juice or as a result of exposure to rain (Watson, 1939). Magnesium may be released from the chlorophyll forming phaeophytin, which gives silage a brown color (Woodman, 1923). Due to the formation of organic acids and other ether-soluble compounds, the ether extract fraction of silage is higher than that of the fresh crop.

b. Control of Undesirable Fermentation. (1) Lowering pH. Virtanen (1934) reported that lowering the pH to 4.2 prevented the growth of butyric acid organisms and van Beynum and Pette (1936) showed that these organisms were killed at pH 3.5. Virtanen also found that 1.5 per cent of the total nitrogen of fresh clover was present as ammonia. In the silage made therefrom at pH 3.6 ammonia constituted 2.0 per cent of the nitrogen, at pH 4.3 12.0 per cent, and at pH 4.5 21 per cent. Virtanen (1933) reported that below pH 4.0 both plant enzymes and anaerobic microorganisms could not cause protein breakdown as measured by soluble nitrogen and ammonia, but later work indicated that the breakdown is not prevented except at pH of 3.0 or lower (Virtanen, 1934). However, the growth of bacteria of the coli-aerogenes group and butyric acid bacteria is prevented at pH 4.0. At pH 4.0 lactic acid organisms produce appreciable quantities of lactic acid and some acetic acid, and the proteins undergo marked hydrolysis to soluble nitrogenous compounds, but the increase in ammonia nitrogen and decrease in digestible protein is small (Watson, 1939; Martos, 1941). Thus, rapidly lowering the pH to about 4.0 is an effective way, and is the method usually used, for controlling butyric acid formation and undesirable proteolysis in ensiled crops. Decreasing the pH to this desired level is usually accomplished by encouraging lactic acid fermentation or by direct acidification with acids. In carbohydrate-rich plants, lactic acid fermentation normally occurs with a decrease in pH to 4.0 or less, if the crop is harvested at the desired stage of maturity (Peterson *et al.*, 1925). In protein-rich crops, such as legumes, active lactic acid fermentation may be

lacking. Legumes, in particular, are high in bases which form a strong buffer system and cause more acid to be required to lower the pH (Wilson, 1935).

(a) Lactic Acid Stimulation. Lactic acid fermentation in silage is encouraged, since by lowering the pH and possibly also by the antagonism of the lactic acid organisms, butyric acid and proteolytic bacteria are suppressed (Rodenkirchen, 1939; Waksman, 1947). Numerous workers have conducted studies on the possibility of inoculating silage crops with bacterial cultures to insure the proper fermentation. Occasional benefits have been observed from this practice, but the general conclusion is that inoculation is of little value. It has been concluded that the green crop carries sufficient quantities of acid-forming bacteria, but their growth and development is dependent upon the existing environment (Watson, 1948).

One of the factors which favors the growth of lactic acid organisms is an adequate supply of carbohydrates, which are ordinarily lacking in hay and pasture crops. Several early workers found that lactic acid fermentation could be encouraged by mixing hay crops with high-carbohydrate crops, such as corn or sorghum, or with high carbohydrate materials (Reed and Fitch, 1917). The use of molasses containing about 50 per cent sugars at rates of 15 to 100 lbs. per ton of green forage gives very successful results when ensiling meadow grasses and legumes. As the amount of legume increases or as the material is less mature, the amount of molasses needs to be increased (Watson, 1948).

Among other carbohydrate products which have been added successfully are crude sugar, ground grains, potato flakes, whey paste or dried whey (Watson, 1939; Bender and Bosshardt, 1939). Fresh whey and raw potatoes have been found too high in water for use unless the crop has been wilted to a moisture content of 60 per cent or less (Kirsch *et al.*, 1934; Brouwer, 1937; Watson, 1939; Shepherd *et al.*, 1946). Many other materials including beet pulp, straw, cob meal, and hay have been used with varying degrees of success. These latter products do not materially increase the quantity of potentially fermentable carbohydrates but tend to decrease the moisture content of the mass, and their effect is akin to wilting (Watson, 1939).

Even if fermentable carbohydrates are added to succulent protein-rich crops, a silage high in lactic acid will not be produced unless the surplus water drains out of the silage (Crasemann and Heinzl, 1949). Water-logged silage is high in acetic acid and may contain some butyric acid (Archibald, 1946).

In contradiction to the hypothesis that certain crops, such as hay and pasture forages, do not contain sufficient quantities of carbohydrates

for lactic acid fermentation, it has been suggested that sufficient carbohydrates are present but that the physical conditions are unsuitable for the growth of the desirable acid-producing organisms. A good quality lactic acid-type silage can be produced from protein crops with moisture contents of 70 per cent or less without addition of supplements (Cooper, 1917; Woodward and Shepherd, 1936).

Immature forages which are cut, chopped and rapidly put in the silo usually contain well over 75 per cent moisture at the time of ensiling. The material packs well, little air is entrapped, and a large amount of liquid is released. As a result, the amount of aerobic respiration is small, the temperature of the mass does not rise materially, and the formation of acetic and butyric acid and ammonia results, but little lactic acid accumulates. On the other hand, if forages have a lower moisture content because of partial wilting or approaching maturity, or are stored unchopped in shallow layers, the conditions are reversed and good lactic acid fermentation develops (Watson, 1939, 1948).

The success of the wilting method is attributed to the greater amount of oxygen entrapped within the crop as it is ensiled. Most of the lactic acid organisms do best at low concentrations of oxygen (microaerophilic) or are facultative anaerobes (Martos, 1941). On the other hand many butyric acid-forming bacteria are true anaerobes, although some are facultative anaerobes (Watson, 1939). Acetic acid appears to be present in larger relative amounts when butyric acid formation is favored (Archibald, 1946).

Another factor in wilting which may encourage lactic acid formation is the concentration of sugars (Wilson, 1948a). Although wilted forage does not contain greater amounts of sugar at the time of ensiling than unwilted material (dry matter basis), the resultant silage from wilted crops is higher in sugars (Stone *et al.*, 1943; Autrey *et al.*, 1947).

A number of workers have maintained that the temperature of the mass during fermentation determines the type of silage produced. Temperature increases, chiefly caused by the amount of aerobic respiration, can be controlled by regulating the stage of maturity, the degree of chopping and packing, the moisture content and depth of the silage. Generally, material which is packed loosely and allowed to heat to 50°C. or higher (warm fermentation process) produces a sweet smelling silage low in volatile acids with no production of butyric acid (Dijkstra, 1948; Roseveare, 1948).

The cold fermentation practice is used in Germany because butyric acid supposedly is formed if the temperature rises. The forage is chopped, tramped as it is ensiled, and heavily weighted to exclude as much air as possible. If properly handled the temperature does not rise above

20°C. The moisture content must be 70 per cent or less because excessively wet material will not make a silage that will keep satisfactorily, even though a preservative is added (Crasemann and Heinzl, 1949).

In England silage is made successfully from immature forage by ensiling the crop unchopped. It is added to the stack or silo in layers of 5 to 8 feet in depth and allowed to heat so that all of the mass will reach temperatures of 27 to 38°C. This process also develops a desirable fermentation yielding lactic acid in excess of acetic acid with no appreciable amounts of butyric acid (Watson, 1939, 1948; Bohstedt, 1944).

The proponents of controlling fermentation by regulating the temperature of the silage mass, whether it be below 20°C., between 27 to 38°C., or above 50°C., explain the success of their methods on the basis that lactic acid organisms are favored at the temperatures they advocate while the growth of the undesirable organisms is suppressed. Other work indicates that the optimum temperature for both the lactic acid and butyric acid bacteria is variable, but near 37°C. for most of the species in both groups. Thus it would appear that the difference in temperature is not the chief reason for the presence of butyric acid in wet immature silage (Watson, 1939).

(b) Direct Acidification. The addition of acids to decrease the pH of silage to below 4.0 has been extensively used for crops which normally do not produce a rapid lactic acid fermentation when ensiled. The addition of acids to silage dates back to 1885 when citric, tartaric and hydrochloric acids were compared (Giglioli, 1914). The two organic acids were unsuitable, but the addition of hydrochloric acid was recommended. Gerlach *et al.* (1929) found that the growth of undesirable organisms in silage is suppressed materially at one per cent concentration of lactic acid and prevented at the 1.5 per cent level. Due to its high cost the direct addition of lactic acid is impractical but indirect sources such as sour whey or molasses may be used.

In 1926 and 1927 Fingerling in Germany patented a process which consisted of adding sufficient quantities of hydrochloric acid to produce a pH of 2.0. The process resulted in excellent preservation, but was exacting and the problem of feeding such an acid feed to livestock prevented the method from being widely accepted (Watson, 1939). In 1929, Virtanen (1934) established the process, known as the A.I.V. process, of direct acidification in the making of silage. Virtanen rapidly lowered the pH of the crop to at least 4.0 but not lower than 3.0 by the use of mineral acids, usually a mixture of hydrochloric and sulfuric acids.

The acid in the A.I.V. or other processes must be uniformly applied to the crop at an accurate rate determined by the type of crop, its moisture content and the soil upon which it is grown. Immature and

legume-rich forages require more acid to lower the pH than do other crops. Apparently the acid requirement for any particular lot of forage is proportional to its dry matter content. Changes in the moisture content of the crop require an adjustment of the rate of acid applied. A crop produced on a neutral or alkaline soil requires more acid to lower its pH than one produced on an acid soil (Virtanen, 1934; Watson, 1939).

Shortly after the A.I.V. process was introduced, the Defu process, which consisted of adding molasses equal to 0.20 per cent of the green crop and hydrochloric acid containing one per cent phosphoric acid, was suggested (LeClerc, 1939; Bender and Bosshardt, 1939; Watson, 1939). Liquid phosphoric acid and solid acid materials such as phosphorus pentachloride and sulfur trioxide have also been used to lower the pH of the crop. All these materials successfully lower the pH if properly used and produce a good quality silage from protein-rich crops (Virtanen, 1932; Wilson and Webb, 1937; Watson, 1939).

An effective way of counteracting the acidity and avoiding most of the feeding problems of mineral acid silage is the feeding of legume-rich hay, sodium bicarbonate or limestone (Lepard *et al.*, 1940; King, 1943). However, Ingham (1949) reports that although the cattle were fed 2 per cent ground limestone, phosphoric acid-silage was inferior to molassess-silage in palatability, phosphorus retention, economy of milk production and absence of physiological disturbances.

(2) Sterilization. A number of other chemicals which do not materially lower the pH of silage have been used to encourage desirable fermentations or to prevent any fermentation. By aerobic and anaerobic respiration the carbon dioxide content can increase to 70 to 90 per cent (volume basis) of the gases in an airtight silo (Neidig, 1914; Peterson *et al.*, 1925; Watson, 1939). At these concentrations it has been theorized that both respiration and fermentation would be checked. The Cremasco process, developed in Italy, consists of placing well-wilted material containing 60 to 70 per cent dry matter into airtight silos which are heavily weighted and sealed. According to Samarani (1922) this results in negligible bacterial activity with about 5 per cent loss of sugars and very slight breakdown of proteins. Other work indicates that lactic and acetic acid formation is of about the same magnitude as has been observed in ordinary silage made by the wilted process (Schmidt, 1934; Mikhin *et al.*, 1937). Butyric acid formation is low and surface spoilage is essentially absent. Although a carbon dioxide atmosphere may prevent undesirable fermentations in wilted forages it has little or no effect in preventing undesirable fermentations in crops ensiled with over 70 per cent moisture content (Mikhin *et al.*, 1936; Albada, 1946).

Wilson (1948b) reviewed the literature and found that salt has no

sterilizing effect, and has little affect in preventing a rise in temperature. Apparently salt increases the initial rate of drainage which may have a slight beneficial effect on lactic fermentation.

Procopio (1942) treated fodder with sulfur dioxide as it was ensiled and found that a concentration of 0.8 to 1.0 per cent sulfur dioxide inhibited all biological and enzymatic processes while 0.25 to 0.30 per cent sulfur dioxide suppressed their action. No free sulfur dioxide could be found after 5 months. Kvasnikov and Raev (1939) found that 0.15 per cent sulfur dioxide was lethal in pure cultures of lactic, acetic, and butyric acid bacteria. Workers in New Jersey (unpublished) treated silage with concentrations of 2, 4, and 6 lbs. of sulfur dioxide per ton of green crop and found that the ether-soluble fraction was not materially increased in the silage. This would indicate that little organic acid formation occurred. Overholser and Cruess (1923) and Sisakyan and Vasil'eva (1945) found that sulfur dioxide inhibits oxidizing enzymes, especially peroxidase, and Voinovitch *et al.* (1949) report that sulfur dioxide in combination with thiamine or nicotinic acid is an effective antioxidant. A legume-grass silage treated with 0.25 per cent sulfur dioxide at the time of ensiling is being fed to dairy cattle by Pennsylvania workers with no adverse effects.

Other chemicals which have been used for controlling fermentations in silage are sulfamic acid, acid salts, calcium hypochlorite, phenol, benzoic acid, borax, salicylic acid, oxalic acid, carbon disulfide, formic acid, and formaldehyde. Either the results have not shown them to be advantageous or the data concerning their value is questionable (Watson, 1939; Johnson *et al.*, 1941b).

The application of heat to the ensiled crop has been tested with the aim of producing a sweet silage similar to that obtained in the warm fermentation process. Warm air, steam and electricity have been used to heat the silage. Results indicate that the application of heat probably delays the fermentation. The resultant silage, however, contains nearly the same amounts of lactic and acetic acids as are present in untreated silage (Knisely, 1903). Butyric acid also has been found in heated silage along with the usual amount of protein breakdown. It appears that the use of heat has no practical application in silage making (Hoffman, 1923; Watson, 1939).

(3) Complete Exclusion of Oxygen. The possibility of storing silage in a vacuum has been studied by Schmidt (1934), but sufficient carbon dioxide is released to result in essentially the same system and type of silage as obtained following the addition of carbon dioxide or enclosure in an air-tight container in which normal respiration processes exhaust the oxygen.

The application of pressure is an effective means of compressing the silage, excluding air and preventing the subsequent entrance of air. By limiting the amount of air, excessive heating and aerobic losses are prevented. Pressure *per se*, however, at least over a large range, has no influence on the silage processes (Dijkstra, 1945; Crasemann and Heinzl, 1949).

c. Losses of Dry Matter and Nutrients. The losses of dry matter, crude protein and carotene which occur in the preservation of hay crops are discussed in VII. The losses which occur after the crop is ensiled are due to surface spoilage, drainage and fermentation. In general, the surface losses can be reduced to essentially zero in tower silos which are air-tight or have properly protected surfaces, but approach 30 per cent for small stack silos (Watson, 1939; Rogers, 1949). Additional losses due to aerobic respiration occur on the exposed surface of opened silos. Spoilage due to mold growth is prevented when at least a 1½ to 2 inch layer of silage is fed each day during the winter and when somewhat larger quantities are fed during the summer (Morrison, 1948), but the magnitude of the dry matter losses which occur even when visible mold growth is prevented is not known. Probably it is considerably higher during the summer than during the winter.

The loss of dry matter due to drainage usually does not exceed 3 per cent and approaches zero if the dry matter content of the ensiled material is 30 per cent or higher (Godden, 1923; Archibald and Gunness, 1945; Monroe *et al.*, 1946). Internal losses of dry matter due to fermentation have been reported as being from 2 to 30 per cent, but probably a 7 to 10 per cent loss is the minimum that can be expected (Taylor *et al.*, 1940; Camburn *et al.*, 1942; Shepherd *et al.*, 1947, 1949). Rapid lowering of the pH by the addition of acids or fermentable carbohydrates and partial wilting of the crop appears to result in less dry matter loss than when no preservatives are added to unwilted material. Severe heating of silage with the temperature of the mass rising as high as 70 to 75°C. may cause charring and excessively high losses of dry matter with over 80 per cent loss of digestible crude protein (Woodman and Hanley, 1926).

The carbohydrate undergoes the greatest loss of any nutrient, with 20 to 30 per cent of the starch and pentosan fractions disappearing (Peterson *et al.*, 1925). Regardless of whether silage is stored unwilted, with or without a preservative such as molasses or mineral acids, or after partial wilting, the forage undergoes fermentation. Normally lactic acid fermentation results in less loss in feeding value than butyric and acetic acid fermentations. The loss of energy is less than 3 per cent in

converting glucose to lactic acid, but is about 23 per cent when butyric acid is formed, and 38 per cent when acetic acid is the acid product (Buchanan and Fulmer, 1928). According to Watson (1939) the loss in starch equivalent is slightly less than 25 per cent from silage receiving preservatives and slightly higher than 33 per cent from unwilted material receiving no preservatives. These losses appear to be high in view of the recent investigations by Hodgson (1949) and Shepherd *et al.* (1949) discussed in VII.

The loss of digestible crude protein is greater if acidification or rapid lactic acid fermentation does not take place (Brouwer *et al.*, 1933; Watson, 1939). In all silages the amount of soluble nitrogen materially increases during the ensiling process, although if amino acid breakdown does not occur the percentage of digestible protein is not markedly decreased (Peterson *et al.*, 1937; Watson, 1939).

The "grass juice factor" also is retained in legume and grass silage especially when molasses or acids are added (Johnson *et al.*, 1941a). Vitamin C is of little importance and is almost completely lost through the action of the peroxidases in untreated silage, but the addition of mineral acids may cause the retention of 50 per cent of the vitamin C. Vitamin B and D are not known to undergo any appreciable change, but are generally present in small quantities (Watson, 1939).

3. Questions Needing Further Research

It has been contended that the important chemical changes occurring in silage are the result of cell respiration and enzyme activity, but microbial activity may be equally or even more important. All widely used methods of silage production are based on the principle of controlling undesirable fermentation and encouraging or at least not limiting desirable fermentations.

In controlling undesirable fermentations, the importance of lactic acid production has been attributed to its causing a decrease in the pH of the silage. The control of butyric acid organisms at a pH of 4.0 to 4.4 when lactic acid organisms are present (van Beynum and Pette, 1936) alternatively may be accounted for by the antagonism existing between the two groups of microorganisms, as indicated by Rodenkirchen (1939). Regardless of the reason, vigorous lactic acid fermentation appears to control undesirable fermentation. Gorini (1942) points out that the "native" lactic acid organisms are not present in sufficient quantity and quality on many crops to promote a vigorous lactic acid fermentation that will effectively lower the pH and permanently control the butyric acid and proteolytic bacteria.

The practice of inoculating silage with lactic acid bacteria has not

been universally successful; however, there has been sufficient success with inoculation to indicate that it might have a place in silage making (Watson, 1939). Gorini (1942) has contended that inoculation of silage has not been more successful because the lactic acid cultures were unsuited to "vegetal sugars" and to the environmental conditions which exist in a particular silage making process. Special emphasis needs to be placed on the selection of an organism which will grow vigorously on succulent, immature protein-rich crops and suppress undesirable fermentations by increasing the acidity, or by other forms of antagonism. Since legumes, in particular, have a strong buffer capacity and the pH is difficult to lower, the control of undesirable organisms by means other than lowering the pH would be desirable.

In addition to the search for more efficient strains of bacteria to control undesirable fermentations, a detailed study of the relationship of environment and undesirable fermentations is needed. Why do undesirable fermentations occur when high moisture crops are ensiled? Is it due to the amount of the liquid phase *per se*, the amount and type of the gaseous phase, or the amount and type of the solid phase? Does the carbon-nitrogen ratio or the insoluble-soluble carbohydrate ratio of the crop have any significance in determining the type of fermentation? Does the wilting process merely concentrate the chemical constituents of the plant or does it alter their physical and chemical properties? Does the addition of insoluble carbohydrates only alter the physical condition of the mass and thus encourage lactic acid fermentation of existing sugars, or are they hydrolyzed to fermentable carbohydrates which lactic acid organisms can attack? Is the temperature of the mass during fermentation important or is it merely a modifying factor? There is a lack of fundamental information from which conclusive answers to the above questions can be derived.

The problems of ensiling immature protein-rich crops have not been adequately solved. The wilting process is widely advocated but requires going over the field two or more times, requires considerable experience in judging the proper degree of wilting, and is not possible in rainy weather. The addition of molasses, other carbohydrate-rich materials, or acids also has several limitations. Obtaining the materials is usually an extra expense, the addition of the materials requires time and supervision, molasses may cause clogging of the blower pipe, and the acids may corrode machinery and damage clothing. If preservatives are not applied uniformly, the under-treated portions of the silage may undergo undesirable fermentation. Even though a very small portion of the silage undergoes butyric acid fermentation, van Beynum and Pette (1940) point out that when it is fed, the milk becomes contaminated

and cannot be used in making certain high quality cheese. These difficulties often discourage many farmers from adding preservatives even though mechanical devices are available for simplifying the process. Can better methods of applying the existing preservatives be developed? Are there other preservatives which are easier to apply?

Frequently the roughage is low in protein due to the low amount of legumes in the hay and pasture crops. Although generally the protein content of the roughage is best increased by the growing of more legumes, the possibility of improving the protein level of low protein silage needs further investigation. Brigl and Windheuser (1931), Windheuser *et al.* (1935), and Cullison (1943) have added nonprotein nitrogen to silage with the expectation that the silage organisms would convert the nitrogen into proteinaceous material. Urea, ammonium carbonate and ammonium bicarbonate have been used. The protein level appears to be improved without decreasing the palatability; however, more data are needed before the addition of nonprotein nitrogen to silage can be recommended.

Silage is a very palatable feed and one of the most satisfactory methods of preserving roughages, but the losses in feeding value are nevertheless considerable. Nearly 15 per cent loss in feeding value occurs due to the ensiling process even when the best accepted methods of making silages are used. In other words, 6 or less tons of total digestible nutrients are fed for every 7 tons ensiled. The loss due to surface spoilage can be reduced to a negligible amount if due care is taken in topping off and sealing a well constructed silo; however, considerable spoilage frequently results from the accidental entrance of air. Little is known about the magnitude of the surface losses which occur when a silo is opened and fed during warm weather. The surface of the silage is an excellent medium for mold growth which is exemplified by the speed with which the silage must be fed to prevent visable mold growth. Even though mold growth is not observed, aerobic respiration is taking place and an appreciable loss of nutrients is probably occurring.

Pentzer *et al.* (1933) report the use of sulfur dioxide to control mold growth and respiration in grapes. The possibility of treating the surface silage with sulfur dioxide as a fungicide to prevent surface spoilage is under investigation at Ohio State College. Dawson *et al.* (unpublished) are studying the prevention of mold growth in hay by the use of certain phenol compounds. These may be applied to prevent surface spoilage in silage.

Recently a steel, glass coated tower silo which is air tight has been offered for sale in the United States. In this aerobic losses are limited to those supported by the entrapped air. The silo is sealed when the

filling operation ceases and no air can enter the silo except that necessary to compensate for the decrease in volume as the silage is removed by a mechanical unloader operating in the bottom of the silo. The unloader digs its way into the silo after it is filled and is then sealed into position. Such a silo eliminates the topping off and sealing required in conventional silos.

While improved methods of controlling surface spoilage have been developed, the losses within the mass due to fermentation have been classified as "unavoidable losses," yet they are frequently greater than surface spoilage. Rapid lowering of the pH and wilting appear to decrease fermentation losses, but what effect does the external temperature during fermentation have upon the preservation of a crop and the dry matter losses which occur? No loss in dry matter occurs with complete sterilization which causes the cessation of cell respiration, enzyme activity, and growth of microorganisms, but to date, workable procedures for such sterilization have not been developed.

The possibility of using bactericides which will inhibit silage fermentations and still not be toxic to the flora of the rumen when the silage is ingested should be investigated. The use of sulfur dioxide may decrease the amount of "unavoidable losses" in silage by inhibiting bacteria and by repressing certain of the enzymic changes without causing the silage to be toxic to animals. Perhaps other chemicals would be of equal or more value.

Advances in methods of producing high quality silage from protein-rich crops are needed, and until some of the problems of ensiling such crops are eliminated the proper conservation of much of the surplus pasture and first cutting hay crop will not be accomplished. The validity of the contention that losses of approximately 15 per cent of the digestible nutrients are unavoidable needs to be questioned and further attempts made to prevent them.

IV. Field-Cured Hay

1. Factors Influencing Rate of Drying

The final quality of field-cured hay as it is removed from storage is largely determined by the extent of the losses taking place in the field. Field losses are directly related to the length of time required for drying. Unfortunately the highest quality forage as cut usually requires the longest curing period. This has been attributed to poor drying weather prevailing at the time hay crop plants reach their maximum vegetative growth. However, high moisture content (Archibald *et al.*, 1946) and hygroscopicity of the plant tissue (Dexter *et al.*, 1947)

have been proposed but not proven to be as important as weather in determining the rate of drying of early cut hay.

a. Time of Day to Cut. Henson (1939) noting hourly variation in moisture content of some plants, determined the moisture content of alfalfa at hourly intervals from 8 a. m. to 8 p. m. and concluded that in this plant and in probably all common hay crops there is not sufficient change during the day to justify using plant moisture as a guide to time of day to mow. Hartwig (1942) found that hay cut in the morning with the dew on it was usually as dry at the end of the first day of curing as was hay cut after the dew had dried off. Hay cut in the late afternoon traps the day's production of photosynthate in the tops (Curtis, 1944). This may result in hay of higher nutritive value if the method of curing controls subsequent respiration.

b. Raking, Cocking, Crushing and Tedding. Swath curing in most trials has been more rapid than windrow curing (Henson, 1939; Higgins, 1932; Kiesselbach and Anderson, 1927). However, swath curing for 1 to 4 hours followed by windrowing has compared well with complete swath curing as to rate and has produced hay sufficiently better with respect to leafiness and color that it is recommended for alfalfa.

Raking should be done before the plants dry to below 40 per cent moisture content because leaves begin to shatter at this point (Zink, 1936). He observed, however, that alfalfa under some conditions may be dried to 20 per cent moisture content and yet retain its leaves during handling. He considers the problem needs further study to delineate the controlling factors.

Cocking wilted hay delays the time for storage still more than windrowing (Rather and Morrish, 1935). Watson (1939) reviewing his own work and that of others shows that in good drying weather cocking frequently produces hay of poorer quality than faster methods but decidedly better hay under poor drying conditions.

Crushing the stems of hay between rollers as it comes off the cutterbar decreases the field drying time under nearly all conditions. Crushed soybean *Glycine max* (L.) Merrill hay retained its leaves and pods and was stored with much higher carotene content than uncrushed hay in tests by Jones and Dudley (1948). Uncrushed hays of sudan grass, *Sorghum vulgare,* Pers., var. SUDANENSE, Piper, and Johnson grass, *Sorghum halepense,* L., absorbed more water during the night than crushed hay in contradiction to the usual statement that crushed hay not only dries out faster but will absorb greater quantities of dew or rain (Terry, 1948).

Trials with tedding in the United States have shown very little ad-

vantage in speeding up the curing, and farmers have largely discontinued the practice (Henson, 1939).

2. Field Losses of Dry Matter and Digestible Nutrients

Field losses of carbohydrates, crude protein, minerals and vitamins occur as a result of respiration, leaching and leaf shattering (Hodgson *et al.*, 1948). Field losses of dry matter from 8 lots of hay made in England by hand methods amounted to over 16 per cent (Watson *et al.*, 1937). This compares with more recent studies in the United States where drying conditions may be better but where the haymaking job is done mechanically. Mixtures containing a large proportion of alfalfa, made into hay with the use of a tractor power mower, side delivery rake and hay loader, have given an average dry matter loss of 25 per cent during 4 trials in as many years (Shepherd *et al.*, 1947, 1949). Grass and legume crops when made into hay lost an average of 11.7 per cent of dry matter in 8 trials in Vermont (Camburn *et al.*, 1942, 1944).

Respiration accounts for a loss of up to 10 per cent of the hay during field curing. Mechanical losses including shattering and leaching make up the remainder (Wiegner, 1925). If the drying is rapid only the simpler carbohydrates are lost through respiration, while with prolonged drying, nitrogen also is lost especially when there is leaching.

Very few data have been reported showing the total loss of leaves during field curing. Kenney (1916) reports an average loss of 12.43 per cent from 41 lots of alfalfa. Henson (1939) working also with alfalfa found leaf losses of 5 to 10 per cent during the loading operation following various curing practices. In the Vermont studies, the average total field losses from 3 alfalfa, one red clover and 4 timothy crops were 16.2, 32.5, and 4.2 per cent of dry matter respectively (Camburn *et al.*, 1942, 1944). If a small respirational loss is assumed for the timothy crop the mechanical loss must have been practically nil. Gerlach found that grass hay lost 3 per cent while Bokhara clover, *Melilotus alba,* Desr., M., lost 28 per cent of its dry weight as a result of leaf shattering in 4 trials (Watson, 1939). It is generally recognized that grass crops suffer less loss through shattering than legume crops.

The seriousness of leaching, mechanical and respiration losses, as has been pointed out in II-3c, is evident when it is recognized that the dry matter lost may be 100 per cent digestible. Under certain conditions an approximate percentage decrease in the nutritional value of hay during field curing may be obtained by doubling the percentage of dry matter lost because the dry matter of hay is only about one-half digestible.

3. Changes in Vitamin Content during Field Curing

Vitamin D develops in hay during the field curing period. Wallis (1944) found that this development is as rapid in hay raked into small windrows as when left to cure in the swath. Raking into large windrows or cocking slows down the rate of development. Turning the windrows before the final period of curing increased the vitamin D content approximately 10 per cent. Good increases occurred even in periods of cloudy, rainy weather since the intensity of the ultraviolet rays is not decreased as much as the longer light rays. The content of vitamin D ranged between 300 and 1,000 International Units per lb. when the alfalfa hay was sufficiently dry for storage. This content was more than doubled by a prolonged field exposure of 6 days.

Vitamin C and several vitamins in the B group are well preserved in field-cured hay but are considered to add little to the value of hay (Watson, 1939). The influence of curing conditions on the content of tocopherols in hay has not been studied to date.

Carotene loss varies directly with the amount of exposure to light, and the length of time required for curing and temperature. Enzymatic action (Mills and Hart, 1945) photolysis and oxidation (Guilbert, 1935) are the processes causing the loss of carotene. The loss is usually at least 50 per cent, and when hay is exposed to extreme weathering essentially 100 per cent of the carotene is lost (Camburn *et al.*, 1942, 1944).

4. Storage Losses

a. Carotene. As would be expected from the processes causing its destruction carotene continues to diminish after hay is stored. Generally the higher the carotene content the greater is the absolute storage loss. In the studies by Camburn *et al.* (1942, 1944) losses during one year of storage have ranged from 46 to 78 per cent of the content as stored. Greater losses occur in summer than in winter (Kane *et al.*, 1937). Hay which heats badly in storage undergoes nearly a complete loss of carotene.

b. Heating. The amount of heat which accumulates in stored hay depends on the moisture content, nature of the crop, density, size and shape of the storage mass. Hay which is stored at a moisture content under 13 per cent will not heat (Wright, 1941). Under climatic conditions prevailing in most of the hay-producing regions this low content is rarely attained for two reasons. Curing periods with relative humidities low enough to obtain such moistures are infrequent, and farmers avoid such extreme drying for fear of excess leaf shattering and a brash, unpalatable product. With moisture contents between 13 and 25

per cent the heat given off in respiration is sufficient to volatilize the water in excess of 13 per cent. The vapor escapes from normally-packed long hay; drying is accomplished and thereby respiration and heating are checked. Hay with 25 to 35 per cent moisture can dry down without serious heating provided it is placed in a bin with a relatively large amount of surface exposure, which increases radiation losses and facilitates the escape of moisture. Roethe (1937) found that for undercured long hay the bin should not be wider than 12 or 14 feet.

Early cut hay made with a small amount of field loss may undergo greater heating in storage than that cut at the ordinary time (Watson, 1939). It is not clear whether this is due to a higher percentage of respirable materials or to the greater density resulting from the better packing of a more finely divided and pliable product. Greater density, besides placing a larger quantity of respirable material in a unit of space, also slows down the drying by inhibiting vapor and air movement.

Both chopped and baled hay attain higher temperatures when stored at a given moisture content than does long hay. Miller *et al.* (1934) and Woodward and Shepherd (1936) found dry matter losses of about 5 per cent whether the hay was chopped and stored at near 25 per cent or near 15 per cent moisture content. This indicates very similar quantities of heat produced yet the maximum temperatures attained varied from 41° to 66°C., and density, as measured by the storage space per ton, varied from 227 to 152 cubic feet. Both moisture content and fineness of chopping affected the density but neither significantly affected the loss of dry matter.

Hay stored above 30 to 35 per cent moisture, through the processes of microbial respiration and chemical oxidation, may heat to the point of ignition. According to Hoffman (1940) heating up to about 66°C. is caused primarily by microorganisms. Such heating causes the production of oxygen-absorbing materials which generate more heat as they are oxidized. He warns that hay which has heated to the 66° to 110°C. range may rise very rapidly to about 226°C. at which ignition takes place. Dobie (1948) has developed an inexpensive temperature probe with which hot zones can be located quickly when excessive heating is suspected. Keeney (1941) has found that forcing carbon dioxide into zones of overheated hay lowers the temperature long enough for the hay to be removed.

The heating of undercured hay is utilized in the production of brown hay. According to Watson (1939) this method of hay making originated in England. The heat produced by bacteria and fungi growing on hay stacked at about 50 per cent moisture is sufficient to dry it down to the equilibrium level. At the same time sufficient carbon dioxide is pro-

duced to destroy the green color, and heat develops a brown color which may grade into black at very high temperatures (Henson, 1939). Brown hay may also develop in the center of large stacks of hay containing much less than 50 per cent moisture and is frequently found in the centers of bales of undercured hay.

The amount of dry matter lost in the successful production of brown hay varies enormously. Woodward and Shepherd (1936) found a loss of 6.5 per cent but Hoffman and Bradshaw (1937) observed a maximum loss of 22 per cent. The losses in digestible nutrients are very high because the heating, besides consuming a large part of the digestible nutrients, renders the remainder less digestible (Watson, 1939).

Hay stored under 25 to 30 per cent moisture usually retains its color (Henson, 1939). The storage loss of dry matter from such hay is remarkably constant at about 5 per cent. The carbohydrates found in the nitrogen-free extract constitute most of the loss according to Camburn *et al.* (1944).

c. Preservatives. Numerous experiments with salting undercured hay as stored have rarely shown any beneficial effects other than delaying the time at which the maximum temperature is reached (Henson, 1939; Roethe, 1937). Musgrave and Dawson (1946) found that preservatives containing sodium bicarbonate as the active ingredient had no inhibiting effect on the respiration of undercured hay.

V. Barn Hay Drying

1. Introduction

Hay for barn drying is gathered from the field and placed in storage at much the same moisture content as is brown hay. Unlike brown hay it is kept cool during the storage drying period by forcing air through it.

This method of preservation as evolved by Weaver (1937) eliminates at a moderate cost most of the usual losses occurring in field cured hay. It takes advantage of the rapid removal of moisture occurring in the first part of the field drying cycle without incurring undue weather hazard. Raking, loading, handling and hauling are performed before the crop is dry enough for the leaves to shatter. The system is simple, and requires only a small capital investment; labor requirements and operating costs are low and it eliminates the danger of fire from spontaneous combustion (Finn-Kelcey, 1948).

2. Basic Barn Drier Designs

A fan which will deliver large quantities of air against only low static pressure is used to force air into a duct system. This system may consist of a large main duct vented to laterals or to a raised slatted floor through which the air is distributed under the hay. The floor on which the drier is built must be air tight. By terminating the laterals or slatted floor 4 to 6 feet from the edges of the mow a greater percentage of the air is caused to pass up through the hay. The main duct and openings from it are of such dimensions as to create an air velocity of about 1,600 feet per minute when handling sufficient air to yield, as a rule, not less than 10 nor more than 20 cubic feet per minute per square foot of mow floor area. Under these conditions the air in the system is under a static pressure of approximately ⅜ inch of water. With 10 or 15 feet of long hay over it the static pressure goes up to between ¾ and 1 inch of water (Schaller *et al.*, 1945).

The fan is either powered by an electric motor or internal combustion engine, the former having the advantages of automatic operation with little fire hazard, while the latter is damaged less in case of overloading, its speed is easily varied and it may be useful in contributing waste heat to the drier (Terry, 1947). Only a general description has been given because the engineering features of barn driers vary so much with the numerous sizes and shapes of mows, barn designs, total depths of loading, and types of hay.

3. Operation of Barn Driers

a. Moisture Content. Experience with driers for long hay has established the most desirable moisture level at about 35 per cent (Duffee, 1947). This figure assumes an air flow of 10 to 15 cubic feet per minute per square foot of mow area and a normal 8 to 10 foot loading depth. In actual practice when partially cured hay is threatened with rain it is often placed over the driers at much higher moisture contents. Frudden (1946) points out that hay wetter than 35 per cent can be placed on the drier with no danger from spontaneous combusion, but that if moldy hay is to be avoided the amount of water going on the drier should not exceed that which can be evaporated in 7 days. However, the time required to evaporate a given amount of water with unheated air will depend somewhat on atmospheric conditions which cannot be predicted with certainty. Numerous reports indicate that most drying cycles required at least 10 days and that the majority of cycles permit some molding. This may be in the form of a light, fine mold scattered throughout the mass or it occurs in heavy concentrations in spots receiving inadequate air flow.

Since drying progresses slowly from the bottom of the mow to the top, the upper layers remain moist until drying is complete. This gives an easy means of determining when the mow of hay is dry but at the same time provides conditions favorable to top molding.

A thin layer of moist hay will cool the incoming air to very near its wet bulb temperature (Frudden, 1946). This cooling, together with the small amount of water vapor added, creates relative humidities of 85 to 95 per cent. This suggests that during periods of high humidity occurring at night and in cloudy, rainy weather no drying will take place, but Jennings (unpublished data) showed that when air is blown through hay continuously the rate of drying is only slightly reduced at such times. Likewise, Davis (1947) found that drying goes on in the hay above the thin layer which exhausts all of the air-borne heat available for drying. Dawson and Musgrave (1946), using a laboratory technique, explained these occurrences by demonstrating that over 60 per cent of the heat consumed during a drying cycle is produced by the respiratory activity of microorganisms growing on the moist hay. Hendrix (1947) found that heat produced in the hay accounted for over 60 per cent of the drying of chopped hay even when the air was blown continuously at the high rate of 25 cubic feet per minute per square foot.

b. Density. Density of the hay over the drier influences the rate of drying by its effect on the amount and path of air flow. Increasing the density increases the static pressure and thereby cuts down the fan capacity per unit of power. It also causes greater side losses of air. Where the density of loading is variable air will tend to channel up through the loose zones resulting in poor efficiency (Kalbfleish *et al.*, 1947). This condition is noticeable when the hoist and fork or sling are used to load the drier. Dropping the hay develops a packed zone under the track. This can be eliminated by dropping the hay first to an elevated platform from where it can be scattered over the system in small loose bunches (Finn-Kelcey, 1948).

Hay with more than 40 to 45 per cent moisture will become quite dense when it settles. According to Jennings (unpublished data) settling occurs as fermentation softens the stems. His data also show that better air flow can be maintained through an 8-foot depth of hay which is built up at the rate of 2 feet per day than when all of it is loaded on the drier at one time.

After one 8 or 10-foot layer has been built up and completely dried it is possible to repeat the process with another layer on top of the first (Weaver and Wylie, 1939). As the depth of hay increases the static pressure goes up and increasing losses of air occur by leakage out

the sides of the lower part of the mow. This can be lessened by closing off the laterals and opening vents along the sides of a centrally located main duct (Bruhn, 1947a).

Baled hay has been successfully dried over air duct systems by spacing the bales 2 inches apart on the sides and ends and placing successive layers at right angles to the ones below (Weaver *et al.* 1947). This creates an extreme example of variable density but apparently the chief function of the air is to remove the vapor from between bales while the energy released by fermentation vaporizes the water. Weaver *et al.* (1947) found very little difference in the rate at which heat could be dissipated from bales spaced 2 inches apart and from a single bale through which air was forced. The moisture content of baled hay for barn drying should not be over 35 per cent and air at a rate of 20 cubic feet per minute per square foot should be provided (Shedd and Barger, 1947).

Coarsely chopped hay (cutter set at 2 inches) is well adapted to barn drying. Its density is slightly higher than long hay. Therefore the maximum depth desirable is about one-fifth less than that for long hay (Frudden, 1946). Field chopping from the windrow followed by loading the drier with a blower and distributor pipe provides the best means of mechanizing the handling of moist hay for barn drying (Whisler, 1947).

c. Supplemental Heat. In some northern regions with short growing seasons the hay crop must be harvested rapidly in order to catch it at the optimum stage of maturity. Cold air driers do not dry hay fast enough to keep pace with the developing crop. To correct this deficiency, Bruhn (1947b) and Strait (1944), working in Wisconsin and Minnesota, respectively, have tried out the addition of heat to the system. As mentioned above gasoline engine drives provide waste heat and will raise such air as they can move 3 to 5°C. Where special heating units are attached to cold air systems usually only a 5° to 8°C. temperature rise is attempted. With a greater differential more air must be circulated to avoid condensation and molding on top of the mow. Providing extra forced ventilation of the mow space above the hay will also lessen the amount of condensation. Heated air systems work efficiently early in the drying cycle and then become very inefficient as dry flues develop in loosely packed zones through which much of the heated air escapes (Kalbfleish *et al.*, 1947). Calculations from experimental data reveal that the efficiency of utilization of the heat in the fuel to vaporize water, ranges from 10 to 40 per cent, depending on such factors as the initial moisture content, uniformity of packing, insulation and the type of heat exchanger

(Kalbfleish, *et al.*, 1947; Musgrave and Loosli, unpublished data; Bruhn, 1947a; Davis and Barlow, 1948).

In spite of such low efficiency however, many heated systems have produced dry hay for as little fuel and power expense as cold air systems. The latter are producing hay with 100 to 200 kilowatt-hours per ton of dry hay. The cost of the electricity amounts to about one-half of the overall expense of barn drying.

4. Dry Matter and Nutrient Losses during Barn Curing

The dry matter losses during barn curing arise primarily from fermentation apparently accompanying infestation with a mixed population of microorganisms. The amount of dry matter consumed or destroyed by these organisms will depend primarily on the rate of drying and therefore to some extent on the initial moisture content. Temperature, rate of air flow, relative humidity, and nature of the crop are modifying factors. The average loss as determined to date is about 10 per cent (Blaser and Turk, unpublished data; Musgrave and Loosli, unpublished data; Shepherd *et al.*, 1947, 1949). The hays in which this average loss was observed went onto cold air driers at moisture contents slightly above the currently recommended 35 to 40 per cent range. Where losses were measured on heated air driers the initial moisture was higher but the dry matter loss was only 5 per cent.

The protein of hay suffers a much higher loss in heated air driers than does dry matter. The total protein content was reduced 9 to 10 per cent when heated air was used, and 11 per cent without heat, which was only slightly higher than the dry matter loss. Three New York tests of drying baled hay with air heated 25°C. at moisture contents ranging from 26 to 64 per cent resulted in an average total protein loss of 18.6 per cent while the dry matter loss was only 4.2 per cent. The variations in initial moisture had no measurable effect on the protein losses (Musgrave and Loosli, unpublished data).

Elliott (1947) measured the loss of digestible nutrients during barn drying of bloom stage timothy. Compared to quick drying at 70°C. barn curing caused a loss of 29.2 per cent of the total digestible nutrients. The ether-extract and crude fiber fractions suffered the greatest percentage decreases but they made up only a small fraction of the digestible dry matter as determined by rabbits. Absolute losses in the different nutrient groups contributed equally to the digestible dry matter loss. Dexter *et al.* (1947) comparing the feeding value of hay dried at various depths on a barn drier found that the quality decreased from bottom to top.

As would be expected by the favorable conditions for oxidative and

enzymatic activity during barn drying, carotene undergoes considerable destruction. However, numerous reports indicate that this loss, serious as it is, leaves the hay with satisfactory levels, ranging roughly from 10 to 50 micrograms per gram (Shepherd *et al.*, 1947, 1949). This level is further decreased during subsequent storage at a rate comparable to that following other drying techniques. Additional estimates of the preservation of nutrients by barn driers can be found under VII.

5. Fungicides

Efforts have been made to eliminate the losses occurring in barn cured hay by killing the microorganisms or inhibiting their respiration with gas. Sulfur dioxide, ammonia, carbon dioxide, chlorine and formaldehyde have been tried without much success (Weaver and Wylie, 1939; Curtis, unpublished data). Curtis did succeed in cutting the respirational loss to about one-half with either sulfur dioxide or ammonia but experienced difficulty in barn drying hay so treated, presumably because an important source of heat was lost. Some organic fungicides have been found to be effective in inhibiting respiration but these demand further study to determine their effect in the rumen (Dawson *et al.*, unpublished data). It would seem that a fungicide would be beneficial only in a heated air system where the loss of respirational heat would not seriously prolong the drying cycle.

VI. Artificial Drying

1. Types of Driers

The process of artificial drying, as it is generally considered, differs in several ways from barn curing with supplemental heat. Artificial driers are used to process green forage which remains in the drier just long enough to evaporate the water. Barn driers on the other hand are large batch driers. The continuous flow of forage through artificial driers is accomplished automatically by endless belt, rotary drum, or air blast. Hand transfer is used with tray driers. Thus the forage is agitated, and rapid, uniform drying occurs without the possibility of channeling and loss of hot air through dry zones as is experienced with barn driers. The temperature of the air blast can be much higher in the artificial drier because the forage is discharged as soon as it is dry, with little chance for heat damage.

The efficiency of the utilization of the heat in fuel to evaporate water from forage during artificial drying is about 50 per cent. This can be raised to about 80 per cent by employing additional expensive equipment to reclaim the heat of condensation of water in the outgoing air.

2. Losses

The loss of dry matter during artificial drying usually does not exceed 5 per cent. There is practically no field loss because the standing crop is transferred directly to truck or trailer by a field chopper which cuts, chops, and elevates it. The only place where a loss can occur is between the elevator and the conveyance and then only in the absence of adequate sideboards and screen or cloth hood. As the time between mowing and drying is short very little respiration loss takes place.

At the drier, however, even when care is taken to clean up all of the fine material which collects in and around the machine, a loss of dry matter always occurs (Barr, 1933). Camburn *et al.* (1942, 1944) experienced drier losses ranging from about 1 to 12 per cent. The higher losses apparently occurred when the final product contained moistures above 10 or 11 per cent. This is opposite to most of the work reviewed by Watson (1939), which showed that the greatest dry matter loss occurred when there was overdrying of the forage. He concluded that the dry matter loss should not exceed 5 per cent when the drier is operated carefully.

No loss in the digestibility of the nutrients occurs during artificial drying so long as the dry forage is not exposed to temperatures above 176°C. (Hodgson *et al.*, 1935). Protein digestibility was seriously reduced when an exhaust gas temperature of 205°C. was used.

Artificial dehydration preserves carotene well and is the method used to produce carotene-rich leaf meals. Carotene is lost rapidly in storage and therefore the superior preservation during drying should not receive too much weight in estimating the relative merits of various methods of preservation (Ferguson, 1949).

There is practically no loss of nutrients during storage because there is insufficient moisture in the dried product to permit fermentation. Wright (1941) has shown that rehydration in storage may cause a loss unless precautions are taken to keep the relative humidity of the storage shelter below 65 per cent.

3. Limitations

The capacity of an artificial drier is constant. The growth curves of crops for drying fluctuate enormously. In order to secure economical production from a drier continuous operation is necessary to minimize a very high overhead expense. This problem is accentuated by the fact that only the very highest quality forage justifies the minimum cost of artificial drying. As was pointed out under II grass and legume crops remain in optimum condition for short periods only. Thus for a drier

to operate economically a sequence of crops must be made available. This type of cropping is in itself expensive and difficult to manage. Probably the most practical arrangement, if any exists, is to combine other methods of preservation with a drier of moderate to small capacity. Such a drier can be kept in operation rather steadily by growing crops or mixtures with varying maturity dates, and by using nitrogen and other fertilizers where needed for aftermath cuts. These cuts can be spread out fairly well over the remainder of the season because of the variety of crops, and good distribution of initial times of cutting which can be attained with the various methods of preservation (Moskovitz, 1941).

Partially drying a crop in the field will increase the output of a drier because its capacity in terms of dry produce is determined by the amount of water to be evaporated. This practice, however, has the two serious drawbacks of permitting field curing losses and of making the management of the drier difficult. Crops which contain both dry and wet material, a condition which usually exists following partial field curing, may be either variable in moisture content when coming from the drier or have part of the material damaged by scorching.

VII. Experiments Comparing Silage, Barn-Cured and Field-Cured Hay

With the different methods of harvesting, preserving, and storing forage crops used at the present time, the loss of nutrients is inevitable, but the magnitude and type of losses are governed by the particular method employed. In general, dry matter losses are smallest for dehydrated forages; are intermediate in rank and about the same for barn-cured hay and silage; and greatest for field-cured hay, with most of it occurring during harvesting (Table I). Harvesting losses are lower for barn-cured than field-cured hay because by removing the forage from the field when it has a higher moisture content, fewer leaves are lost by shattering, and weather damage is decreased. The magnitude of dry matter losses in field-cured hay is largely governed by the amount of loss which occurs in the field. Harvesting losses in field-cured hay under unfavorable conditions were over 75 per cent higher than when hay was cured without rain (Shepherd *et al.*, 1947, 1949). The amount of harvesting loss occurring in silage probably increases as the degree of field wilting increases, however, wilting usually improves the quality of the silage and decreases fermentation losses. Little field loss occurs in dehydrating forages if the crop is harvested by a direct cut and loading machine. Hodgson (1949) reported that barn-curing hay with heated

air resulted in about 6 per cent less dry matter loss in the mow than when unheated air was used.

Protein in forage crops is best preserved by ensiling but undergoes appreciable loss during harvesting when field cured (Table II). Protein losses during the actual dehydration process are considerably larger than the dry matter losses. The higher the temperature of the material during drying the larger the loss of protein as well as the decrease in digestibility of the protein. Hodgson (1949) showed little benefit in protein preservation from using heated air as compared with unheated air in the barn curing of hay.

The percentage of carotene retained is usually higher in silage than

TABLE I

Mean Dry Matter Losses in Roughages Resulting from Different Methods of Preservation

Method of Preservation	Dry matter losses reported by: Camburn *et al.* (1938, 1942, 1944) Newlander *et al.* (1938, 1940, 1942)	Turk and Blaser (Unpublished)	Shepherd *et al.* (1947)	Shepherd *et al.* (1949)
	%	%	%	%
Silage				
Harvesting	—	7.7	6.3	2.0
Spoilage	3.3 [a]	5.0 [b]	—	—
Fermentation	8.1	8.9	10.7 [c]	11.8 [c]
Total	11.4	21.6	17.0	13.8
Field Cured				
Harvesting	—	21.3	20.3	36.4
Storage	—	7.4	4.7	3.2
Total	15.0	28.7	25.0	39.6
Barn Cured				
Harvesting	—	9.4	12.0	4.0
Storage	—	8.7	7.0	4.5 [d]
Total	—	18.1	19.0	8.5
Dehydrated				
Harvesting	—	—	—	1.6
Dehydrating process	—	—	—	1.8
Total	9.0	—	—	3.4

[a] Dry matter loss calculated for silo 36 feet high.

[b] Dry matter loss was 5.0 per cent for top spoilage and 9.1 per cent for side spoilage. The amount of spoilage probably would be smaller in a tight-wall silo.

[c] Including spoilage and fermentation losses.

[d] Heated air was used.

in other forms of preservation (Table III). However, the method of silage making apparently is an influential factor, for Camburn *et al.* (1944) reported only 4 per cent preservation of carotene in silage made with no preservative, but 49 per cent retention with silage preserved with mineral acids. Carotene is well preserved by dehydration of forage crops, but field curing and barn curing result in extremely low carotene retention. According to Hodgson *et al.* (1947) the butter fat from cows fed alfalfa silage contained approximately twice as much vitamin A during January, February and March as the butterfat from cows receiving U.S. No. 2 alfalfa hay.

TABLE II

Mean Protein Losses in Roughages Resulting from Different Methods of Preservation

Method of Preservation	Protein losses reported by: Camburn, *et al.* (1938, 1942, 1944) and Newlander *et al.* (1938, 1940, 1942)	Shepherd *et al.* (1947)	Shepherd *et al* (1949)
	%	%	%
Silage			
Harvesting	—	10.7	8.1
Spoilage	—[a]	—	—
Fermentation	6.6	4.3[b]	8.5[b]
Total	—	15.0	16.6
Field Cured			
Harvesting	—	29.7	47.2
Storage	—	1.3	3.4
Total	22.8	31.0	50.6
Barn Cured			
Harvesting	—	16.0	7.8
Storage	—	9.0	9.1[c]
Total	—	25.0	16.9
Dehydrated			
Harvesting	—	—	6.2
Dehydrating process	—	—	10.2
Total	22.1	—	16.4

[a] Protein losses due to spoilage were high in their small experimental silos, but of the same magnitude as the dry matter losses. The loss of dry matter was 3.3 per cent for a silo 36 feet high.

[b] Includes spoilage and fermentation losses.

[c] Heated air was used.

The pounds of total digestible nutrients recovered for each 100 lbs. dry matter ensiled or hayed reported by Newlander *et al.* (1940) and Camburn *et al.* (1942, 1944) are: 42.2-45.8 lbs. for silage, 51.4-60.2 lbs. for dehydrated hay, and 42.2-52.0 lbs. for field cured hay. On the acre basis, Shepherd *et al.* (1947) found that in comparison with field-cured hay, milk production was higher by 12.5 per cent for silage, 16.0 per cent for barn-cured hay with heated air, and 8.1 per cent for barn-cured hay with unheated air. They also reported a 20 per cent reduction in milk production if the hay was damaged by rain while being field cured. In another study Shepherd *et al.* (1949) found that in comparison with poor quality field-cured hay, milk production was higher by 40.3 per cent for silage, 48.2 per cent for barn-cured hay with heated air, and 49.6 per cent for dehydrated hay.

In comparing the feeding values, Turk and Blaser (unpublished) did not observe any significant difference for unit weight of dry matter preserved as silage, barn-cured hay or field-cured hay. Shepherd *et al.* (1949) and Kane *et al.* (1949) reported that field cured hay was slightly lower in feeding value than silage, barn-cured and dehydrated forages. Thus, in comparing the four methods of preservation, the loss of dry matter from the entire crop accounted for the major losses in feeding value.

TABLE III

Carotene Retention in Roughages Resulting from Different Methods of Preservation

Method of Preservation	Carotene preservation reported by: Camburn *et al.* (1942)	Camburn *et al.* (1944)	Shepherd *et al.* (1947); Hodgson, (1949)	Shepherd *et al.* (1949)
	%	%	%	%
Silage	62	4-49	34	3.8
Field Cured	15	9	3	0.6
Barn Cured	—	—	12	5.3
Dehydrated	53	33	—	22.1

VIII. Conclusions

The feeding value of a forage crop per acre is at a maximum for only a very short time during its development. Therefore, in order to retain the full value of a crop, a system of handling, preservation and storage must be employed which removes the crop from the field rapidly, and at the same time preserves it so that minimal loss will occur. These operations often have to be done when weather conditions are not ideal for

the preservation of the forage as dry roughages. Delayed cutting will result not only in an inferior quality of roughage, but it also may result in the elimination of certain legumes such as Ladino white clover, *Trifolium repens* L., from legume-grass mixtures. If the legume is eliminated from the mixture the yield and quality of the succeeding crops usually are reduced. Thus the early harvest and storage of forages, although adverse weather conditions may persist, are necessary for preserving the quality of the existing crop as well as ensuring that of succeeding ones.

Artificial drying results in the best preservation with least storage loss, but the low capacity of economically sized units necessitates the use of other methods when large volumes of forage need to be handled within a short time. Ensilage is the best system for this purpose because of its high efficiency for timely handling, though it causes nearly a 20 per cent deterioration of the feed value in the product. Rapid crop removal may also be accomplished when hay is field cured, but large field and storage losses result especially with immature, succulent crops. Barn curing is intermediate with respect to both losses and handling capacity.

Although silage-making appears to offer the best method of preserving forages during inclement weather, many unsolved problems contribute to the uncertainty of the process and hinder its adoption by farmers. In the future, however, probably a higher percentage of roughage grown in humid regions will be stored as silage because of the progress being made by research in solving these problems, the limitations of artificial heat for drying roughage, and the difficulty of speeding the field curing process to a point where it can be accomplished during short periods of fair weather.

Regardless of the difficulties experienced in producing high quality field-cured hay in humid regions, hay probably will continue to be produced. Some hay is a valuable and almost essential component of the roughage ration of high producing animals, even though large quantities of silage are fed. Hay is also a more concentrated form of roughage in terms of digestible nutrients per pound of roughage than is silage. Unlike silage, it can be transported to areas where stored roughage is scarce and can be handled more easily when mechanical equipment is lacking.

It is essential that improved preservation practices prevent the dilution of the energy content of roughages through the loss of the more digestible portions of the crop as well as the overall loss of dry matter. More emphasis should be placed on the concentration of roughage nutrients than on total yield of nutrients. Roughage quality should be evaluated in terms of the amount of supplemental grain feeding required

when the energy content of the roughage is reduced by faulty preservation methods or by later harvesting with the purpose of obtaining higher yields. The preservation and storage of high quality roughage is the most serious problem in the field of forage crop improvement and management.

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The Reclamation of Coal Mine Spoils *

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I. Introduction

More than a fifth of all the coal mined in the United States in recent years has been produced by the open cut method. (Fig. 1). This "strip mining" of coal started about the time of the Civil War but remained insignificant until the beginning of the twentieth century. In 1914 only 0.3 per cent of the total coal production in the United States was mined by stripping. By 1948 this proportion had climbed to 23.3 per cent (Young *et al.*, 1949). Less labor is needed to produce a ton of coal by stripping than by underground mining. Fewer accidents occur in stripping (Adams and Geyer, 1944; Sinks, 1946). As a rule strip mining recovers over

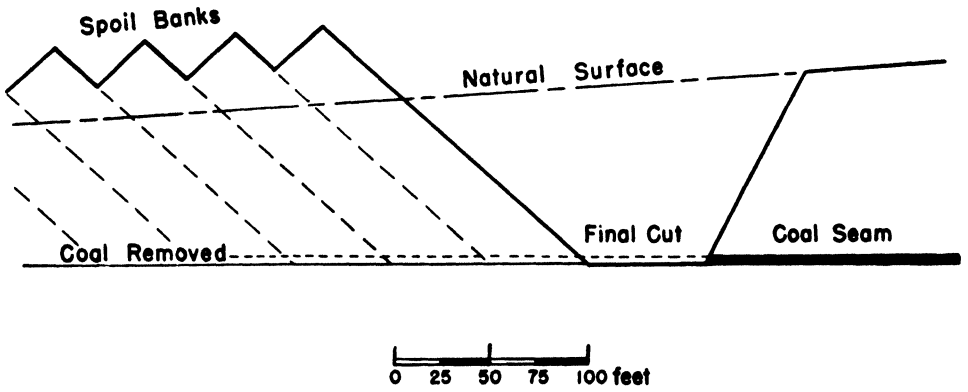


Fig. 1. Schematic cross section of abandoned strip coal mine.

95 per cent of the coal in place while underground mining recovers only 50-60 per cent, largely because of the necessity of leaving pillars for roof support. The equipment needed to remove overburden economically to greater depths has only become available during the last 30 years.

Strip mining leaves the overburden in steep and jagged ridges that make the landscape appear desolate and unproductive (Figs. 2 and 3). About a quarter million acres have been stripped for coal so far (January, 1950) in the United States and at least half again this area has been covered with overburden or otherwise made unfit for farming purposes. The end of strip mining for coal is not in sight. No accurate estimates of the potential coal field acreage exist but there is little doubt that the half way mark has not yet been reached. The states in which strip mining is of importance are Indiana, Illinois, Ohio, West Virginia, Pennsylvania, Missouri, Kansas, Oklahoma, Kentucky, Alabama, Arkansas and Iowa.

This article is written in an attempt to clarify the physical conditions

of coal mine spoil banks as they affect plant growth and consequently land use and to discuss the reclamation of these areas.



Fig. 2. Coal stripping operations. (Courtesy Indiana Coal Producers Association.)

II. The Condition of the Spoil Banks

To plan reclamation work of the coal mine strippings a detailed knowledge of their conditions is necessary. In the following paragraphs topography, erosion, soil material, water, vegetation and wild life will be considered as they are found on worked out strip mines.

1. Topography and Erosion

Topographically, coal mine strippings consist of a series of parallel ridges and troughs and a deep, long cut with one very steep slope on one side and a somewhat flatter one on the other. The origin of these features is illustrated in Fig. 1. The ratio between these two components

depends largely on the original slope of the terrain. In steep country only one or two cuts of coal are possible because of the increasing thickness of the overburden. The final cut takes up as much space as the series of ridges but generally the area covered by the troughs and ridges greatly predominates.

Where the overburden has been removed with a power shovel the ridges are of approximately the same height for some distance; where a drag-line is used they are composed of a series of hillocks. As these machines are operated to deposit the overburden as far from the exposed coal

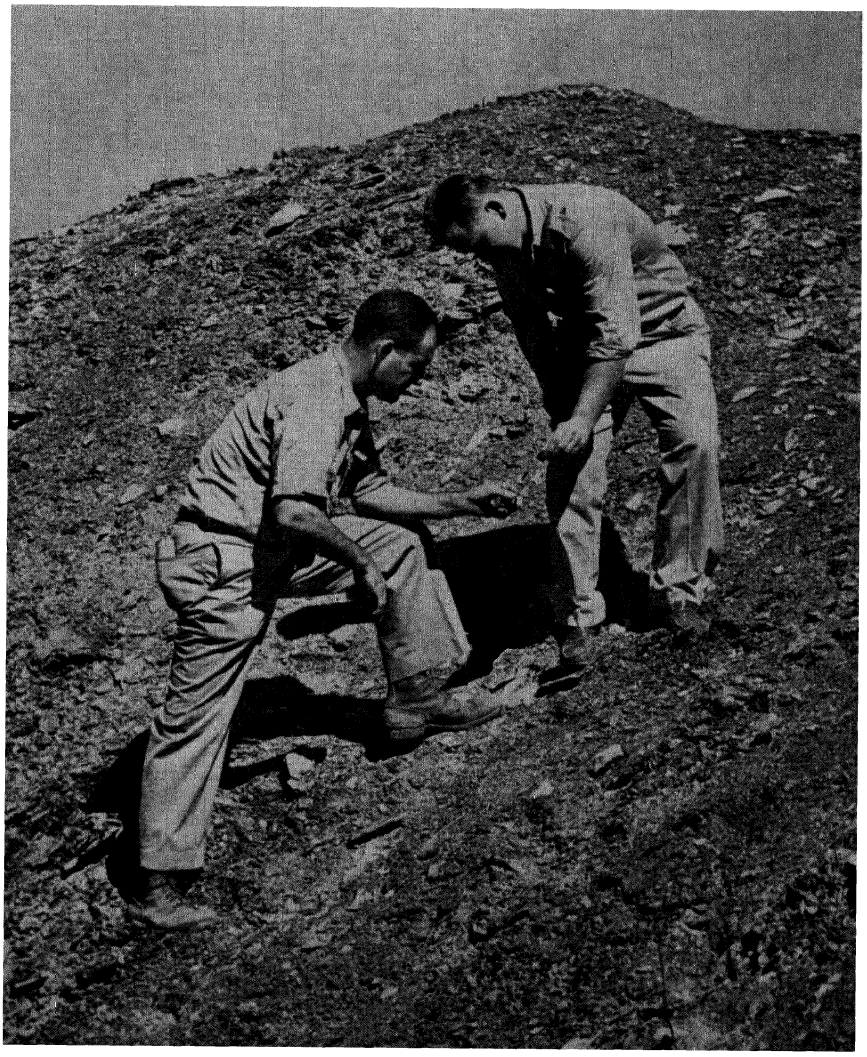


Fig. 3. Fresh coal mine spoils. (Courtesy Indiana Coal Producers Association.)

as possible, no uniform spreading of the material over the area is attained. Each bucket load is dropped on or near the previous one and the earth and stones slide down on both sides forming a ridge. The natural angle of repose of this material is from 80 to 90 per cent. The more stony the overburden the steeper is the angle of repose. During the first year or two considerable settling occurs. Since in the center of the ridge the depth of material and therefore the total depth of settling is greater than in the troughs, the slopes of the older spoils may be reduced to 60 and 70 per cent. Very shaley spoils may stay as steep as 80 per cent after as much as 25 years.

Erosion is intense on fresh spoils, as long as they are not covered by a mantle of vegetation. No water stable aggregates exist in this material which is practically devoid of organic matter. Only the many rock and shale fragments protect the banks from erosion. In spite of the fact that the ridges are too short for runoff to concentrate these are frequently riddled by gullies. Since the steepness of the slopes permits any soil material that is detached from the ground to be transported downhill by splash or run-off the sandy spoils erode faster than the banks which contain enough clay to give some cohesiveness. Under the less sloping conditions of an ordinary field, sand is usually less easily eroded than clay loam. Frequent observations and actual measurements (Stiver, 1949) show that erosion rounds off the tops of the ridges and takes away sheets of soil material along the sides but does not actually reduce the slopes of the ridges. The eroded material accumulates in the troughs and creates a nearly flat colluvium composed of sand, silt and clay. In many cases erosion in the troughs is sufficiently active to prevent such an accumulation, and the eroded material is carried on down into the larger depressions within the spoil area. In flat or slightly rolling country it is an exception for coarse eroded material to be washed more than 50 feet beyond the slopes of the spoil banks on to unmined land. Some of the clay and the finer silt is sometimes carried in the streams issuing from a mined area but no damage resulting from this has been reported or observed. In hilly land erosional debris sometimes covers creek bottoms, overloads small streams and increases flood hazards (Tyner and Smith, 1945).

The distance from ridge to ridge varies with the stripping method even within the same operational area. It ranges from 35 to 70 feet with an average near 50 feet. The differences in elevation between the tops and the troughs depend on the distances from ridge to ridge, on the steepness of the slopes and on the amount of previous smoothing of the ridges and filling of the troughs. Differences of from 5 to 30 feet have been measured. Most of them are between 10 to 20 feet.

The final cut from which coal is taken remains open, since no more overburden is moved. This pit is about 50 feet wide at the bottom. The side toward the spoil banks has the normal angle of repose of unconsolidated material. The other side, facing the unmined land, is much steeper. It is called the "high wall." Usually enough sloughs off from this wall so that the lower 5 or 10 feet are covered with rock and earth debris of about 80 per cent slope. The area from which the coal was removed and which has not been covered again is frequently nearly horizontal since most coal deposits which are strip mined do not have much of a tilt. The depth of the final cut depends entirely on the depth of overburden removed. This varies from a few feet to as much as 90 and even 100 feet.

2. Soil Material

The overburden which has been deposited represents potential soil material. Definitions for soil vary, but here it is considered as the unconsolidated covering of the earth capable of supporting plant growth. On this basis the bulk of the material that makes up the spoils is soil. Since it is rock material that is just beginning the normal processes of soil formation, it may be thought of as soil at zero time. Some of the spoil material that is initially so acid that plants cannot exist on it may be called soil material, or potential soil, since it too will eventually support vegetation.

a. Physical Conditions. The outstanding characteristic of the spoil material is its rockiness. It is difficult to make quantitative statements on the proportion of rocks and "fine earth" (material that can pass a 2 mm. sieve) that are of any general application. Some spoils are covered with an abundance of large and small rocks, while elsewhere only a few small stones indicate that the site is not just another field. The amount of rocks at the surface depends on the geologic strata overlying the coal, on the excavation methods employed and on the time elapsed since the mining operations. All coal is deposited between layers of shale, sandstone, or sometimes limestone. Occasionally soil has been formed directly from these rocks. In other cases much of these sedimentary rocks has been eroded and replaced by glacial drift alluvium or loess. The uncovering of the coal is done in the most economical manner. Occasionally this calls for depositing the large rocks at the bottom of the growing pile of spoil material in order to prevent slipping of the spoil upon the unexcavated coal. In other mines the earthy material of the top 6 to 12 feet of overburden is pushed into the pit after the coal is taken out and the rocks of the lower strata are then deposited on top.

The fine earth material on the spoil is predominantly loam, with

smaller areas consisting of clay or of sand (Limstrom, 1948; Stiver, 1949). An interesting feature is the complete absence of any soil horizons in the fresh spoil banks. The structure of spoil material is generally loose initially but as time goes on it settles to a rather compact mass. The high concentration of electrolytes, especially calcium sulfate, in the spoil tends to keep the clay in a flocculated condition. The dearth of organic matter prevents the formation of truly water-stable aggregates.

Of particular importance are the moisture conditions of the spoils, since they determine to a large extent the plant growth potential. The rather loose structure and the resulting large pores existing in many spoils allow water to accumulate in the soil without being pulled down by the combined effects of capillarity and gravity that regulate the moisture content of field soils. In spoils the capillarity is broken in many points of the soil body and the result is a local accumulation of nearly tension-free water. On hot, sunny days, a week after rain, it is not difficult to find water drops at 5 or 6 inches depth in shaley spoils. All observations indicate that spoils are well supplied with soil moisture. While surface runoff is large on fresh spoil, little water is lost by transpiration, and after vegetation is well established the infiltration capacity increases. The surface crust of soil on bare, exposed spoil banks dries out considerably during the summer months. The growth of such water tolerant plant species as black willow, *Salix nigra,* Marsh, river birch, *Betula nigra,* L., and large smart weeds, *Polygonum sp.,* on the crests of many of the ridges is clear evidence of the abundance of water. Stagnant water occurs only in some of the depressions of the troughs.

Temperature conditions in spoils are similar to those in field soils. This is especially true after vegetation has been established. On bare spoils summer temperatures on the sides facing the sun exceed by 5 to 8°C. corresponding field soil temperatures (Stiver, 1949). This causes difficulties in the establishment of young seedling plants in such exposed positions.

b. Chemical Conditions. Of the chemical soil conditions reaction is the most important on the spoil banks. pH values of 2.5 and 8.0 can sometimes be found only inches apart. Roof coal and other strata of the carboniferous age contain pyrites and other forms of iron sulfide. Upon oxidation in the presence of water the sulfide forms sulfuric acid:

$$2\ FeS_2 + 7\ O_2 + 2\ H_2O \rightarrow 2\ FeSO_4 + 2\ H_2SO_4.$$

The concentration of acid may be so high that water vapor from the atmosphere is attracted hygroscopically and during dry periods the acid appears as wet spots on the spoils. The many limestone fragments and

the calcareous till account for the high pH areas. Some of the shales are approximately neutral but usually they are slightly acid. Much of the sandstone is strongly acid. The original surface soil is sometimes also quite acid, depending upon parent material and the period of weathering. While such great variations of reaction occur on most spoils, it is generally possible, nevertheless, to classify them according to the dominant pH.

The amount of total nitrogen in the fresh spoils is even lower than that of poorer field soils (Stiver, 1949) and many observations show clearly that nitrogen is the prime limiting factor of plant growth on most spoils.

By chemical quick tests available phosphate has frequently been shown to be higher in spoil material than in the neighboring undisturbed field soil. Detailed greenhouse experiments by Stiver (1949), however, clearly pointed to a deficiency in phosphate in 3 entirely different materials from spoil banks.

Available potash has practically always been found in adequate amounts similar to those in field soils. Calcium is usually plentiful even in spoils of low pH because of the many calcium bearing rocks present. Sulfur has always been abundant, whenever spoils have been tested for this element. Studies for other nutrients have not been reported. The ready seed set of alfalfa, lespedeza and birdsfoot trefoil on calcareous spoils might serve as an indication that no serious plant nutrient deficiencies exist, except nitrogen.

The studies of the plant nutrient status of spoils have been few, but application of our knowledge of soil fertility and plant nutrition point to the fact that continuous cropping without fertilization will be as impossible on spoils as it is on field soils. It is probable though that the fresh material on the spoils will contain some of the nutrients in relative abundance that have been depleted in many ordinary soils. At any rate it is not *a priori* obvious, as some people think, that stripping the ground for coal decreases soil fertility. In many cases it does, but sometimes it is advantageous. It has been observed that cattle may prefer to graze on spoils in preference to a neglected old established pasture nearby.

The question is open whether toxic materials exist in spoil banks in addition to the acid formed from the sulfide and the ions brought into solution by this acid. Occasionally spoil banks remain bare of any vegetation for a number of years in spite of a nearly neutral reaction. Perhaps this points to some toxic condition since seed sources for some of the pioneer vegetation are always available. If such a condition exists, it is not of long duration and therefore of no concern.

c. Soil Profile Development. At the time the overburden is piled into mounds and ridges, no differentiation into horizons exists. Within less than a year soil formation at the surface becomes apparent. The first evidence is the breaking down of rocks. The sudden change from the depths of the earth, where the rocks have been in equilibrium with the environment, to the surface, where they are exposed to the extremes of the atmosphere causes rapid disintegration. Shales, sandstones and some types of limestones break down to soil size within a few years. Many

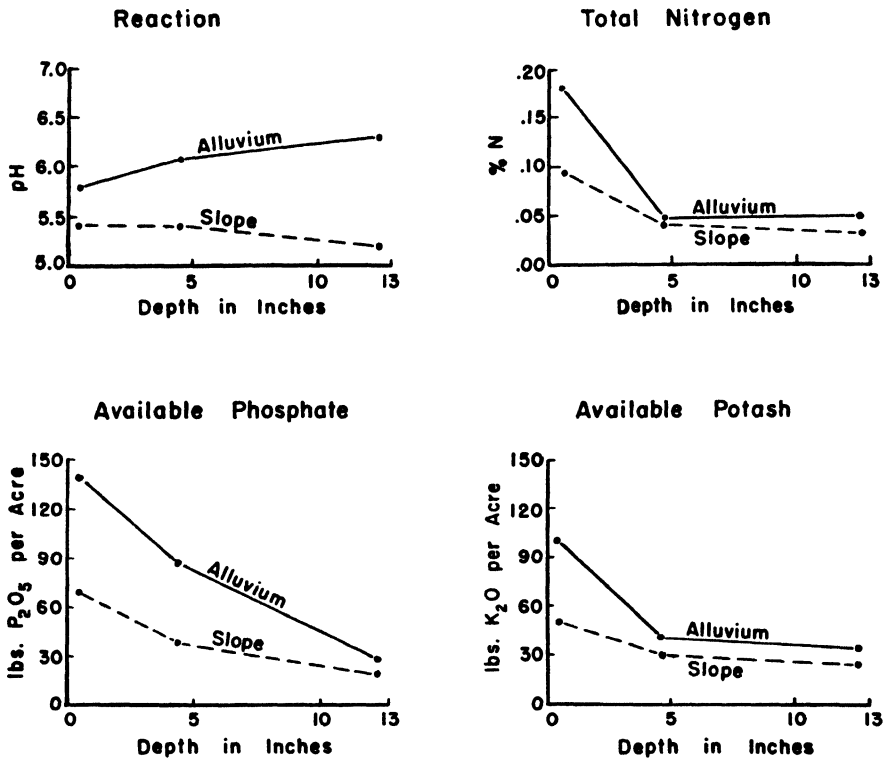


Fig. 4. Soil characteristics of spoil bank material as affected by slope.

limestones and igneous boulders are more resistant, but none have been encountered lying on the spoil banks that have not suffered considerable exfoliation during 2 or 3 years' exposure. Very few large rocks exist on surfaces of spoils that are over 20 years old, indicating that they have disintegrated in the interim. With the growth and decay of the pioneer plants organic matter is added to the soil. The visible change of soil color on the slopes of spoils has not been found to exceed a depth of one inch in a quarter of a century. The mechanical breakdown of the rock extends considerably farther. But it is difficult to ascertain the

exact depth of this development, since the boundary is imperceptible. While only this very shallow change of soil color, or development of an A horizon, occurs on the slopes, soil of desirable texture, color and productivity accumulates in the troughs. These widen out as a result of continuous additions of erosional debris and increase in fertility as the nutrients wash down on them from the slopes.

Figure 4 shows the different types of soil profile developed on the slope and in the troughs of a spoil area that had been planted to red pines 20 years previously. The conclusion is inescapable that a deepening of the soil profile and an increase in soil fertility on the spoil banks will be slow, if it occurs at all, as long as the slope remains around 60 per cent. Experience with naturally steep soils substantiates this assumption.

One of the most important problems of soil development on the spoils is the changing of the sulfuric acid spots into "soil." Since sulfuric acid is water soluble it will be leached out and washed off freely by rain water. The oxidation of sulfide is a slow process. Fortunately, fair amounts of calcareous materials occur in most spoils and help to neutralize the sulfuric acid and also serve as starting points for vegetation. Tyner and Smith (1945) have shown that the rate of sulfur removal on spoil banks is quite rapid.

3. Water

Most of the strip coal mines of the United States are in areas of generous rainfall. In many mines water must be pumped out of the pit to permit mining. After operations end, water accumulates in the pit unless the slope of the coal has been in the direction of the general slope of the land. Within the ridge and trough area the lower depressions are also frequently filled with water. As a matter of fact strip mining adds a great number of ponds and lakes to regions that have had little open water previously.

To evaluate this newly created resource the following items require consideration: chemical quality of the water, permanence of the pond or stream, area and depth of the water.

Wherever pyrite is exposed to air and moisture it oxidizes and forms sulfuric acid and ferrous sulfate. Ponds that receive drainage from such material are strongly acid (up to 0.1*N* acid) and high in iron unless the inflow of the acid is relatively small and is neutralized by a corresponding influx of lime. Such very acid waters permit no biotic development and corrode machinery if an attempt is made to utilize them industrially.

If most of the iron sulfide is below the water level, oxidation is

prevented and the water is nearly neutral to slightly alkaline as a result of the abundance of calcareous material frequently found. Such water can be used as fish grounds, water supply for livestock, swimming, and for industrial purposes. (Fig. 5).

Practically all mine waters are high in sulfate, but contain little or no chloride. They contain much iron and aluminum if they are more acid than pH 3.5 and much calcium and some magnesium if they are above pH 4.5. The smaller ponds have no economic value, as they readily dry up during the late summer.

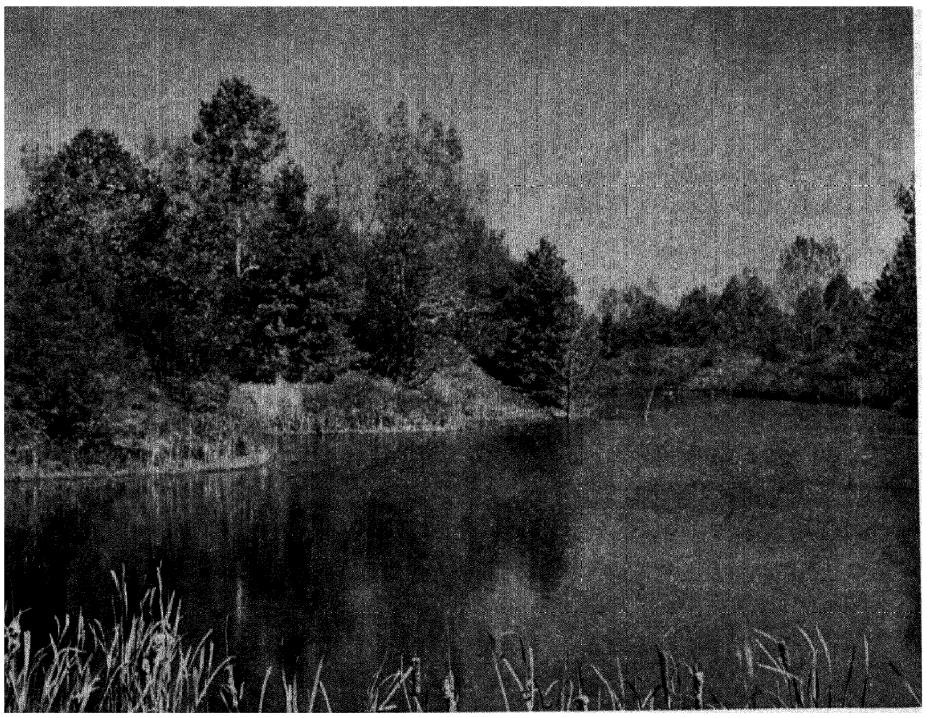


Fig. 5. Pond in final cut of strip mine. (Courtesy Indiana Coal Producers Association.)

The final cuts of the mines present the best possibilities for deep, reliable and sound water. This is of course only the case where all surrounding land is higher so that the water will cover the pyritic material. It has sometimes been observed that a mine pit first fills up with acid, iron bearing water, but eventually, as the water covers the pyrites and as lime washes into the pond, the water is neutralized so that it becomes a good habitat for vegetation and fish.

While much of the pond water in the strip mine areas is nearly neu-

tral, most of the running water is acid. The reason for this is that the presence of a stream presupposes entry of air into the strata above the sources of the stream and, therefore, washing of the products of the oxidation of pyrites into the creeks is a probability. The degree of acidity depends on the relative amounts of pyrite, lime, and water. Generally the farther away from the mine the higher is the pH of the creek water because of the neutralization by calcareous material and by the calcium bicarbonate present in most natural waters.

By comparison with drift mines the production of acid stream water by strip mines is of minor importance. In areas of extensive drift mining, even larger rivers have reactions near pH 3.0.

4. Volunteer Vegetation

Very soon after land has been stripped for coal, vegetation of some sort appears on the spoil banks. If the soil reaction is very acid, and sometimes for other reasons, this takes a number of years, but usually a few individual plants make their appearance in the first year. Depending on the potential fertility of the spoil banks and the source of seed the rate of establishment of a plant cover will vary. The multitude of volunteer species that grow on spoil banks is truly amazing. McDougall (1925), Croxton (1928), Maloney (1941), Riley (1947) and Stiver (1949) have enumerated such species. They are predominantly those with airborne seeds, or those that have been introduced into the spoils in those portions of the original top soil that were deposited at the surface of the spoils. Of the trees, cottonwood, *Populus deltoides,* Bartr., sycamore, *Platanus occidentalis*, L., and black willow, *Salix nigra,* L. are the most common invaders. All three of these species normally grow in a rather humid environment. Their occurrence and vigorous growth on the spoils bespeaks the moist conditions found on recent strippings. Wherever calcareous material occurs sweet clover, *Melilotus* spp., invades the banks. After a few plants of it are established, it spreads quickly over large areas. Without artificial inoculation it seems never to suffer from nitrogen deficiency. It is clearly one of the best site preparers for grasses on the spoils because it provides nitrogen and surface mulch.

Among the other early pioneers on the spoils are the wild aster, *Aster,* spp., the prickly lettuce, *Lactuca scariola,* and the blackberry, *Rubus alleghenicnsis,* Porter. The rate of establishment of vegetation and of the complete covering of the spoils is a rather clear and simple key to their potential ability in supporting crop plants. Practical foresters use the appearance of the first "fuzz" on the banks as an indication that the spoils may safely be planted to trees.

The troughs are usually more quickly and more densely vegetated

than the slopes and the ridges. This difference is particularly obvious on the more acid spoils where generally a marked differential in pH exists in favor of the troughs. Here the abundant water has removed the free acid while lime fragments have been deposited and neutralize the acid as it is formed.

The occurrence of some weeds in very acid conditions is one of the ecologic puzzles of the spoil banks. Cattails, *Typha latifolia,* L. have been found to thrive in mine water of pH 2.5 (Stiver, 1949) while vigorous plants of ragweed, *Ambrosia elatior,* L. grow on spoil material below pH 3.0.

5. Plantings

Reclamation of coal mine spoils in the United States by planting orchard and forest trees was started about 1918. The first plantings were rather sporadic and many of them were done only along the outside of spoils especially near highways. Gradually an increasing percentage of the spoils was planted to forest trees, with pines and black locust predominating. The adapted species of pine have grown well on many of the spoils (Fig. 6). After a promising start, black locust, where planted alone, has, in many cases, succumbed to the ravages of the locust borer. Nevertheless foresters believe that it has been valuable as a site conditioner for other trees. Tree plantations on coal mine spoils have been discussed by many authors (Chapman, 1944, 1947, 1948, 1949; Mather



Fig. 6. Pine plantation on coal mine spoils. (Courtesy Indiana Coal Producers Association.)

and McIntosh, 1947; Den Uyl, 1946, 1947; Limstrom, 1948; Sawyer, 1946a, 1946b, 1949; Schavilje, 1941; Stiver, 1949; Toenges, 1939; Winchell, 1948). Beside many other timber species, fruit trees and shrubs have been planted with varying success. On coal spoils in Clay County, Indiana, there is an abandoned pear orchard that was planted in 1918 and still produces fruit. At that time strip mining was shallow, much top soil was mixed into the surface of the banks and the height differences between troughs and ridges are only 4 to 5 feet. Productive orchards and vineyards have been observed on flattened spoils in Illinois. Many of the calcareous spoils have been seeded to pasture. The establishment of forage plants on spoils is described by Brown (1949), Croxton (1928), Grandt (1949), Holmes (1944), Sinks (1946), Stiver (1949), Tyner and Smith (1945), and Tyner, Smith and Galpin (1948). The seed set of legumes on calcareous spoils is frequently better than on undisturbed field soils. Where the areas are large enough and where non-mined land belongs to the same holding, reasonable profits have been obtained. The abundance of minerals in the spoils and the many ponds present unquestionably contribute to such encouraging results.

6. Wildlife and Fish

Where spoil banks are left to revegetate themselves or where forest trees have been planted, not much feed for wildlife exists. Nevertheless, the good cover and the many ponds seem to encourage some of the species, especially near the borders of the mined areas. Increased numbers of rabbits and of non-game birds have been observed in the spoils (Riley, 1947) but also foxes and raccoons seem to thrive. In certain regions the spoils are regularly visited by deer which evidently appreciate their inaccessibility and the shelter provided by the tree plantations.

Most of the larger bodies of nonacid water are stocked with fish. The land owners or neighboring fishermen have stocked some of the ponds in anticipation of some good sport but in many cases birds must have been responsible for the introduction of the spawn.

III. Methods of Testing Spoil Bank Materials

In view of the tremendous variability of soil material in the spoils quick qualitative methods of testing are of more immediate need than quantitative and time-consuming analyses. On most spoils soil conditions change so much from spot to spot that it becomes difficult to take a representative sample.

The three outstanding tests are for carbonate, for free acid and for sulfide.

Dilute hydrochloric acid (HCl, 1:10) dropped on the ground reveals the presence of carbonate (usually calcium carbonate) by gas bubble formation.

Potassium thiosulphate (10 per cent solution of KCNS) combines with ferric iron to form a complex ion of deep red color. This reaction occurs only in a very acid medium because ferric iron is practically insoluble at reactions above pH 3. The appearance of red color indicates the presence of hydrogen ion concentrations considerably in excess of those produced by hydrogen clay and therefore too acid for plant growth. This test is simple in the extreme as it only consists in dropping the solution on the ground and in watching for the color. The intensity of the color is somewhat indicative of the concentration of the acid.

Sodium azide (3 g. sodium azide dissolved in 100 ml. 0.1 N iodine solution) is used to detect the presence of sulfides. This test is unnecessary after the material has been lying on the surface of the bank for several months. By that time enough of the sulfur has oxidized, so that its presence, in the form of acid, can be detected by the potassium thiocyanate test. But the azide test is invaluable to detect acid forming substances in the "highwall" and in fresh spoils. For this test a piece of the size of a pinhead is placed in a small glass vial with a conic bottom, a drop or two of the azide solution is added. Sulfide acts as the catalyst in the following reaction:

$$2NaN_3 + I_2 > 2NaI + 3N_2(gas).$$

Therefore the formation of gas bubbles indicates the presence of sulfide.

Indicators of the hydrogen ion concentration within the range from pH 3 to pH 7 are next in importance. They can be used as solutions or in impregnated paper. Any of the customary organic dye indicators can be used.

Other soil tests are also applicable to spoil material, for instance those for total nitrogen, available phosphate and potash and lime requirement. A more reliable picture of the plant nutrient condition can be received by plant tissue tests (Thornton *et al.*, 1939).

The physical conditions within spoils also have a great influence on their land use capability. The two most important ones for this purpose are the texture and the rate of decomposition of the rocks.

The content of the medium-sized and smaller rocks can be determined by screening through a half inch hardware cloth screen. The texture of the finer material can be determined by the use of screens and the pipette or hydrometer method of mechanical analysis.

The rate of decomposition of rocks can be estimated during the first inspection of the spoil bank by observing the appearance of the medium

sized and larger rocks. Where doubt exists it is best to photograph a number of rocks and to mark the locations and to return one or several years later and to compare the condition of the rocks.

IV. Land Use Capabilities

To the casual observer of a fresh spoil with its ragged mounds, its stony surface and its forbidding colors any land use seems out of the question. But a closer scrutiny of its topography, its soil and its biotic characteristics makes it clear that such land can well be made to serve mankind. In the preceding pages an effort has been made to give a picture of these conditions in order to provide the background for the decision as to which land use may be appropriate in each individual case.

The forms of potential land use of coal mine spoils include any use possible under the given climatic and economic conditions, *i.e.*, various forms of agriculture and horticulture, pasture, forest, fish production, and recreation. The most adapted land use for a given spoil will depend on the present slope conditions and our willingness to alter them, on the stoniness, texture and reaction of the spoil, on the distribution and nature of the surface water, and the total area involved. In order to classify spoils according to their land use capabilities, we have first to decide whether to smooth down the topography to a certain desired maximum slope or to utilize the banks as they are left after the mining operation.

1. Land Use Capability; Classification of Ungraded Spoils

If it is assumed that no mechanical smoothing out of the ridges will be done most forms of agriculture and horticulture are excluded and forestry and range type pasturing remain. Obviously, fish raising and recreation are always possible if there is sufficient good water available and after vegetation has covered the spoils.

It is rather simple to decide whether a certain spoil area would be better adapted to forestry or pasture. Since pasture is normally the higher form of use, a spoil capable of supporting forage plants over its entire surface and readily accessible to livestock should be used for pasture. It must be remembered that the steepness of ungraded spoils precludes liming, fertilizing, and mowing. This means in practice that the majority of the spoil should contain enough calcareous material to support legumes. Legumes are necessary for a pasture on an unleveled spoil because they are the only major source of nitrogen. On the other hand, an excess of large, slowly disintegrating rocks makes a spoil unsuited for pasture. This means that spoils generously inter-

mixed with glacial, alluvial or loessial material or with soft limestones are the only ones valuable for pasture. Even then the type of livestock is restricted to beef cattle and sheep. The steep topography and the roughness of the forage preclude the profitable use of dairy cattle. Other features in addition to topography and soil material determine the value of a given spoil for pasture. Large size of the potential pasture area, the possibility of its integration with an existing farming enterprise and the presence of well distributed ponds enhance its usefulness.

All other spoils, having an average reaction below pH 6.5, or having an excess of rocks, are potential forest land. Wherever sufficient free acid exists to depress the reaction below pH 3.5 no revegetation should be attempted until sufficient oxidation of the pyritic materials and leaching of the acid has occurred. Fortunately only a very minor percentage belongs to this latter group.

2. Land Use Capability; Classification of Graded Spoils

This classification presupposes the grading of excessively steep slopes where considered necessary, but no resurfacing of the mined area with the

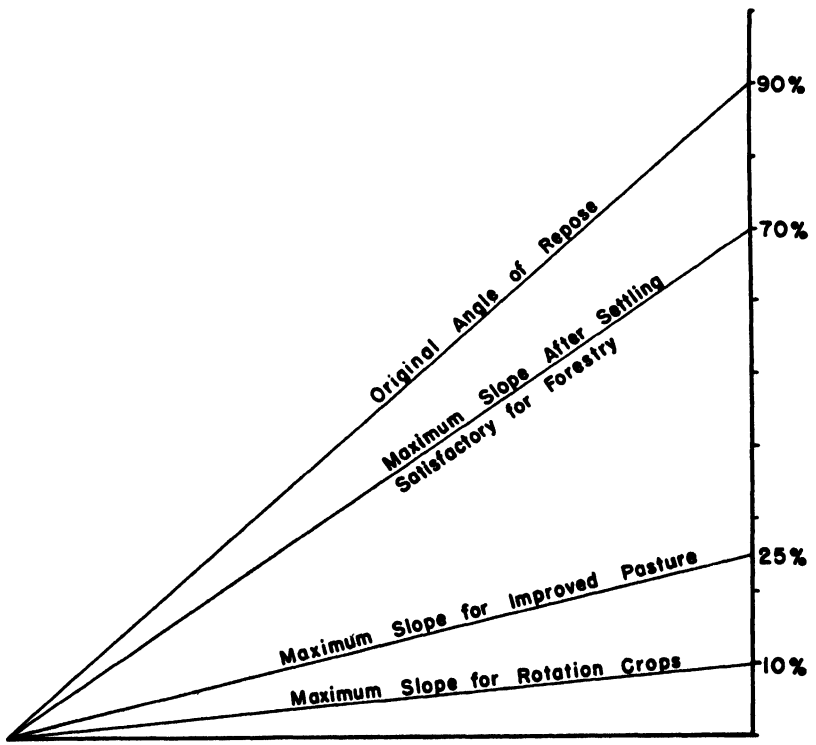


Fig. 7. Maximum slopes for various land uses on spoil banks.

original top soil. Where this latter elaborate improvement is undertaken, as for instance in England (Brown, 1949), the land is fit for practically any use after an initial 5- to 10-year period in a well-fertilized grass and legume mixture to reestablish soil structure.

Grading of spoils to smoother slopes or to nearly level topography permits the use of any implement required for the improvement of the soil, and for planting, treating, and harvesting any crop (Fig. 7).

a. Rotation Crops and Orchards. Spoils containing few stones and no free acid can be developed into rotation and orchard land by grading them to slopes of less than 10 per cent. They will require intensive improvement during the first years to raise the pH if necessary, to supply the necessary plant nutrients and to develop a satisfactory structure. Only a small fraction of the spoil observed can be included in this group. The majority has too high a rock content. Of course, if time is allowed for rock disintegration to occur after leveling, much more land could be included in this group.

b. Improved Pastures. The soil material requirements for potential pasture land are much lower if the spoils are graded than if they are left in steep ridges. The grading for pasture land need only reduce the slopes to an extent that fertilization, cultivation and mowing are possible by use of power driven implements. This means grading to a maximum slope of 25 per cent. With this prerequisite the range of potential pasture land on spoils becomes quite large. It includes all sites not excessively rocky or sandy. If a quick return from the pasture is desired this excludes areas of excessive free acid, since these will not permit plant growth for some time. It is very important to recognize that the lower pH range of potential pasture land is around 6.5 if the spoils are not smoothed out, but that it can go as low as pH 4.0 if leveling is practiced. This is because of the possibility of liming and fertilizing. Moreover, there is no restriction on the type of livestock used on graded spoil pastures.

c. Forests. The growth of trees on ungraded spoils indicates that no leveling work is required to prepare forest sites. Experiments by the U.S. Forest Service (Chapman, 1949) showed even a decrease in height growth of young hardwood plantations on graded spoils when compared to ungraded spoils. Whether this site impairment is temporary or permanent and whether eventually the situation may be reversed is an open question that will receive attention under VI.

All spoils that cannot be used for crops, orchards, or pastures by

grading and that have a reaction above pH 3.5 are best used for forest. The only grading required then is for the establishment of access roads and fire lanes.

d. Other Uses. Spoils containing large areas affected by free acid cannot be reasonably used for any plant growth because the amount of lime required to neutralize the acid is excessive. Even then more acid is formed by the further oxidation of sulfides. The only practical method is to wait until most of the sulfides have been oxidized and the resulting acid leached out.

The suggestion has been made to grind highly pyritic material and to use it to neutralize alkaline mucks and greenhouse soils. So far this has not been tried.

The use of the ponds for fishing and other forms of recreation is rather obvious and requires no elaboration. The same is true for hunting and picnicking on the spoil areas. Where these uses are to be enjoyed by more than a few people, grading of some areas near the water and for roads, paths, and building and camping sites becomes necessary.

V. Methods of Revegetation

1. Forest Trees

Trees should be planted on spoil banks only after they have settled and eroded sufficiently so that no excessive changes in topography are to be anticipated. As trees are to be planted on the more acid spoils, it is wise to permit sufficient time to pass until volunteer vegetation shows up in many places. Hand labor is required for planting trees on ungraded spoils. A mattock or planting bar is used to open the holes. Fertilization is not practicable although it has been found that additions of nitrogen have greatly stimulated the growth of pines on spoils. Trees are usually planted 6, 7, or 8 feet apart in both directions. Special attention is needed to see that the crews do not bend the roots and neglect to tamp the ground around the roots. Since planting by hand is very time-consuming, attempts at direct seeding of trees on spoils have been made, but so far with no success.

The species of trees to be used on spoils depend on their adaptation to the local climate and to the soil conditions. Although pine trees have a definite place in the reforestation of spoil banks because of their low nutrient requirements and their acid tolerance, a number of successful plantings of hardwoods show that these should be used more extensively. Black locust, *Robinia pseudoacacia, L.,* sycamore, *Platanus occidentalis,* L., cottonwood, *Populus deltoides,* Marsh, tulip poplar, *Liriodendron*

tulipifera, L., black walnut, *Juglans nigra,* L., and red oak, *Quercus borealis, var. maxima,* Ashes are some of the species that show promise in Indiana and neighboring states. Both in the case of pines and hardwoods, seedling trees are cheaper, easier to plant and have a better survival percentage than transplants.

For further detail on reforestation of spoils reference should be made to Technical Paper No. 109 of the Central States Forest Experiment Station (Limstrom, 1948).

2. Pastures

a. Unleveled Spoils. Seeding of forage crops on unleveled spoils is done either by hand with a whirlwind seeder or from an airplane; which of these methods is more economical depends largely on the size of the areas to be seeded.

Due to the nitrogen deficiency of the soil material, legumes should be seeded previously to or simultaneously with grasses. Late winter is generally the best time for legume seeding, and since the establishment of legumes is the prime requirement for developing a pasture on unleveled spoils, the first seeding should be done at that time. Stiver (1949) found that seeding in the middle of February gave the best stands of legumes on Indiana spoils as compared to later seedings. The surface crust of unleveled spoils without cover is dried out by March winds and sunshine, and development of the young plants is impaired. He also noticed that seeding legumes on spoils less than a year old gave better stands than seeding on older spoils. The loose soil surface of fresh spoils is the reason. Where no perfect catch has been obtained with the first seeding it usually will be achieved in the third year when the few plants that did grow have spread prolific amounts of seed and this seed has germinated. Since seeding unleveled spoils is rather expensive it is probably better to include grass seed with the legume seed and to sow the mixture in late winter, than to make two separate seedings. The species to be used should combine vigor in establishment with sufficient palatability to be of value as pasture plants.

The following legumes and grasses have shown promise on unleveled calcareous spoils in Illinois, Indiana, and Ohio:

White sweet clover, *Melilotus alba,* Desv.
Yellow sweet clover, *Melilotus officinalis,* (L) Lam.
Alfalfa, *Medicago sativa,* L.
Ladino clover, *Trifolium repens,* L.
Korean lespedeza, *Lespedeza stipulacia,* Maxim.
Birdsfoot trefoil, *Lotus corniculatus,* L.

Kentucky blue grass, *Poa pratensis,* L.
Brome grass, *Bromus inermis,* Leyss.
Orchard grass, *Dactylus glomerata,* L.
Tall fescue, *Festuca elatior, arundinacea* Schreb.

Other species may be useful, especially in other regions. Where non-calcareous spoil is to be used for pasture, more acid tolerant species should be included but seldom much success can be expected. Since no ground preparation is possible and a great variety of soil materials exists, it is best to use a mixture of several, if not all, of the species listed.

The rate of seeding depends largely on the time when the land is to be ready for pasture. If pasturing is to begin 3 years after seeding, rates similar to those used in ordinary field plantings are adequate. If the spoils are to be ready in the year after seeding, about double these rates are required.

b. Graded Spoils. The establishment of pasture on graded spoils presents problems other than those encountered where ungraded spoils are used. The use of power driven equipment offers the possibility of cooperating with nature to develop a productive soil. The first task is to control erosion and to develop a good structure. A vigorous growth of a grass and legume mixture is the best means to achieve both of these ends. While only spoils with small amounts of stones are recommended for grading for pasture establishment, there will still be difficulty in the first years to cultivate such an area until some of the rocks have disintegrated. It may be difficult, therefore, to produce a conventional seed bed. Under such conditions a good catch can be obtained by covering the land with a thin layer of mulch. Manure, straw, chopped corn stover or other similar material can be used. This cover also reduces the erosion hazard.

Liming should be adequate to bring the surface soil to a pH of about 6.5. The fertilizer applied should be particularly high in phosphorus, but should also include nitrogen and potassium. About 12 to 25 lbs. of nitrogen (N), 25 to 75 lbs. of phosphate (P_2O_5) and 25 to 50 lbs. of potash (K_2O) per acre are recommended for initial application at the time of seeding. As graded spoils are accessible to all agricultural implements improvement treatments can be similar to those on ordinary pasture land. The same species as those mentioned for ungraded spoil pastures should be used. Other more acid tolerant plants can be included on acid spoil material, even if it be limed. Whether the seeding

is done with a companion crop of small grain or alone is of little importance.

Grazing should not begin until the second and preferably the third year to permit the formation of a continuous sod. Fertilization at lower rates should be repeated every second or third year and weeds should be clipped whenever necessary.

In addition to establishing a dense vegetative cover soon after grading, diversion ditches may be needed to control erosion. During the grading operations the location of future fences should be smoothed out so that the fences will not follow dips and hills. In all cases some of the ponds resulting from the mining operations should be retained.

3. Rotation Crops and Orchards

One of the main considerations in using smoothed out spoils for rotation crops is to create good soil tilth. A thick growth of grasses and legumes for 5 to 10 years is the surest way to achieve this. After that period any rotation suited for the given soil conditions, slope and climate can be started. No experience of planting rotation crops on smoothed spoils after such an improvement of several years exists. In Germany (Meyer, 1940) and in England (Sisam and Whyte, 1944; Robinson, 1945; Brown, 1949) the original soil is replaced on the graded spoils and therefore the establishment of rotation crops is much simpler.

Orchards can be established as soon as the erosion danger on the freshly graded spoil has been controlled, provided the reaction of the spoil is not too acid as it is practically impossible to lime the total potential root zone of the fruit trees.

VI. Grading

No other item in the reclamation of coal mine strippings has been as bitterly discussed as the grading or "leveling" of the banks. It is obvious that opinions clash on a subject where emotion, ethics and economics are involved and where very few facts have been established by research.

1. Reasons for Grading Spoils

Grading spoil banks permits the use of power machinery and therefore widens greatly the land use capabilities. Ungraded strippings belong to land use capability classes VII (Forestry) and VIII (Wildlife), according to the Soil Conservation Service classification. These are the two lowest groups. In many cases grading can bring the spoils into groups VI or V (Permanent Pasture) or even III or II (Cultivated Crops).

Grading can thus make it possible to grow more food and feed. Grading greatly speeds up the establishment of forage plants (Groves, 1949). Grading permits the soil formed from the raw spoil materials to stay in place and eventually to develop a deep and productive soil profile. On ungraded spoil, with slopes of over 50 per cent, a deep profile cannot form because erosion, even under dense cover, removes much of the freshly formed soil. An example of this situation is shown in the differences in pH and total nitrogen in the soils on the slope (60 per cent) and the alluvium of a 20 year old pine plantation on spoils in West Central Indiana (Fig. 4.)

Another reason for grading spoils frequently mentioned is the improvement of the scenery. Many people object to the ridge and valley topography and prefer a smoother landscape. As soon as dense forest covers the spoils, their surface configuration is largely hidden. Near towns and cities grading is esthetically desirable, and may also furnish valuable building sites.

2. How to Grade Spoils

In planning to grade spoils prime consideration should be given to the eventual land use and the drainage system desired. As previously stated, only land that is potential pasture, crop or orchard land need be graded. Pasture land should have no slope steeper than 25 per cent in order to permit safe operation of agricultural equipment, while for crop land and orchard land the maximum slopes should be 10 per cent in order to avoid serious erosion hazards. The slope pattern should be designed in such a way that water does not flow far before reaching a fairly level drainage channel. This can be accomplished frequently by merely sloping down the ridges without completely eliminating them. In some cases diversion ditches may be necessary. Where the spoil material is of particularly porous nature, one can dispense with such precautions.

A complete leveling of the land is of little value. It is costly, it compacts the soil and it creates erosion hazards. Also, under most conditions, grading to the original contour is not necessary. In very hilly territory it is much better to smooth out the spoils more nearly level, allowing for runoff on protected waterways than to attempt to regain the original topography (Tyner *et al.*, 1948). It is preferable to leave the "highwall" as a steep and valueless escarpment in order to gain some level land that may be put to a higher form of use than could be practiced before stripping.

Generally it is not desirable to fill in the larger and deeper ponds and lakes that contain good water. They are a byproduct of strip mining

which can be regarded as an asset in areas deficient in natural open water. On the other hand ponds containing water that is useless because it is too acid or too shallow or because it dries out during the summer, should be filled in, if possible. The same is true of final cuts that remain dry. It seldom will be practical to fill in final cuts completely since the overburden has all been deposited on one side, but by grading down the last one or two ridges of spoil it is generally possible to include the final cuts into the land use pattern.

One form of grading frequently employed is called "striking off the ridges." A bulldozer or similar machine pushes the material of the ridges aside so that a smooth surface of from 8 to 16 feet in width results. This makes the area more accessible, gives the raw spoils a less ragged skyline and simplifies tree planting to a certain extent. Striking off the ridges does not permit operation of agricultural equipment since only a small portion of the area is accessible.

As the available evidence points to the fact that leveling does not help the growth of forest trees the only grading that should be undertaken on potential forest land is to prepare access and fire lanes. Since individual spoils are usually of restricted area not much consideration need be given fire lanes. It is advantageous to locate access roads along the ridges. They should be crowned so that water will not flow in the lanes and cause severe gullying. Some lanes connecting the ridge lanes with the main road should be provided. Where it is necessary to cut across the ridges it is well to do this at relatively high points so that water and erosional debris will not damage the lanes. In many cases the original coal haulage road may serve as part of the system.

Frequently damage to soil structure has been observed as a result of grading spoils. Probably the reason for this is that the lower strata of spoils are almost continuously wet, because of the loose nature of the spoils. Working heavy soils wet tends to puddle them. During the mining process the overburden increases from a third to a half over its original volume. Many large pores are created in the resulting overburden that stop the downward flow of all but the tension-free water. In natural soils no such impediment exists. It is the obvious conclusion that grading spoils, where desirable, should be done as soon as possible after mining so that there will be no accumulation of percolating rain water in them. The best method would be to do it as an integral part of the deposition of the overburden in the banks. The rotating shovel excavators used today in a few of the strip mines come closest to accomplishing this feat. The ordinary power shovels and draglines cannot do it without special operations.

3. Objections to Grading of Spoils

The main objections against grading spoils are the expense and the possibility of impairing soil structure. Trees have been found to grow slower on leveled spoils than on ungraded ones (Chapman, 1949; Sawyer, 1949). It is difficult to say how the same trees would have grown on the same material, had the grading taken place immediately after mining when the spoils had not had time to collect much water.

Another objection against grading is the increased erosion hazard. If the smoothing out is done in such a way that water has a chance to accumulate over larger sloping areas, grading can result in considerable gullying, which makes successful revegetation difficult. The necessary precautions have already been described.

VII. Economic Aspects

While ethics and esthetics play important roles in planning the reclamation of coal mine strippings, an economically sound approach must be the first consideration. Even under the most favorable conditions spoil banks are "unimproved" land, and no quick returns from any use can be expected. The choice exists between complete abandonment, inexpensive improvement and intensive improvement. Where no improvement is made, it will be many years before desirable trees become established and grow to merchantable size. Where calcareous spoils are seeded to grass and legume mixtures grazing will bring returns within very few years. While the returns per acre will be considerably less than from improved pastures, the investment for seeding and fencing will soon be amortized.

Planting trees on spoils has been costing around $25 per acre during the last few years. This investment is much greater than the cost of seeding grass and legumes but still is a rather modest figure. Occasionally costs of establishing a forest cover have been a good deal higher where trees had to be planted for a second or third time on account of poor survival of the first plantings. Such extra expense can be avoided, if the banks are checked for pH and planting is delayed until a scant cover of pioneer plants is established. Obviously returns from the trees begin only 10 or 12 years later when fence posts can be cut from black locusts. The main income, however, will not materialize until pulpwood or saw lumber can be harvested, usually after 30 to 40 years. As practically all tree plantings on coal mine strippings in the United States are less than 30 years old, little can be said about the value of the produce and the expense of harvesting the trees. But the vigorous growth of the

adapted tree species on spoils and the constantly increasing demand for lumber and pulpwood make it very probable that this form of land use will bring a certain, if modest revenue commensurate with the expense of planting.

Any form of spoil bank reclamation that includes grading is of necessity quite expensive except where the grading is restricted to

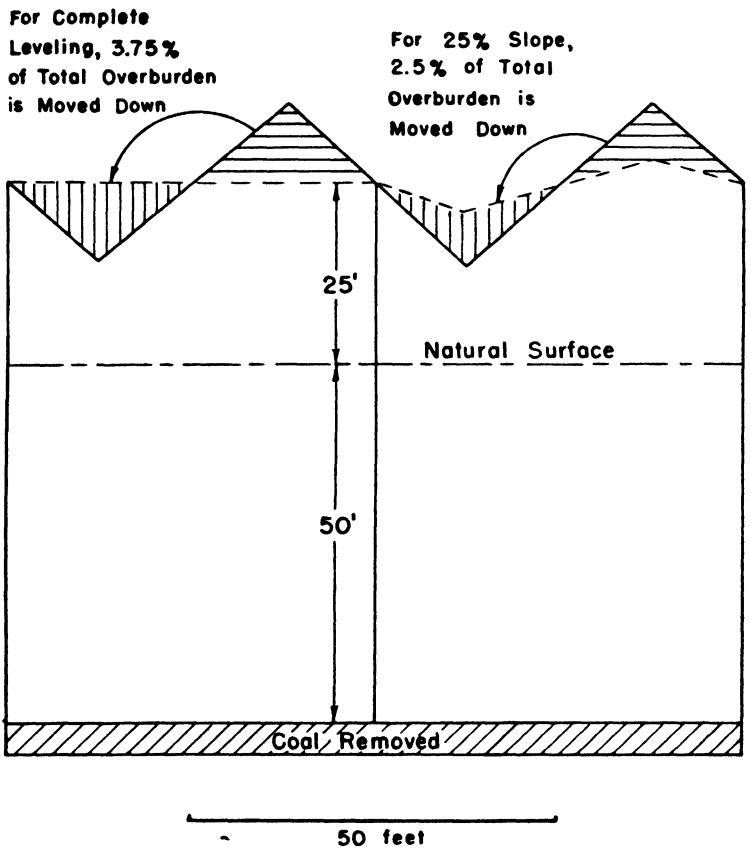


Fig. 8. Amount of earth movement needed for grading spoils.

striking off the ridges. In addition to the cost of grading are the expenses for liming, fertilizing, seeding and fencing which may be considerable, especially on the more acid spoils. The aggregate of these costs may actually be higher than the purchase price of improved, high quality farm land. Where only spoil material is graded which is adapted for the intended land use there can be little doubt that an income is assured that will be greatly in excess of that produced by forest plantations and one that will start much earlier. Nevertheless in many cases the expense of grading will make this form of reclamation an unprofitable under-

taking for the individual, if viewed as an independent business operation.

Grading may be regarded as part of the original earth-moving operation that is necessary to uncover the coal. Assuming an overburden thickness of 50 feet, a volume increase of 50 per cent (personal communication L. L. Newman, U.S. Bureau of Mines), spoil ridges 50 feet apart and average slopes of ninety per cent, the complete leveling of the spoils would require a second moving of less than 4 per cent of the total overburden material (Fig. 8). Moreover, this movement is of loose material in generally downhill direction while the original material was solid earth and rock and had to be lifted to considerable heights.

One very important item of the reconversion of spoils into improved pasture land or crop land is that the adjacent land is benefited. Since coal mine boundaries have irregular patterns, fields may be cut to small sizes and sometimes made essentially inaccessible from the farm buildings. If the spoils are left ungraded and planted to trees they have to be fenced out from pastured land. As a result much of the land neighboring ungraded spoils is left idle. Grading increases the eventual field size, permits fencing at more practical locations, and can help to bring the entire original farm back into agricultural production.

Communities with strip coal lands suffer an eventual decrease in tax income since usually the tax valuation of stripped coal lands is lower than it was originally (Walter, 1949). Proper reclamation can minimize or even eliminate this loss in tax revenue. The increased production from agriculturally reclaimed coal land will also contribute to the economic life of the area.

In the discussion of the economics of spoil bank reclamation a clear distinction has to be made between the viewpoints of the individual and of the country as a whole. Returns too small or too remote to pay for the investment offer no incentive for the individual to reclaim spoils. The nation, however, has to consider the potential productive power of an area that may contribute materially to the furnishing of life's necessities to the increased population of the future. Whether the individual shall bear the full cost of restoring the productivity of the land is a matter of state or national policy. In view of the lower cost of producing coal by the strip method compared to underground mining it seems possible that the reclamation cost be included in the price of coal. Only the technical aspects of the reclamation of coal mine spoils are discussed here. Walter (1949) has given a masterly presentation of the economic problems facing agriculture as a result of strip mining of coal.

VIII. Legislation

Soil destruction brought about by strip mining in the United States is very minor compared with that due to erosion. Yet, while no laws force a farmer to conserve his soil, legislation regulating reclamation of coal mine spoils exists in 4 states: West Virginia, Pennsylvania, Indiana and Ohio. In all cases revegetation of the stripped land is required, in West Virginia and Ohio a certain amount of grading is also compulsory. In all 4 states the legislation recognizes that different methods of reclamation are appropriate for different types of spoil materials. The West Virginia law also distinguishes between former arable and former forest land. No grading is required in the latter case.

Illinois also had a reclamation law. It was declared unconstitutional, however, on the ground that it was discriminatory legislation since it regulated the reclamation of coal mine spoils while it ignored spoils of other mining operations, such as gravel pits.

It is difficult to say what the most reasonable form of legislation would be. One thing is certain, however, that it involves first of all the establishment of a policy concerning the obligation of an individual toward a piece of land to which he has full title. Since the United States has passed the pioneer era of unlimited land resources it seems appropriate that restrictions be imposed on the destruction of the productive capacity of land. If this philosophy were accepted, regulations concerning the protection and reclamation of land would have to extend to all land, and not only to mined areas.

Whatever the moral and constitutional background of coal spoil bank legislation, it has to be based on well understood physical and economic facts and to differentiate between the various conditions of spoils.

IX. Discussion

1. Establishing a Reclamation Policy

It is impossible to view the coal mine strip bank problem as a separate entity and to arrive at an equitable solution. Reclamation of the spoils is just a fragment of the general problem of conservation. As a nation we have become conscious of the value of our natural resources.

Soil losses by water, wind and alkali have received widespread attention. The researches and practical experiences of the past 2 decades have shown the tremendous possibilities of regaining and increasing the productive capacity of abused soils by proper management. Great strides have been made in halting the further inroads of excessive erosion but the road ahead is long before the goal can be reached. The destruc-

tion of the soil by strip mining is merely a faster and more spectacular way of decreasing the food and feed producing area than erosion, excess water, alkali or inadequate fertilization. We have established the principle in this country that all land should be brought to its highest economic use so that the United States as a nation can continue to enjoy a satisfactory standard of living. Today there are about 3 acres of arable land per inhabitant in the United States. Diminishing the crop-producing area in the face of a rapid increase of population would eventually lead to disastrous results.

Smoothing out spoil banks to a more stable topography will permit the soil that is formed to accumulate and eventually to become fertile agricultural soil. It seems advisable, therefore, to grade down those spoils that give promise of producing pasture or field crops. While the material in the spoils varies greatly, most of it is of a nature that will decompose rapidly and form soil. Besides, the majority of the coal strip mines are in an area with excellent climate for plant growth. Half of them lie in the Corn Belt and most of the others nearby.

The land involved in strip-mining operations represents only a small fraction of the country and other lands deserve our watchful interest in the same way. It has been interesting to see many old gravel pits graded by bulldozers and put back into agricultural production. Such voluntary reclamation work is the one best befitting a democratic nation. Whatever the details of the eventual policy will be, everybody seems to agree today that a temporary gain should not be paid for by the permanent impairment of land resources. It is pertinent to inquire whether there is a moral obligation on the part of the land owner to leave his land in as good or better condition as when he took it over. No such viewpoint prevailed in nineteenth century America. But viewpoints change and today such an obligation is slowly developing. So far other miners have not been required to smooth out their spoils and to improve and revegetate them. The reason for this inconsistency may be found in the smaller size of many of these undertakings, *e.g.*, gravel and clay pits, and the distance from centers of population of others, *e.g.*, gold, iron, and copper mines. Reclamation work on the spoil banks of phosphate mines in Florida is under way.

In other more densely populated countries reclamation is obligatory. In Europe, saving the original surface soil and spreading it over the leveled spoils is either required or suggested. The attitude of German farmers toward this problem is demonstrated by this quotation from Gray *et al.* (1938): "A German land owner, asked how he could justify an outlay of about $100 an acre for reforesting stripped coal land, replied that he considered it his duty to leave the property to his successors in at least

as good condition, as when he took it over. Whether or not the expenditure would earn compound interest or show a profit did not enter into his calculations. This epitomizes the prevailing attitude of enlightened forest owners in much of central and northern Europe." Another example is the reclamation of land from the North Sea which cost Holland $1250 per acre (Bear, 1949).

2. Future Research Needs

Much work has been done to find the best ways of reclaiming coal mine spoil banks. The coal operators themselves have supported such research with funds and facilities. The results of these studies together with established facts of soil science, forestry, agronomy and ecology give sufficient tools to reclaim the banks. Many improvements are still needed. Future research may include some of the following items: improved methods of removing the overburden and placing it in proper sequence and in smoother surface on the spoils, developing better tests and criteria to determine the potential land use capability of the spoil material, finding the plant species best adapted for profitable growth on the spoils, and study of the economic relations involved.

3. Contributions of Spoil Bank Research to Science

Since conditions on coal mine spoil banks are entirely different from those on undisturbed land many interesting and valuable facts of soil science, ecology, forestry and other fields present themselves for study. One of the outstanding ones is the rate of soil formation. The moment when the overburden is deposited in the spoil bank is zero time of soil formation. Every year changes can be observed. Actual rates of soil formation as well as criteria of soil formation can be discovered in such research.

The steep slopes of soil material practically devoid of organic matter give an opportunity of studying fundamentals of erosion. The high calcium concentration of many spoils in spite of low pH values offers a unique possibility of separating the effects of these two factors on plant growth. Temperature effects on soil formation, erosion and plant growth can be studied by comparing north and south facing slopes of the same spoil bank. The differences between the effects of calcium ions and hydrogen ions on flocculation of clay and aggregation of soil can be investigated in the absence of organic matter. The many ponds give an opportunity to determine the pH ranges of adaptability of various plants, fish and plankton. Similarly interesting observations are possible on the growth of various plant species in an unusual environment. It has been said in connection with the ecology of the spoil banks that "you have

to throw away the book," but more properly it seems that a new chapter has to be added. Spoil banks offer a fertile and fascinating field of research to the biologist.

X. Summary

While the total area stripped for coal in the United States is only about a quarter million acres, the problem of reclamation of the spoil banks is important for various reasons. Each acre mined affects the land use of at least one more acre of the neighboring land. The public resentment against the despoilation of the land in the most fertile climatic belt of the country calls for a clear understanding of the situation. In the face of nationwide efforts to control the destruction of soil by erosion, the destruction of soil by mining calls for the establishment of a policy concerning the conservation of natural resources for future use.

The strip mining of coal leaves the overburden in steep ridges with only little of the original top soil near the surface. The material is extremely heterogeneous; from finest clay to large rocks, and from pH 2 to pH 8. Nitrogen and organic matter are present in only very small amounts but otherwise the potential fertility is generally similar to that of natural soils. The nonrocky part of the spoil is generally of desirable texture.

Soil tests to determine the potential land use capabilities of spoils have to be rapid because of the variability of the material. Hydrochloric acid shows the presence of carbonates, potassium thiocyanate the presence of free acid and sodium azide the presence of sulfides. Ordinary pH indicators and the interpretation of the occurrence of natural pioneer vegetation as well as observation of the texture and rockiness are additional aids in planning land use.

On all spoils, except those of reactions below pH 3.5, natural vegetation is established in a few years. The calcareous areas are soon covered with legumes which are followed by grasses. Practically all native and many introduced plant species thrive on the spoil banks.

Plantings bring such areas more quickly into production and help to camouflage the ragged topography. For more than 30 years trees have been planted on spoil banks and many attempts at revegetation have been successful.

The wildlife population has increased as a result of creating rather inaccessible shelter and many ponds. These latter give an opportunity to raise fish in regions deficient in natural lakes.

The land use capability of the spoils is dependent on the reaction, the rockiness and the texture of the soil material as well as on our willingness to grade down the ridges to suit a certain use. Ungraded spoils are

principally forest land and the calcareous and least rocky ones are potential pasture land. Where grading is done pasture can be the dominant use even though the reaction and fertility may not be very favorable, and the areas with the best texture are suitable for cultivated crops and orchards.

Trees are planted as one- or two-year old seedlings about 7 by 7 feet apart. Legumes and grasses for pastures are seeded either by hand or from an airplane. Once spoils are graded the possibility of using any kind of agricultural implement permits a variety of methods of establishing vegetation. Grading spoils calls for extra precautions to avoid erosion because of the lack of water-stable aggregates in the spoil material and the resultant low infiltration capacity.

Grading of spoils raises the potential land use capability. The majority of graded spoils can be used for pasture and some of them after a period of improvement for rotation crops. The greatest advantage of grading is that the weathered soil can remain in place and eventually develop considerable depth. Complete leveling is unnecessary and frequently undesirable.

The main objection to grading is its high cost. The grading may cost more than the purchase price of similarly productive natural land. Legislation regulating the reclamation of coal mine spoil banks exists in West Virginia, Pennsylvania, Indiana and Ohio. One of the most essential features of such legislation is that it does not treat all spoils alike but considers each case according to the physical and economic situation. It seems that the development of an overall conservation policy has to precede this type of legislation.

Further research on grading and revegetation of spoils is needed.

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Irrigated Pastures

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I. Introduction

Irrigated pastures have provided feed for the livestock of the western United States since its settlement. The acreage has expanded to an estimated 2.7 million in the 17 western states, according to the 1940 Census of Irrigation. Twelve per cent of the irrigated land of the west was in pastures, 37 per cent in Nevada and nearly 25 per cent in Oregon. The California acreage was estimated at about 560,000 in 1949, most of which developed since 1930 and nearly half since 1946. Five acres planted in the Werribee District of Victoria, Australia in 1914, was the beginning of a development which reached approximately one-third million acres by 1947 according to Morgan (1949).

Factors which have contributed to a large irrigated pasture acreage are the development of new irrigated land, selection and use of species which are highly productive on a wide variety of soils, and the need for additional forages to supplement other sources, particularly rangeland. The low labor requirement for this kind of irrigation farming has appealed to many operators during recent years of scarce and costly labor.

Many of the Agricultural Experiment Stations of the West included studies on irrigated pastures in their earliest projects. Recent research has been directed both towards improvement of existing pastures and development of new pastures on various types of soils including some of the best.

The writers have placed greatest emphasis in this review on recent experimental data but the lack of information on numerous points has necessitated the use of some less well authenticated evidence.

II. Pasture Soils

The soils upon which irrigated pastures are grown vary widely in physical and chemical characteristics. In recent years some of the most fertile and productive soils in the West have been seeded to irrigated pastures. A large part of the acreage, however, is on soils not well suited for tillage because of poor drainage, excessive salts, shallowness, or the presence of stones, steep slopes and other conditions unfavorable to cultivation. The many species of grasses and legumes used in pastures show wide differences in soil adaptation and tolerance to adverse situations.

Characteristics of the soil which influence production and selection of species are fertility, texture, depth, drainage, and salinity and alkalinity. For a more thorough treatment of the management of irrigated soils, the reader is referred to Thorne and Peterson's (1949) book on this subject, and to the manual by Richards (1947) on the diagnosis and improvement of saline and alkaline soils. The present discussion is confined to the adaptation of species to particular soil conditions.

Much of the irrigated pasture acreage is on soils which are typical of arid conditions. Thorne (1948) characterizes these soils as being low in organic matter and containing adequate or excessive quantities of calcium, sodium, magnesium, potassium, carbonates and sulfates. He further indicates that these soils, when placed under irrigation, often contain insufficient phosphorus and nitrogen for maximum production. With irrigation and growing of crops, organic matter is increased, microbial activity stimulated, and many mineral constituents are brought into solution.

The irrigated land of the western United States is on valley bottoms

and terraces which developed from material transported and deposited by water. Most of the streams emerged from mountain canyons to deposit sediment at floodtime in alluvial fans. Pastures are mostly on heavy textured soils laid down under slow moving water or lacustrine deposition. The latter soils are particularly heavy and may be quite high in organic matter. Some of the older depositions have developed profiles with heavy textured or cemented hardpan subsoils. Varying degrees of salt accumulations are found.

Soil texture and depth are important factors in species adaptation. Deep rooted plants such as alfalfa (*Medicago sativa*) are used on the deep, coarse to medium textured soils. Hamilton *et al.* (1945) point out that good pastures are not readily established and maintained on very sandy soils. The low water holding capacity of these soils and injury to ladino clover (*Trifolium repens latum*) stolons by trampling limit the use of this species. On fine textured soils, the shallow rooted species such as ladino clover are quite satisfactory. Ladino clover and narrowleaf birdsfoot trefoil (*Lotus corniculatus tenuifolius*) are two of the few species which produce satisfactorily on the extremely heavy adobe soils in central California. These same species are grown successfully on soils underlain with a claypan layer a few inches below the soil surface. This impervious subsoil increases the efficiency of water use by preventing downward percolation below the root zone.

Excessively wet soils in irrigated regions are caused by (1) direct application of water, (2) seepage from canals and ditches, and (3) subsurface flows from areas receiving excessive precipitation or irrigation, (Thorne and Peterson, 1949). Wet conditions arising from direct water application are generally localized and result from over-irrigating, improper leveling, failure to provide drainage, or to unsatisfactory balance between the head of water and the size of the check or basin. These conditions are normally avoidable and are discussed under later headings.

More extensive wet areas are found where drainage is difficult or not practical such as in large valley bottoms and along natural waterways which are subject to flooding or seepage. Because of wet conditions, and often the presence of salts, these areas are difficult to manage and productivity is low because the most productive species are not well adapted.

These valley bottoms or mountain meadows are used extensively for spring and fall grazing and the production of wild hay for wintering range cattle. Pittman and Bennett (1948) were able to double yields in the second and third year after alsike clover (*Trifolium hybridum*) and red clover (*Trifolium pratense*) were broadcast on undisturbed sod. An additional significant increase was obtained by plowing and seeding timothy (*Phleum pratense*) and redtop (*Agrostis alba*) or bromegrass (*Bromus*

inermis) and meadow fescue (*Festuca elatior*) with the clovers. The above treatment when combined with fertilization, frequent light irrigations and control of water to prevent prolonged flooding, resulted in nearly 4 times the yield of native sod.

Reed canarygrass (*Phalaris arundinacea*) in combination with strawberry clover (*Trifolium fragiferum*) produced excellent pasture on land too wet for alfalfa in unpublished studies conducted at the Utah Station. In preliminary trials at the California Station, Reed canarygrass, perennial ryegrass (*Lolium perenne*), tall fescue (*Festuca elatior arundinacea*), narrowleaf trefoil, and strawberry clover ranked in the order named in total production when grown under continuous flooding over a period of several months.

Research is being initiated by federal agencies in cooperation with several of the western states on the improvement of natural meadows. This is an important source of livestock feed and the problem of improvement warrants greater attention than it has received in the past.

According to Magistad and Christiansen (1944), "A large part of the 20,000,000 acres under irrigation in the 19 Western States contains enough soluble salt to depress crop yields. A much smaller area contains so much alkali that crop production is greatly curtailed and unprofitable. Thousands of acres have been abandoned because of salinity." In arid regions, salts accumulate chiefly because of irrigation and poor drainage (Richards, 1947). Since poorly drained soils are not easily tilled, they are used extensively for the production of forage. Thus, in irrigated regions the problem of saline and alkali soils is one of great importance in connection with forage production.

Richards (1947) has classified salted soils into saline, saline-alkali, and nonsaline-alkali soils. The saline soils are defined as soil "for which the conductivity of the saturation extract is greater than 4 millimhos per cm. (at 25°C.) and the exchangeable-sodium-percentage is less than 15. The pH of the saturated soil paste is usually less than 8.5." These soils are characterized by white crusts on the surface or by streaks of salt in the soil. They are reclaimed by leaching and drainage, after which they become normal soils. The saline-alkali soils are defined as "soils for which the conductivity of the saturation extract is greater than 4 millimhos per cm. (at 25°C.) and the exchangeable-sodium-percentage is greater than 15. The pH of the saturated soil paste may exceed 8.5." The nonsaline-alkali soils are those "for which the exchangeable-sodium-percentage is greater than 15 and the conductivity of the saturation extract is less than 4 millimhos per cm. (at 25°C.). The pH values for these soils generally range between 8.5 and 10." The latter two types

of soil are more difficult to reclaim because of the low rate of water penetration.

Hamilton *et al.* (1945) point out that the roots of salt-tolerant forage plants increase the permeability of salty soils and speed up the rate at which salt may be leached from them. According to Richards (1947) alkaline soils require measures to improve the soil structure after suitable base exchange and leaching has removed harmful amounts of sodium. For this purpose they consider grass roots especially effective.

Bartels and Morgan (1944) consider the degree of reclamation of salty soil to be proportional to the amount of water applied. They found that when sufficient leaching had occurred to permit growth of barley

TABLE I

Salt Tolerance of Forage Crops According to Richards (1947). Tolerance Decreases from Top to Bottom in Each Division. Scientific Names have been Added

GOOD SALT TOLERANCE	MODERATE SALT TOLERANCE (*Continued*)
Alkali sacaton (*Sporobolus airoides*)	Tall fescue (*Festuca elatior arundinacea*)
Salt grass (*Distichlis spp.*)	Rye (hay) (*Secale cereale*)
Nuttal alkali grass (*Puccinellia nuttalliana*)	Wheat (hay) (*Triticum aestivum*)
Bermuda grass (*Cynodon dactylon*)	Oats (hay) (*Avena sativa*)
Rhodes grass (*Chloris gayana*)	Orchardgrass (*Dactylis glomerata*)
Rescue grass (*Bromus catharticus*)	Blue grama (*Bouteloua gracilis*)
Canada wild rye (*Elymus canadensis*)	Meadow fescue (*Festuca elatior*)
Beardless wild rye (*Elymus triticoides*)	Reed canary (*Phalaris arundinacea*)
Western wheatgrass (*Agropyron smithii*)	Big trefoil (*Lotus uliginosus*)
	Smooth brome (*Bromus inermis*)
MODERATE SALT TOLERANCE	Tall (meadow) oat (*Arrhenatherum elatius*)
White sweet clover (*Melilotus alba*)	Cicer milk vetch (*Astragalus cicer*)
Yellow sweet clover (*Melilotus Officinalis*)	Sour clover (*Melilotus indica*)
Perennial ryegrass (*Lolium perenne*)	Sickle milk vetch (*Astragalus falcatus*)
Mountain brome (*Bromus carinatus*)	POOR SALT TOLERANCE
Barley (hay) (*Hordeum vulgare*)	White (dutch) clover (*Trifolium repens*)
Birdsfoot trefoil (*Lotus corniculatus*)	Meadow foxtail (*Alopecurus pratensis*)
Strawberry clover (*Trifolium fragiferum*)	Alsike clover (*Trifolium hybridum*)
Dallis grass (*Paspalum dilatatum*)	Red clover (*Trifolium pratense*)
Sudan grass (*Sorghum vulgare sudanense*)	Ladino clover (*Trifolium repens latum*)
Hubam clover (*Melilotus alba annua*)	Burnet (*Sanguisorba minor*)
Alfalfa (California Common) (*Medicago sativa*)	

grass (*Hordeum maritimum*), the land would support wimmera ryegrass (*Lolium rigidum*). Morgan (1947) considers land leveling essential to reclamation of salty land. Leveling makes possible the uniform application of water, to leach salts downward. He reports that a field which had a salt concentration in 1939 of 0.84 to 1.01 per cent in the 6- to 60-inch zone was leveled, sown to pasture, and irrigated 12 to 19 times a year. By 1946 the salt was reduced to 0.10 to 0.25 per cent. Light irrigations were given the pasture, the annual average totaling approximately 2.5 acre feet. During the course of the study the productivity of the pasture steadily increased.

Many native species possess marked tolerance of salty soils, but they are almost without exception of relatively low forage value. Experience gained through the years has been sufficient to permit a rough classification of plants as to their salt tolerance. In recent years the work of the U.S. Regional Salinity Laboratory at Riverside, California has greatly expanded and refined our conception of the adaptation of plants to salty soils. The salt tolerance of a number of forage species, as reported by Richards (1947) is reproduced in Table I. The scientific names have been added to aid in identification. The growth made by wheat, oats or barley on salty land serves as a useful guide in choosing the best species for seeding the area to pasture.

The principal effect of salt on crop production is a reduction in growth of plants. Since the salts in the soil solution retard the movement of water into the plants, it should be kept as diluted as possible by frequent irrigation. The applications should be light if there is danger of raising the water table, but heavier applications may be made if adequate drainage has been provided. Magistad (1945) and Hayward and Wadleigh (1949) have presented reviews of plant growth relations on saline and alkali soils, and Hayward and Magistad (1946) state the problem and describe the work of the Laboratory at Riverside.

III. Choosing Productive Mixtures

Relatively few species are extensively used in irrigated pastures. These are listed together with some of their characteristics in Table II. Smooth bromegrass, reed canarygrass, and tall oatgrass (*Arrhenatherum elatius*) are used most widely in the cooler regions as contrasted to dallis grass (*Paspalum dilatatum*) and rhodesgrass (*Chloris gayana*) which are confined to the hot southern regions and areas of mild winter temperatures. Similarly, bur clover (*Medicago hispida*), a winter annual is used only in areas with mild winters. Italian ryegrass (*Lolium multiflorum*) and perennial ryegrass are most widely used in the Pacific Coast states.

TABLE II

The Major Irrigated Pasture Species, Some of their Characteristics, and the Conditions under which they are Likely to be of Greatest Value

Species	Growth habit	Palatability	Length of life	Probable best use [a]	
				Land	Water
Tall Oat (*Arrhenatherum elatius*)	Bunch	High	Short perennial	Arable	Moderate
Smooth Brome (*Bromus inermis*)	Rhizomatous	High	Perennial	Arable	Limited
Rhodesgrass (*Chloris gayana*)	Stoloniferous	Moderate	Perennial	Salty	Moderate
Orchard (*Dactylis glomerata*)	Bunch	Moderate	Perennial	Arable	Abundant
Tall Fescue (*Festuca elatior arundinacea*)	Bunch	Low	Perennial	Salty	Moderate
Italian Ryegrass (*Lolium multiflorum*)	Bunch	High	Annual	Arable	Moderate
Perennial Ryegrass (*Lolium perenne*)	Bunch	High	Short perennial	Arable	Moderate
Dallis Grass (*Paspalum dilatatum*)	Bunch	Moderate	Perennial	Arable	Abundant
Reed Canary (*Phalaris arundinacea*)	Rhizomatous	Moderate	Perennial	Wet	Excess
Narrowleaf Birdsfoot Trefoil (*Lotus corniculatus tenuifolius*)	Creeping	High	Perennial	Salty	Moderate
Broadleaf Birdsfoot Trefoil (*Lotus corniculatus arvensis*)	Nonspreading	High	Perennial	Arable	Moderate
Bur Clover (*Medicago hispida*)	Nonspreading	High	Annual	Arable	Moderate
Alfalfa (*Medicago sativa*)	Nonspreading	Moderate	Perennial	Arable	Limited
Sweet Clover (*Melilotus spp.*)	Nonspreading	Low	Biennial	Wet or salty	Limited
Strawberry Clover (*Trifolium fragiferum*)	Stoloniferous	High	Perennial	Wet and salty	Excess
Red Clover (*Trifolium pratense*)	Nonspreading	Moderate	Short perennial	Wet arable	Abundant
Ladino Clover (*Trifolium repens latum*)	Stoloniferous	High	Perennial	Arable	Abundant

[a] Some species are of much wider usefulness than here implied, but are relatively superior under conditions indicated.

Narrowleaf trefoil is used extensively in Oregon and California. Broadleaf trefoil (*Lotus corniculatus arvensis*) is coming into some use at higher elevations where winter temperatures exclude the narrowleaf trefoil. Strawberry clover has as yet achieved little importance except on wet lands in widely scattered areas. The remaining species listed in the table, show a wide range of adaptation throughout the western states.

Many writers have pointed out that if several species are used in a mixture, the grazing animal has a more varied diet, stands may be improved, and higher and more uniform yields are obtained. Reasons given for using a number of species in a mixture are differences in seasonal growth habits, depth of rooting, and soil nutrient requirements. Studies at the Utah Experiment Station have at least partially supported these statements but data are also available showing that simple combinations may be highly productive.

Pasture mixture studies are difficult to conduct because of the large number of possible combinations which can be compared. Only 3 grasses and 3 legumes give rise to 49 different mixtures containing one or more grasses with one or more legumes. Eight grasses and 8 legumes provide 64 mixtures of a single grass with a single legume, 784 mixtures of 2 grasses with 2 legumes, 3,136 mixtures of 3 grasses with 3 legumes and 4,900 mixtures of 4 grasses with 4 legumes. There are a possible 65,025 different mixtures, using 1 to 8 grasses with 1 to 8 legumes, not including differences in seeding rates. Most pasture mixture studies have included selected species put in combinations considered of most value by the experimenter.

Some early studies brought forth excellent recommendations although they were not always carried over into agricultural practice. Sanborn (1894) rated tall oatgrass, timothy and alfalfa in the order named, and pointed out that Kentucky bluegrass (*Poa pratensis*) was relatively unproductive as a pasture grass. French (1902) recommended 4 mixtures for pasture, none of which contained Kentucky bluegrass although he stated that it, and some other species, might be added. He pointed out that a simple mixture of 10 pounds orchardgrass (*Dactylis glomerata*) and 6 lbs. red clover per acre was good for hay or pasture. He recognized the difference between meadow fescue and tall meadow fescue, characterizing the latter as a coarser, less desirable species. Welch (1914) recommended a mixture of Kentucky bluegrass 8, orchardgrass 5, smooth bromegrass 5, meadow fescue 4, timothy 4, and white clover (*Trifolium repens*) 2 lbs. per acre. It was a modification of a mixture he had grown for 4 years with excellent results. Later, Welch (1917) pointed out that orchardgrass and bromegrass were the more important components, while Kentucky bluegrass, meadow fescue and timothy

were of lesser importance. Hansen (1924) reported on a study of 3 mixtures, all quite similar except that one lacked legumes. On the basis of both hay yields and grazing tests on these 3 mixtures he proposed a fourth, which became widely known as the Huntley mixture. It is much like Welch's (1914) mixture, differing only in seeding rate, the omission of timothy and the inclusion of alsike clover. In a slightly modified form the Huntley mixture became widely used in Utah and some adjacent areas under the name of Standard mixture No. 1.

Current recommendations of most experiment stations in western United States omit Kentucky bluegrass from pasture mixtures. Common white clover has been largely replaced by ladino clover. Several experiment stations include tall fescue in nearly all mixtures (Jones and Brown, 1949; Klages *et al.*, 1948; Rampton, 1945). Tall oatgrass is recommended as a component of mixtures by Law *et al.* (1945) and Keller *et al.* (1947b).

Pasture mixtures for well-drained irrigated land have received increased attention in Utah since 1943. Reports by Keller *et al.* (1945, 1947a, 1947b) and by Bateman *et al.* (1949) have shown that the modified Huntley mixture is a relatively low producer when utilized by dairy cattle under rotation grazing. These studies have shown that high producing mixtures were those dominated by smooth bromegrass, orchardgrass, tall oatgrass, tall fescue or reed canarygrass, or combinations of these, with 50 to 60 per cent alfalfa, red clover or ladino clover. In contrast, mixtures dominated by Kentucky bluegrass, meadow fescue, meadow foxtail (*Alopecurus pratensis*), or perennial ryegrass, with strawberry clover, alsike clover or any of several sources of ordinary white clover, would be much less productive.

Because of the low palatability of tall fescue in these studies, and the difficulty of obtaining good stands of reed canarygrass, these species are not recommended in Utah for well-drained irrigated land. The mixture currently recommended (Department of Agronomy, 1949) is based on 6 years' study of 36 mixtures and 3 years' study of 32 mixtures. It includes bromegrass 4, tall oatgrass 4, orchardgrass 3, wilt resistant alfalfa 3, red clover 3, and ladino clover 2 lbs per acre. In this mixture tall oatgrass and red clover reach high production quickest, following seeding. Bromegrass, orchardgrass, wilt resistant alfalfa and ladino clover are the more permanent components of the mixture. They have remained productive through 6 grazing seasons.

Many problems surrounding pasture mixtures need further investigation. Tall fescue is widely used in California, Oregon and other states. However, Cunningham (1948) reports tall fescue is poisonous to cattle

in New Zealand. There have been no reports of poisoning from areas where tall fescue has been extensively used in the United States.

Almost no research has been carried out on seeding rates. A wealth of experience indicates that under favorable conditions for both germination and establishment, 50 to 60 per cent legumes will result if the legumes comprise one-fourth to one-third of the total weight of the seed. Size and viability of seed and vigor of seedlings may considerably modify these proportions. Excellent stands of ladino clover have been obtained with one-half lb. of seed, although 1 or 2 lbs. are more commonly recommended per acre. Mixture totals vary with the species used, but usually range between 10 and 20 lbs. per acre.

IV. Establishing Pastures

1. Preparation of Land for Irrigation

The method used for irrigating pastures is determined by topography, soil and subsoil texture and the amount of water available (Hamilton *et al.*, 1945; Jones and Brown, 1949) and in different regions is strongly influenced by local custom (Stewart, 1945). Although numerous types of irrigation systems are used, all may be grouped into either sprinkling or flooding methods. Land leveling is required for most flooding systems.

The strip check or border method of flood irrigation is widely used on relatively flat areas (Hamilton *et al.*, 1945; Bartels and Morgan, 1944; Rayner, 1941; Jones and Brown, 1949). Land is graded to provide 0.2 to 0.5 foot fall per 100 feet, although steeper slopes are used in some areas on soils which resist erosion. On land which has considerable side fall, the width of the checks should be adjusted to keep elevation differences between adjoining checks to 0.2 foot. Levees which guide the water moving across the field are about 2 feet wide at the base and have a settled height of about 6 inches. They are spaced at regular intervals but these may vary in width from field to field.

Factors which influence width of levee spacing are soil texture, slope, length of strips and rate of water delivery to each. The relationship which exists between availability of water and the size of strip checks for clay loam and clay soils is shown in Table III. For porous loam or sandy-loam soils, the delivery rates should be increased from 2 to 5 times those indicated in the table or the size of checks correspondingly decreased. Levees are often discontinued a few feet from the lower end of the field and the excess water is carried away by a drainage ditch. This avoids ponding of water and retards the encroachment of water tolerant species. Advantages of the strip check method of irrigation are low-labor requirements for irrigation and reasonably good control

of water application. The cost of land preparation for irrigation may be large because of the leveling which is required.

The contour check method is used on heavy soils where the land is nearly flat or gently sloping. Levees are constructed on the contour to form irregular shaped basins of varying sizes. The vertical interval between levees is usually 0.2 foot, or less on very level land. Jones and Brown (1949) recommend that contour levees have a base width of 30 to 36 inches and a settled height of at least 12 inches. Fields are irrigated from basis to basin starting at the upper side of the field. Drainage following irrigation is improved by construction of a broad shallow ditch from the upper to the lower levee near the center of the basin. The ditch also serves to carry water for irrigating each next lower basin in the pasture.

TABLE III

Size of Strip Checks for Clay Loam and Clay Soils at Various Rates of Water Delivery to each Strip [a]

Flow delivered to each strip cu. ft. sec.	Length of check for various widths of strip			
	10 ft. wide	15 ft. wide	20 ft. wide	25 ft. wide
0.2	440	—	—	—
0.3	660	440	—	—
0.4	880	660	440	—
0.5	880	660	—	440
0.6	1320	880	660	—
0.7	1320	880	660	—
0.8	—	1320	880	660
0.9	—	1320	880	660
1.0	—	—	1320	880

[a] Jones and Brown (1949).

Little land moving is required for contour check irrigation other than to fill small depressions and remove high points with a land plane. Therefore, the initial preparation costs are much less than for the strip check method. Labor requirements are low although large heads of water are required and it is difficult to control the amount applied. Some modifications of this method are being tried in an effort to avoid difficulties resulting from slow or improper drainage.

Wild flooding is used for irrigating pastures in the Sierra Nevada foothills and throughout much of the Intermountain Region. Irrigation ditches are built on grades of 1½ to 2 inches per 100 feet and spaced at intervals of 50 to 300 feet depending upon the steepness of the slope. Water is distributed from the ditches at frequent intervals by raising the

level with a dam at the downstream edge of the section to be irrigated. Little or no land preparation is required other than the construction of irrigation ditches. The initial cost is therefore very low, but constant attention and considerable skill is required by the irrigator if he is to make efficient use of his water. Thus the cost of labor for irrigation is large compared to other methods.

Little or no land preparation is required for sprinkler irrigation. A sprinkler system may have an advantage on shallow soils, and especially those underlaid with hardpan because the removal of surface soil may be very detrimental. Veihmeyer (1948) states that other advantages of sprinkling include effective use of a small flow of irrigation water, uniform distribution, and ease of adjusting water needs of different soils in the same field. He lists disadvantages of sprinklers as their high cost, more water lost by evaporation, and slow penetration of water on some soils which results in runoff before an adequate amount is applied. Various types of sprinklers are discussed in the abovementioned publication.

2. Seedbed Preparation and Seeding

Methods used in the preparation of a seedbed for irrigated pastures are similar to those used for all small seeded species. Hamilton *et al.* (1945) list the requirements of a good seedbed as fine textured, firm, moist, fertile, and free of weeds. Tillage operations to accomplish the desired results usually involve plowing or disking, harrowing, and packing except when seeding in pea or grain stubble. A springtooth harrow is sometimes used in place of the plow or disk on land relatively free of weeds.

Jones and Brown (1949) in California recommend an irrigation before seeding to settle the fills, firm the soil, and provide subsoil moisture. The field is then planed if irregular settling has occurred, and harrowed just before seeding. Nitrogen fertilizers, if used, are applied just before or at seeding time. Manure and phosphate fertilizers are normally worked into the soil during the seedbed preparation. Irrigation before seeding is seldom necessary in the Intermountain Region.

Pastures can be seeded at any time that favorable moisture conditions and temperature can be maintained. In areas having cold winters, 6 to 10 weeks of growing weather are required for the young plants to become winter hardy. Hamilton *et al.* (1945) point out that cool-season grass seedlings attain winter hardiness at an earlier age than the associated legumes. In the Intermountain Region of the Western United States it has been customary to seed pastures in the spring, on fall plowed land. However, an increasing number of farmers are seeding in

August in grain stubble or on land from which canning peas have been harvested. Post and Tretsven (1939) and Hamilton *et al.* (1945) recommend fall seeding if the land is not weedy, the grain has not shattered, and adequate irrigation water can be applied. Bingham and Monson (1946) consider grasshopper injury is avoided by late summer seeding in grain stubble.

In areas having mild winters, Jones and Brown (1949) recommend fall and early winter seeding. Matlock (1943) recommends seeding in August and September for various sites in Arizona. Robertson *et al.* (1948) recommend spring seeding but state that at high elevations where snow cover is dependable in winter, good success has resulted from late fall planting, germination occurring in early spring. This practice takes full advantage of spring precipitation, and saves some irrigation water and the labor of applying it. In California, the seeding time is adjusted to take advantage of the natural winter rainfall. It is seldom possible to establish a stand in dry weather by flood irrigation. However, a few farmers have established successful stands of ladino clover in the Sacramento Valley by airplane seeding in standing water. Ladino clover germinates rapidly in water and the seedlings are established by the time the field dries.

Drilling the seed is preferred if the seedbed is firm, but broadcasting is satisfactory on loose soil. Double seeding in different directions insures good broadcast distribution. Robertson *et al.* (1948) also recommend double seeding in drilling. Companion crops, if used, are seeded first. When planting a pasture in grain stubble the seed should be drilled, otherwise it is not easily covered.

Airplane seeding of pastures is becoming increasingly important in California on fields which are large enough to justify this method. From 300 to 500 acres can be seeded in a day at a cost of $1.00 to $2.00 per acre for double seeding. This method costs slightly more than ground broadcasting, but has the advantages of speed and the ability to seed when the field is too wet for ground equipment. Winter seedings in California are normally broadcast without covering.

Depth of seeding can be rather accurately controlled on a firm seedbed, but may be improved by the use of depth regulators on the drill. Shallow seeding of not more than one-half inch is normally recommended. Deeper seeding may be advisable on sandy soils or under conditions where adequate surface moisture is uncertain. The legume fraction of the mixture is usually seeded through the alfalfa hopper and the grass fraction through the grain side of a drill. Southworth (1949) has recently reported the use of rice hulls to improve the mechanical seeding qualities of chaffy grass seeds. A drill set to seed 160 lbs. barley per acre

will seed an acre of pasture grasses and legumes mixed with 2 bushels (16 lbs.) rice hulls. Many grasses which are otherwise impossible to put through a drill, can be processed in a hammermill to remove awns and appendages. Instructions on seed processing and some effects of processing on germination of tall oatgrass are reported by Schwendiman *et al.* (1940) and Schwendiman and Mullen (1944).

The cultipacker-type seeder developed at the Wisconsin College of Agriculture and reported by Ahlgren and Graber (1940) and Ahlgren (1945) is ideal for seeding pastures. It covers the seed lightly, and firms the seedbed.

Irrigated pasture seedings are made either with or without companion crops. Companion crops are almost never used in California. Hamilton *et al.* (1945), Klages *et al.* (1948), and Davies and Christian (1945) consider a companion crop desirable to prevent wind damage. Bracken and Evans (1943) regard a companion crop as useful in helping to establish pastures on land that crusts easily. Companion crops have been used successfully in the establishment of experimental pastures in Utah by Keller *et al.* (1945, 1947b). Bateman (unpublished) at the Utah Station has successfully established both pastures and alfalfa while producing high yields of barley. He considers a companion crop worthwhile if in the Intermountain region proper management practices can be followed during its growth. Barley is an ideal companion crop when seeded at not over 50 to 60 lbs. per acre. Further information on companion crops is found under IV-3.

3. Management of the New Stand

New stands should be managed to promote rapid development of the seedlings. Prolonged close grazing or grazing when wet are conditions to be avoided. The stand should have a good top growth before winter temperatures cause growth to cease. Frequent light irrigations may be required until the roots become well developed. Davies and Christian (1945) in Australia, and Levy (1945) in New Zealand report satisfactory establishment of pastures under periodic heavy grazing during the seeding year, whether with or without a companion crop. Stands are grazed when the plants are 6 to 9 inches in height, usually at 8 to 12 weeks after planting. This grazing is repeated whenever the plants have made a 6 to 9 inch regrowth. Bartels (1947) points out that heavy grazing of young pastures is sometimes necessary to prevent perennial ryegrass from smothering out slower growing white clover.

Careful irrigation is required when a companion crop is seeded with the pasture. In a study conducted at the Utah Station it was found more profitable to harvest the companion crop for grain than to graze it. In

an unpublished report, Bateman showed an advantage of 1,424 lbs. total digestible nutrients (T.D.N.) per acre plus 3,644 lbs. of straw for this method compared to grazing. During the seeding year (1946) the companion crop harvested for grain yielded 2,952 lbs. T.D.N. plus 3,644 lbs. straw per acre, while the grazed companion crop yielded 1,078 lbs. T.D.N. per acre, or a difference of 1,874 lbs. T.D.N. plus the straw. In the following year (1947) plots periodically grazed in 1946 yielded 450 lbs. more T.D.N. per acre than those taken through to grain. In 1948 and later, yields from the 2 treatments have not differed. Excellent stands were obtained under both treatments. The study was part of a pasture experiment containing 32 different mixtures (Keller *et al.*, 1947b). Bateman *et al.* (1949) point out that in 1947 this pasture yielded 5,342 lbs. T.D.N. per acre, or the equivalent of 5.31 tons alfalfa hay.

V. Management of Pastures

1. Grazing Management

The objectives of grazing management are (1) to maintain the desired balance between species, (2) to obtain continuous high production, and (3) to obtain utilization of the forage when it is most nutritious. Some forage species will tolerate close or continuous grazing while others will not. Most of the pasture mixtures now being recommended because of their high production of nutritious forage consist of species that require periods for regrowth, provided by rotation grazing, and will not survive if continuously closely grazed. With rotation grazing, two and preferably three or more pastures are grazed in rotation. After grazing, each pasture is irrigated and allowed to recover. The animals return to the first pasture from 3 to 6 or 8 times in one season. The system is highly flexible, and can be adjusted to fit into the other operations and requirements of each farm. Important considerations in developing a rotation grazing system are the number of subdivisions in the pasture, the number of days grazing in each, and the interval between grazings. Maximum yield of milk or beef will result only when the proper regrowth interval is used. If the interval is too short (the herbage too young) vigor of the plants will decline, and the grazing animals will expend an unduly large amount of energy in grazing. If the interval is too long the herbage will have lost palatability, and probably nitrogen also, and the grazing animals will not clean it up eagerly. Likewise, if the grazing period is too long in each subdivision the least desirable components of the pasture will be left until last. California dairymen have observed fluctuation in milk flow when the grazing period was as short as 5 days.

Rotation grazing was advocated many years ago by Harris (1913) and Welch (1914, 1917) and is widely used for irrigated pastures (Hamilton *et al.*, 1945; Starke, 1947; Bartels, 1944a; Semple and Hein, 1944), even though there are no experimental data under irrigation to indicate its value. The work of Hodgson *et al.* (1934) reporting a gain of 8.82 per cent from rotation over continuous grazing, has been referred to by Hamilton *et al.* (1945) and by Bracken and Evans (1943). According to Semple *et al.* (1934) rotation grazing increased production 10 per cent at Beltsville, Md., while studies in Missouri, Virginia, and South Dakota have given like results. Apparently these studies were conducted on pastures containing species that are tolerant of close grazing. Levy (1949) reports that close continuous grazing reduces production of New Zealand pastures by 50 per cent, and permits entry of weeds and undesirable grasses.

When a pasture is rather heavily stocked for a short period, the forage can be consumed when it is most nutritious, and fuller utilization and less selective grazing results. 't Hart (1949) reports that in Holland dairy cows grazing continuously achieved a utilization of 50 to 75 per cent of the forage. If the grazing period was reduced to 5 to 10 days, utilization was increased to 60 to 80 per cent but by reducing the grazing period to 1 to 2 days utilization was increased an additional 10 to 20 per cent. These data suggest a trend toward heavier stocking rates, for shorter periods under rotation grazing. The advantage of many subdivisions in a pasture, with short grazing periods is strikingly illustrated by data from the Blaettler Dairy in Santa Clara County, California, reported by Assistant Farm Advisor M. S. Beckley. In 1948 a 52-acre pasture was used in 3 subdivisions and grazed by 92 cows. Grazing 10 days in each subdivision they obtained forage with a feed replacement value of 2.5 tons alfalfa hay per acre. In 1949 the 52 acres was divided into 30 subdivisions that were grazed one day each by 110 cows. In 1948, milk production was uniformly maintained only 4 days out of the 10-day grazing period in each subdivision, with an average loss of 3 cans of milk per day for the last 6 days of each grazing period. In 1949 continuous high production was maintained. Feed replacement in 1949 was 5.5 tons alfalfa hay per acre.

Investigations at Werribee (Australia, 1947) have shown that sheep made similar gains when on rotations of 10 to 30 days. The more frequent grazings of a field did not alter the grass-legume ratio, but at 10-day intervals orchardgrass thinned out. Bartels (1944a) found that a 3-weeks' rest period between grazings enabled all seeded species to remain in the mixture; this is in agreement with observations in Utah.

In South Africa, Starke (1947) lists the following 5 reasons for ro-

tation grazing of sheep: (1) less selective grazing, (2) less fouling of the forage, (3) more regular irrigation, (4) less internal parasite infection, and (5) better quality and more palatable forage. He used pastures of approximately 4.25 acres for 150 to 200 sheep.

According to Hamilton *et al.* (1945) and Klages *et al.* (1948), a pasture is considered ready to graze when about 6 inches of growth has occurred if tall species are used, and when 3 to 4 inches high if low-growing species predominate. Schoth (1944) considers ladino clover ready to graze at 3 to 4 inches, but recommendations of California investigators include not grazing ladino clover closer than 3 to 4 inches in order to permit rapid recovery.

It is generally considered good grazing management to allow the pasture to go into the winter with at least 3 to 4 inches growth. Schoth (1944) stresses the importance of avoiding close fall grazing of ladino clover, and points out that the fleshy stolons are damaged if ladino is pastured when the ground is frozen or wet.

Selective grazing cannot be avoided entirely, but it will be reduced to a minimum under rotation grazing if the various species in the mixture are of approximately equal palatability. Mowing the pasture occasionally, with the cutter bar raised to about 3 inches, does much to keep the pasture fresh and the forage palatable. Bartels (1944a) found clipping especially worthwhile if the pasture contained orchardgrass or *Paspalum.*

Continuous close grazing is still common in the Intermountain Region of the United States. Under intensive use, it leads in a few years to pastures consisting of Kentucky bluegrass and white clover. In experimental plots Keller *et al.* (1947a) and Bateman *et al.* (1949) found this combination a consistently low producer. The clover will be reduced or even eliminated, with further reduction in yield, if use is heavy, fertility low, and irrigation applications erratic.

2. Prevention of Bloat

The prevention of bloat has been a major problem in the management of irrigated pastures in some areas. Although surveys show the actual percentage loss from bloat to be small, individual stockmen have had catastrophic losses (Cole *et al.,* 1945). Practical experience has shown that there is little likelihood of bloat on pastures containing 40 to 50 per cent or more grass. It is difficult, however, to maintain a proper proportion of grasses and legumes at all seasons. The percentage of legumes in pasture can be reduced by applying nitrogen fertilizer or barnyard manure and withholding phosphate fertilizer (Klages *et al.,* 1948).

Another practical solution suggested by Cole *et al.* (1945) is to pasture legumes only after they reach the early bloom stage although these workers admit that no well-controlled experiments have been conducted relating to this factor. Bartels (1944a) supports this idea in suggesting 3 weeks for recovery in rotation grazing which gives the forage enough maturity to reduce bloat. This procedure may be expected to be more effective in pasturing a legume like alfalfa than with ladino clover which has an indeterminant habit of growth and low fiber content. Schoth (1944) recommends continuous grazing except for animals that bloat easily, which should be removed. Cole *et al.* (1945), however, discount the value of continuous day and night pasture and grain feeding as a means of preventing bloat. The feeding of minerals and the pasturing of legumes only when free of dew or rain also appear to lack supporting evidence.

The feeding of dry hay or straw before pasturing legumes is advocated by Robertson *et al.* (1948). This method was tested experimentally by Cole *et al.* (1943) who found that overnight feeding of alfalfa hay did not always prevent bloat although coarse-stemmed hay was more effective than fine stemmed hay. Cole and Kleiber (1945) found overnight feeding of 17 lbs. of sudan hay (*Sorghum vulgare Sudanense*) completely effective, while 4 to 7 lbs. fed 2 hours preceding pasturing was ineffective in preventing bloat. Mead *et al.* (1944) found that 5 lbs. of barley straw was not sufficient to prevent bloat.

Overnight pasturing of sudan was effective in preventing bloat on alfalfa the following day in studies by Cole *et al.* (1943). Advantages of sudan pasture suggested by these authors were high palatability and a growth habit permitting rapid ingestion. It might also have been added that this procedure is less costly than hay feeding. Starke (1947) states that dry sheep and pregnant ewes are less likely than lactating ewes to bloat on alfalfa.

According to Professor Glen Staten (unpublished data) alfalfa-grass mixtures are less productive in Southern New Mexico than alfalfa alone, while over a considerable area water economy prohibits use of ladino clover. Here, pasturing alfalfa is very common. Danger from bloat is somewhat reduced by grazing only relatively mature plants, but this results in considerable waste from trampling and fouling of the forage. Staten reports that some large operators are now obtaining full forage utilization, and have eliminated bloat, by harvesting each day's requirements and feeding as green chopped material.

Birdsfoot trefoil apparently does not cause bloat in either cattle or sheep. For this reason, some farmers are using this legume in preference to ladino clover or alfalfa.

3. Irrigation

For rapid growth and high production the soil occupied by the roots of pasture plants should have readily available moisture at all times. Depth of rooting determines the volume of soil available for supplying water to the plant. Although pasture plants vary in depth of rooting, the depth of soil is often the principal factor limiting root penetration.

The capacity of different soils to hold water varies greatly. The amount of readily available water (field capacity to permanent wilting percentage) held by a group of California soils ranged from 0.67 to 2.66 inches per foot depth of soil. This range, which is approximately 4-fold, emphasizes one of the reasons for the wide differences in amount and frequency of irrigation required.

Kramer (1949) discusses factors affecting the absorption of water and points out that poor aeration may cause a considerable reduction in absorption of water by plants and that the accumulation of carbon dioxide may be a more important factor in reduced water absorption than lack of oxygen. Poorly aerated conditions are common on many of the heavy clay soils used for irrigated pastures.

The total amount of irrigation water used during the year will depend upon the length of the growing season, natural rainfall, temperature, frequency and depth of wetting, and the species involved. Frequent light irrigation increases the percentage loss from evaporation. Too heavy irrigation on permeable soils will cause water to penetrate below the root zone and be lost. However, uniformity of penetration is difficult to attain.

Water used by transpiration and evaporation of 3 pasture crops under the climatic conditions at Davis, California are shown in Table IV. In 1943, Sullivan and Winright obtained records of acre-inches of water used per acre on 7 farm pastures in the Imperial Valley which indicated a range from 48 to 81 acre-inches with an average of 68.2 inches. Similar studies in San Bernardino County, also in Southern California, by Shultis and Campbell in 1943 showed a range from 36 to 80 acre-inches per acre, the average being 65. Jones and Brown (1949) state that 33 to 36 acre-inches of water were used on shallow clay loam soils applied in 12 irrigations over a 6-months' period in the Sierra foothills of Nevada County in Northern California. Robertson *et al.* (1948) recommend 2 to 4 acre-inches of water per irrigation at 10- to 14-day intervals during June through September for most areas of Colorado. Total water requirements for the season were 2½ to 3 acre feet.

The frequency of irrigation required depends upon how soon after irrigation the soil moisture within the root zone will again be reduced

TABLE IV

Water Used (Acre-Inches per Acre by Months) by Transpiration and Evaporation of Three Pasture Crops Grown at Davis, California [a]

Crop	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Total
Alfalfa	1.5	3.9	5.3	6.5	8.0	6.6	5.0	2.0	1.2	40.0
Ladino clover	1.8	4.5	6.0	7.5	9.0	7.5	5.5	2.2	—	44.0
Sudangrass	—	—	2.0	3.2	4.0	3.4	2.2	1.2	—	17.0

[a] Data from Irrigation Division, California Agricultural Experiment Station.

to the permanent wilting percentage. The water holding capacity of the soil, temperature, and the crop influence the rate of water extraction. Many of the pastures in the interior valleys of California which contain ladino clover are irrigated at approximately 10-day intervals. On soils which are porous, irrigation may be required as frequently as every 7 days during the heat of summer. Pastures composed primarily of deeper rooted species, such as alfalfa and birdsfoot trefoil are irrigated at 2- to 4-week intervals depending upon the soil and temperature conditions.

Bartels *et al.* (1932) carried out extensive studies on frequency and amounts of irrigation water required for pastures in Victoria, Australia. The soil was described as a shallow clay loam which was slow to absorb water. Production of the pasture under prevailing conditions was best when 24 inches were applied in 6 irrigations of 4 inches each. Equal total amounts applied in either 4 or 8 irrigations were inferior.

The rate at which water is applied during irrigation has much influence on penetration. Doneen (1948) has pointed out that 50 per cent or more of the total water applied may be lost through deep percolation. Loss is greatest when the head of water is insufficient to reach the end of the check in a relatively short time. Deep percolation takes place near the head ditch. He suggests a large head be used to force the water through to the end of the check after which the head may be reduced to maintain an even flow to wet the length of the check until the desired depth of penetration has been reached.

The relationship of water delivery rate to size of the check is shown in Table III. The large delivery rates are desirable for the contour check method of irrigation because individual basins may contain up to 4½ or 5 acres (Jones and Brown, 1949). These require rapid flooding to obtain uniform penetration.

Sprinkling systems often can be advantageously used where only a small head of water is available. Frequent, light irrigations are also

possible on porous soils which normally would require rather large amounts of water if flood irrigated. Veihmeyer (1948) has pointed out that while sprinkling can save water loss from deep penetration, more water will be lost by evaporation.

Problems of drainage should be considered along with irrigation. Poor drainage inhibits growth of desirable pasture plants and encourages water tolerant weedy species. Poorly drained pastures are so slow to dry out after irrigation that the likelihood of grazing while wet is increased. Salts may accumulate under poor drainage conditions in some of the arid regions. Careful preparation of the land for irrigation is the best method of avoiding improper drainage. Some of the adobe soils of lacustrine origin in the Sacramento Valley present a drainage problem because the soil is very heavy and extremely flat so that downward percolation is almost nonexistant. If good drainage is not possible, the choice of species for the pasture should include only those capable of growing on wet land. Bartels *et al.* (1932) have pointed out the importance of the method of irrigation upon the balance of species in the pasture. Ryegrass and white clover were more favored by frequent heavy waterings than cocksfoot and subterranean clover.

Ladino clover, alfalfa and other legumes may "scald" if irrigated during extremely hot weather. The difficulty usually occurs on impervious soils on still days when temperatures exceed 100°F. and water stands for several hours. This difficulty is avoided by providing good drainage and by irrigating at night during very hot weather.

4. Fertilization

In the United States, fertilizers have been used less extensively on irrigated pastures than on most cultivated crops. In recent years, however, experimental studies have shown large increases in yield are obtained from the fertilization of pastures under many conditions. According to Hamilton *et al.* (1945) the average farm in the irrigated west produces enough barnyard manure to provide 8 to 10 tons per acre every 3 years. Robertson *et al.* (1948) in Colorado recommend top dressing with manure in February or March to provide 2 weeks more of early spring grazing. Boyd (1945) in Wyoming suggests using 8 to 10 loads of manure every few years, applied in fall or winter. Klages *et al.* (1948) consider top dressing with manure the best fertilization for pastures, supplemented with phosphorus (40 to 50 lbs. P_2O_5 per acre) in southern Idaho and with sulfur (100 lbs. gypsum per acre) in parts of northern Idaho.

It is generally recognized that manure stimulates the growth of grasses more than legumes (Bateman, 1940; Hamilton *et al.*, 1945; Klages *et al.*,

1948; Schoth, 1944). To maintain a vigorous growth of legumes in pastures that are manured, phosphate fertilizer should also be applied. Schoth (1944) recommends 8 to 10 tons manure per acre, supplemented with 300 lbs. superphosphate or the equivalent. Bateman (1940) recommends that farmers in Utah apply 10 to 15 tons manure with 200 lbs. "treble" superphosphate (43 per cent P_2O_5) to their pastures every 3 years. He reports that Pittman found that one application of 600 lbs. of treble superphosphate increased yields 63.6 per cent over a 5-year period, the gain the first season amounting to 211 per cent. He found that phosphorous fertilizer increased the nitrogen content of the herbage, by increasing the per cent legumes in the pasture. One application of treble superphosphate at 200 lbs. per acre resulted in a 22.7 per cent increase in the phosphorus content of the forage over a 3-year period. In another study Bateman (1943) found that one application of 6.8 tons manure with 200 lbs. treble superphosphate, applied to the pasture plots between March 27 and April 6, increased the first grazing 27 per cent, the second grazing 108 per cent, the third grazing 117 per cent, the fourth grazing 102 per cent, and a small fifth grazing 187 per cent, the year's gain amounting to an increase of 95.7 per cent. Ewalt and Jones (1939) report a 75 per cent increase in production over a 5-year period from annual applications of 300 lbs. superphosphate (16 per cent P_2O_5). This treatment did not alter the chemical composition of ladino clover in the pasture.

Pittman and Bennett (1948) in a study of irrigated meadow pastures in ranching areas of northern Utah, report a 50 per cent increase in production from either 10 tons manure or 200 lbs. ammonium sulphate per acre. One application of manure stimulated growth through 4 years. Applications of 200 lbs. treble superphosphate per acre were profitable where legumes were abundant. Liquid manure containing some solids, urine, and barn washings is especially valuable pasture fertilizer (Hamilton *et al.*, 1945). Yearly applications equivalent to 10 tons of barnyard manure per acre may be used in light applications after each grazing. Fertilization costs may be much reduced if the manure can be applied with the irrigation water.

The rapid development of irrigated pastures in Victoria, Australia is attributed by Bartels and Morgan (1944) to the universal response of these pastures to phosphate fertilizer. At Werribee, Morgan (1949) reports profitable responses from applications of superphosphate (22 per cent P_2O_5) at 400 to 500 lbs. per acre per year if moisture is not limiting, and under similar conditions Rayner (1941) recommends 400 lbs. Annual applications of 200 lbs. superphosphate increased production 77 per cent with 6 irrigations totaling 2 feet of water per year (Australia,

1947). Additions of 100 lbs. ammonium sulphate, nitrate of soda, or potassium sulfate, or 3000 lbs. lime or gypsum, failed to increase yields further, and in some instances lowered them. Rock phosphate was found to be highly inefficient. In northern Victoria Morgan and Rayner (1941) recommended annual applications of 300 lbs. superphosphate. According to Bartels (1944a) many farmers apply as much as 500 lbs. superphosphate per acre to their pastures each year. Applying phosphorus at one time (in the fall) was as effective as several fractional applications during the year (Australia, 1947; Morgan, 1949; Rayner, 1941). Rayner (1947) found that liberal top dressings of superphosphate not only increased yield but fostered development of the more valuable species to the exclusion of weeds and other less desirable forage.

In a few instances pastures have responded to fertilizers other than manure and phosphorus. According to Schoth (1944) in Oregon, and Andrew (1947) in Victoria, potash has been profitably applied on some soils. Both Schoth (1944) and Klages *et al.* (1948) report beneficial responses from sulfur on some soils of Oregon and northern Idaho. Although the response to manure and phosphorus is widespread, use of other fertilizers should be based on prior tests conducted on the land.

5. Molybdenum Toxicity

Britton and Goss (1946) reported an ailment in cattle and sheep which had been prevalent for many years along the southwest edge of San Joaquin Valley in central California. Ingestion of green feed containing abnormally high quantities of molybdenum was found to be the cause. The symptoms in cattle are excessive scouring, loss of weight and roughening and gradual fading of the hair. Loss of hair and eventual death of the animal may result. Ferguson *et al.* (1943) and Lewis (1943a, 1943b) have reported a similar condition in England. Barshad (1948) has shown that, in general, abnormality in cattle occurred when a large portion of the pasture plants contained 20 or more parts per million of molybdenum but no difficulty was observed if less than 10 p.p.m. was found. Analysis of soils in the affected area of California indicated the molybdenum content was only slightly higher than normal soils although the solubility was relatively high. The alkalinity of these soils was responsible in part for the high solubility.

Legumes growing on affected soils absorb greater quantities of molybdenum than grasses. *Lotus corniculatus* and *Trifolium repens latum* contained as much as 150 p.p.m. dry matter compared with 33 p.p.m. in *Lolium perenne* and 9 p.p.m. in *Paspalum dilatatum*. The total molybdenum content of soils ranged from 5 to 10 p.p.m. where these

samples were taken, but Barshad (1948) points out that cattle may be affected on soils containing as little as 1.5 p.p.m.

Grazing and livestock management systems for control of molybdenum poisoning are as yet based upon limited evidence and only partially published. Barshad (1948) states that feeding of dry roughage tended to reduce scouring. Rotation of livestock between badly affected and less badly affected areas has been suggested. Emrick (1948) recommends a special pasture mixture from which legumes are eliminated for soils that may contain excessive amounts of molybdenum.

Use of copper in the form of copper sulfate in the drinking water has been successful in overcoming molybdenum poisoning in some instances according to an unpublished report of the California Agricultural Experiment Station. Acidifying the soil with sulfur or other acidifying materials has been suggested as a method of reducing the availability of molybdenum. The use of nitrate fertilizer has reduced the uptake of molybdenum and its value on a field scale should be determined.

Even though very low concentrations of molybdenum in the soil may be taken up by plants in concentrations that become toxic, the element is essential to plant growth, and particularly to thrifty development and nodulation of legumes. Anderson (1946) has shown that some soils of south Australia are so deficient in molybdenum that applications of 1 or 2 ounces per acre were associated with very large increases in forage, particularly on land not deficient in phosphorus.

6. Weed Control

Annual weeds are seldom, if ever, a serious problem in well-managed irrigated pastures, particularly if the initial establishment is good. Occasionally pastures become infested with perennial thistles or other unpalatable perennial weeds. It is not advisable to seed pastures on land known to be badly infested with weed seeds. Management practices which help to keep weeds under control are fertilization, careful irrigation, and mowing. Scattered weeds can be removed with a sharp shovel. If the infestation is general, resulting in greatly reduced productivity of the pasture, it is advisable to plow and return the land to row crops or fallow until the weeds are controlled.

According to Hamilton *et al.* (1945) many perennial weeds that commonly occur in pastures will be eaten by cattle if mowed about 2 days before the end of a grazing period. In the Intermountain Region irrigated pastures often become infested with dandelion (*Taraxacum officinale*). Dandelion can be controlled in pastures by spraying with 2,4-D, without permanent damage to legumes, but whether this is a prac-

tical measure is not now known. Spraying has been used with some success on curly dock (*Rumex crispus*) in California.

VI. Economy of Pastures

1. Productivity

The carrying capacity and productivity of irrigated pastures have been measured and reported in various ways. Methods for evaluating pasture research have been reviewed by Ahlgren (1947) who emphasized the advantages of using grazing animals. Comparison of results from different experiments is often complicated by the variety of measuring units used. Some effort has been made to standardize the measuring and reporting of grazing studies (Report, 1943).

Production in terms of live weight gains of lambs and steers was between 400 and 500 lbs. per acre of irrigated pasture in studies conducted on farms in the Sacramento Valley in California (Burlingame, 1949). Albaugh and Sullivan (1949) in Monterey County, California compared gains per acre made by cows and calves on irrigated pasture with gains per acre on alfalfa cut and fed green in the dry lot. Gains on pasture alone were 458 lbs. per acre compared with gains on alfalfa of 581 lbs. Over 2,000 head of cattle were used in this study. Bartels (1944a) in Australia reports gains from young sheep of over 1,000 lbs. per acre per year.

Burlingame (1949) in California obtained production records of dairy cattle, sheep and beef cattle on irrigated pasture through the use of "Animal unit months." All classes of livestock were compared on the basis of total digestible nutrients required per day. Morrison's feeding standards were used with minor rounding for ease of calculation. An Animal unit month (A.U.M.) was estimated to be 400 lbs. T.D.N. for a mature cow giving 200 lbs. of butter fat per year. He found that irrigated pastures in the Sacramento Valley had an average production of 10 A.U.M. per acre. Over 90 per cent of the pasturage obtained was during the eight-month period of March through October.

Bateman and Packer (1945) report pasture production of 253 standard cow days per acre, over a 3-year period. This is an equivalent of approximately 4 tons alfalfa hay per acre. A standard cow day was taken to equal 16 lbs. T.D.N. as proposed in the Preliminary report on pasture investigations technique (Report, 1943). In another study Bateman *et al.* (1949) found that an unimproved pasture, without fertilization, produced 2,921 lbs. T.D.N. per acre, or 183 standard cow days of grazing (4-year average). This pasture was fertilized with 5 tons manure and 87 lbs. 43 per cent phosphate annually and yielded 4,111 lbs. T.D.N.,

or 257 standard cow days of grazing annually during the following 5 years. New mixtures now being studied, with fertilization, yielded 5,204 lbs. T.D.N., or 325 standard cow days of grazing. This production is equivalent to 5.1 tons alfalfa hay per acre, and with a herd averaging 366 lbs. butter fat per year amounted to 230 lbs. butter fat per acre.

In a 5-year study of some improved dairy pastures in Utah, Rich *et al.* (1950) report an average of 303 standard cow days of grazing by high producing cows during a grazing season averaging 156 days per year. The alfalfa hay equivalent averaged 4.85 tons per acre and in different seasons ranged from 4.42 to 5.43 tons.

Annual production of good irrigated pastures ranged from 20 to 25 tons green weight in Australia (Andrew, 1947; Rayner, 1947). Bartels (1944a) reports experimental plots yielding 31 tons green weight per acre from 12 clippings. Unpublished data from experimental plots in California showed a range from 22.1 to 35.8 tons green weight per acre, depending upon the mixture. In Utah, with a comparatively short grazing season, new mixtures in experimental plots have yielded 16 to 17 tons per acre green-weight, according to Bateman *et al.* (1949) but with identical treatment the mixture in general use in the area produced only 10 tons. The data are based on 4 clippings, each preceding a grazing period. Jones and Brown (1949) state that an irrigated pasture should yield as large a tonnage of feed per acre as alfalfa, although there may be a few exceptions.

2. Economic Studies

Initial costs for developing irrigated pastures for flood irrigation include surveying, leveling, land planing, construction of irrigation ditches, drainage ditches and levees, turnout structures, seedbed preparation and seeding. As of 1948, the total costs of preparing land for flood irrigation by the strip-check-method varied from $30 to $130 per acre in California (Jones and Brown, 1949). Total annual costs of production of established irrigated pastures ranged from $17.43 to $58.35 per acre for different operating units in the Sacramento Valley in 1948 (Reed and Geiberger, 1948; Burlingame and Kolb, 1948). Cost items included labor, materials such as irrigation power and fertilizer, taxes, general expenses, depreciation and interest on the investment.

Burlingame (1949) found that labor for irrigation, fencing and other purposes accounted for slightly over one-fourth of the total costs per acre. Interest on land values, facilities, and the pasture stand approximately equaled labor costs. Total costs averaged $32.62 per acre on 24 records totaling 1,188 acres in 1947, as shown in Table V. On an

average, a little over 60 per cent of total cash and labor costs was for water and irrigation labor. Water costs ranged from about $2.00 per acre on land in some irrigation districts to over $20.00 where pumping from considerable depths was required. Irrigation labor varied from

TABLE V

Principal Items of Cost in the Production of 24 Irrigated Pastures Totaling 1,188 Acres in the Sacramento Valley, 1947 [a]

Item	Cost
Labor for irrigation, fencing, etc.	$ 8.67
Water costs, fertilizer, and other materials	6.90
Taxes and general expenses	3.42
Depreciation on stand, irrigation system, etc.	4.88
Interest on land values, facilities, and stand	8.75
Total cost per acre	$32.62
Animal unit months of pasturage per acre	9.4
Total cost per animal unit month	3.48

[a] Burlingame (1949).

less than $3.00 to more than $17.00 per acre depending upon the method of irrigation, size of head of water, and efficiency of the irrigation system. Irrigated pastures have decided economic advantage in regions of abundant cheap water and relatively level land.

Total costs per acre are of much significance only when considered in relation to productivity. Gorton (1941), Burlingame and Kolb (1948), and Hedges (1948) have shown that high producing pastures usually have lower costs per unit of feed produced than low producing pastures although total costs per acre may be higher. Three California studies are reported in Table VI. Burlingame and Kolb (1948) obtained costs ranging from $1.60 to $8.61 per Animal unit month (A.U.M.). Differences in productivity were primarily responsible for this range. These average costs per A.U.M. were used to calculate the equivalent value of alfalfa hay per ton on the basis of equal amounts of total digestible nutrients from the pasture and alfalfa. The alfalfa hay averaging 50 per cent total digestible nutrients could cost only $10.73 per ton to equal the average cost of $4.28 for an Animal unit month. The seasonal average price of alfalfa hay in California during this same year (1948) was $22.10 per ton. Gorton (1941) found that in Oregon, costs per acre decreased as the size of the pasture increased. The production of pastures also decreased with increasing size, however, result-

ing in the size of pastures having little or no relationship to costs per unit of production.

TABLE VI

Irrigated Pasture Costs per Acre and per A.U.M. in the Sacramento Valley, California in 1948

Author	No. units studied	$ Cost per A.U.M. Low	High	Av.	Equiv. value Alfalfa per ton [a] $	Av. total cost per acre, $
Reed and Geiberger (1948)	3	3.00	5.55	3.58	8.95	37.59
Burlingame and Kolb (1948)	9	1.60	8.61	4.23	10.57	25.07
Hedges (1949)	17	2.90	7.02	5.05	12.63	30.82
Average	—	2.50	7.06	4.28	10.73	31.16

[a] Calculated on the basis of 400 lbs. total digestible nutrients per A.U.M. at average costs indicated in table.

Seventy-nine dairy records obtained in 1947-1948 were reported by Shultis and Miller (1949) in the San Joaquin Valley and classified according to high and low use of pasture for market milk dairies and manufacturing milk dairies. The market milk dairies making high use of pasture showed an advantage over those making low use of pasture, amounting to $33.99 per year in feed costs per cow and $28.31 profit per cow. Corresponding comparisons for manufacturing milk dairies was $24.62 advantage in feed costs and $42.24 greater profit per cow. For both types of dairies the pounds of butterfat sold per cow were greater under low use of pasture but added costs for hay, concentrates, silage and green feeds decreased profits.

Bateman and Packer (1945) have reported production and cost studies on the Utah Agricultural Experiment Station Dairy Experimental Farm herd. A summary of their 3-year study is reported in Table VII. On the basis of butterfat at $.90 per lb., they obtained a return of $5.15 per dollar of production cost, and a gross return, above feed production cost, of $149.39 per acre. They conclude "that pasture, when planted on fertile soil and well managed, is an economical feed for the production of milk and butterfat and gives a high return per acre when grazed by good dairy cattle."

Albaugh and Sullivan (1949) made a direct comparison of costs of pasture feeding and feeding of green alfalfa hay to beef cattle in the dry lot. The alfalfa was mowed daily, mechanically loaded, hauled by truck to the feed lot and unloaded by hand. Costs per 100 lbs. gain

TABLE VII

Per Acre Returns from Pasture; Utah Agricultural Experiment Station Dairy Experimental Farm [a]

Item	3-Year average
Standard cow days of grazing [b]	253
Supplemental feeds fed: alfalfa (lbs.)	1127
grain (lbs.)	1707
Gain in body weight (lbs.)	224
Total production: milk (lbs.)	8704
butterfat (lbs.)	303
Butterfat produced from supplement feeds fed (lbs.)	98
Production from pasture: milk (lbs.)	5909
butterfat (lbs.)	206
Value of butterfat produced from pasture at $.90 per lb.	$185 40
Production cost per acre	36.01
Gross return above feed production cost	149.39
Dollars returned for each dollar cost of pasture production	5.15
Pasture feed production cost of 1 lb. butterfat	.18

[a] Bateman and Packer (1945).

[b] A standard cow day is defined as an animal obtaining 16 lbs. of total digestible nutrients from pasture per day.

were less on pasture than from dry lot feeding of green alfalfa. Although the alfalfa produced more feed per acre, costs of harvesting and feeding more than offset this advantage. After considering purchasing and selling prices, pasture feeding was the more profitable.

Hedges (1948) studied 17 pasture units in the Sacramento Valley ranging in size from 60 to 490 acres. In these studies gains from beef cattle and lambs were obtained in addition to costs and carrying capacities. This method avoided the limitations of the above reported studies of carrying capacities which provided no information on costs in relation to gain in weight or milk production. Gains per acre ranged from 154 to 440 lbs. per acre with an average of 275 lbs. Animal unit months per acre averaged 6.1. Costs per 100 lbs. gain ranged from a low of $6.47 on a 440 acre unit to a high of $14.94 on a 310 acre unit. Average costs per 100 lbs. gain was $11.20.

3. Effect of Pastures on Crops that Follow

The beneficial effects of sod crops on soil structure, and fertility have been extensively investigated by many State Experiment Stations. There apparently have been no studies conducted specifically with irrigated pastures in crop rotations. General farm practice has been to

maintain pastures so long as they are productive. Many irrigated pastures in California are still producing satisfactorily after 20 years.

However, several writers have emphasized the importance of using irrigated pastures in a rotation and have mentioned increased yields of crops which follow (Klages *et al.*, 1948; Robertson *et al.*, 1948; Starke, 1947; Bartels, 1944b; and Hamilton *et al.*, 1945). Klages *et al.* further mention that sweet clover with mountain brome leaves the soil in better condition for the crops to follow than sweet clover alone when these plants are used for temporary irrigated pastures. These writers also suggest that 4 years are usually long enough for a field to remain in pasture, although the exact length of time may be influenced by many factors.

VII. Pastures in Relation to Other Sources of Feed

1. Relation to Other Forage Resources

Irrigated pastures are depended upon as the sole source of forage in relatively few areas. Throughout the western United States they are used most extensively for dairy cattle. Irrigated pastures are used to supplement the range in the production of both beef and sheep. Guilbert and Hart (1946) report that one and a half million beef cattle and calves derived 13 per cent of their feed from 150 thousand acres of irrigated pasture, while also harvesting the forage from 40 million acres of range land. About half as many dairy cattle utilized the forage from 224 thousand acres irrigated pasture and one million acres of range, while nearly 3 million sheep grazed 120 thousand acres of irrigated pasture and 18 million acres of range. The use of irrigated pastures for the production of beef and sheep is increasing in the western United States.

Throughout much of the western range country beef cattle are wintered on wild hay produced on irrigated mountain meadows. The common practice is to remove the cattle from the meadows as early in the season as forage is available on the spring ranges. The meadows then produce a crop of wild hay which is cut in midsummer. The aftermath is grazed by the cattle after they return to the home ranch in the fall. The cattle remain on these meadows throughout the winter, being fed the wild hay produced there. Stewart and Clark (1944) found that greater total yields, and higher quality forage were produced when the meadows were grazed 20 to 35 days longer than customary in the spring, and the hay crop cut at the bloom stage, which is earlier than most ranchers harvest. This practice benefited spring ranges by reducing grazing on them, and at the same time kept the animals at the home

ranch during calving and immediately after, allowing the rancher to give them better care than when they are on the range. Stoddart (1944) reported that in northern Utah dairy bred heifers did not make as good gains on summer range as beef, but that they did make satisfactory development for subsequent milk production. Collins (1945) has reported the successful operations of several ranchers in improving the productivity of their irrigated mountain meadows.

Jones and Mumford (1944) in Oregon, recommend sudangrass as a supplement to permanent pasture in late summer, and Abruzzi winter rye for late winter and early spring on well drained land. In South Africa, Bonsma (1947) found winter cereals, where adapted, a cheaper source of succulent feed for dairy cows than silage. Madson and Love (1948) report that in California silage is made from a variety of crops, but that while pasturage is available it is a much more economical source of feed. In Australia, Bartels (1944b) reports the effective use of a number of annual forage crops, both as a supplement to irrigated pastures and to take livestock from nonirrigated areas through drought years. Corn, millets, and sorghum have been used for this purpose.

2. Supplemental Feeding

Jones and Brown (1949) recommend having dry roughage available to cattle and sheep at all times while on irrigated pasture, to reduce bloat and increase dry-matter consumption. Jones and Mumford (1944) point out that the capacity of a dairy cow to consume green forage is limited, and that high producing cows on pasture will require a supplement of grain for maximum production. If cows on pasture are liberally fed such supplements as ryegrass hay or corn silage, some protein concentrate may be needed, in addition to grain. According to Klages *et al.* (1948) dairy cows will produce one lb. of butterfat daily and maintain body weight on irrigated pasture alone but production is increased if alfalfa hay is also fed. Hamilton *et al.* (1945) recommend feeding an increasing amount of concentrate to high producing cows, as the productivity of the pasture declines. Ewalt and Morse (1942) and Bateman (1945) have prepared tables to guide dairymen in feeding grain to cows on irrigated pasture.

Beef cattle will make excellent growth on irrigated pasture without any supplements. Carbohydrate concentrates are frequently used in the fattening process.

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Example: Adams, J. E., 20 (see Rigler) means that Rigler *et al.* will be mentioned on page 20, the *et al.* accounting for Adams. This article can be located under Rigler in the list of references.

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