UNIVERSAL
LIBRARY
OU_156911
UNIVERSAL
LIBRARY

OSMANIA UNIVERSITY LIBRARY

Call No. 631.4/ M21 S Accession No. 31568

Author Malhotra a. Dc. V.

Title Soil fertility. 1950

This book should be returned on or before the date last marked below.

SOIL FERTILITY

SOIL FERTILITY

BY

I. DE V. MALHERBE

B.A. (CAPE); PH.D. (MUNICH)

Professor of Agricultural Chemistry
in the University of Stellenbosch

SECOND ENGLISH EDITION

GEOFFREY CUMBERLEGE
OXFORD UNIVERSITY PRESS
LONDON NEW YORK CAPE TOWN
1950

Oxford University Press, Amen House, London E.C.4
GLASGOW NEW YORK TORONTO MELBOURNE WELLINGTON
BOMBAY CALCUTTA MADRAS CAPE TOWN
Geoffrey Cumberlege, Publisher to the University

English version first published 1948
Second English Edition 1950

PRINTED IN GREAT BRITAIN

PREFACE TO FIRST ENGLISH EDITION

THE real wealth and the greatest heritage of a nation is its soil. There is therefore no need to stress the desirability for the appearance of a book dealing with the principles of Soil Fertility as applied primarily to South African conditions. For the last fifteen years this book has been available to the Afrikaans-speaking public, and I have at last acceded to the repeated requests of many English-speaking students and farmers to have the text translated into English. My reason for this decision is that the moment is indeed opportune, because figuratively speaking South African Farming stands on the threshold of a New Era and there is great need for enlightenment on soil matters. With the adoption by the Union Parliament of the Soil Conservation Act in June 1946, the legal machinery has been established for enforcing systems of conservation farming throughout the length and breadth of this subcontinent; in other words, all slipshod farming activities entailing avoidable soil wastage will henceforth be banned.

The book has been written to fulfil the requirements of the following categories of readers: (*a*) high school pupils who have chosen Agricultural Science as one of their subjects for the Matriculation or Senior Certificate examination; (*b*) prospective young farmers and soil-conservation officers who are attending the two-years' diploma and other courses at the Colleges of Agriculture; (*c*) university students who follow degree courses in Agriculture, Forestry, and Soil Conservation as an introductory reader; (*d*) farmers of all ages who are desirous of increasing their knowledge of the medium on which their prosperity depends. After all, they are the people who have 'to deliver the goods', and they must accomplish this without leaving to posterity an impoverished soil.

The book covers the whole field of scientific and applied Agricultural Chemistry, albeit mostly in elementary fashion, and some of the above categories of readers may therefore find portions of the book which do not interest them particularly. For example, the practical farmer may, without being handicapped in his further reading, skip the chapters on minerals and rocks, weathering, and soil-formation processes, &c. However, if he has the time and inclination it would do him no harm to study and ponder over these subjects. He would then get an inkling of the countless ages that it took nature to produce a couple of feet of agricultural soil from the hard, intractable rock, and he might possibly obtain a greater reverence for the soil upon which his livelihood and that of posterity depend. This knowledge might spur him on to do all in his power to avert soil wastage and to be a convinced fighter in the struggle against the loss of 300,000,000 tons of surface soil which is stated to be erosion's *annual* levy on the Union's heritage; in other words, the equivalent of 300,000 acres of topsoil.

To readers outside the Union of South Africa it should be explained that the official land unit in the Union is the (Cape) *morgen* which for all practical purposes may be taken to be equivalent to *two acres* (actually 2·117 acres). Where morgen rates of application of fertilizers, &c., are stated in this book, the acre figures may be obtained by simply halving the morgen figures.

In conclusion I desire to express my sincere gratitude to my collaborators. In the first place my thanks are due to Mr. H. F. Meyer, one-time agricultural teacher in secondary schools of Natal, who undertook the arduous task of rendering the Afrikaans text into fluent English. He performed the 'heavy spade work' but I take full responsibility for the final version. In the second place I am greatly indebted to Doctors Thos. D. Hall and H. H. Dodds, both recognized authorities in their respective fields, who so willingly contributed the articles on the 'Manuring of Natural and Established Pastures' and the 'Manuring of Sugar-cane' respectively. Their contributions were written in English.

May this book find as favourable a reception among our English-speaking community as it did in the Afrikaans section, and may it be instrumental in placing South African Farming on a firmer and more prosperous foundation.

I. DE V. M.

STELLENBOSCH
January 1948

CONTENTS

PART ONE

THE NUTRITION OF PLANTS

CHAPTER I. INTRODUCTION . . . 1
Agricultural Chemistry and what it Comprises 1
Fundamentals of Chemistry . . 2

CHAPTER II. THE CHEMICAL COMPOSITION OF PLANTS 5

CHAPTER III. NUTRITION OF GREEN PLANTS . 10
What Plant Foods Mean . . 10
Absorption of Nutrients from the Air . . 11
Absorption of Water by Plants 15

CHAPTER IV. SOIL NUTRIENTS . . 23
Nitrogen Nutrition of Plants 23
The Ash Constituents 25
The Trace or Minor Elements 32
Absorption of Nutrient Salts 34

PART TWO

SOIL SCIENCE

CHAPTER V. INTRODUCTION . . . 36
The Chemical Composition of the Earth's Crust 38
The Most Important Rock-forming Minerals . . 38

CHAPTER VI. SOIL-FORMING ROCKS . . 44
A. Igneous Rocks 44
B. Sedimentary Rocks 47
C. Metamorphic Rocks 50

CHAPTER VII. THE ORIGIN OF SOILS . . 52
Weathering of Rocks and Minerals 52
Transportation of Soil Material 57

CHAPTER VIII. FORMATION AND DECOMPOSITION OF HUMUS IN SOILS 61
The Origin of Organic Matter in Soils . 61
Organic Weathering and Formation of Humus . 61
The Decomposition of Humus 63

CHAPTER IX. THE MECHANICAL COMPOSITION OF SOILS . 66
The Mechanical Analysis of Soils 66
How Soil Samples should be Taken and Prepared . . . 67

CHAPTER X. THE IMPORTANCE OF THE SOIL TEXTURE . 72
Soil Texture and Physical Properties 74

CHAPTER XI. SOIL COLLOIDS AND THEIR PROPERTIES 77

CHAPTER XII. THE STRUCTURE OF SOILS 83
Crumb Structure—Its Importance and Formation . 85
Pore Space and Weight of Soils 88
The Specific Gravity of the Solid Soil Constituents 89
The Volume Weight of Soils 90

CHAPTER XIII. WATER RELATIONSHIPS OF SOILS . 92
The Water Capacity of Soils 94
The Movement of Soil Moisture . . 96
The Available Soil Moisture . 98
Loss of Water from Soils . . . 103

CHAPTER XIV. SOIL AIR . 105
Composition of Soil Air . 105
The Importance of Soil Gases . 106
Soil Aeration . . 107

CHAPTER XV. SOIL TEMPERATURE . 109
The Heating of Soils . . 109
The Cooling of Soils 111
Temperature Fluctuations in Soils . . 112

CHAPTER XVI. THE CONTROL OF SOIL MOISTURE . . 115
(*a*) Absorption of Water by Soils and Soil Erosion . 115

CHAPTER XVII. THE CONTROL OF SOIL MOISTURE (*cont.*) . 127
(*b*) Dry-land Farming 127

CHAPTER XVIII. THE CONTROL OF SOIL MOISTURE (*cont.*) . 135
(*c*) Irrigation 135

CHAPTER XIX. THE CONTROL OF SOIL MOISTURE (*cont.*) 146
(*d*) Drainage 146

CHAPTER XX. THE CHEMICAL PROPERTIES OF SOILS . . 153
The Chemical Analysis of Soils . . 153
Reserve Plant Food 154
Available Plant Food . . 158

CHAPTER XXI. SOIL ACIDITY 160
Where are Acid Soils found? 163
Degrees of Soil Acidity 163
The Practical Importance of the Soil Reaction . . . 164

CHAPTER XXII. BRAK SOILS AND THEIR RECLAMATION 166
Properties and Classification of Brak Soils 166
Origin and Occurrence of Brak Soils 168
The Reclamation of Brak Soils 169

CHAPTER XXIII. THE SOIL MICRO-ORGANISMS AND THEIR ACTIVITIES 172
Groups of Micro-organisms 172
Conditions governing the Activities of Soil Microbes . . 174
Functions of Soil Microbes 175

PART THREE

FERTILIZERS AND MANURES, THEIR PREPARATION, PROPERTIES, AND USE

CHAPTER XXIV. INTRODUCTION . . . 184
Classification of Fertilizers and Manures . . . 185
Nitrogenous Fertilizers . . . 186

CHAPTER XXV. PHOSPHATIC FERTILIZERS . . . 195

CHAPTER XXVI. POTASSIC FERTILIZERS 207
Liming Materials 209

CHAPTER XXVII. FERTILIZER MIXTURES . . 214
The Evaluation of Fertilizers . . 215

CHAPTER XXVIII. FARM MANURES . . 219
The Composition of Farm Manures 219
Rotting or Decomposition of Farm Manure . . 222
Treatment of Manure . . 224
Karoo Manure 227
The Effect of Farm Manures on Soils . 228
The Use of Farm Manure . . . 229
Compost 230
Poultry Manure . . 233

CHAPTER XXIX. GREEN MANURING . . . 235
The Aim of Green Manuring . . . 235
Requirements for Successful Green Manuring . . . 237
The Importance of Humus 238
Green Manuring in South Africa 239

CHAPTER XXX. MANURIAL REQUIREMENT OF SOILS . 241
The Law of the Minimum 241
Determining the Manurial Requirement of Soils . . . 243
Pot Experiments 243

CHAPTER XXXI. FIELD EXPERIMENTS 246

CHAPTER XXXII. THE MANURING OF SPECIFIC CROPS . 254
Introduction 254
Manuring of Winter Cereals 255
Manuring of Maize 257
Manuring of Leguminous Crops 259
Manuring of Potatoes and Root Crops 260

CHAPTER XXXIII. THE MANURING OF SPECIFIC CROPS (*cont.*) . 262
Manuring of Natural and Established Pastures. By THOS. D. HALL, B.A., M.SC.AGR., D.SC. (HON.) . . . 262
Manuring of Sugar-cane. By H. H. DODDS, M.SC., D.SC., F.R.I.C. . 266

CHAPTER XXXIV. THE MANURING OF SPECIFIC CROPS (*cont.*) . 273
Manuring of Orchards and Vineyards . 273
Prerequisites for a Favourable Response to Fertilization 274
The Manuring of Orchards and Vineyards . 282
Removal of Plant Food from Soils by Crops 288
Average Composition of Fertilizer Materials 289

INDEX 291

LIST OF PLATES

		facing page
PLATE I.	*a*. Nodules on the roots of Burr clover. *b*. Soil profile.	48
II.	*a*. Granite rock. *b*. Conglomerate rock.	49
III.	*a*. Donga formed by soil erosion. *b*. Broad-based terrace on grain land.	128
IV.	*a*. A well-constructed ditch. *b*. Cauliflower crop on acid soil.	129
V.	*a*. Interior of superphosphate factory. *b*. Limestone quarry.	192
VI.	*a*. Pothouse on Stellenbosch Experimental Farm. *b*. Fertilizer experiment in pots.	193
VII.	*a*. Trolley with pots and scale. *b*. Effect of superphosphate on maize.	240
VIII.	*a*. Sugar-cane at Mount Edgecombe. *b*. Sugar-cane at Umbumbulu, with and without superphosphate.	241
IX.	*a*. Orchard fertilizer experiment. *b*. Effect of potash deficiency on apple branches.	256

PART ONE

THE NUTRITION OF PLANTS

CHAPTER I

INTRODUCTION

AGRICULTURAL CHEMISTRY AND WHAT IT COMPRISES

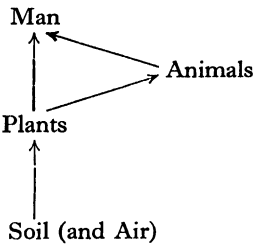
HOW should I treat my arable land in order to obtain the most profitable yield from it?' This is a question which is of the most vital importance to the agriculturalist. It is obvious that many different things will have to be considered before this question is satisfactorily answered. There are two parts to it: Firstly, how can a high yield be obtained, and secondly, how can this yield be sold most profitably? In other words, the agriculturalist has to deal with the production and the marketing of agricultural produce. In agriculture to-day, marketing is becoming an increasingly difficult problem owing to increased competition on world markets as a result of improved transport facilities. In a country like South Africa, which is partly dependent on the export of its agricultural produce, the solution to the problem of marketing lies in the co-operation and efficient organization of the farming community.

In this book only the production aspect of agriculture will be discussed. Statistics show that in western Europe the yield per acre has increased by 200 to 300 per cent. within the last hundred years. The most progressive farmers obtain even higher average yields. This development is the result of the application of scientific principles based on knowledge gained by research. Agriculture is no longer what it has been throughout countless generations of the past, i.e. a purely empirical occupation. It has become an applied science. Although agricultural science is ever developing and there are still many problems to be solved, especially in a young country like South Africa, the South African farmer can, nevertheless, increase his yields considerably by applying these principles.

Agricultural science may be compared with a tree with many branches. The trunk divides into two main branches, one representing all the agricultural crops and the other all farm animals including poultry. Each of these main branches has lateral branches. Thus we find on the side of agricultural crops, the production of ordinary field crops, horticulture, viticulture, vegetable production, the production of tropical fruits, &c. Agricultural crops and farm animals are subject to attack by diseases and insect pests and thus the 'tree' would have branches representing the study of plant diseases (Phytopathology), the study of insects (Entomology), and the study of animal diseases (Veterinary Science). The trunk of the 'tree' represents Genetics (the study of heredity) or Breeding, which aims at the production of new varieties of plants and new breeds of animals, and at keeping these

pure. Finally, the business side of crop and animal production should receive due consideration in order to reduce production costs as much as possible. This branch of agricultural science is called Farm Business Organization and is a subdivision of the wider subject, Agricultural Economics.

In our representation of agricultural science as a tree, we have as yet made no mention of the root system, that part which anchors the trunk and branches and provides the tree with food. This root system represents the study of the soil—Pedology or Soil Science. Without soil or suitable ground no agricultural crops can be grown and without crops or plants the existence of higher animals, including man, would be impossible. If only food relationships are taken into consideration this dependence may be sketched as follows:



The soil (and the air) is the habitat of, and provides the food for, plants. Farm animals are herbivorous and man consumes food from both animal and vegetable sources. This clearly shows that the soil is our most valuable asset—the foundation on which our entire agricultural industry rests.

Agricultural chemistry is the study of soil fertility in its widest sense. The term 'Agricultural Chemistry' is slightly misleading because literally it would seem to include the chemistry of all substances and material changes occurring in agriculture. At a certain period this wide meaning was attached to it in Europe. We shall, however, limit the study of Agricultural Chemistry to the study of all those factors which affect the nutrition of agricultural crops. We shall divide our field of study into three sections:

Firstly, we must learn just what the nutritional and other growth requirements of agricultural crops are.

Secondly, we shall study the soil and its properties, i.e. that weathered top layer of the earth's crust in which plants root and from which they obtain their nourishment.

Finally, we shall deduce from the knowledge gained how growth conditions for plants may be improved by manuring or fertilizing.

FUNDAMENTALS OF CHEMISTRY

Chemistry deals with the composition of substances and the material changes which may occur. The knowledge of chemistry which the reader will need in order to understand this book will be given as simply and clearly as possible where necessary. At the outset we wish to explain the

following fundamentals. Breaking up material and analysing its component parts is an important branch of chemistry. Thus it has been found that most objects may be divided into simpler, elementary substances that cannot be further divided into different substances. Such substances are called *chemical elements*. Iron, for example, is an element because it cannot be split up into components with a simpler composition than iron.

Careful investigation during the last hundred years has shown that most natural objects consist of a comparatively small number of elements, viz. 92. Out of this number only about 25 commonly occur. In chemistry, letters or symbols are used to indicate the elements. This can prove very difficult to the reader who has never studied chemistry. This shortened mode of writing is, however, essential to indicate concisely the chemical composition of the numerous different substances and the many material changes they may undergo. With some concentration it is easy to overcome this difficulty and accustom oneself to it. The symbol is usually the first letter or two prominent letters of the usually Latin name for the element.

The following list contains 26 of the most important elements. Where the Latin name differs completely from the English, the Latin name is given in brackets.

TABLE I

Important Chemical Elements

Name	*Symbol*	*Name*	*Symbol*
Aluminium	Al	Mercury (Hydrargyrum)	Hg
Arsenic	As	Nickel	Ni
Calcium	Ca	Nitrogen	N
Carbon	C	Oxygen	O
Chlorine	Cl	Phosphorus	P
Copper (Cuprum)	Cu	Platinum	Pt
Gold (Aurum)	Au	Potassium (Kali; Arabic)	K
Hydrogen	H	Silicon	Si
Iodine	I	Silver (Argentum)	Ag
Iron (Ferrum)	Fe	Sodium (Natron; German)	Na
Lead (Plumbum)	Pb	Sulphur	S
Magnesium	Mg	Tin (Stannum)	Sn
Manganese	Mn	Zinc	Zn

Most chemical elements have the tendency to combine with one or more other elements. Such a combination of two or more elements is called a chemical compound. Of great importance is the fact that the proportions in which the constituents of a chemical compound are combined never vary by weight. For example, water is a chemical compound consisting of the two elements hydrogen and oxygen, in the proportion of one part of hydrogen by weight to eight parts of oxygen by weight. Whether it is rain-water, sea-water, river-water, or water from a spring, it always has this constant composition. If these different waters have different tastes it is due to the impurities which they contain. If the water is distilled it will always have the same composition and properties irrespective

of its source. The fact that a chemical compound has a constant composition is of fundamental importance, and only since this fact has been discovered has chemistry become an exact science. The properties of hundreds of thousands of different compounds found in nature or produced artificially in laboratories have been studied.

If a piece of pure marble (limestone) is pulverized, it will be found that each particle still has the properties of the marble. It will, for example, effervesce with any strong acid, giving off carbon-dioxide gas. Chemists found that each of these small particles could be further divided into thousands of smaller particles and each one would still possess the properties of marble. Finally the particles become so minute that they cannot be divided further without radically changing the properties of the marble particle. This smallest part of a substance which still possesses the properties of that substance is called a *molecule* (a small mass).

It is known that molecules consist of still smaller particles, i.e. they can be divided further. These different parts of molecules are called *atoms* (indivisible). We have already mentioned that a definite chemical compound always has the same composition. We can now be more precise and say that the molecules of a certain compound always contain the same number and kind of atoms. In the case of a chemical compound there are at least two kinds of atoms because a compound consists of at least two different elements. One molecule of water, for example, consists of two atoms of hydrogen and one of oxygen and the chemist indicates the composition of water briefly as H_2O. In the case of elements, the molecules consist of only one kind of atom. Thus, every molecule of nitrogen is written N_2 (in Agricultural Chemistry it is customary to use the abbreviation N for nitrogen and not N_2).

This abbreviated writing, consisting of letters and numbers indicating what different elements are present in the molecule and how many atoms of each element the molecule contains, is called the *chemical formula* of that substance. Thus, the chemical formula for pure marble is $CaCO_3$, indicating that every marble molecule consists of one atom of calcium, one atom of carbon, and three atoms of oxygen. The molecules of some substances, especially those found in agriculture, contain a very large number of atoms. The molecule of one of the proteins of wheat (gliadine) consists of five different elements (carbon, hydrogen, oxygen, nitrogen, and sulphur) and there is a large number of atoms of every element in the molecule so that this protein molecule contains altogether 2,165 atoms. Its chemical formula is $C_{685}H_{1068}O_{211}N_{196}S_5$. We will, however, not use such frightening formulae in this book and in any case all chemical reactions will also be given in ordinary language.

Finally, it may be mentioned that Agricultural Chemistry does not only concern itself with chemical knowledge in connexion with soil fertility, but also makes use of the other natural sciences such as botany, physics, mineralogy, &c., because they too form an important part of our study.

CHAPTER II

THE CHEMICAL COMPOSITION OF PLANTS

IT is a well-known fact that agricultural crops (and other higher plants as well) grow well and give satisfactory yields only if the following six requirements are met. The plants must have:

(1) sufficient air,
(2) sufficient light,
(3) sufficient water,
(4) a suitable temperature,
(5) an adequate supply of plant foods, and
(6) freedom from the presence of any injurious substances.

If any one of these requirements is lacking the plants will grow poorly even if all the others are favourable. This can easily be understood if we consider that in a desert region, where light, aeration, and temperature conditions may be at an optimum, very little, if any, plant growth is found on account of the lack of soil moisture. This interdependence is not only applicable to the six general growth requirements, but also to all the essential plant foods. As we shall see, there is a whole range of essential plant foods and if a plant gets an insufficient supply of only one of these, its rate of growth will be limited accordingly. The fact that plant growth is determined by the quantity of that plant food which is most deficient in the soil, or by that growth factor which is least favourable, was realized by Justus von Liebig as early as about 1840, and it was called the 'Law of the Minimum'. This 'law' will be discussed in greater detail in Chapter XXX.

It is clear that the word 'sufficient', used with the first five requirements, is vague and difficult to define quantitatively. It is essential that we should realize from the outset that plant growth is a very complicated process and hence it is impossible to prescribe simple recipes for fertilizing which will apply to all crops and be satisfactory in all areas. All the more reason, therefore, why every agriculturalist should be conversant with at least the basic principles of plant growth and soil fertility so that necessary measures may be applied intelligently and not in a haphazard way.

In this chapter we will examine more closely the chemical composition of plants. As will be pointed out later on, all the mineral ingredients found in plants are not essential for their growth. Some may have been absorbed by the plant incidentally, because they were present in the soil solution; but, according to our present knowledge, by far the greater part of the elements present in plant material are essential for healthy growth.

Should we take any plant or part of a plant, e.g. a few blades of grass, and heat them gently in a test-tube over a flame, we would find that the steam or vapour which is given off from the leaves condenses on the upper

part of the test-tube. Thus it follows that water or moisture must be a constituent of plant material. If the amount of moisture in fresh plant material is determined, for example, by heating it in an air-oven at 100° C. (the boiling-point of water) until all the moisture has evaporated, it will be found that water constitutes by far the greater part of plant material—of 100 lb. green lucerne about 75 lb. consist of water. It therefore contains 75 per cent. water. Similarly green maize plants contain approximately 83 per cent. water; cucumbers 95 per cent. water; pumpkins 90 per cent. water; potato tubers 75 per cent. water; grapes 80 per cent. water; oranges 86 per cent. water, &c. Plant organs (roots, stem, leaves, fruit) usually contain 75 to 90 per cent. water. Air-dry plant products such as hay and seed usually contain from 10 to 15 per cent. water. In this case the moisture content will depend both on the humidity and temperature of the air and on the nature of the plant product.

If all the moisture is removed from the plant or plant product, we have 'oven-dry matter'. If a quantity of this is placed in a dish or crucible (of porcelain, quartz, or platinum) and heated over a flame, we find that (sometimes) pungent gases are given off. If we prevent the plant material from being set alight, for example by covering the dish with a lid, we will find that the plant material will turn black, i.e. it will carbonize. From this we gather that carbon compounds form an important part of plant material. If the lid is then removed and the dish or crucible heated strongly for some time, the carbon will also burn away and eventually only a small amount of ash will remain behind. This constitutes the mineral constituents of plant material.

The above experiments have shown us that plants consist of (*a*) *water*, (*b*) *carbon compounds*, and (*c*) *ash*, or *mineral constituents*. The carbon compounds are called organic compounds, in contrast to the inorganic compounds or mineral matter. It is essential that we should understand these terms well. Except for a few simple combinations such as carbon dioxide (CO_2) and carbonates, carbon compounds in nature are only found in living or dead vegetable or animal matter, or in substances of vegetable or animal origin. Up to about 1830, chemists thought that only living organisms (plants or animals) could manufacture the more complicated carbon compounds, and thus they called them 'organic' compounds. They called the study of these substances 'organic chemistry', while 'inorganic chemistry' signified the study of non-living or mineral substances. This distinction is still maintained in chemistry for purely practical purposes, although thousands of carbon compounds, i.e. organic substances, have been and can be prepared in laboratories without the aid of organisms.

The carbon compounds found in plants are many and varied, but quantitatively the two most important groups are carbohydrates and proteins. The carbohydrates consist of the three elements carbon, hydrogen, and oxygen, and the proportion in which the hydrogen and oxygen are present is the same as that in water, i.e. two atoms of hydrogen to one atom of oxygen; hence the name (Gr. *hudōr*, water). The carbohydrates consist of

three groups of compounds: sugars, starch, and cellulose or fibre. Plants consist of numerous small cells, and the cell walls consist of cellulose. Cotton and paper are examples of more or less pure cellulose. Grape-sugar (glucose) and starch are two carbohydrates which, in the first instance, are manufactured in the green leaves of the plants (see p. 11) and are used by the plant for various purposes. Large portions are used for the cell walls where they then change to cellulose and similar substances. Under the latter we find lignin, a substance about which we will learn more when discussing humus. Another portion of the sugar and starch is used by the living plant as energy-giving food, because living plants also breathe or respire, and respiration is nothing but the slow combustion of carbon compounds, by which process energy is set free. The plant needs this energy or heat for several purposes, e.g. in order to absorb its mineral food from the soil. Finally, plants also use sugar for the manufacture of complicated proteins. All seeds and parts of plants that are dormant during winter contain a great deal of starch or sugar or both (maize, potatoes, onions, sugar-beet, wood of fruit-trees).

The cell contents of living plant cells consist of the semi-fluid protoplasm and the more solid nucleus. Both substances consist of protein. The protein of protoplasm consists of the elements carbon, hydrogen, oxygen, nitrogen, and sulphur (CHONS), and the cell nucleus contains phosphorus (P) in addition. A considerable amount of protein is usually stored also in the seeds of plants as reserve food for the embryo. The protein content of different parts of plants and of the seeds of different plants varies considerably, as will be seen from the following examples:

Young lucerne (fresh)	contains about	6	per cent.	protein.
Older lucerne (fresh, flowering stage)	,,	,,	4	,,	,,
Lucerne hay (air-dry)	,,	,,	15	,,	,,
Oat hay (air-dry)	,,	,,	7·5	,,	,,
Oat seed (air-dry)	,,	,,	12	,,	,,
Maize seed (air-dry)	,,	,,	10	,,	,,
Garden pea seed (air-dry)	,,	,,	22	,,	,,
Soya-bean seed (air-dry)	,,	,,	33	,,	,,
Peanut seed (air-dry)	,,	,,	30	,,	,,
Potatoes (fresh)	,,	,,	2	,,	,,
Figs and bananas (fresh)	,,	,,	1·5	,,	,,
Apples (fresh)	,,	,,	0·5	,,	,,

From these examples it is clear that young plant material and seeds are particularly rich in protein.

The following experiment may be carried out to obtain an idea of the appearance of more or less pure starch and protein. Place a handful of sifted flour in a clean, unstarched linen cloth and add water to turn the flour to dough. Hold the edges of the cloth round the dough with one of the hands, then squeeze it with the other hand in a basin of water or under a

tap until all the starch is out of the flour. If a glassful of starch water is set aside, it will be found that after some time the water on top has become clear and that a layer of white starch has settled on the bottom. On the cloth will remain a small yellowish-white sticky mass of gluten which is a mixture of impure wheat proteins.

Besides carbohydrates and proteins all plants also contain fats or oils. Fats also contain carbon, hydrogen, and oxygen, but not in the same proportion as carbohydrates. The green plant contains very little fat, usually only from one-quarter to one-half per cent. of its green weight. Seeds, however, are usually richer in fat and some, such as peanut seed, may contain as much as 50 per cent. fat. Oat and maize seed contain about 5 per cent. fat and wheat seed about 2 per cent. The fat is also an important reserve food for the embryo.

Carbohydrates, proteins, and fats are the three characteristic organic substances of all plants. Several other carbon compounds are present in plants in smaller amounts. Certain pigments, such as chlorophyll, are the most important of these. Chlorophyll will be discussed under carbon assimilation.

The ash constituents or mineral substances are the so-called inorganic substances found in plants. They are taken from the soil and are absorbed through the plant roots.

Until about a hundred years ago, research workers paid no attention to the mineral constituents because they were of the opinion that plants only lived on air, water, and probably 'humus'. Then, however, Liebig expounded the mineral theory, according to which plants use only inorganic, i.e. mineral, substances for their raw food material. Plant ash was then analysed carefully, and growth experiments were made in water and sand cultures to determine exactly which ash constituents were indispensable for plant growth and what functions these indispensable or essential mineral substances performed in plant growth. These two questions are still being examined by research workers and our knowledge in this connexion is still far from complete.

The following elements are always found in plant ash: potassium, sodium, calcium, magnesium, iron, phosphorus, sulphur, chlorine, silicon, and others. The first five elements are metals and are present in the ash in the form of so-called salts. These salts are mainly carbonates, or salts of carbonic acid (H_2CO_3). The carbon of the carbonates comes from the organic substances of plants. Carbonates have the property that they effervesce and give off carbon-dioxide gas (CO_2) when any acid such as hydrochloric acid or acetic acid is brought into contact with them. The other constituents mentioned above are also present mostly in the form of salts: phosphorus, for example, in the form of phosphates.

The total amount of ash in agricultural crops is usually very low, about 0·5 to 2 per cent. of the green or fresh plant material or about 2 to 8 per cent. of the dry matter. Nevertheless, the ash or mineral constituents of plants are very important for healthy plant growth.

Some idea of the proportion in which the constituents discussed in this chapter are present in plants may be obtained from the following analysis of green grass (after Hall, *The Feeding of Crops and Stock*):

TABLE 2

Composition of Meadow Grass

A. Water	74·8 per cent.
B. Organic substances (combustible matter) Consisting of:	23·2 ,,
Carbon (C)	11·7 ,,
Hydrogen (H)	1·3 ,,
Oxygen (O)	9·7 ,,
Nitrogen (N)	0·4 ,,
Sulphur (S)	0·1 ,,
C. Ash constituents Consisting of:	2·0 ,,
Phosphoric oxide (P_2O_5)	0·1 ,,
Sulphur trioxide (SO_3)	0·1 ,,
Chlorine (Cl)	0·1 ,,
Silica (SiO_2)	0·5 ,,
Potash (K_2O)	0·5 ,,
Soda (Na_2O)	0·1 ,,
Magnesia (MgO)	0·1 ,,
Lime (CaO)	0·3 ,,
Iron oxide (Fe_2O_3)	Traces
Sand, &c.	Traces

The above percentages are average figures and may vary considerably at different stages in the growth of the plant, and with soil fertility and climatic conditions. In connexion with this and similar analyses, it is essential that the reader should be well acquainted with the method in which the results are stated. In analyses of plant material, fertilizers, soils, &c., *it is customary to indicate many of the constituents as oxides*, i.e. in combination with oxygen. It should be borne in mind, however, that these constituents do not actually exist as oxides in the plants, &c. As a matter of fact, if the reader has any knowledge of chemistry he will realize that this is impossible because a substance such as phosphoric oxide, which is a white powder that readily absorbs moisture, could not exist as such in plants as it would immediately absorb moisture and so form phosphoric acid. The phosphorus is present in the plant in different and very complicated compounds. The same applies to most of the other constituents.

CHAPTER III

NUTRITION OF GREEN PLANTS

WHAT PLANT FOODS MEAN

WHEN talking about food in connexion with the nutrition of humans and animals, we usually think of a substance having one or more organic constituents such as starch, sugar, fat, and protein. These food materials are digested partly or completely in the body (by the stomach and the intestines) and absorbed into the blood system. The absorbed nutrients fulfil at least two functions. In the first place they combine with oxygen (are oxidized) in the process of combustion, in which they are changed to simpler substances, thus releasing a great deal of *energy* in the form of heat. For various reasons this heat is essential for the animal body. All organic substances are combustible and, therefore, they contain potential energy, i.e. they possess a fuel value. One gramme of starch, for example, gives off 4,100 calories or units of heat on combustion and the products of combustion are water and carbon dioxide.

In order to indicate such material changes in writing chemists make use of *chemical equations*. The equation showing the changes that take place during the combustion of starch is written as follows:

$$C_6H_{10}O_5+6O_2 = 6CO_2+5H_2O(+\text{heat})$$

Starch and Oxygen give Carbon dioxide and Water.

The second function of most nutrients is to act, partly or wholly, as *building material* in the repairing of broken-down tissues and in building up new bone and muscle-tissue. The proteins, especially, provide both energy and 'building material'. The mineral constituents of foods are essentially body-building.

The green plant also needs energy-giving or fuel food and building material. There is, however, the difference between plants and animals that plants are able to *manufacture* a large supply of *energy-giving food* from simple constituents with the help of energy obtained from sunlight. Animals are unable to do this. In this, plants fulfil an important function because they not only manufacture fuel food for themselves and their offspring (seeds), but also supply both men and animals with the substances from which their energy is derived. Thus it is clear that what plants need from outside for their growth is nothing but a number of simple building materials, and so we understand by *plant food* or plant nutrients comparatively simple inorganic or *mineral substances*.

We do not wish to discuss the nutrition of the seedling and conditions necessary for the germination of seeds here. It is sufficient to say that the seedling needs no manuring because the seed contains the necessary fuel food and building material for the first stages of its development. As soon

as the radicle starts developing and the first leaves turn green the seedling starts feeding from the soil and air, as will be seen presently, and increases in weight. Water, air (oxygen), and the right temperature are essential for germination. When cultivating our soils we should see to it that these conditions are present in the seed-bed, otherwise germination will be poor. Seed should naturally be healthy and have a high germination power.

ABSORPTION OF NUTRIENTS FROM THE AIR

The green plant consists of an above-ground or aerial portion (stem and leaves) and an underground portion (root). Raw food materials are obtained from the *air* and the *soil*. From the air, plants absorb the two *gases* carbon dioxide (CO_2) and oxygen (O_2); from the soil, roots absorb (*a*) a liquid (water) and (*b*) a number of solids that can, however, only be absorbed in *solution* by plant roots. The latter include nitrogenous compounds, phosphates, potassium salts, &c. In this chapter we shall discuss the absorption of nutrients from the air and the absorption of water by plants.

Carbon assimilation

If we look at the composition of plants as given on p. 9 we will notice that about 50 per cent. of the total dry matter consists of carbon. This shows that, according to weight, carbon is by far the most important plant nutrient and it would be of great advantage to the agriculturalist if he could increase the rate of carbon assimilation.

As early as 1771 Priestley, the discoverer of oxygen gas, noticed that if air in a confined space 'deteriorated' and became unfit to support animal or human respiration, it was 'purified' and would again support respiration after plants had been growing in it in daylight for some time. In other words, he observed that plants are able to absorb carbon dioxide from the air, giving off oxygen. This absorption of carbon dioxide by plants was investigated by other research workers and the process was fairly well understood by the beginning of the previous century. The term *carbon assimilation* was used to describe it.

By carbon assimilation is meant that process by which green plants, usually through their leaves, absorb *carbon dioxide* from the air and manufacture from it, with the aid of *sunlight*, *chlorophyll* (the green colouring matter in leaves) and *water*, organic substances, viz. carbohydrates. As in the case of all life or biochemical processes the *temperature* is important. Chemically, we can indicate the process by the following equation:

$$6CO_2+6H_2O = C_6H_{12}O_6+6O_2$$

Carbon dioxide and Water give Grape-sugar and Oxygen.

The grape-sugar or glucose is the carbohydrate which is first formed in the leaves. It is, however, immediately changed into starch. This happens by the elimination of one water molecule from every glucose molecule, a large number of these carbohydrate molecules uniting to form one starch

molecule. The starch molecule, therefore, is much more complicated than the glucose molecule. This second process may be represented by the following equation:

$$n\mathrm{C_6H_{12}O_6} - n\mathrm{H_2O} = (\mathrm{C_6H_{10}O_5})n$$

Glucose minus Water gives Starch.

The letter *n* here stands for a large number, about 1,500. We say that starch is the first 'visible' product of carbon assimilation because its presence may easily be shown by the well-known iodine test.[1]

The requirements for carbon assimilation, written in italics on preceding page, will now be discussed briefly.

1. *Temperature.* Carbon assimilation can only take place in living plant cells and life is only possible within certain limits of temperature. As with all life processes we can here also differentiate between a minimum, maximum, and optimum temperature. At any temperature below the minimum temperature or above the maximum temperature carbon assimilation will not take place. At the optimum temperature, the rate of carbon assimilation is at its highest. These critical temperatures are not the same for all plant species, but in general we can say that the optimum temperature is about 37° C. and the maximum temperature is about 45° C. 37° C. (= 98° F.) is very high and it has been found that although it is the temperature at which carbon assimilation takes place fastest it is not at all the most desirable temperature for the growth of our ordinary agricultural crops. Apparently they increase in weight, i.e. grow fastest, at 20–25° C. (68–77° F.). This apparent contradiction may be explained as follows: Plant growth is the result of two different processes, a constructive or anabolic process, and a destructive or katabolic process. Carbon assimilation is the most important constructive process and respiration (p. 14) is a destructive process. Both processes are speeded up by an increase in temperature, but the rate of increase of the destructive process is relatively much faster than the rate of increase in the constructive process. Naturally, an increase in weight is only possible if more material is built up, for example, in 24 hours than is broken down during that same period. The fastest increase in weight, i.e. positive growth, appears to occur at 20–25° C. The temperature of the atmosphere is a climatic factor which we cannot influence to any extent. However, time of planting or sowing may be so chosen as to provide the most desirable growth temperature for the crop. The slow growth of most agricultural and garden crops during winter is due to the fact that the temperature is too low for rapid carbon assimilation and the days are too short. This brings us to the next factor.

2. *Sunlight.* We mentioned at the beginning of this chapter that carbohydrates are energy-giving or fuel foods which release a large amount of heat on combustion. The products of combustion are carbon dioxide and

[1] To-day it is generally accepted that not starch but rather cane-sugar ($\mathrm{C_{12}H_{22}O_{11}}$) is the product which first forms from glucose in the leaf, and also that cane-sugar is the carbohydrate which is transported in the plant.

water. From these two materials, that contain no energy, green plants manufacture carbohydrates. It is clear that plants must have energy for this process and it can easily be proved that sunlight provides the necessary energy. Hence the name *photosynthesis* that is also used for carbon assimilation. Literally it means the building up or synthesizing of food through light or with the aid of light. Therefore, carbon assimilation cannot take place in the dark, i.e. at night. In general we can say that the stronger the sunlight the more quickly carbohydrates will be formed.

Only that light which is retained or absorbed by the chlorophyll can supply the necessary energy. After light-rays have passed through a number of green leaves, they have very little energy left for carbon assimilation. That is why plants cannot thrive in the shade of others unless they are especially adapted to it. For this reason fast-growing crops are grown to smother weeds. Also, when afforesting, trees are planted close together so that the lower lateral branches will die through lack of light—clean stems free of knots being obtained. As the trees grow bigger their number is periodically reduced by thinning.

3. *Chlorophyll*, or the green colouring matter in leaves, is one of the essentials for carbon assimilation. It not only absorbs the light, thus making available its energy for the use of the plant, but it also aids directly in the manufacture of carbohydrates from the two raw materials, as shown on p. 11. The chlorophyll molecule consists of the elements carbon, hydrogen, oxygen, nitrogen, and magnesium and it cannot originate without light. Leaves and stems, for example, that grow under loose flat stones are pale and etiolated. By the iodine test for starch it can be proved that in etiolated leaves no carbon assimilation takes place.

4. *Water*. This is one of the raw materials that are necessary for carbohydrate formation, and, as such, it is an essential plant food. The water is absorbed by the roots from moist soil. The amount of water needed for carbohydrate formation is, however, very small in comparison with the amount used for its entire growth process. As we shall see presently, water has other important functions in plant growth.

5. *Carbon dioxide* (CO_2). This is the second raw material needed for carbon assimilation. Air always contains carbon dioxide and the percentage in the atmosphere is fairly constant, viz. about 0·03 per cent. by volume. This means that every 10,000 litres of air contain 3 litres of carbon dioxide. Plants absorb the carbon-dioxide gas through the stomata in the leaves.

It has long been known that carbon assimilation takes place more quickly, and larger yields per morgen are possible, if the air contains more than the normal 0·03 per cent. of carbon dioxide. In practice it is impossible to improve the first four requirements for photosynthesis because we cannot change the climate or plant species to any extent. The question now is whether it is possible to increase the carbon-dioxide content of the air above the soil surface. Since about 1920 this question has received a great

deal of attention. It has been found that the only practical method of increasing the percentage of carbon dioxide in the air immediately above the soil surface is to increase the production of carbon dioxide in the soil. Carbon dioxide is produced by the countless micro-organisms that are normally present in agricultural soils. Carbon dioxide is the product of their respiration and it is constantly leaving any fertile soil by diffusion. It has been proved that leafy plants whose leaves cover the soil more or less completely, such as potatoes, sweet potatoes, peas, pumpkins, &c., readily use this carbon dioxide during the day-time.

Naturally, production of carbon dioxide in the soil will increase with an increase of microbial activity. We will see in Chapter XXIII that there are many factors which influence microbial life and activity. Of these, sufficient organic matter to supply them with energy-giving or fuel food is undoubtedly the most important. Organic matter may be applied to soils in the form of farm manure, green manure, straw, and other vegetable matter. It is well known that leafy plants grow very well on soils well supplied with organic matter. The present explanation is that such a manuring enhances carbon assimilation because there is more carbon dioxide in the air surrounding the plants. In other words, such a manuring of the soil is at the same time also a manuring of the air.

Respiration of plants

Because growing plants are living organisms they also have to breathe or respire, and like people and animals they need air, or rather the oxygen that is present in the air, for respiration. About four-fifths of the air consists of nitrogen gas and one-fifth of oxygen gas. We have already mentioned that respiration is a destructive process by which stored energy is released. Therefore, the oxygen needed for this process is not a nutrient because it does not provide the plant with building material as such. However, it enables the plant to obtain the functional energy from the fuel food that the plant has manufactured by carbon assimilation. This functional energy is essential for all the normal life processes in plants. Amongst other things it enables plant roots to make their way in between soil particles and to absorb the nutrient salts from the soil moisture. This absorption from the soil of food material requires energy which can only be supplied by root respiration.

The above-ground parts of the plant absorb oxygen from the air through the stomata and they never experience a lack of oxygen. The root system, however, also respires constantly and it obtains oxygen from the soil water in which the oxygen is dissolved. Thus plant roots cannot live in water that has been boiled (and cooled down) and they cannot exist in soil water unless the soil also contains air from which oxygen can dissolve in the soil water. That is why plants die in waterlogged soils. It is, therefore, essential that the agriculturalist should see to the aeration of his soil and that he should drain soils containing excessive moisture. The question will be discussed further in subsequent chapters.

ABSORPTION OF WATER BY PLANTS

Normally plants absorb water through the unicellular root-hairs that grow in the root-hair region near the root-tips. The root-hairs are very short-lived and die as every rootlet extends and new root-hairs develop immediately behind its growing point. The outer cells of the older root parts are suberized (corky) and cannot absorb water. Ordinary plants can also absorb water through their leaves, especially when they are wilted and dew or a shower of rain falls on them, or when the plants are watered from the top. Normally this method of water absorption is not important.

In the past, the general opinion was that the rate at which root-hairs absorb water depends on the osmotic pressure in the cell sap in the root-hairs, or rather on the difference in osmotic pressure between the cell sap and the soil solution which is usually very dilute. Now let us see what osmotic pressure means. In the first chapter we saw that chemical compounds consist of molecules. If a salt, e.g. saltpetre (KNO_3), is dissolved in water, the saltpetre particles split up completely so that the saltpetre molecules move about freely in the water. The molecules of chemicals such as salts even split up into two portions called ions when dissolved in water. We will hear more about this in a later chapter.

In physics we learn that a gas in a confined space exerts a certain amount of pressure on the walls confining it and that this gas pressure increases if the amount of gas is increased, i.e. it increases as the number of gas molecules increases. The gas pressure is the result of the collision of the gas molecules with the confining walls. The same thing happens when a salt dissolves in water. This phenomenon will be easier to understand if we assume that the salt solution is in a confined space, e.g. in the cell of the root-hair. The molecules and the ions of the salt then exert pressure on the cell wall exactly as if there is no water present, but only gases. Pressure exerted by substances dissolved in water is called osmotic pressure and not gas pressure. Osmotic pressure also increases as the concentration of dissolved substances increases, as in the case of gas pressure. In the cell sap of the root-hairs the salt concentration is always much higher than it is in the surrounding soil moisture except in the case of very saline (brak) soils. Thus water absorption and, hence, plant growth are impossible in such soils.

We now come to an apparent contradiction—the bigger the osmotic pressure in the cell sap, the bigger is the suction pressure of the cell sap for more water. In order to understand this phenomenon we must assume what is not quite true and that is, that the cell wall does not allow absorbed salts to move out into the soil water again (semi-permeable walls). However, because the water molecules can move into the cells through the cell walls the suction is inwards, tending to decrease the high osmotic pressure in the cells in order to establish an equilibrium between the concentration in the cell sap and the concentration in the soil solution. Hence the movement of water into the cells. This is called endosmosis.

It has also been found that osmotic pressure increases in cells adjoining the root-hair cells. The farther the cells are removed from the root-hairs, the higher is the osmotic pressure. This means that the suction pressure also increases in cells removed from the root-hairs. Thus the water is first drawn into the root-hair and from there farther up into the adjoining cells in the direction of the vascular bundles. How the water rises in the vascular bundles is rather intricate and we do not wish to discuss it here.

Assuming that the osmotic pressure of the soil solution remains constant, investigation has shown that the suction pressure (*SP*) of the roots for water is not proportional to the osmotic pressure (*OP*) in the cell sap, as was previously held, but that the suction pressure is equal to the osmotic pressure of the cell sap minus the turgor pressure or wall pressure (*WP*) of the cell wall.

Therefore $SP = OP - WP$.

Young cell walls are elastic, and as the amount of water in a cell increases its walls extend, exerting pressure on the contents of the cell and, therefore, also on the cell sap. When the cell wall reaches its maximum distension, wall pressure equals osmotic pressure and no more water can be absorbed ($OP = WP$, thus $SP = 0$). Wall pressure tends to force water out of the cell. In the wilted condition the cell wall is, of course, not distended, hence $WP = 0$ and $SP = OP$, but as soon as the cell starts taking in water the cell wall starts distending and *WP* starts acting. This state not only exists in the root-hair cells but also in the adjoining cells farther from the root-hairs.

These facts enable us to understand why wilted leaves absorb water so readily when they are watered or when dew forms on them. It is due to the fact that the *SP* in wilted leaves is high because *WP* is practically nil.

Water requirements of plants

Water fulfils different functions in plant growth. These are:

1. *Water as building material.* We have already mentioned that water is used as a building material by plants because it is one of the two materials, carbon dioxide and water, out of which plants synthesize carbohydrates. Other organic compounds in plants also need water as a building material.

2. *Water as solvent.* In the plant itself water is necessary to dissolve certain organic substances so that they may be transported from cell to cell and from one part of the plant to another, especially to the growth regions. As we will see presently, the mineral substances absorbed by plant roots from the soil must also be in solution in water. Often the solubility of some of these substances is very low. Therefore the soil should be moist so that there will be sufficient moisture to dissolve the mineral substances.

3. *Water as filling.* On p. 6 we saw that fresh plant material can contain 90 per cent. or more water. The water is present in the plant cells and most of the cell sap consists of water. It keeps the plant fibre rigid by keeping the cells turgid, and this taut or swollen condition is very necessary for the life functions and stability of the plant. The protoplasm in every living cell should also contain sufficient water in order to perform its

numerous functions efficiently. When evaporation of water from a plant is faster than the rate of absorption by the roots and transportation to the leaves, the leaves wilt, the stomata close, and carbon assimilation and other growth processes are reduced or even stopped. If the wilting lasts too long and the loss of water from the cells is excessive, the cells die because the protoplasm becomes disrupted and the cells do not recover even if water is applied. We say that the leaves are 'scorched', which is actually wrong, because failure to recover is not directly due to the heat but to the loss of water. This fact is clear if we notice that the parts of the leaves that are farthest from the veins (vascular bundles), such as the edges of the leaves, are the first to scorch.

4. *Water for transpiration.* Leaves have a large number of microscopic openings on both surfaces and we call these openings stomata. These stomata are essential for the exchange of the two gases oxygen and carbon dioxide. Unfortunately these openings also enable water to evaporate from the inner plant cells. This evaporation of water from the plant is called transpiration and the quantity of water lost in this way is enormous. The amount of water which plants need for the first three functions mentioned above is so small in comparison with that needed for transpiration that it may be ignored. Therefore, if we talk of the water requirement of plants we actually mean the water which is necessary for transpiration.

The term transpiration coefficient or ratio is used to indicate how much water a plant must give off for every unit of weight, e.g. 1 lb. of dry matter, that it produces. This figure varies greatly in different circumstances and it may vary from 200 to 800, which means that 200 to 800 lb. of water are transpired by the plant for every lb. of dry matter that is produced. The first question we would like to discuss is whether this water fulfils any useful function in the plant or whether it is merely a waste of water.

As previously shown, the construction of plant leaves is such that a constant loss of water by evaporation is inevitable. If this loss becomes excessive the leaves wilt; the plants definitely suffer and they can even die. This shows that transpiration can definitely be harmful to plants and some research workers even say that it is nothing but a necessary evil. However, most botanists agree that although transpiration can be harmful, it also has a few useful functions. They are the following:

(*a*) Transpiration causes cooling of the leaves. It is a well-known fact of which much use is made in daily life that when water evaporates the remaining water, or the object from which it evaporates, cools down. Water needs heat in order to evaporate and this heat is taken from the remaining water or the object. During the day plant leaves are mostly exposed to the sun and thus they may become dangerously warm. Accurate measurements have shown that actively transpiring leaves usually only have a temperature of about 1° C. higher than the surrounding air. Wilted leaves on plants, on the other hand, can become considerably warmer—a difference of 9° C. between wilted cowpea leaves and the surrounding air has been recorded. However, the difference is usually much less. Thus

transpiration aids in protecting leaves against high temperatures, although this influence is not very great. Plants adapt themselves to different conditions; thus the so-called succulents, which give off little water, can be heated to 60° C. by the sun without any bad effects.

(*b*) Transpiration apparently aids in the transport of plant food materials from the roots to the above-ground portions. The movement of water and dissolved mineral salts (and organic nutrients) in the plant is a complicated process in which diffusion of salts and root pressure are also very important. Nevertheless, it is assumed that the transportation of mineral salts in any case upwards in the vascular bundles is accelerated considerably by the transpiration current. We must, however, not attach too much importance to this. In the absorption of mineral plant foods by roots from the soil solution, transpiration plays no part as was previously believed. It has been found that there is no close relation between the amount of water that plants transpire, the absorption and transportation of salts, and the mineral content (ash constituents) of plants.

The second question in connexion with transpiration is: What conditions determine the amount of water which a plant will need for transpiration? The following conditions affect transpiration:

(*a*) *The kind of crop.* Different crops do not transpire the same amount of water under the same conditions to produce 1 lb. of above-ground dry vegetable matter. The following average transpiration ratios obtained by the Grootfontein College of Agriculture by growing plants in iron drums over a period of five years, are representative of such experiments carried out all over the world. Only the production of the aerial parts is taken into consideration except in the case of underground crops such as potatoes, where tubers and vines are taken into consideration.

TABLE 3

Type of crop	*Transpiration ratio*
Maize	290
Potatoes	450
Oats	582
Wheat	585
Peas	590
Beans	650
Lucerne	790

From these figures it is clear that maize and also the sorghum species need only about half as much water as wheat, oats, barley, rye, &c. (winter cereals), to produce the same yield in weight. The figures show how economical the different plants are in their water consumption, but it need not necessarily be related to the so-called drought resistance of plants with which it is often confused. The difference is easier to understand if we compare the water requirement of potatoes with that of lucerne. Although lucerne has a much higher transpiration coefficient than potatoes it is much more drought resistant, chiefly because it has a deeper and more widespread

root system. Wheat and oats have more or less the same transpiration ratio but wheat is more resistant to drought than oats, mainly because it has a deeper root system. Maize and sorghums use water more economically than the winter cereals as far as the production of plant material is concerned. They are also more drought resistant, but the main reason is not because their transpiration ratio is lower, but because they have a larger root system in proportion to their stem and leaves and they can also withstand lengthy periods of drought with few bad effects.

(*b*) *Climatic conditions.* These include the humidity of the atmosphere, temperature, and the movement of air (wind). It is obvious that the drier the air, the faster the evaporation and also transpiration within a certain time. There is a direct correlation between the transpiration ratio and the vapour deficit in the atmosphere, i.e. the amount of vapour which is necessary to saturate the atmosphere with water vapour at a certain temperature (100 per cent. humidity). This factor explains the large differences which research workers have noticed in different parts of the same country in connexion with the transpiration ratio of the same crop. Differences on the same land during different growing seasons are also due to differences in the humidity and maximum temperature of the air.

The influence of wind on transpiration is slightly more complicated. If the wind is dry and replaces humid air round the plants by dry air, the wind will naturally increase transpiration. On the other hand, strong winds, especially if they are dusty, cause the stomata to close and then transpiration is greatly reduced. In general, we can say that a moderate wind will increase transpiration but a strong wind may even cause a decrease.

In the first instance, temperature influences transpiration indirectly because a higher temperature causes a decrease in the humidity and as the humidity decreases transpiration increases. Secondly, water will evaporate more easily from a warm surface (the leaves) than from a cooler surface. It must also be remembered, however, that temperature also influences the growth and development of plants to a large extent. Briggs and Shantz (America) found that where crops are grown in cool and warm glass-houses in which all the other conditions, including the relative humidity of the air, are kept constant, plants adapted to a cool climate such as the winter cereals used about twice as much water, per unit of plant material produced, in the warm house than in the cool house. Similarly, plants adapted to a warm climate, such as maize, sorghums, and rice, have a much higher transpiration ratio when grown in the cool house than when grown in the warm house.

In our comparatively warm sub-continent with its dry air and dry winds during a large part of the year, the transpiration ratio for many crops is most likely considerably higher than, for example, in the cool temperate regions of the western part of Central Europe. In South Africa, too, there are large differences in different areas. In the south-western coastal areas with their winter rainfall and humid air, winter cereals use less water than these cereals do when grown in the Orange Free State and Transvaal.

Finally, the influence of light on transpiration may also be mentioned. Probably this relationship is mainly due to the fact that the stomata of most agricultural crops are normally closed during the night. Briggs and Shantz found that in the case of certain agricultural crops, transpiration during the night is only 3–6 per cent. of the total transpiration during 24 hours.

(*d*) *Soil properties.* The influence of the soil on the transpiration ratio is important in at least two respects. Firstly, there is the possible influence of different quantities of available soil moisture on the rate of transpiration. Veihmeyer (California) grew plum-trees in drums and found that with moisture contents varying from the wilting-point to the field water capacity (see p. 94) the availability of the moisture to the trees was the same and neither the growth nor the rate of transpiration was affected by the amount of available moisture in the soil. These results do not agree with those obtained by most other research workers for ordinary agricultural crops. They found that yields rise with an increase in available moisture in the soil up to a moisture content of about 80 per cent. of the maximum water capacity, after which yields drop, evidently because then there is not sufficient air in the soil. As far as the transpiration ratio is concerned, it appears as if it remains fairly constant over a wide range in moisture content, but transpiration does decrease as the moisture content approaches the wilting-point and it increases when the moisture content approaches the field water capacity. In other words, plants in very moist soils use water extravagantly.

The influence of soil fertility, i.e. the amount of available plant food, on the transpiration ratio is somewhat clearer. Many research workers have shown beyond doubt that an application of manure to a poor soil will decrease the transpiration ratio of a crop in that soil considerably. We say that the transpiration efficiency is increased. Widtsoe (America) showed that fertilizer applications to a poor, clayey soil reduced the transpiration ratio from 1,316 to 444. This is exceptional, but a decrease of 50 per cent. or more has often been observed after manuring. The old explanation that in a fertile soil plants have to pass less water through their leaves in order to bring up enough mineral salts to satisfy their wants no longer holds good. It has been proved that there is no relation between the transpiration and the mineral absorption and mineral content of plants. Most probably the effect of a sufficient supply of available plant food on the transpiration ratio is the same as the effect of an optimum temperature, viz. that positive growth, i.e. increase in weight, takes place so much faster that larger crops are obtained and *proportionately* less water is used or transpired.

Thus, manuring with plant foods that are deficient in the soil will mean a saving in water consumption only *in so far as it affects the transpiration ratio*, i.e. the amount of water which is transpired for 1 lb. of dry matter to be produced. However, it must be borne in mind that the total amount of water consumed may actually be higher on a manured land because the yield is so much higher and a large crop would use more water per morgen than a small one though the water used per lb. of dry material is less. This fact is noticed if a drought occurs during the growing season when an

unmanured crop, especially maize, often gives a higher yield of grain than a manured crop. The reason for this is that the crop on the manured soil grows rapidly and luxuriantly during its early stages and thus its transpiration or water consumption is higher than that of the slow-growing crop with much smaller leaves. If the fertilizer is applied superficially the root system will also be much shallower in the fertilized than in the unfertilized soil. The result of all this is that crops in fertilized soil are not as resistant to drought as unfertilized crops and thus, where the former may yield hardly any grain after a drought, one might still reap a small crop from the unfertilized soil. Because nitrogen stimulates vegetative growth, it should be applied with discretion where the rainfall is limited or erratic, and then it should be well worked into the soil and evenly distributed throughout the ploughed depth. In the case of phosphatic fertilizers there is not the same risk, and potash fertilizers, if applied where necessary, even cause the crop to use water more sparingly, as will be shown in a subsequent chapter.

Apart from large amounts of water transpired by agricultural crops, water is also lost from the soil in other ways. For example, all weeds growing between crops use moisture and therefore they should be eradicated by cultivation. Water also evaporates from the soil surface and the amount of water lost in this way may be considerable. Evaporation of water from the soil surface is influenced by many factors, such as temperature, dryness of the air, prevailing winds, and plant covering. At the beginning of the growth period evaporation of water from the land will be considerably higher than at a later stage when the crop shades the soil, provided that climatic conditions remain relatively unchanged. A loose soil mulch also causes deeper soil layers to lose less moisture, and from a soil with a hard crust on the surface or with cracks in it a great deal of moisture evaporates. The significance of a soil mulch will be discussed in a later chapter.

The amount of water that will evaporate from the soil during the growing period of a crop will vary greatly with different conditions and therefore it is difficult to give accurate figures. The total amount of water lost from a soil during the growing period (excluding run-off and percolation of rainwater) is called the transpiration-evaporation ratio. It will obviously be considerably higher than the transpiration ratio. Under the variable South African conditions we can say that the amount of soil moisture necessary for one unit of weight of dry plant material is about 400–800.

Water is by far the most important factor limiting plant growth in South Africa as is illustrated by the immense fluctuations in yield and the relatively low yields per morgen. In the winter rainfall area the rain is much more regular and reliable than in the summer rainfall area. Thus we find, for example, that the yields of winter cereals in the south-western districts of the Cape Province are fairly constant when compared with the maize yield in the summer rainfall area, which may vary from, say, 12 to 24 million bags per year. The total annual rainfall may be sufficient for large crops, but unfortunately the distribution is often so unfavourable that the crop

may suffer from drought during a critical stage in its growth. Thus the question of available water is one of the most serious problems facing the South African agriculturalist, and in subsequent chapters we will often return to this subject.

Finally, we would like to refer to one more factor in connexion with the water economy of plants which in the past has received little attention from research workers, but is, nevertheless, of great importance to many crops. This is the dew that condenses on plants. The dew that is formed on the soil surface will be discussed under water relationships in soils. Pioneer work in connexion with dew has been done by E. Hiltner (Germany) since about 1927 and the following conclusions were reached:

It is generally known that the formation of dew is heaviest in the mornings just before sunrise, after a windless night and with a clear sky. Furthermore, it depends on the degree of cooling of the atmospheric temperature, the humidity of the atmosphere, and on the extent of the cooling plant surface. Thus it was found that a heavy dewfall on a potato field can amount to 5,070 gallons per morgen (0·034 inches). In Germany it was found that the lower the rainfall the higher the dewfall during the summer months provided there is little wind.

The question now arises: Is the dewfall on the leaves of any importance in connexion with the water economy of plants? Taking into consideration what we said about water absorption by root cells, it would appear that leaves would normally be unable to absorb dew because at night, and especially in the morning, leaves are very turgid even if they were temporarily wilted during the previous day. And yet Hiltner and others have proved beyond doubt that leaves can absorb a large portion of the dew even if they are not at all wilted. It has even been found that oats and other plants growing in water cultures, where there can be no question of a water shortage, absorb artificial dew through their leaves, and benefit to such an extent by it when they receive dew twice to three times per week that they produce considerably higher yields (up to 35 per cent. dry matter) than plants that did not receive any dew.

Hiltner explains the beneficial results of dew on plant growth as follows: dew naturally is pure water without any dissolved salts, and by the absorption of such water into the leaf cells, the saline solution in the leaves is diluted and this is beneficial to plants that are sensitive to a high salt concentration. It has been found that such plants benefit most from dew.

Although no research work has been done in this connexion in South Africa and we therefore have no details about dewfalls here, we may safely assume that dew is of considerable agricultural importance. For instance, good crops are produced on the Langgewens Experimental farm (Malmesbury) in years when the winter rainfall is only 8–10 inches and when it is dry during September and October, but during these months there is a high dewfall. Wine farmers know by experience that vines last much better during January if there are cool windless nights with heavy dew than if there are light rains followed by continuous south-easterly winds.

CHAPTER IV

SOIL NUTRIENTS

NITROGEN NUTRITION OF PLANTS

Effect of nitrogen on plant growth

NITROGEN is used in relatively large quantities by plants and is essential for their growth. This fact is apparent when we consider that 15–18 per cent. of the weight of albuminous compounds or proteins consists of nitrogen, and that protein exists in all living plant cells in the protoplasm as well as in the nucleus. To act as building material in the formation of proteins is the most important function of nitrogen in plant growth. There are also other plant constituents that contain nitrogen. Of these, chlorophyll is the most important because of its important function in carbon assimilation.

The most noticeable effect of nitrogen on plant growth is the healthy green colour and rapid growth of the vegetative parts of plants, i.e. leaves, stems, sprouts, and shoots. Thus we may state that nitrogen gives foliage, i.e. promotes growth in plants. Strictly speaking, this is not only so in the case of nitrogen, because an application of any essential plant food of which there is a deficiency in the soil will promote plant growth. Nitrogen, however, gives special vigour to plants. Hence the symptoms of a nitrogen deficiency in the soil are easier for the practical farmer to recognize than are those of any other plant food. Nitrogen shortage is immediately perceptible in the colour and vigour of plants. One has only to ascertain whether the absence of vigorous vegetative growth is not the result of some unfavourable conditions in the soil such as a high degree of acidity or alkalinity, an impervious soil layer below the topsoil, a high water table, or a shortage of water.

Because plants growing in a soil rich in nitrogen exhibit luxuriant vegetative growth they transpire much water and hence there is a close relationship between available moisture on the one hand and the effect of nitrogen on plants on the other. Thus a heavy application of nitrogen to a soil is only advisable where the moisture supply is definitely sufficient and ensured throughout the growing season. Not only is a nitrogen application less effective where there is a shortage of soil moisture, but it may even be the direct cause of a crop failure (see p. 21). Because the rainfall in South Africa is generally so unreliable one should bear the effects of nitrogen on plant growth in mind in order to derive maximum benefit from nitrogen applications.

The excessive vegetative growth which results from a heavy application of nitrogen also causes a lengthening of the growing period. Such plants set seed and mature later than is normally the case. We say that maturity is delayed. Plants which received an excessive nitrogen supply are also more susceptible to attack by fungus diseases (e.g. rust) and insect pests. Such

plants, on the whole, are weaker stemmed, and winter cereals which receive too much nitrogen are apt to lodge during heavy rains or strong winds.

These bad effects may be counteracted to a certain extent by applying sufficient phosphatic and potassic fertilizers together with the nitrogen, but usually it is advisable not to apply nitrogen too abundantly.

Plants satisfy by far the most of their total nitrogen requirement during the first few months of their growing period. (The same applies, more or less, in the case of the other mineral plant foods.) The result is that young plants are much richer in nitrogen and hence in protein than older plants. As plants grow older their seeds and fruits store much of the nitrogen.

Forms of nitrogen at the plant's disposal

1. *Elementary nitrogen gas.* As previously mentioned, about 80 per cent. of the atmosphere as well as the air in the soil consists of free nitrogen, i.e. nitrogen gas in its elementary form and not in chemical combination. It has been calculated that there are about 20,000,000 tons of nitrogen gas over every square mile of land surface; in other words, an inexhaustible supply. Unfortunately agricultural crops are unable to utilize this source directly. They cannot assimilate it, i.e. change it to nitrogenous compounds as, for example, they assimilate carbon dioxide from the air.

There are, however, a few kinds of bacteria that are able to assimilate nitrogen gas and manufacture complicated proteins from it. One group, viz. the nodule-forming bacteria, is characterized by the nodules which they form on the roots of legumes (Leguminosae) (see Plate I*a*). Nitrogen gas is soluble in water to a certain extent. One litre of water (at 15° C.) dissolves about 13·5 c.cm. of nitrogen. In well-aerated soils, soil moisture is saturated with nitrogen gas, and as the water moves upwards in the plant roots the bacteria in the roots remove the nitrogen from the water and use it in the building up of proteins. These bacteria are very short-lived with the result that they are constantly dying off. Their nitrogenous compounds then become available to the plant so that the plant is not dependent on the soil for its nitrogen supply. The bacteria fix the elementary nitrogen and the plant obtains its nitrogen from the nodules. The bacteria also need energy-containing food such as carbohydrates (sugars) and the legume provides them with this through carbon assimilation. We have here an example of two dissimilar organisms (the green plant and the bacteria) that live together and render one another mutual service in their nutrition. The scientific term to express this state is symbiosis, which means living together. These nodule-forming bacteria are also called symbiotic bacteria.

Many of our agricultural crops belong to the Leguminosae, such as peas, beans, lucerne, lupins, clover, and also many shrubs and trees such as thorn trees (mimosas) and Port Jackson. Such plants can make use of the inexhaustible supply of nitrogen in the atmosphere with the aid of nitrogen-fixing bacteria. This, however, does not mean that they cannot utilize the available nitrogen supply in the soil, as all other plants do. As a matter of fact, they always do and the bacteria only help them when the nitrogen

supply in the soil is not sufficient. In a subsequent chapter we shall see how the nodule-forming or nitrogen-fixing bacteria may be used in practical agriculture.

2. *Proteins.* Every agricultural soil always contains a considerable amount of nitrogen originating from the proteins in plant residues and soil microbes or from organic manures. These proteins are present in the so-called humus or organic matter in soils, of which we will hear more later.

Generally, a considerable amount of protein is supplied to the soil, for example, when the soil is manured with farm manure, green manure, bird guano, dried blood, &c. The proteins are almost completely insoluble in water and thus it is easy to understand that plants cannot absorb them directly. They form the nitrogen reserve in the soil and only become available to higher plants after having been decomposed to simpler compounds by soil microbes.

3. *Ammonium compounds.* As far as the nitrogen is concerned, ammonia (NH_3) is the final product of the decomposition of proteins. Ammonia is a gas which is very soluble in water and it combines with carbonic acid and the other acids that may be present in the soil moisture to form ammonium salts, e.g. ammonium carbonate ($(NH_4)_2CO_3$). There are also several fertilizers which are ammonium salts. The most common one is ammonium sulphate ($(NH_4)_2SO_4$).

Ammonium salts are readily soluble in water and plants can absorb them as a source of nitrogen. In the soil, however, ammonium compounds are usually rapidly changed by certain bacteria to nitrates.

4. *Nitrates.* Nitrogen in the form of nitrates is, from a certain point of view, the final product to which the nitrogen in complicated compounds is changed by bacteria. Being also readily soluble in water, nitrates are by far the most important source of available nitrogen for higher plants. Ordinary saltpetre is potassium nitrate, but sodium nitrate or Chilean saltpetre ($NaNO_3$) is the most common nitrogenous fertilizer containing nitrogen in the nitrate form. Thus plants absorb nitrogen mainly in the form of nitrates which are dissolved in soil moisture. They can also absorb other soluble nitrogen compounds but normally such compounds are very soon changed by soil microbes to nitrates. The legumes form an exception because they can also utilize the gaseous nitrogen with the help of the nodule-forming bacteria that live in their roots. The activities of bacteria and other soil microbes are of special importance in connexion with nitrogen assimilation by our agricultural crops, and therefore this subject will be discussed in greater detail in a subsequent chapter.

THE ASH CONSTITUENTS

As previously mentioned, every plant contains a small though very important amount of ash constituents, i.e. mineral substances, that come from the soil. As in the case of nitrogen, these substances are also absorbed by the roots of growing plants in a dilute solution in water in the form of compounds or salts. As regards the absorption of mineral plant foods there

are two important points to be remembered: the mineral plant food must be at least partly available to plants, and secondly, the solution should be very dilute as previously mentioned. In brackish soils soil moisture contains too much salt and such a high salt concentration also impedes water absorption by roots.

Before discussing briefly the different ash constituents we would like to give a table indicating the mineral composition of some of our agricultural crops. It should, however, be borne in mind that the percentages are not constant. There are wide variations even in the case of one particular crop, as a result of variations in soil fertility, manuring, climate, and other growth factors. The composition also varies at different stages in the growth of any crop. The figures represent average percentages and they were calculated on *air-dry* plant material except for potatoes and mangels, in which case they were calculated on the fresh plant material.

Figures, such as these given in the table, are important for two reasons. They give us an indication of the mineral plant food requirement of any crop, and secondly, they enable us to calculate more or less what amount of plant food is removed from the soil, provided we know the weight of the crop.

A general conclusion that we can draw from the table is that the total amount of ash constituents is higher in the vegetative parts, e.g. the straw, than in the seed, but that the seed is richer in phosphorus, nitrogen, and sometimes magnesia than the straw. On the other hand, the straw is richer in potash and lime than the seed.

TABLE 4

The Mineral Composition of Crops (percentages)

	Nitrogen (N)	*Ash content*	*Phosphoric oxide* (P_2O_5)	*Sulphur trioxide* (SO_3)	*Potash* (K_2O)	*Lime* (CaO)	*Magnesia* (MgO)
Wheat seed	1·60	1·73	0·85	0·28	0·50	0·07	0·15
Oat seed .	1·80	2·88	0·85	0·32	0·50	0·16	0·17
Maize seed .	1·60	1·23	0 57	0·27	0·37	0·03	0·19
Wheat straw	0·45	4·86	0 20	..	0·90	0·28	0·11
Oat straw .	0·65	6·45	0·35	..	1 60	0·38	0·12
Maize stalks	0·75	4·37	0·30	..	1·64	0·49	0·26
Pea seed .	3·65	2·63	1·00	0·50	1 25	0·09	0·13
Pea straw .	1·40	3·91	0·35	..	0·50	1·82	0·27
Lucerne hay	2·60	6·29	0·43	0·47	1·50	2·52	0·31
Potatoes .	0·32	0·97	0·14	0 06	0·60	0 03	0·06
Mangels .	0·19	0·86	0·07	..	0·40	0·03	0·04

Phosphorus

Phosphorus, or, as it is more commonly stated, phosphoric oxide, is absorbed by the plants in the form of phosphate salts that are not readily

soluble in water. This important point will be discussed further under manuring. The most important function of phosphorus in the plant is in the building up of nucleoproteins. If we consider that the formation of new plant cells, and thus growth, can only take place by the division of the cell nucleus and that this nucleus contains phosphorus, we realize how essential this nutrient is for plant growth. Phosphorus, like nitrogen, is therefore abundant in the young growing parts of the plant. As plants grow older and reach the flowering and seeding stages most of the phosphorus goes into the seeds. That is why all seeds are so rich in phosphorus.

Apart from this primary function of phosphorus, viz. to act as building material in the formation of nucleoproteins, this nutrient also has other specific effects on plant growth. Firstly, phosphorus enhances the fertility of plants and thus the formation of flowers and seeds. It also hastens maturity of the crop or fruit; in other words, it shortens the growing period. This effect of phosphorus is the opposite to that of excess nitrogen, where vegetative growth is stimulated and the growing period lengthened as a result. For normal growth, yield, and ripening of the crop, supplies of phosphorus and nitrogen with their opposite effects should be well balanced. Even very heavy applications of phosphates will seldom have harmful effects on plant growth but with nitrogen it is very easy to give too heavy an application. In practice it is advisable to apply average quantities of phosphatic fertilizers regularly to soils deficient in phosphates—and such is the case with the vast majority of South African agricultural soils—and to regulate applications of nitrogenous fertilizers according to the amount of growth required from the crop under the particular climatic conditions.

In the case of fruit-trees and other crops that do not bear well and grow too luxuriantly, a large application of a phosphatic fertilizer will often restore greater fertility and therefore better fruit and seed crops. A hastening of maturity is often of great economic importance, e.g. in the case of early fruit, Turkish tobacco, and maize that may be affected by early frost, &c. The timely ripening of the wood of deciduous fruit-trees and of vines is important, otherwise the immature wood may die off in winter.

A second effect of phosphorus on soils that are poor in phosphates is the striking development of the root system of plants. Possibly it is due to the fact that phosphorus is essential for the formation of new cells. There are at least two instances where a well-developed root system is especially desirable. Firstly, in the case of dry-land farming a deep and widespread root system will enable plants to withstand shortage of rainfall better than a shallow root system. Secondly, in clayey soils plants are apt to have a shallow root system, and thus clayey soils should receive regular applications of phosphatic fertilizers.

The last effect of phosphorus that we would like to mention is the improvement in the quality and nutritive value of many agricultural products. In the case of fruit, it has been proved in South Africa that phosphatic

fertilizers improve the general quality and especially the keeping quality of fruit. Also, where trees grow too luxuriantly and do not bear satisfactorily, an application of phosphate will often result in a bigger crop of better quality. In France it has been proved beyond doubt that soil with a high phosphorus content will produce a better wine than that with a low phosphorus content.

The phosphorus content of human and animal food is very important in the nutrition of humans and animals. Since 1920 a great deal of attention has been paid to this problem in South Africa. It has been proved that the low phosphorus content of the pasture grasses in many districts in the Union, especially during the dry season, is the cause of *Stywesiekte* (aphosphorosis), and this deficiency is also indirectly responsible for the disease *gallamsiekte* (botulism).

To supplement the phosphorus shortage in the grazing, food rich in phosphorus, such as bone-meal, should be fed regularly to the animals. Where the rainfall renders it possible, agricultural lands and pastures should receive phosphate applications in order to ensure healthy livestock.

The external symptoms of the plant do not indicate a phosphate shortage as distinctly as they indicate a shortage in nitrogen. For this purpose fertilizer experiments or soil and plant analyses provide the correct answer. However, South African soils are generally so poor in phosphates that phosphatic fertilizers should always be applied where the natural rainfall or irrigation makes crops possible, unless otherwise advised by agricultural authorities.

Potash

There is a higher percentage of potash in the leaves than in the seeds of plants and all leafy crops are, therefore, rich in potash. Potash is the metallic base used in largest quantity by plants and it is absolutely essential for plant growth. The leaves, where metabolism largely takes place, are by far the most important laboratories of plants and it is also in the leaves that potash fulfils its most important function. Young leaves are very rich in potash but towards the end of the growing season the potash content diminishes while the lime content increases right to the end. In contrast with almost all other ash constituents in plants, all the potash is present in the plant in compounds that are soluble in water. Thus it can easily be extracted from the leaves with water.

Much has been written in the past about the function of potash in plant growth and much of this is controversial. In the light of recent research, however, it seems as if all the different effects on plant growth, attributed to potash, can be traced back to one important function that can only be performed by potash. The contents of living plant cells consist of at least a slightly saline solution (cell sap), a jelly-like layer of protoplasm, and a more solid cell nucleus. The *physical condition* of the protoplasm seems to be very important in connexion with the many biochemical reactions that take

place in the cell and also in connexion with its longevity. Apparently potash gives to the protoplasmic colloids (for colloids see Chapter XI) this desirable gelatinous consistency which is necessary for the activity and longevity of the plant cells. For example, if the cells contain too much lime and too little potash, the protoplasm is drier and more granular and the cell only lives for a short while.

Thus potash ensures healthy leaves that can carry out their functions normally for a long time. Previously it was thought that potash must in some way or other affect carbon assimilation, because crops that produce a large quantity of carbohydrates (sugars or starch) or are rich in foliage, such as potatoes, sweet potatoes, the brassicas, tobacco, fruit-trees, vines, &c., use much potash. Similarly, it was thought that the formation of proteins was influenced by potash because a high protein content is usually concomitant with a high potash content (e.g. in legumes). The explanation now is that potash does not influence carbon and nitrogen assimilation directly, but because it keeps the leaves healthy and active larger amounts of carbohydrates and proteins can be manufactured during the growing season.

It is a well-known fact that plants which are well supplied with potash do not wilt or scorch as easily as those growing in a soil that is deficient in potash. The leaves of apple-trees and berry fruits are apt to scorch when these plants grow on soils which are deficient in potash. Thus it is clear that leaves that are well supplied with potash transpire less, and in this sense we can say that potash causes plants to use water more economically. This reduction in transpiration is no doubt related to the physical condition of the protoplasmic colloids that are well supplied with potash. Possibly potash salts have other functions in addition, but we cannot discuss them here in detail.

In connexion with the influence of potash on the quality of agricultural products, the following may be said: seeds such as those of wheat, oats, barley, rye, &c., are plumper and have a higher bushel weight when the plants are well supplied with potash than when there is a deficiency of potash. Apparently potash does not influence the baking quality of meal directly. Pasture crops are more palatable to animals when pastures are well supplied with potash. In the case of oranges it has been proved that a one-sided application of potassic fertilizers will increase the acidity of the oranges, but if sufficient phosphate is also applied, so that the oranges can ripen properly and contain enough sugar, fertilizing with potash will not cause deterioration in the quality of the fruit. Similar observations were made in connexion with deciduous fruits and grapes. From these effects of manuring with only one plant food we must not deduce that potash is detrimental to the quality of fruit, but rather that only trees receiving a balanced food supply can yield fruit of a high quality provided all the other growth requirements are favourable.

Deficiency in potash is not very noticeable in the external appearance of plants. It is only when the deficiency is very acute and when one section

of the field receives potash and the other not that differences in yields and appearances are noticeable. A typical symptom of a shortage of potash is the curling, bronzing, and scorching of the leaves in the later stages of the growth period. This is especially noticeable in the case of tobacco, potatoes, peas, berry fruits, apples, &c. To prove definitely that there is a deficiency of potash in the soil, it is necessary, as in the case of phosphate, to conduct fertilizer experiments and soil analyses.

Potash is absorbed by plant roots in the form of potassium salts. The two salts that are most commonly used for fertilizing are potassium sulphate and potassium chloride, or, as they are generally known, sulphate of potash and muriate of potash.

Other ash constituents

We know by experience that soils are most likely to be deficient in phosphorus and potash and, therefore, we must supply them in the form of fertilizers. However, there are still other constituents (considerably more than we mentioned in the table on p. 26) that are essential for plant growth or that are present in the plant ash. Some ash constituents, although not absolutely essential, may fulfil some useful function in plant growth. There are cases where soils may have a deficiency of one or more of these essential but minor plant foods, and then they should be applied. It is the work of the Research Stations to investigate such cases and advise farmers accordingly. We will thus discuss the following mineral plant foods only very briefly.

Calcium. Calcium is indispensable to plant growth, and, as in the case of potassium, it is found mostly in the vegetative parts of plants. Seeds usually contain very little calcium. The result is that the young seedling very soon requires calcium from the soil. Usually soils contain sufficient calcium to satisfy the requirements of plants. Moreover, calcium is in most cases supplied to soils if a phosphatic fertilizer is applied.

Very little is known about the functions of calcium in the plant. Evidently it promotes healthy development of the plant, especially of the root-hairs of the root system. It has been proved that calcium tends to reduce the toxicity that sodium, potassium, and magnesium have when present in excessive amounts. That is why plants are more resistant to brak soils or irrigation water if the soil contains sufficient calcium.

Sometimes large amounts of calcium are applied to soils in the form of lime (slaked lime or ground limestone), but then the aim is to render sour soils sweet or to improve the structure of a heavy clay soil. This subject will be discussed later. It has already been mentioned that there may be great variations in the amounts of ash constituents, either individually or collectively. The more abundant any mineral nutrient is in the soil, the more of it the plant will absorb. Because calcium compounds play an important role in the nutrition of man and beast, as does phosphorus, it is essential that the farmer, in order to have healthy livestock, should see to it that the food contains sufficient calcium. By applying basic fertilizers

or lime to acid soils one will produce more suitable fodder and pasture crops.

Magnesium. Magnesium (i.e. magnesium salts) is also an essential mineral plant food, especially because it forms part of the chlorophyll molecule that is essential for carbon assimilation. Cases are known abroad where plants are chlorotic because there is not sufficient magnesium food in the soil, with the result that chlorophyll cannot form. Thus far a definite lack of magnesium has, in South African soils, only been recorded in some citrus orchards at Nelspruit (Tvl.) (Dr. Oberholzer). The deficiency may be corrected by applying dolomitic limestone or the fertilizer potash-magnesia (see p. 208).

Iron. Plants use iron salts in very small amounts, but iron is, nevertheless, essential for plant growth. It has been found that although iron does not form part of the chlorophyll molecule it is essential for its formation. Plants that do not absorb sufficient iron salts suffer from chlorosis. Usually soils contain iron compounds, especially hydrated oxides, in large amounts, but if the soil contains too much lime, i.e. if it is alkaline, the iron may be quite insoluble so that plants will not be able to absorb it. Such calcareous soils are of frequent occurrence in the dry areas of the Karoo. Some plants are better able to utilize relatively insoluble iron compounds than others. Thus peach-trees often suffer from chlorosis. Application of decayed straw, farm manure, and also sulphur will help in such cases to render the insoluble iron available to the plant. The more acid a soil is, the more soluble is the iron.

Sulphur. Sulphur is an essential plant food because it is a constituent of all proteins. The sulphur content of proteins varies from about 0·17 to 1·09 per cent. The richer the plants are in proteins the greater is their need for sulphur (compare cereals and legumes). Brassicas (the cabbage family) contain also other sulphur compounds such as the mustard oils, and thus they have a greater sulphur requirement than the ordinary agricultural crops.

Plants absorb their sulphur in the form of sulphate salts. Sulphates are generally fairly soluble in water so that the sulphur content of soils is low in high rainfall areas. In South Africa, soils that contain too little sulphur and require sulphur applications have not yet been found. Besides, farm manure and many of the fertilizers (such as superphosphate, ammonium sulphate, potassium sulphate) contain sulphur compounds so that applications of such fertilizers also supply sulphur to the soil. In vineyards and orchards, insecticides and fungicides that contain sulphur also add sulphur to the soil. Rain-water also always contains a small amount of sulphur compounds.

We have now discussed the *ten classical nutrient elements* which were up to about 1930 considered to be the only essential plant food elements. By way of a summary, we once again give the ten, and in brackets the forms in which they are absorbed: *Carbon* (as carbon dioxide), *Hydrogen* and *Oxygen* (as water), *Nitrogen* (as soluble nitrogen compounds, especially nitrates), *Sulphur* (as sulphates), *Phosphorus* (as phosphates), *Potassium*

(as potassium or potash salts), *Calcium* (as calcium salts), *Magnesium* (as magnesium salts), and *Iron* (as iron salts, ferrous and ferric). Plant ash also contains many other mineral constituents, of which the elements *Sodium*, *Silicon*, and *Chlorine* are considered to be 'useful' although not essential, especially for certain crops.

TRACE OR MINOR ELEMENTS

Research work in connexion with plant nutrition, especially since 1930, has proved beyond doubt that all plants require, in addition to the above ten, certain other elements—again in the form of salts—for healthy normal development. These elements are required in *minute quantities* or *traces*. Hence these elements are to-day known as *trace elements* and of these, *Manganese*, *Copper*, *Zinc*, *Boron*, and probably *Molybdenum*[1] also, are absolutely essential for higher plants. Because *Iron* is also used in very small quantities by plants, it is now usually bracketed with the trace elements. As yet, not very much is known about the role of the trace elements in plant metabolism and therefore we will not discuss their possible functions. Furthermore, we shall limit the following summary to the deficiency of such trace elements in South Africa, because there already exists abroad a huge literature on the subject.

Manganese. Research officers of the Stellenbosch-Elsenburg College of Agriculture discovered in 1940 that the sandy soils of the Cape Flats, which are usually calcareous, and which may be termed the 'vegetable garden' of Cape Town, have a chronic deficiency in manganese. Chemical analyses show that the total manganese content varies from 6 to 10 parts per million whereas other soil types usually contain more than 100 parts per million and the red loam of Pretoria (originating from diabase) may contain more than 900 parts per million. It is a general rule in the case of the above-mentioned trace elements that if the soil becomes sweeter (pH rises above 6·0), especially if the soil contains free carbonate of lime and is deficient in humus, the trace elements are very unavailable. Thus the calcareous white sandy soils of the Cape Flats not only contain very little total manganese, but this small amount is also exceedingly insoluble.

Experience has taught the vegetable growers that even in the case of legumes such as garden beans a heavy application of stable manure or compost, up to 30–40 tons per morgen, is necessary for healthy plant growth, otherwise the crop remains small and chlorotic. Farm manure and compost, of course, contain a small amount of manganese and also other trace elements. The following experiment with potatoes, which are not even very sensitive to a manganese deficiency, shows clearly that fertilizers without manganese produce a very poor crop. (Experiment by I. S. Perold on deep sandy soil with pH of 8·04.)

[1] Australian workers seem to have proved that a minute quantity of molybdenum compounds is essential to enable nitrogen-fixing bacteria to accomplish the fixation. In contrast to the other trace elements the availability of molybdenum is increased by liming acid soils.

TABLE 5

Potato Experiment with Manganese (Cape Flats, 1941)

Fertilizer treatment per morgen	*Yield per morgen (bag = 150 lb.)*	
	Absolute	*Relative*
NPK Fertilizer	63 bags	100
,, ,, +44 lb. manganese sulphate	129 ,,	205
,, ,, +88 lb. ,, ,,	131 ,,	208
,, ,, +132 lb. ,, ,,	123 ,,	195

The differences in yield with different quantities of manganese sulphate per morgen are insignificant and thus 44 lb. per morgen was quite sufficient. Many other similar experiments on the Cape Flats have proved that an application of more than 100 lb. of manganese sulphate per morgen may definitely be toxic, thus reducing yields. Animal manure or compost is essential for vegetable production on the sandy soils of the Cape Flats, and the following applications are considered to be the most economical for most vegetables (all quantities per morgen): 10–15 tons of farm manure or compost, about 600 lb. of a suitable fertilizer mixture, and 50 lb. of manganese sulphate.

In different localities in the Western Province, orchards and vineyards that react on applications of manganese have been found, and the Division of Horticulture at Pretoria has also reported the occurrence of manganese deficiency in other parts of South Africa.

Copper. In 1941 it was proved beyond doubt that there is a copper deficiency in the southern coastal regions (calcareous sandy dune soils) of the Cape Province, after it had become known in Australia in 1937 that the well-known swayback disease of sheep which occurs there on similar soils could be cured by dosing with copper. In South Africa it was also proved experimentally that lambs would be born healthy if pregnant ewes were given timely doses of copper sulphate. As a matter of fact, many farmers in our coastal regions discovered this fact on their own. The following experiment conducted in 1941 by I. S. Perold on wind-blown sandy soil (pH 8·04) on a farm near Vredenburg shows clearly how crops respond to applications of copper.

TABLE 6

Wheat Experiment with Trace Elements

Fertilizer treatment per morgen	*Yield per morgen (grain)*	
	Absolute	*Relative*
310 lb. NPK Fertilizer	503 lb.	100
,, ,, +30 lb. copper sulphate	805 ,,	160
,, ,, +30 lb. zinc sulphate	11 ,,	2

The experiment proves that 30 lb. of copper sulphate per morgen gave an increase in yield of 60 per cent. over ordinary fertilizers. On account of the scanty rainfall the yield was not high, but the one with copper was of first-class quality. Furthermore, the experiment shows how careful farmers should be when applying trace elements. An application of 30 lb. of zinc sulphate per morgen had such a toxic effect that the crop was a complete failure. The other trace elements were also included in the above experiment but there was neither an increase nor a decrease in yield.

Zinc. The so-called 'little leaf disease' of deciduous fruit-trees occurs commonly in South Africa, especially in the Western Cape Province, and it was accidentally found in California (Chandler) in 1928 that it could be cured with zinc salts. In citrus-trees mottled leaf is the first sign of a zinc deficiency and according to the Division of Horticulture it occurs fairly commonly in the Union. Such orchard soils may be treated with zinc sulphate, but it is much more economical to spray the affected trees. A safe solution for trees in foliage is 4 lb. of zinc sulphate and 2 lb. of slaked lime in 100 gallons of water. However, stronger solutions may be used in severe cases of the disease. For deciduous trees a strong dormant spray is very effective.

Boron. A deficiency of boron is very common, e.g. in New Zealand where it causes internal cork of apples or in Europe where it causes brown heart of mangels and sugar-beet on calcareous soils. In Southern Africa it has only been observed in citrus orchards, by Dr. A. A. Morris (1937), on the Mazoe Citrus Estate, Southern Rhodesia. The 'disease' is known locally as 'hard fruit disease' because oranges remain small and have a hard, gummy appearance. Applications of small amounts of borax to the soil cured the disease.

ABSORPTION OF NUTRIENT SALTS

Finally, we would like to say something about the way in which plants absorb mineral nutrients, including nitrogen compounds, from the soil. This absorption is even more intricate than water absorption by roots, and it is not yet possible to give an entirely satisfactory explanation of the process. In any case, the root-hairs are again the principal organs through which the salts are absorbed. At once we come up against the difficulty that the salt concentration (osmotic pressure) is much higher in the cells than in the surrounding soil moisture. We saw that this difference enabled roots to absorb water from the soil; but how do we account for the absorption of salts from the very dilute soil solution, because salt and water absorption are two entirely different processes? According to physical laws (diffusion), dissolved salts move from concentrated to less concentrated solutions and not vice versa.

Firstly, we should not consider the total concentration of all the salts. We should rather take the different constituents one by one. Then the difference between the inside and outside concentration of those substances, such as nitrates, potassium salts, and phosphorus, which the plant uses a

lot, is no longer so great although it may still be considerable. Also, plants absorb mineral constituents mainly in the form of ions and not in the form of molecules. In the cells the ions may be attached to colloids so that a lower concentration of ions would be established within the cell than outside and thus diffusion would be possible. The question of ion absorption will be clearer if we know more about the properties of colloids (see Chapter XI), because it seems to be mainly a case of an exchange of ions between soil colloids and plant colloids.

The mineral nutrients finally come into the vascular bundles, whence they are transported by water to the growing points of the plant, and this upward movement takes place in the xylem (sapwood) and not in the phloem (bark).

PART TWO

SOIL SCIENCE

CHAPTER V

INTRODUCTION

BY *soil* we understand the layer of loose material that covers the earth's crust (the rock layer). However, because we wish to study the soil from an agricultural aspect in this book, we would define it as follows: Soil consists of more or less weathered rock particles that, together with organic matter, water, and air, provide a medium in which plants can grow. This definition contains a few strange words that will become clearer presently.

Thus an agricultural soil consists of four kinds of constituents: two kinds of solids, one derived from rocks and the other, the organic matter, mainly from plant residues. Furthermore, the soil contains a liquid (water) and a mixture of gases (air). The following diagram indicates the volume percentage of these constituents in a definite volume of moist soil, say, one cubic foot.

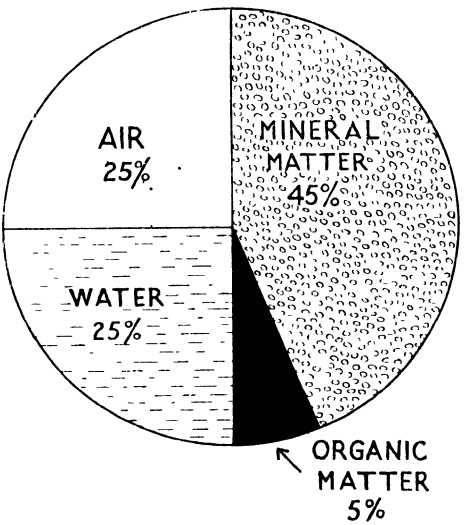


FIG. 1. Diagram showing the composition of a moist soil, consisting of mineral matter, organic matter, water, and air.

However, not only is an agricultural soil a mixture of the above constituents, but it also contains a teeming population of invisible, living

organisms called micro-organisms or, shortly, microbes. These microbes play a very important part in the fertility of soils, as will be seen in subsequent chapters.

We said in our definition that the rock particles are more or less weathered. That means that the rock constituents (minerals) are not only broken up, but they have also been changed by the so-called weathering agencies to different chemical compounds. Plants cannot absorb their mineral food from rock that has only been pulverized mechanically. The rock particles must first undergo chemical changes and become more or less soluble in water before they are suitable for plant nutrition. The weathering processes will be discussed in a subsequent chapter.

The depth of agricultural soils varies widely, but usually we are able to differentiate between the following two layers: the *topsoil* or *surface soil* which in agricultural soils is usually as deep as the depth of ploughing and is usually dark-coloured or brown, and the *subsoil* below the plough depth. The subsoil is usually lighter in colour.

In other respects also the two layers differ from one another. Usually the subsoil becomes [redacted]e stony or gravelly as one penetrates into it, until the parent rock on w[redacted] the soil rests is reached. Sometimes the subsoil is more clayey at certain depths than the topsoil and often hardpans of ironstone (*ouklip*) or limestone occur in the subsoil. The origin of such pans and concretions in the subsoil will be discussed later on, but it must be borne in mind that it is very important that the agriculturalist should be acquainted with the nature of his subsoils, because on it depends, to a large extent, the productivity of the soil. *Soil profile* is the scientific name given to the vertical section of a soil. The physical nature and chemical composition of the different horizontal layers of the soil profile are very important in the study of soils. In ditches, railway cuttings, gravel pits, &c., the different soil layers can often be seen distinctly. When these soil layers still rest on the parent rock from which they originated by weathering through countless ages, the soils are called *primary* or *sedentary* soils.

There is a second soil class called *secondary* or *transported* soils, and they consist of soil material which has been transported from some other place to its present position by gravity, water, or wind. They did not originate from the rock on which they are resting. Often such soils rest on primary soils, burying them completely. Such buried primary soils may also be called fossil soils.

Transported soils are often very deep as in the case of alluvial soils on river-banks or in the valleys at the foot of mountains and hills. Naturally there are many transitional stages between the two soil classes, and almost all primary soils contain a greater or less amount of material deposited by water or wind. Later on we shall have more to say about the real alluvial soils, i.e. those deposited by water, and aeolian soils, i.e. those deposited by wind.

Because the inorganic or mineral portion of a soil always originates from the solid rock of the earth's crust we shall discuss the composition of the most important rocks, their disintegration and change to soil material, and the eventual transportation of this material, before we discuss the different properties of soils.

THE CHEMICAL COMPOSITION OF THE EARTH'S CRUST

Geology teaches us that the solid crust of the earth is about thirty miles thick and that it consists of many different kinds of rocks. The average chemical composition of the rock material in the outer crust of the earth is more or less as follows:

Oxygen	49·20 per cent.
Silicon	25·67 ,,
Aluminium	7·50 ,,
Iron	4·71 ,,
Calcium	3·39 ,,
Magnesium	2·93 ,,
Sodium	2·63 ,,
Potassium	2·40 ,,

The above elements are present in the form of compounds in rocks and together they form about 98 per cent. of the weight of rocks. Some of the elements that are of great importance to plant growth occur only in small quantities in the rocks of the earth's crust, e.g.:

Phosphorus	0·11 per cent.
Sulphur	0·06 ,,

Valuable chemical elements such as gold, silver, copper, and platinum do occur in considerable quantities in various localities, but on the whole they form such a small part of the earth's crust that they are not worth mentioning.

If we inspect a freshly broken rock fragment, such as a piece of granite, we will notice immediately that it contains different substances or compounds. In fact nearly all rocks consist of miscellaneous substances called minerals. Every rock also has its own characteristic minerals of which it mainly consists. We cannot learn to recognize either the minerals or the rocks from text-books. It is essential for us to have specimens in order to get to know them properly.

THE MOST IMPORTANT ROCK-FORMING MINERALS

General properties of minerals

We can define a mineral as any inorganic substance occurring in the earth's crust, and having a constant chemical composition. Apart from this chemical characteristic of minerals, there is also a range of physical

characteristics which minerals possess and which usually enable us to recognize them.

Many minerals have a characteristic *colour* but sometimes they show a variation in colour due to the admixture of impurities. The following summary gives examples of minerals and their characteristic colours:

Colourless	Quartz.
White to pale	Felspars, Calcite, Dolomite, Gypsum, Kaolin.
Yellow	Iron pyrites.
Greenish	Olivine, Serpentine.
Reddish-brown	Garnet.
Black	Biotite, Hornblende, Augite, Hematite, Magnetite, Graphite.

The *lustre* or reflection of light from the surface of minerals is often characteristic. To judge the lustre one should inspect the fresh rock surface with the light playing on it. Quartz has a fatty, vitreous lustre. Felspars also shine visibly and their cleavage surfaces in light are easily distinguishable from the rough angular cleavage of quartz. Kaolin has a dull appearance and iron pyrites and hematite, for example, have a metallic lustre.

Cleavage is the separation along smooth planes which is exhibited by many minerals when they are struck or pricked with a hard object. It is an important property in identifying minerals. A mineral may show no cleavage, such as quartz, or a cleavage in one, two, or three directions. Thus some, such as the micas, only split in one direction, while others, such as the felspars, split in two directions, and others again split in three directions, such as calcite, rock salt or halite, and gypsum. The angle between two cleavage planes may be a right angle as in the case of rock salt and orthoclase, or it may be an oblique angle as in the case of calcite, gypsum, and plagioclase. The cleavage plane may be quite smooth or perfect as in the case of the micas, calcite, and rock salt, it may be distinct as with felspar and fluorite, or it may be quite rough and angular as in the case of quartz and pyrite, in which case the mineral actually possesses no cleavage.

Minerals differ in their degree of *hardness* and mineralogists differentiate between ten degrees of hardness. Talc, soapstone or French chalk, is the softest and thus it possesses hardness 1, while diamond is the hardest and thus possesses hardness 10. According to the acknowledged scale of hardness a copper coin possesses a hardness of about 3 and the steel point of a knife possesses a hardness of 5–6. The hardness of the different minerals will be given when they are discussed.

The colour of the *streak* left by a coloured mineral on an unglazed white porcelain surface when rubbed against it also aids in the identification of such minerals. Often the streak of the mineral powder is not at all the same

as the colour of the mineral in its natural crystalline state. Examples will be given later.

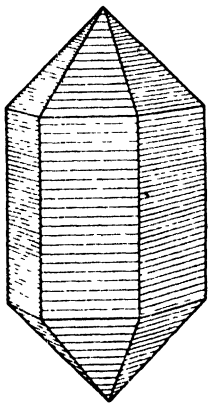


FIG. 2. A perfect quartz crystal with hexagonal prism and two hexagonal pyramids.

A crystal is an object with regular faces, and the angles between the faces are always the same for the crystals of any given substance. Almost all the minerals that occur in rocks have characteristic *crystalline structures*. However, in rocks the crystals are seldom perfect and complete with the result that it is not generally possible to recognize the crystalline form clearly without a microscope. Nevertheless, in cracks in rocks one sometimes finds perfect crystals, especially of quartz, of which the crystalline form can easily be recognized by the naked eye. A mineral is said to be amorphous when it possesses no crystalline structure but is of an earthy or glassy nature.

The *specific gravity* of the most important minerals varies from 2·3 (gypsum) to 5·3 (hematite). The specific gravity of quartz, which is the mineral that is most common in nature (also in soils), is 2·65.

We shall now give a brief description of the most important minerals occurring in rocks and soils.

Quartz and silicates

Quartz (SiO_2) is a constituent of most rocks and the so-called sand fraction of soils consists mostly and sometimes exclusively of quartz. In rocks it is usually colourless and has a rough surface and fatty vitreous lustre. By these properties and by its hardness (it cannot be scratched with a knife, hardness 7) it is easy to identify quartz. Because quartz is subject to very little, if any, chemical weathering, it is usually the chief constituent of soils. The yellowish or red colour that sand usually has is due to a thin layer of iron hydroxide on the quartz particles, or it may be very fine dust. If such sand is boiled in hydrochloric acid, colourless quartz crystals remain behind. Flint is also impure quartz. Sometimes quartz is coloured so beautifully that it is sold as a semi-precious stone or gem under different names: amethyst (violet), jasper (red), opal (bluish), chalcedony, sardonyx, agate.

The *silicates* are very important rock-forming minerals. They are salts of various hypothetical silicic acids and usually they contain aluminium and naturally also silicon in their molecules. The following are the most important:

The *felspars* are silicates of aluminium that may contain different bases and hence they are divided accordingly into two groups:

(*a*) *Orthoclase* ($KAlSi_3O_8$) is the potash felspar. It is colourless when pure but usually it has a grey or yellowish colour although it may also be red or greenish. It is the typical constituent of the so-called acid igneous

rocks, of which granite is the most important in South Africa. It usually occurs in fairly large visible crystals that are easily recognizable in newly broken rocks by their smooth shiny cleavage planes. Its hardness is about 6, so that a knife would not scratch it. In weathered or decomposed granite the felspar has a dull appearance. It then has a yellow rusty colour or it may have changed completely to soft white clay. When weathering takes place the potash is released from the molecule and becomes available to plants. A small amount of silicic acid is also released. The rest of the molecule changes to clay.

(*b*) *Plagioclase* can contain only sodium ($NaAlSi_3O_8$), or only calcium ($CaAl_2Si_2O_8$), but usually it contains both and thus the plagioclases are also called the soda-lime felspars. They are also greyish in colour and with the naked eye they are not distinguishable from orthoclase. However, they preponderate in basic igneous rocks such as norite and dolerite where we can recognize them by the same properties found in orthoclase. Like orthoclase, the plagioclases also weather to form clay, but instead of potash, lime and soda are released as plant foods. Thus, soils that originated from rocks containing much plagioclase will contain a considerable amount of calcium (lime) if the rainfall is not too high.

The *micas* are a second very important group of rock-forming silicates. Especially two of them are common:

(*a*) *Muscovite* is the white mica, also called potash-mica ($KH_2Al_3Si_3O_{12}$).

(*b*) *Biotite* is the black mica, also called magnesia-mica ($KH(Mg.Fe)_2Al_2Si_3O_{12}$).

They are easily recognizable by their perfectly smooth shiny cleavage planes that are often hexagonal. They are very soft (hardness 2–2·5) and flexible when fresh. They are typical constituents of granite and mica-schists. Owing to the presence of iron, weathered biotite has a yellowish-rusty colour and slightly resembles gold (cat's gold).

Hornblende and *Augite* are two black minerals that belong to the group of ferro-magnesium silicates, as does biotite, but they are much harder than biotite and not as cleavable. Thus it is easy to distinguish them from biotite. However, it is impossible to distinguish between the two of them with the naked eye. Fortunately they occur in different rocks so that we can always guess with which black mineral we are dealing. Hornblende occurs more in the acid igneous rocks, e.g. sometimes in granite. Augite again occurs in the basic igneous rocks such as norite and dolerite. Both of them form clay on weathering and simultaneously iron, magnesium, and calcium are released and become available as plant nutrients. Blue-asbestos is also a hornblende mineral.

Kaolin, china clay or white clay, is hydrous acid aluminium silicate ($H_2Al_2Si_2O_8.H_2O$). It occurs in crystalline form in certain sedimentary rocks but usually it is a soft, non-crystalline (amorphous) product of weathering. It may originate from the weathering of all aluminous silicates, and we can at this stage regard the so-called clay in soils as impure kaolin;

red potclay and blue potclay contain ferruginous compounds and other 'impurities'.

Serpentine is hydrous acid magnesium silicate ($H_2Mg_3Si_2O_8.H_2O$). It is usually greenish in colour and occurs in serpentine rocks and some marble rocks. White-asbestos also belongs to the serpentine minerals.

Talc, soapstone or French chalk, is also a hydrous magnesium silicate, but contains more silica (SiO_2) than serpentine. It is white or yellowish in colour, very soft, and usually occurs in massive form in talc-schists.

Olivine (Mg_2SiO_4) is a very hard green mineral that possesses no cleavage. It is an accessory mineral in some basic rocks such as dolerite.

Iron minerals (ores)

Hematite (Fe_2O_3) is a blackish iron-grey mineral that leaves a *red* streak on porcelain. It has a metallic lustre, is very hard, and usually weathers to form iron hydroxides. It occurs in small quantities in many rocks and sometimes also in large quantities as iron ore, e.g. near Pretoria.

Magnetite (Fe_3O_4) is also a black mineral with a metallic lustre, but, in contrast with hematite, it has a greyish-*black* streak. As the name indicates, it also has magnetic qualities. It is also very hard and heavy (specific gravity 5·0). It occurs in small quantities in many rocks, e.g. dolerite. In norite rocks it may occur in the form of thick veins as at Brits, Transvaal. It weathers comparatively slowly so that we still find it in soils that originated from magnetite-containing rocks.

Limonite or bog iron ore is an iron hydroxide ($2Fe_2O_3.3H_2O$) and usually it is the final product of weathering of most ferruginous minerals in soils. Thus it is not so much a rock constituent as it is a soil constituent. It gives the brown colour to soils. Sometimes it occurs in a mixture with other substances forming a hard layer or immense concretions of ironstone or *ouklip*. More often it is found in the soil in the form of more or less round black pellets that are dark brown in the inside when broken. Although it is black on the outside, it leaves a yellowish-brown streak on white porcelain. Red and yellow ochres are other forms of iron hydroxides.

Pyrite or, more commonly, iron pyrites is iron sulphide (FeS_2). It is a golden-yellow or bright-yellow mineral (Fools' gold) but it leaves a greyish-black streak on white porcelain. It occurs as small crystals, often as cubes, in a great number of rocks, even in coal. It weathers comparatively easily and forms brownish-black limonite. Sometimes it occurs as an ore and is then mined and burnt for the manufacture of sulphuric acid.

Carbonates, sulphates, phosphates

Calcite or calc-spar ($CaCO_3$) is a constituent of many sedimentary rocks and is the main constituent of limestone. It occurs in diverse crystalline forms but splits easily in three directions to form a rhombohedron. It can easily be scratched with a knife (hardness 3) and it effervesces on coming into contact with an acid. When pure it is colourless.

Dolomite is a compound of calcium and magnesium carbonate

($CaMg(CO_3)_2$). It crystallizes like calcite, is also colourless when pure, but it is slightly harder (hardness 4) and it does not effervesce easily with dilute hydrochloric acid. Like calcite, it is a constituent of many sedimentary rocks and the chief constituent of dolomitic rocks. If limestone contains considerable quantities of dolomite it is called dolomitic limestone. It occurs fairly commonly in Western Transvaal and in Griqualand West.

Gypsum is calcium sulphate that has crystallized with two molecules of water ($CaSO_4.2H_2O$). It is a constituent of some sedimentary rocks, especially sea-sediments. It is also often a constituent of soils in dry areas such as the North-western Cape Province and the Karoo where it may form strata or pans in the soil. It is a white or yellowish-brown soft mineral (hardness 2). It is usually crystallized but sometimes it is fine-grained and compact, in which case it is called alabaster. Gypsum is fairly soluble in water; about 1 part dissolves in 400 parts of water, with the result that it is not found in humid areas. When gypsum is heated until it has lost almost all its water of crystallization it is called plaster of Paris.

Apatite ($3Ca_3(PO_4)_2.Ca(Cl.F)_2$) is the crystalline form of calcium phosphate but it also contains calcium fluoride and/or calcium chloride. It occurs commonly in all rocks, though in small amounts, in the form of small hexagonal crystals and it is the ultimate source of phosphates in soils. Usually it is slightly green in colour, fairly hard, and it weathers very slowly. Occasionally it is also found in large quantities in the form of veins in rocks, e.g. in the North-eastern Transvaal.

CHAPTER VI

SOIL-FORMING ROCKS

A ROCK is an aggregate of one or more (usually more) minerals and is the solid material which forms the crust of the earth. However, rocks are not only classified according to their mineralogical composition, but also according to their mode of origin. We find that the colour, specific gravity, and the size of the mineral crystals are also more or less constant and characteristic of every kind of rock. According to their mode of origin rocks may be divided into three main classes.

A. IGNEOUS ROCKS

Igneous or eruptive rocks are rocks that at some time existed in a molten, fluid state before they solidified. During a volcanic eruption we can still observe to-day how the fluid lava pouring from the crater runs down the side of the mountain until it solidifies as a result of cooling. Geologists call the fluid mass that is forced from the depths of the earth to the surface magma. It is clear that only a portion of the magma would reach the earth's surface. When the pressure that is responsible for forcing the magma to the surface diminishes, the magma that is still in the passage or cleft in the earth's crust will cool down gradually and solidify. The farther the moving magma stops from the earth's surface the longer will it take to cool down because the temperature in the earth's crust increases with an increase of depth from the surface. The longer it takes for the magma to cool down to that temperature where crystallization can take place, the more time the chemicals constituting the magma have to 'grow' into big mineral crystals.

Igneous rocks thus originated from the cooling down and crystallization of the hot magma that was forced from the interior of the earth to the surface. According to the size of the chief minerals in such rocks it is possible to state where the cooling took place. Thus we have three classes of igneous rocks:

1. *Volcanic rocks* or lavas. They form as a result of the sudden cooling of the magma at the (cool) surface of the earth. As a result, no large crystals can form and thus the rocks have a glassy or a so-called porphyritic structure. Pumice, obsidian, and basalt are examples of this class of rock. Geologically speaking, active volcanoes have not occurred in South Africa for a very long time and therefore such rocks are very scarce in South Africa. Basalt is found in the Southern Drakensberg and at the Victoria Falls.

2. *Plutonic rocks* are rocks that were formed deep down in the earth's crust (2–3 miles) under high pressure, as can easily be imagined. The cooling process was necessarily slow so that comparatively large crystals were formed. Thus, such rocks are usually completely crystalline. Examples of

this class are granite and norite that occur fairly commonly in South Africa. The fact that they are now found near and at the surface of the earth may be attributed to the folding of the earth's crust or to its weathering and erosion which have taken place over lengthy geological periods.

3. *Dykes and intrusive rocks.* These rocks occupy an intermediate position between the two classes discussed above, i.e. the magma cooled down and solidified on its way to the surface. Because cooling was comparatively rapid, mineral crystals are small and thus these rocks have a fine-crystalline structure. Our best example of this class of rock is dolerite which is especially found in *koppies* or small hills in the Karoo areas.

According to the chemical composition of the magma, the rocks that result from it are either so-called acid rocks or basic rocks. The biggest difference between these two is that the acid igneous rocks contain much quartz and the basic igneous rocks contain little, if any, free quartz. Accordingly, acid rocks such as granites form, on weathering, sandy soil types while basic rocks such as norite and dolerite weather to form heavy loams or clays. Under conditions of average rainfall, e.g. in large areas of the Transvaal, the sandy soils are fairly acid, while the heavier soil types, that were formed from basic rocks, have a more or less neutral ('sweet') reaction. We shall only discuss three of the most important igneous rocks found in South Africa.

Granite is an example of an acid igneous rock and its three chief mineral constituents are felspar (orthoclase), quartz, and mica. Being a plutonic rock the minerals are relatively large and easily recognizable to the naked eye. Of the micas, biotite is the one which is usually present in our granites except in George district where muscovite usually takes its place. The colour of the orthoclase decides the colour of the granite at a distance. In the Southern Cape Province the orthoclase is whitish-grey so that fresh granite has a whitish-grey colour. In the Transvaal the orthoclase is usually reddish so that granite from this area is a red rock.

As can be seen on a geological map of South Africa, granite occurs fairly widely in the South-western and North-western Cape Province, in Eastern Transvaal, Eastern Natal, and in Rhodesia.

It is necessary for us to mention something about weathering here. This subject will be discussed in greater detail in the next chapter. Of the so-called chemical agents of weathering, water and carbonic acid are the most important. Natural waters always contain carbonic acid in solution. The effect of such waters on silicates is that they finally change to clay, the basic plant foods being released. Thus the orthoclase and mica in granite are changed to clay by weathering, but the quartz undergoes no chemical change and forms the sand of granite soils. Usually the topsoils of granite soils are very sandy. Under the sandy topsoil we usually find a layer of ironstone or *ouklip*, and deeper still a layer of potclay which, however, usually contains many quartz grains. In the South-western Cape Province the sandy soils that originate from granite usually have a

greyish-white colour; but in the Transvaal they are reddish. Fruit-trees and especially vines do very well in granitic soils. Such soils are fairly rich in potash but they lack phosphates and are acid. Characteristic of granitic mountains is the round shape of the hills and also the isolated rocks (e.g. Paarl Mountain, Matoppos, &c.).

Norite is a basic igneous rock, in other words, it contains hardly any quartz. Its two chief minerals are both silicates, viz. plagioclase (a white felspar) and augite (black). The general colour of the rock is bluish-grey. Like granite, it is also a plutonic rock, but the crystals of the above two minerals are seldom as big as those of granite. It occurs fairly commonly in Central and Northern Transvaal. Because the rock actually only consists of two silicates, it forms on weathering a heavy clayey soil. The two typical Transvaal soils that have originated from norite are the black 'turf' soils such as are found at Brits and the red clayey loams (also called red 'turf') such as are found at Potgietersrust. Because these two silicates both contain calcium these soils have a fairly high lime content, a medium-low potash content, and a low phosphate content. The black 'turf' soils of the Springbok Flats originated from basaltic lava rock that has a chemical composition similar to norite although it is porphyritic and finer-grained.

Characteristic of the norite rock of the Transvaal is the occurrence of the iron ore, magnetite, in the form of veins. The presence of platinum in norite, as in the Rustenburg district, is of economic importance.

Dolerite is also a basic igneous rock, but in contrast with those previously mentioned it is a dyke or intrusive rock. It is fine-grained and dark-coloured on a freshly broken surface and the separate minerals cannot be distinguished by the naked eye. Like norite, the two chief mineral constituents of dolerite are plagioclase and augite, but their chemical composition is somewhat different from those of norite. Dolerite also contains olivine, magnetite, and other accessory minerals. On weathering, dolerite turns to a rusty-brown colour and eventually decomposes to form red clayey-loam soils that have a fairly high lime, but a very low phosphate content.

Dolerite occurs in the Northern Karoo formations (Northern Cape Province, Free State, Natal, South-eastern Transvaal). The shales of the Karoo formations weather faster than the dolerite and thus the *koppies* and higher parts of the landscape consist of dolerite.

Diabase, found at Pretoria, for example, is an older rock which otherwise resembles dolerite closely and on weathering a red clayey-loam soil is also formed from it. Table 7 (opposite) gives the chemical analyses of the three eruptive rocks that have been discussed. The difference in the lime, magnesia, potash, and silica content of granite on the one side and the basic rocks, norite, and dolerite on the other, is striking. The granite of the Western Cape Province is considerably poorer in potash than the red (younger) granite of the Transvaal. The old granite of North-eastern Transvaal, Swaziland, Rhodesia, &c., also has a comparatively low potash content.

TABLE 7

Chemical Composition of Igneous Rocks

	Granite (Paarl)	*Red Granite (Soutpan, Tvl.)*	*Norite (North Pretoria)*	*Dolerite (Karoo)*
	%	%	%	%
Silica (SiO_2)	76·8	74·1	52·7	52·2
Alumina (Al_2O_3)	13 9	13·2	21·5	15·3
Iron oxide ($FeO+Fe_2O_3$)	1·6	2·5	6·3	10·5
Lime (CaO)	0·82	1·1	12·6	9·8
Magnesia (MgO)	0·32	0·15	4·2	6·1
Potash (K_2O)	2·74	5·0	0·3	0·98
Soda (Na_2O)	2·66	3·4	2·1	2·3
Phosphoric oxide (P_2O_5)	0·19	Traces	0·2	0·18

B. SEDIMENTARY ROCKS

The sedimentary rocks originated under the influence of wind, water, ice, and organisms from the products of weathering of other, older rocks.

The geological and biological sciences teach us that the earth is very old. We can conceive this immense age and the far-reaching metamorphosis that the earth's crust underwent during countless ages if we recollect that, in the Ceres district, for example, fossils of real sea-shells are found in shale. Evidently this shale is hardened clay or a hardened mud sediment from the ocean bed that contained dead shell animals. To-day these rocks are found a few thousand feet above sea-level and far from the coast.

If we take water from a river which is in flood and leave it in a beaker for some time we will find a sediment of silt at the bottom of the beaker. If we take the clear water above the sediment and analyse it chemically we will find that it is not pure, but contains dissolved substances (salts). From where do these silt and dissolved substances come? From soils in the catchment area of the river. The soils again originated through weathering, i.e. the disintegration and chemical decomposition of rocks.

The Drought Investigation Commission, appointed by the Government in 1920, estimated that nine of the biggest rivers in the Union annually transport 187,000,000 tons of soil material. Unfortunately this soil material is usually largely transported into the ocean. Thus, in the course of ages, new rocks form in the sea and also on land, as a result of the deposition of sand and silt transported by water. Naturally, the same thing happens in inland lakes into which rivers drain.

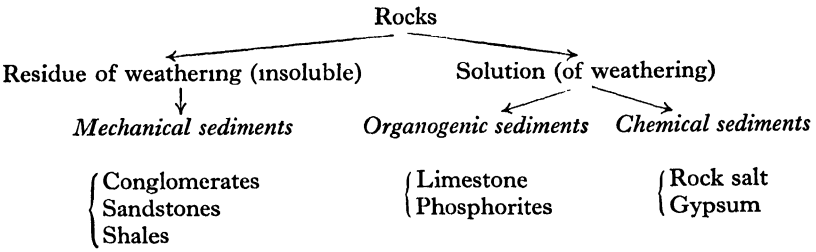
Strong winds also transport fine soil material from one part to another and very often it is deposited in the sea or in lakes, thus helping to build up the ocean bed. In Arctic regions, glaciers transport soil material and, sometimes, fairly large stones to the sea. In this way water, wind, and glaciers transport and deposit solids that afterwards turn into hard layers of rocks. Rocks formed in this way are called *mechanical sediments.*

Plants living in salt or fresh water absorb their mineral nutrients from the water. The dissolved substances in such waters originated from the soil, i.e. weathered rock particles. Small marine animals use these plants as food and these animals again provide food for bigger sea animals such as fishes. Dead sea animals, big and small, settle on the bed of the ocean where their inorganic skeletons, sometimes mixed with mechanical sediments, form thick layers in course of time and these layers are cemented together to form rocks. In this way limestone and siliceous sandstone (diatomaceous earth) originate, the stony corals with their calcareous skeleton likewise form limestone rocks. Phosphatic rocks originate from the skeletons of dead vertebrates, as also from the accumulated excrements of sea-birds. Such guano deposits can eventually change into phosphatic rocks as a result of the leaching out of potash and nitrogen. Undoubtedly the phosphatic rocks along the Malmesbury coast (Mamre, Langebaan, Saldanha Bay) originated in this way.

In the above-mentioned cases the chief constituent of the rock concerned is derived from dissolved substances, but living organisms were necessary to change these substances to a form in which they would again become solid rock-forming ingredients. Thus we call such deposits *organogenic sediments*.

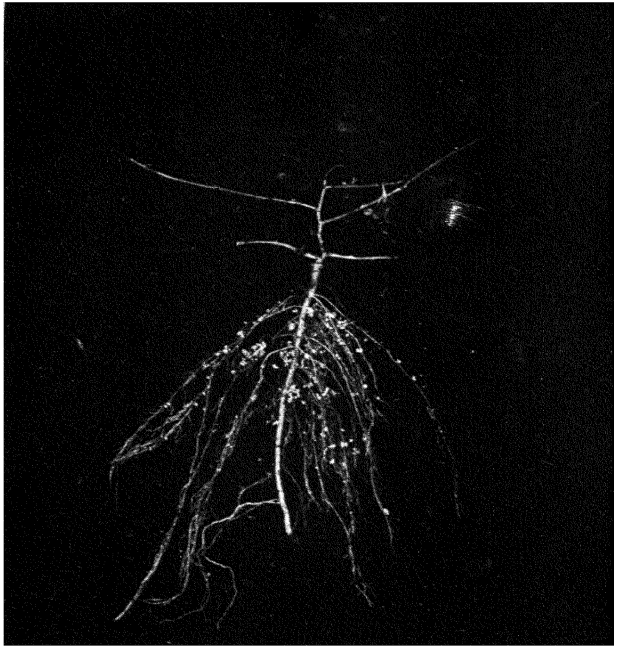
Finally, it may also happen that a cut-off part of the ocean or an inland salt lake such as the Dead Sea might lose its water through evaporation. The dissolved salts then crystallize out and rocks form from them, consisting of gypsum, rock salt, and even potash salts as, for example, in Germany. Such deposits are called *chemical sediments* which is, perhaps, not a very good name.

We can represent the origin of the three classes of sedimentary rocks schematically as follows:

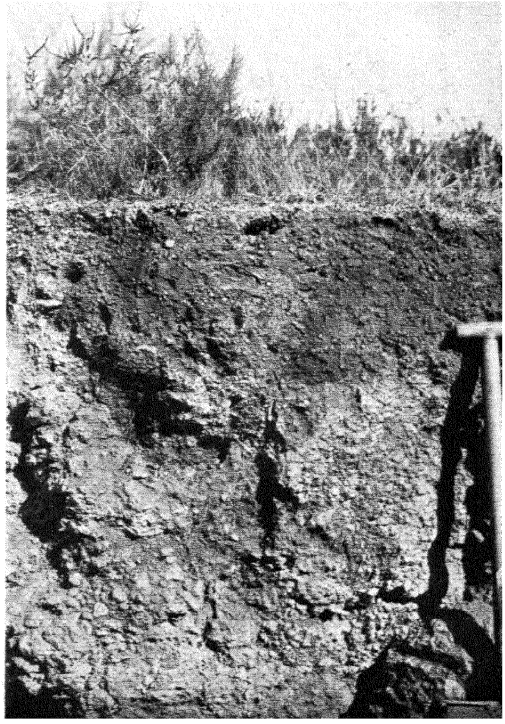


To-day sedimentary rocks cover the greatest portion of the Union of South Africa. This is especially the case in the Cape Province, Orange Free State, and Natal. On the other hand, the surface rocks of the Transvaal and Southern Rhodesia are largely of igneous origin.

The mechanical sediments are by far the most important of the sedimentary rocks found in South Africa. They usually have a stratified or bedded structure, i.e. we can see clearly how the rock was built up in more or less horizontal layers. This deposition in layers is due to the fact that deposition of material by wind and water is not constant but varies according to the seasons and perhaps also according to cycles lasting for several years.



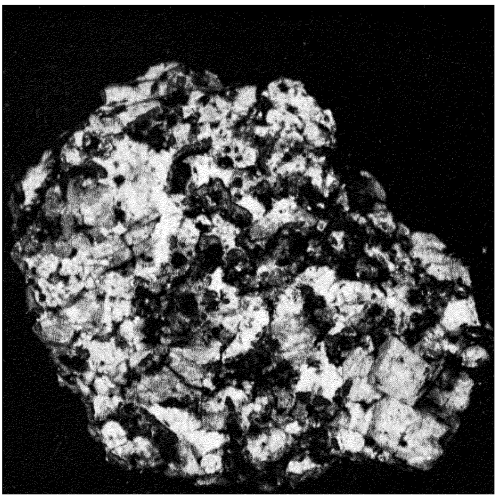
a. Nodules on the roots of Burr clover (*Medicago hispida*)



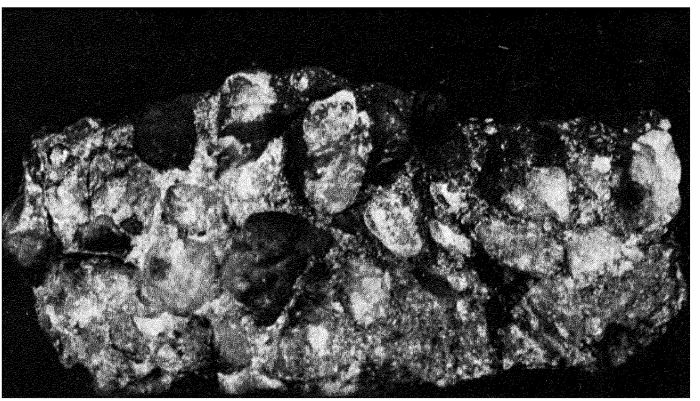
b Soil profile, showing the dark-coloured surface soil, and the gravelly subsoil, under which there is a layer of potclay

PLATE I

PLATE II



a Granite rock, consisting of black mica, white orthoclase felspar, and dull white quartz.



b Conglomerate rock (half natural size)

In the case of shales or mudstones this stratification is very clear and the material can easily be split into layers like the pages of a book. Shales are naturally formed from fine material such as clay, silt, and fine sand. *Shales* are often hardened by compression and are then known as *slates.*

In the South-western Cape Province we find two important types of shale that are the parent rocks of large tracts of arable land:

(*a*) *Malmesbury Shale* in the Malmesbury, Piquetberg, Tulbagh, Paarl, Cape, and Stellenbosch districts, and

(*b*) the *Bokkeveld Shale* which is the most important parent rock of the soils in the Ceres, Robertson, Caledon, Bredasdorp, Swellendam, Ladysmith districts, &c.

The Bokkeveld shale is younger than the Malmesbury shale and contains fossils. In other respects they are very similar. Both often contain much fine sand and are further characterized by white quartz veins that on disintegration give rise to 'white-pebbly soils'. On the whole these soils are fairly fertile except that they have a very low phosphate content and are rather shallow. In some places the 'rotten' shale is only 4–6 inches below the surface of the soil (*nabank*). Physically these soils are of a gravelly and stony nature and, especially the Malmesbury type, can become very compact if rain falls on the ploughed soil. They are mostly the soils on which winter cereals are grown in the South-western Cape Province.

Sandstones are the second group of sedimentary rocks that are of great importance to agriculture. A sandstone is a coarse rock and we can see clearly with the naked eye that it consists of large and small sand grains. The sand grains are usually quartz and the fine material that cements them together can be clay, iron compounds, silicic acid, or lime. Sandstones differ in colour according to the admixture of other substances: white, grey, blue, red, &c. The more quartz a sandstone contains, the poorer are the soils that originate from it. On the other hand, the more clay it contains, the better are the agricultural soils formed from it.

Most of our mountain ranges consist of sandstone and in the Cape Province the most important kinds are the Table Mountain and Witteberg Sandstones. The so-called Karoo formations also consist largely of sandstone. Thus sandstone is the parent rock of many of the agricultural soils in South Africa. As we have said before, the quantity of sand in a soil depends on the quartz content of the rocks. Sandy soils can be quite productive soils provided the rainfall is sufficient and manuring is efficient.

The third type of mechanical sediment is the *conglomerate.* A conglomerate is a rock containing original rock fragments, mostly pebbles, with a diameter of an inch or more. The finer cementing material may be sand or clay. The pebbles and boulders are usually well rounded by the abrasive actions to which they were subjected in river-beds or on the sea-shore. Conglomerates are not abundant in South Africa. The most important is that found in the Waterberg and Potgietersrust districts. In these areas it disintegrates to form a very poor, stony, sandy soil. The

gold-bearing quartz-conglomerate of the Witwatersrand is another example of this type of rock, but it differs considerably from the ordinary type.

Of the organogenic sediments, limestone and dolomite are the two most important rocks.

The chief constituent of *limestone* is carbonate of lime ($CaCO_3$). According to its origin and the admixture of sand, clay, iron compounds, phosphate, &c., limestone can vary considerably in colour (white, grey, brown, blue), in hardness, and in composition. The purer the limestone is, i.e. the more carbonate of lime it contains, the poorer the soil that originates from it. Apart from the fact that it can be the parent rock of soils, limestone is also important as building material, agricultural lime, mortar, &c. Limestone weathers comparatively easily and thus limestone mountains are characterized by their steep cliffs, ravines, and caves. The Karoo formations do not contain much original limestone. However, apart from these, limestone is fairly abundant in South Africa. The following are some of the places where it is found:

Cape Province: Piquetberg, Bredasdorp, Robertson, Oudtshoorn, Cradock, Taungs.

Orange Free State: Kroonstad, Vrede, Harrismith.

Transvaal: Pretoria, Ventersdorp, Marico, Lydenburg.

Natal: Weenen, Ladysmith, Undeni.

Dolomite. The chief constituent of dolomite is a mixture of calcium and magnesium carbonates. If the ratio of the two constituents is approximately as it is in the mineral dolomite, we have an actual dolomite rock. Usually however, especially in South Africa, it contains considerably more lime than magnesia and then it is called a dolomitic limestone. Dolomite occurs especially in the Transvaal (Irene, Lichtenburg, Potgietersrust) and in Griqualand West.

On weathering, dolomite forms a poor sandy soil, but, like limestone, the rocks can be used for agricultural as well as industrial purposes. Both rocks are fairly porous and permeable to water, i.e. ground water moves easily in such rocks and appears on the surface in the form of springs, where the limestone or dolomite formation adjoins an impervious rock formation.

C. METAMORPHIC ROCKS

Metamorphic rocks are thus named because they are rocks that have undergone a metamorphosis or change. Usually the rock has become harder, contains new minerals, and often assumes a stratified structure. We will not attempt to discuss the complicated geological aspect of the matter here, especially as metamorphic rocks are not of great agricultural importance in South Africa because they occur so seldom. The following are examples: Quartzite is metamorphic sandstone; marble is metamorphic (crystalline) limestone; and gneiss is metamorphic slate or, sometimes, granite.

Geological formations

Before concluding this chapter we would like to say something about the geological history of the earth's crust. If we were to look at a geological map of South Africa we would notice immediately that most of its surface consists of sedimentary rocks. Most of these rocks were formed as marine deposits and to-day they may be far in the interior. Most of these sediments are also very thick. The Table Mountain Sandstone, for example, in some places consists of a layer 5,000 feet in thickness. There are many proofs that the earth's crust has undergone many changes during countless ages. Movements and folds in this crust caused high mountain ranges where, previously, there had been a level surface. Other mountain ranges and plateaux again were worn away by the eroding action of wind, rivers, and glaciers and from their sediments new rocks originated. What was once the bed of the ocean became dry land and vice versa.

According to the nature and succession of sedimentary rocks and especially according to the fossils (petrified remains of animal and vegetable organisms) which many of them contain, geologists attempt to determine the approximate age of every big deposit. Such a deposit which originated during a certain Geological Age is called a Geological Formation or Series and it is given a special name which is usually taken from the place where the particular rock sediment was first noticed and studied. Thus there exists the Malmesbury Series, the Bokkeveld Series, the Pretoria Series, &c. A group of Series again forms a System such as the Cape System, the Karoo System, &c.

Even the age of igneous rocks that occur at the surface can be estimated. Thus we know that the granite of the Western Cape Province is younger than the Malmesbury Shale but older than the Table Mountain Sandstone, because we find everywhere that the granitic magma penetrated the Malmesbury Shale but not the Table Mountain Sandstone.

On a geological map of South Africa the sequence and distribution of the different geological formations can easily be seen. (The best book on the geology of South Africa is that of Alex L. du Toit, *The Geology of South Africa.*)

CHAPTER VII

THE ORIGIN OF SOILS

WEATHERING OF ROCKS AND MINERALS

MANY agencies act together to change rocks into arable soil. Although these factors will be discussed individually, it must be borne in mind that usually several of them are active simultaneously.

Under weathering of rocks we understand the physical, chemical, and biological processes which bring about the disintegration of rocks and changes in their chemical composition. Thus weathering may be said to consist of the breaking down or disintegration of the original rock material (i.e. a purely physical process) as well as the chemical change or decomposition of this material.

Physical weathering agents

It is a general physical phenomenon that objects increase in size (volume) when they are heated, i.e. they expand, and they decrease in volume on being cooled, i.e. they contract or shrink. Every chemical substance also has a specific rate of expansion or contraction for a given change in temperature. We say that every such substance has a definite coefficient of expansion. This change in volume as a result of change in temperature is actually very small under ordinary conditions. However, taking into consideration that rocks consist of different minerals, each with a different coefficient of expansion and remembering that these changes in volume take place day after day and year after year, it is clear that this process can have a marked effect. The outer layers of exposed rocks are heated and cooled more than the inner layers. This irregular expansion and contraction of the different minerals and of the different layers in rocks, which is constantly taking place, causes a tension within the rock material, with the result that rocks crack, crumble, and the outside layers 'peel off'. Naturally this slow crumbling process can only take place in exposed rocks and it is much faster when the range in temperature or amplitude is great and changes are sudden. This is especially the case on high mountains and in desert regions. Such 'peeling' and crumbling of rocks is especially noticeable when a sudden thunderstorm cools down heated rocks.

When at freezing-point water changes from a liquid into its solid phase (ice) its volume is increased by about 9 per cent. Thus, if water freezes in a confined space it exerts a terrific outward pressure, equal to about 150 tons per square foot. During cold seasons, when night temperatures drop below freezing-point, water, freezing in cracks and fissures in rocks, may cause such rocks to crack apart and so start their disintegration.

Disintegration of rocks and stones by abrasion takes place in running river-water and in glaciers. Especially when in flood the river causes the

rocks to bump and rub against each other so that pieces may be broken off and the surfaces of such rocks are worn down by surface friction. These rocks acquire the typical smooth round shape common to river stones. At the same time gravel and sand are formed and transported by the water until they are deposited lower down as sand-banks and alluvial soils. The steeper the gradient of the river-bed and the greater the volume of water, the faster is the rate of disintegration. We see the same mechanical weathering process along sea-shores where crumbling takes place, and rocky shores are slowly but surely worn away by the action of the waves in rolling loose stones against one another and against firm coastal rocks. Along low shores the sand is then partly washed out at high tide and, together with broken shells, it forms sand-dunes. During dry seasons this sand may be blown inland. This is the origin of the soils on the Cape Flats and of many other sandy coastal areas.

In Arctic regions and in the high mountains of cold countries glaciers have the same pulverizing effect on rocks which they carry along with them and over which they move. During and after the Ice Age, which preceded our present geological era in the Northern Hemisphere, large areas in that hemisphere were covered with so-called glacial deposits from which glacial soils were formed.

Finally, sand carried by strong winds may wear down exposed rocks by surface friction. This phenomenon can be seen especially along the sea-shore and in deserts.

Chemical weathering agents

The chemical changes which the minerals in rocks and soils undergo are of a varied and complicated nature. Here we shall only discuss briefly the most important chemical factors responsible for such changes.

Water is the first essential for most of the chemical changes in rocks and in the soil. Water on its own accord brings about changes in minerals although we must remember that the reactions take place very slowly. We must never lose sight of the fact, however, that in nature's laboratory changes are brought about over exceedingly long periods. Thus, according to ordinary laboratory tests, we are quite justified in saying that silicates, which we know as the most important rock-forming minerals, are insoluble in water. Nevertheless, a very small amount of silicate will dissolve in, say, a gallon of water. When these minerals are in contact with water or moisture, from year to year, as in the case in deeper soil levels and with underground rocks, they dissolve to a considerable extent over a long period of time.

The solvent action of water on silicates is accompanied by a splitting of the silicate molecule. A process known as *hydrolysis* of the silicates takes place. In the case of orthoclase this process may be represented as follows:

$$K_2O.Al_2O_3.6SiO_2+11H_2O = Al_2O_3.2SiO_2.2H_2O+4H_4SiO_4+2KOH.$$

Orthoclase and Water give Kaolin (clay) and Silicic acid and Potash.

All the other silicates are changed by water in a way similar to that in which orthoclase is changed. It is a very important reaction for two reasons:

1. Clay, silicic acid, and bases are the substances found in ordinary soils and some of them are available as plant food.
2. The reaction causes the hard mineral to be changed to soft and partly soluble substances so that the structure of the rock is disintegrated into a gravel. This fact can be observed very well in partly weathered granite, norite, shale, &c.

In sedimentary rocks we sometimes find minerals, such as gypsum, that are readily soluble in water. Such rocks weather very easily. Some minerals again absorb water (water of hydration), forming new compounds. Thus hematite is hydrated to form limonite.

$$2Fe_2O_3+3H_2O = 2Fe_2O_3.3H_2O.$$

Hematite and Water give Limonite.

The solvent and hydrolysing actions of water are largely aided by a second chemical weathering agent, namely, *carbonic acid*. All natural waters contain carbonic acid and thus the hydrolysis of silicates, which is so important in the formation of soil from rocks, takes place much faster than when the reaction is dependent on water alone.

Carbonic acid is, however, also responsible for some other characteristic changes. Firstly, it changes the bases or hydroxides (hydrates), which are set free in the previously mentioned silicate hydrolysis, to carbonates or salts of carbonic acid. This process is known as *carbonation*. For example, when plagioclase, augite, &c., weather in the above-mentioned way, lime is set free. The carbonic acid then changes the lime to carbonate of lime.

$$Ca(OH)_2+H_2CO_3 = CaCO_3+2H_2O.$$

Lime and Carbonic acid give Carbonate of lime and Water.

The small concretions of carbonate of lime which are found in turf soils in the Transvaal, originated in this way from norite. In dry areas so-called surface limestone may even form in the soil in this way.

Iron hydroxide, one form of which is called limonite (hydrated ferric oxide), is another base which originates from the weathering of silicates containing iron and of other iron minerals. The changes which iron compounds (mainly iron hydroxide) undergo when reacting with carbonic acid are slightly more complicated than is the case with other bases.

Firstly, two groups of iron compounds exist: ferric compounds which are stable in the presence of oxygen; and ferrous compounds which are the so-called reduced forms, i.e. a portion of their oxygen has been removed. Ferrous compounds are fairly soluble in water and hence move about more freely in soils (Latin *ferrum* = iron). They are formed in the absence of oxygen (air) and in the presence of organic matter in soils. Thus, if soils are waterlogged or submerged for any length of time, i.e. if they contain too much water and too little air, ferric compounds are

changed to ferrous compounds which are comparatively soluble in carbonic acid. Ferrous bicarbonate ($Fe(HCO_3)_2$) is then formed in the soil. When the topsoil dries out, soil water rises from the deeper layers with iron in solution. When the ferrous compounds are brought to the top layers where there is oxygen (air) they are oxidized, i.e. they take up oxygen, and insoluble iron hydroxide (ferric hydroxide) is precipitated. This reaction may be represented as follows:

$$2Fe(HCO_3)_2+O+H_2O = Fe_2(OH)_6+4CO_2.$$

Ferrous bicarbonate and Oxygen and Water give Ferric hydroxide and Carbon dioxide.

This process is repeated every rainy season and iron is brought up from the lower soil layers to layers nearer the surface. During the dry season these precipitates change into hard, dark-brown pellets of limonite. Over very long periods, in some soils these pellets become cemented together and hard layers of ironstone gravel or *ouklip*[1] are formed. The concretions of limonite pellets and of ironstone gravel are typical of many agricultural soils in South Africa. They are clearly due to the alternating wet and dry seasons and indicate that the soils in which they appear are acid because free carbonate of lime prevents the movement of iron in soils. Drainage-water from acid soils contains iron bicarbonate and iron hydroxide is then precipitated in ditches and at natural drainage outlets. The brown film on such water, which eventually forms a sediment when present in sufficient quantities, is iron hydroxide.

Calcium carbonate (and also magnesium carbonate) dissolves fairly readily in water containing carbonic acid. All natural waters contain carbonic acid so this fact is of considerable importance.

$$CaCO_3+H_2CO_3 = Ca(HCO_3)_2.$$

Calcium carbonate and Carbonic acid give Calcium bicarbonate.

Thus limestone, when dissolved, forms calcium bicarbonate. Spring and river waters which originate from calcareous formations (rocks and soils) are hard—so called because they do not lather easily with soap. As is commonly known, when such water is heated in boilers or for household use, calcium carbonate is precipitated. Hence the 'scale' or 'fur' of calcium and magnesium carbonates in kettles and boilers. The process is exactly opposite to the process that takes place when carbonate of lime dissolves in soil water. Carbon dioxide escapes and the calcium bicarbonate is again changed to calcium carbonate (carbonate of lime).

$$Ca(HCO_3)_2 = CaCO_3+CO_2+H_2O.$$

Calcium bicarbonate gives Calcium carbonate, Carbon dioxide, and Water.

In nature, a continuous dissolving and precipitating of carbonate of lime takes place. Limestone is gradually dissolved and hollowed out by circulating water. In this way caves or grottoes are formed in limestone and

[1] 'Laterite' according to Pendleton; often used as building stone in South Africa.

dolomite (magnesium limestone) mountains. In the caves carbonate of lime is again usually separated from the slowly evaporating water, stalactites and stalagmites being formed. In soils of dry regions carbonate of lime is also deposited, because rain-water which has percolated deep into the soil rises to the surface again as a result of evaporation, bringing up calcium bicarbonate in solution from deeper levels. The more calcareous the parent rock, the greater is the amount of lime deposited in the topsoil layers in comparatively arid regions. In this way, hard secondary layers of limestone can be formed in dry regions. This occurs in many parts of South Africa (Prieska, Postmasburg, Somerset East, &c.). In humid regions no limestone, either in the form of hardpans or even in the form of small concretions, is formed because soil water moves mostly downward and any dissolved lime is transported by seepage water into rivers.

Apart from water and carbonic acid, the *oxygen* dissolved in soil water is another important chemical weathering agent. One hundred grammes of water will dissolve about 3 c.cm. of oxygen gas from the air at ordinary temperature. Thus, water circulating in soils and rocks usually has oxygen in solution and it is mainly in this dissolved form that oxygen brings about chemical changes (oxidation).

It is principally certain iron minerals which undergo changes when combining with oxygen. We have seen that there are two groups of iron compounds. The ferrous compounds combine readily with oxygen to form ferric compounds. The ferrous compounds of rocks (such as the minerals biotite, augite, hornblende) have a bluish-black colour. When they oxidize or combine with oxygen, they change to yellowish-brown or rusty colour to which fresh dark-coloured rocks such as dolerite and norite change when subjected to weathering. Thus the colour of the rock is a good indication of whether it has started weathering chemically or not, because the iron in rocks is mostly present in the ferrous form. In the case of iron sulphide or iron pyrites, both the iron and the sulphur are oxidized and, together with the action of water, limonite and sulphuric acid are formed. Sulphuric acid, however, is a very strong acid and immediately dissolves other bases with which it comes into contact, sulphates being formed; thus gypsum (calcium sulphate) may be formed.

In the soil itself many other weathering agents, produced mostly by soil microbes, are present. They cause further changes in minerals and the primary products of weathering. Growing plants also aid in changing rock material in subsoil layers both chemically and physically. Plant roots grow through the minutest cracks and fissures in rocks and stones and as the roots increase in size these cracks are widened, the rocks being literally broken apart and changed physically. Plant roots also secrete carbonic acid which dissolves rock material chemically. We call these agents the *biological weathering agents.*

Enough has been said for us to realize clearly at least two facts: firstly radical changes must take place before rock material can be changed into soil and, secondly, these natural weathering processes take place very

slowly. If we bear these facts in mind and consider what an immeasurable period of time has to pass for a few feet of soil to be formed out of rock, we will value our soil more and do everything possible to prevent its loss, either by water or wind erosion.

TRANSPORTATION OF SOIL MATERIAL

Soils still resting on the parent rock out of which they were formed by weathering are called primary or sedentary soils or *in situ* soils. Such soils are generally found on the more or less level plains of the Great Karoo, Western Free State, and Transvaal. Even such soils, however, often contain a large percentage of material deposited by wind. In mountainous and hilly areas and also in dry desert regions, soil material is, to a large extent, transported from one place to another, so that secondary or transported soils occur extensively.

The transportation of soil material from one place to another is mainly due to the topography of the earth's surface. With the exception of wind, the force of gravity is responsible for the transportation of the bulk of soil material, i.e. the soil is transported from higher to lower levels. Because the interior of South Africa is largely a level or undulating plateau, the fall to the coast is very steep. Consequently the rivers flow very fast—when they have water. Apart from this, the soil surface of the interior is only covered with a sparse vegetation and rains are mostly in the form of thunderstorms which often occur after lengthy dry periods. The result of all this is that soil erosion takes place extensively and enormous amounts of soil material are transported from higher to lower levels.

We have already quoted certain findings of the 'Drought Investigation Commission', viz. that nine of the biggest rivers in the Union annually transport about 187,000,000 tons of soil from the interior. This amount of soil is equal to a layer one foot in depth covering an area of 91 square miles. The direct harmful effects of soil erosion must be very clear to everyone and may be summed up as follows: loss of valuable agricultural soil that took thousands of years to form; destruction of plant growth; lowering of the ground water table and desiccation of soils by gullies (*dongas*); intensification of droughty periods; silting up of expensive irrigation dams and reservoirs; floods, and destruction of valuable settlement farms as a result of such floods.

Under no system of permanent agriculture can extensive transportation of soil be tolerated and it must be combated with all our resources; but transportation of soil material has been going on since the beginning of time, and thus we find to-day, in our coastal districts and other mountainous regions and along river-banks, large tracts of land consisting of transported soil material. These soils may be classified under the following headings, according to the agent by which they were transported.

Colluvial soils (Latin *colluvies* = a mixture) are found on mountain slopes and at the foot of steep cliffs. Continuous rains or heavy thunderstorms may cause landslides on mountain slopes, especially when they are

not sufficiently covered with vegetation to bind the soil. Loose rocks may slip down carrying soil and stones with them. Although water is usually the primary cause, a colluvial soil is not considered to be one transported by water, but rather material which was loosened and moved downward purely by force of gravity. Colluvial soils differ radically from alluvial soils (which will be discussed later) in that they contain much coarse rocky material, such as sharp-edged stones and rocks. They are usually inferior for crop production, but, provided climatic conditions are suitable, they may be used for afforestation and if they are not too stony or steep, olives, fruit-trees, and vines may be grown on them.

Alluvial soils are transported and deposited by water. The distance which a stream can transport an object will depend on the size and specific gravity of the object, on the rate of flow of the stream, and, in the case of fine material, on the chemical composition of the water.

At a given rate of flow, material will be transported according to its size and specific weight. We can also say that the faster the rate of flow, the coarser and heavier the material that can be transported. The following table gives the approximate relationship between rate of flow and size of soil particles that can be transported:

Speed of stream in inches per second	*Size of particles transported or moved by water*
4	Silt and clay.
8	Fine sand.
12	Coarse sand.
24	Fine gravel.
36	Coarse gravel.
72	Stones up to 1 lb. in weight.

In a subsequent chapter the particle size of the soil constituents will be defined more exactly. A rate of flow of 72 inches per second is about 4 miles per hour. Many South African rivers flow even faster than this when they are in flood. The relationship between rate of flow and size of transported soil material is, briefly, that the water sorts out the transported material according to its particle size. If we take as an example a river which has its source in the mountains and which has no big tributaries, we find that near the mountains where the incline is steep and the water flows rapidly, the river-bed will be strewn with round boulders and stones; farther down where the river widens out and the bed is more level flow will be slower and first the coarse sand and then the fine sand is deposited. When the river is in flood, these materials are transported farther down or left along river-banks in the form of sand-banks. Fine soil particles such as silt and clay can remain in suspension for a long time and may even be transported to the sea. In the salt-water of the sea, the suspended fine particles are eventually flocculated. At many level shores where the tide reaches far up the river rich delta soils are formed in this way (Nile, Mississippi, &c.).

In the centre of the river and on the outside of river bends the speed of the stream is greatest. That is why sand-banks and stony deposits are found

along the edges of rivers and on the inside of river bends. When the river is in flood it may overflow and fine silt and clay may then be deposited in lower-lying areas along the river-banks. That is how the alluvial soils (mostly sandy silt soils) originated along the banks of our big rivers (Vaal River, Orange River, and Fish River). If the water in the river is low, or if the river dries up, prevailing winds can blow the fine sand from the river-bed. That is how sandy aeolian soils and even sand-dunes along river-banks originate. Thus alluvial soils may contain a considerable amount of material transported by wind although it was in the first place brought to the vicinity by water.

Thus alluvial soils may differ widely in their mechanical make-up, and in a single spot alternating layers of silt, sand, and gravel may be found. This is especially the case in an arid country such as South Africa where torrential rains and long dry periods may cause a considerable mixing of alluvial material. An accurate soil survey of such deposits is essential before large sums are spent on irrigation settlements.

As regards the effect of the chemical composition of river-water on its ability to hold fine soil particles suspended we find the following: hard water contains calcium (and magnesium) compounds and soon causes flocculation of transported silt, clay, and humus; thus the particles settle and the river-water becomes clear. Such river-waters are scarce in South Africa. More generally the water is slightly alkaline containing a little soda and other brak salts. Such water has a suspending effect on soil particles which are being transported, i.e. the particles remain in suspension and the water remains muddy until it reaches the sea. The Great Fish River and other Karoo rivers are examples of this. When in flood, the Great Fish River sometimes contains as much as 10 per cent. silt at Cradock—a terrific amount.

Finally, there are the acid, dark-coloured river-waters of the wooded coastal areas, such as George, Knysna, and Elgin. Such waters keep soil particles in suspension and they also contain a considerable amount of iron and humus which give the coffee colour to the water.

Aeolian soils originate as a result of wind (Latin *Aeolus* = God of Wind). Coastal and inland dunes and the sandy soils in their vicinity are excellent examples of aeolian soils. Especially fine soil particles (smaller than 0·25 mm.) can be blown away (by dust storms) in arid areas and can settle again if the speed of the wind decreases or if it rains. In South Africa most soils contain some fine wind-borne material.

After the Ice Age which existed in the Northern Hemisphere in the latest geological era, prevailing winds transported fine soil particles from glacial and other soils for centuries, and deposited them in parts of Europe and especially in Asia. The famous deep and fertile *Loess* in these countries is said to have originated in this way.

Wind erosion, just as erosion by water, has many bad effects and it should be prevented in all possible ways. Again in this case a plant covering is the best protective measure, because plant roots bind the soil and

the vegetal covering breaks the force of the wind on the soil surface. Cultivated soils, subjected to strong winds, should be protected by wind breaks (avenues of trees, &c.) as far as possible. Rows of maize or rye, planted across the direction of prevailing winds, are very effective in preventing the blowing of sandy soils in young vineyards, orchards, and vegetable gardens; such blowing sands may cause great damage to crops.

The Division of Forestry conducted a survey of soils which are subject to wind erosion and found them to comprise an area of about 92,000 acres, situated mainly in the coastal districts of Bredasdorp, Riversdale, Caledon ('Strandveld'), Cape, Malmesbury, and Clanwilliam ('Sandveld').

Soil erosion will be discussed in detail in Chapter XVI.

CHAPTER VIII

FORMATION AND DECOMPOSITION OF HUMUS IN SOILS

THE ORIGIN OF ORGANIC MATTER IN SOILS

BY organic matter we understand material or substances produced in the first instance by living organisms (either animal or vegetable). According to our definition every agricultural soil contains a certain amount of such substances. Because organic matter always contains carbon it is combustible, and the approximate organic matter content of any soil may be determined by heating a certain amount of absolutely dry soil in a crucible until the weight of the heated soil remains constant after cooling. This loss of weight on ignition may be calculated by weighing the crucible and soil before and after heating and it is approximately equal to the organic matter content of the soil.

In virgin soil the organic matter content is derived from animal and vegetable life in and on the soil. The root systems of plants are naturally in the soil and after a plant dies the organic matter of the roots becomes part of the soil. The above-ground portion of the plant falls on the soil surface after the death of the plant. Insects and other small animals that live in the soil, such as ants, termites, spiders, earthworms, &c., take this plant residue into the soil bit by bit to be used in their nests or as food. Sometimes this only takes place after the plant material has been decayed by fungi. On low-lying soils, leaves and branches, &c., may be covered by soil deposited on them out of running water during the rainy season and in this way they will be incorporated with the soil. The excrement of these small soil creatures and their bodies after death are additions to the organic matter of the soil.

In cultivated soils organic matter is added to the soil when weeds, including shrubs, or green-manure crops are ploughed into the soil or when farm manure or compost is applied. Usually animal excrements are nothing but digested and undigested plant material. Even when an agricultural crop such as wheat is reaped from a land, the stubble and roots remain behind on the land. In the case of cultivated soils almost all the organic matter put into it is usually of vegetable origin. Some fertilizers containing organic matter, such as whale guano, dried blood, and government guano, are of animal origin but as sources of humus they are of minor importance.

ORGANIC WEATHERING AND FORMATION OF HUMUS

A moist agricultural soil teems with microscopic living organisms, the so-called micro-organisms or microbes, and they belong chiefly to the vegetable kingdom. The two most important groups of soil microbes are the bacteria and fungi. If living conditions for them are favourable they multiply surprisingly rapidly. Their food consists mainly of the residue of dead plants and animals. Thus it is clear that if, for example, a green-pea

crop is ploughed into the soil, all the soil microbes will immediately be supplied with an abundance of food and will devour it greedily. We know from experience that about a month after a green-manure crop has been ploughed into the soil there will be hardly any visible remains of plant material in the soil except perhaps some hard stems, provided the soil was kept sufficiently moist by rain or irrigation. This destruction of organic matter is called decay or also decomposition or fermentation, but because a special meaning is attached to these terms in bacteriology we shall call the process *organic weathering*.

What then has happened to the organic material, i.e. the leaves, stems, and roots of the crop of peas that was ploughed into the soil? In order to answer this question it is necessary that we should again turn to the composition of plants as we discussed it in Chapter II. Carbohydrates and proteins are the two groups of organic constituents that are present in the largest quantities in plants. The soil microbes utilize carbohydrates and proteins both as energy-giving food and as building material for their 'bodies'. Like animals, the majority of the soil microbes need the organic carbon of plant material for carbonaceous food. However, for every part of carbon that the microbes utilize in the production of new cells, at least two parts of carbon are lost in the oxidation process (respiration) that supplies them with the necessary energy for their activities. The products of this process of oxidation or combustion are the usual products of respiration, carbon dioxide and water.

Plant carbohydrates consist of different compounds such as sugars, starch, cellulose, hemicellulose, and lignin. Strictly speaking, lignin is not a carbohydrate. Careful investigation has proved that soil microbes digest these compounds more or less in the order in which they are given above. The sugars are the easiest to digest or decompose and lignin is the most difficult to decompose. Many microbes do not seem to be able to decompose lignin at all. The result is that it remains in the soil for a relatively long time and is to-day considered to be the most important constituent, in a changed form, of the so-called humus in soils. The older plants become, the less sugar and starch their tissues contain and the richer in cellulose and lignin they become. Thus the composition of plant material is important in connexion with the amount of humus that can be formed from a specific weight of plant material.

The proteins, the second important group of organic substances in plants, are very complex compounds and contain nitrogen. Soil microbes can split up these substances into their simpler constituents, the so-called amino-acids. The amino-acids contain the four elements carbon, hydrogen, oxygen, and nitrogen and microbes can utilize amino-acids as nitrogenous food. However, when the easily digestible carbohydrates that supply energy and carbon have been used up, the microbes are forced to turn to the amino-acids for energy-giving food. Ammonia (NH_3) is then released as a by-product, together with carbon dioxide and water. This ammonia, or rather the compounds formed from it, is then changed by another

group of soil bacteria, the nitrifying bacteria, to nitrates. This and other interesting material changes for which soil microbes are responsible will be discussed in greater detail in a subsequent chapter.

From the above it is clear that when fresh plant material or animal products are incorporated with moist soils a rapid decomposition of most of their constituents is brought about by living microbes. Numerous new microbe cells are formed in this process but the majority of the constituents are 'mineralized' or changed into simpler substances such as carbon dioxide, water, ammonia, &c. Dry vegetable matter such as wheat-straw, chaff, maize stalks, and woody material such as sawdust and woody shrubs do not decompose as quickly in the soil. They may take six to twelve months and even longer if the soil remains dry for lengthy periods. In the case of rotted farm manure the quick decomposition has already largely taken place in the kraal with the result that such organic matter also disappears comparatively slowly in soils. Old Karoo manure decomposes very slowly in the soil.

After the relatively rapid decomposition of the above-mentioned organic substances a small, variable residue that is very fine and mainly dark in colour is left in the soil. This residue is called *Humus*, a word which we have already used several times and which we now wish to define more clearly.

Humus is a very complex mixture of fine organic substances and both its formation and composition are not yet fully understood.

Undoubtedly it contains, among other ingredients, ligneous compounds and naturally also a mass of microbial products, i.e. dead microbe cells. Thus humus may be described as a mixture of the very fine (colloidal) organic residue and the newly formed organic products, mainly proteins. It is generally dark in colour and no longer recognizable as plant tissue under the microscope. It is thoroughly mixed with the mineral particles; in other words, it constitutes an inherent part of every agricultural soil. It not only contains the ordinary elements that are present in organic matter such as carbon, hydrogen, oxygen, and nitrogen, but also the so-called mineral constituents such as phosphorus, sulphur, potassium, calcium, &c. The composition of humus varies in different soils and under different climatic conditions, but in round figures humus contains more or less the following:

Carbon	50 per cent.
Oxygen	35 ,,
Hydrogen	5 ,,
Nitrogen	5 ,,
Mineral constituents . . .	5 ,,

THE DECOMPOSITION OF HUMUS

Humus can be considered as a comparatively permanent constituent of every agricultural soil, but it also undergoes a further *slow* decomposition by new generations of soil microbes. As in the case of the rapid

decomposition of fresh organic substances, the inorganic or mineral products, carbon dioxide, water, ammonia, and nitrates, phosphates, and sulphates of potassium and calcium, &c., are also formed in the case of the slow decomposition of humus.

Apart from the nutrients that organic substances contain, the soil microbes also need certain conditions for their development, such as sufficient moisture and air in the soil, a suitable soil temperature, and soil reaction, i.e. the soil must be neither too acid nor too alkaline. As these conditions improve, both the rapid and the slow weathering of organic matter are speeded up; in other words, not only is humus formed more quickly in the soil, but it is also decomposed more quickly. As a result of continuous cultivation of soils in order to incorporate fertilizers, control weeds, and bring about the most desirable physical condition for plant growth, the humus content of a soil may become dangerously low. Therefore, in order to maintain a sufficient humus content in the soil one should constantly apply fresh amounts of organic matter in the form of farm manure, green manure, straw, &c., to the soil. The continuous single-cropping system (monoculture) practised in South Africa, in which either only maize or only winter cereals are grown, has resulted in a severe depletion of the humus content of our older agricultural soils. To this their present low productivity and their erodibility can chiefly be attributed. It is easy to realize that such systems are disastrous in South Africa because here the 'slow' decomposition of humus takes place comparatively rapidly as a result of our warm climate. The importance of a sufficiently high humus content in soil fertility and how it may be maintained will be discussed in a subsequent chapter.

To sum up, we wish to explain again a few of the terms used in this chapter. The organic matter of soils includes the humus and it is the combustible portion of the soil that corresponds approximately with the loss in weight that soils undergo on ignition. All the humus is organic matter, but all the organic matter is not humus. The residue of leaves, stems, and roots that can still be distinguished as such in the soil is not humus. Humus is only the very fine, difficultly recognizable, organic products in soils that are intimately mixed with the soil and which undergo a slow further process of decomposition. The larger the supply of organic matter to soils and the less favourable conditions are for the development of microbes, the higher will be the humus content of the soil. Thus marshy soils and other soils with a very high water content usually have a high humus content because certain plants grow luxuriantly on such soils but they contain too little air and are too acid for active microbial life.

Topsoils usually have a higher humus content than subsoils because roots grow mainly in this layer and plant residues and organic manures are also incorporated with the surface soil. Soils consisting chiefly of inorganic or mineral particles, as is the case with most South African soils, are called *mineral soils* although they may contain up to 10 per cent. organic matter. If the soils consist largely of organic matter they are called *peaty*

soils. Such soils only occur in very moist localities and so they are seldom found in South Africa. In the northern parts of Europe, Asia, and North America peaty soils are common and they have originated mostly from 'water' plants growing in marshes and shallow lakes.

'Turf' soils. This is a specific South African name and does not signify a peaty soil. A 'turf' soil means a dark-coloured clayey soil that is very sticky and plastic when wet. It occurs fairly commonly in certain areas of the Northern Provinces, especially the Transvaal, and it does not contain as much humus as its colour would indicate. Usually it contains about 2–4 per cent. humus. The word 'turf' does not refer to the humus content, but rather to the 'heaviness' of the soil. Hence the name red turf for a heavy red loam. The name 'turf soil' should only be used to indicate a dark-coloured clayey soil because it is a definite and very interesting soil type in South Africa. We should call a heavy reddish soil a red-loam or a red-clay. The following analyses give the percentage of organic matter, mainly humus, of surface soils (accurate analyses).

	Organic matter
Grain land—been cultivated for a very long time (Moorreesburg)	0·88 per cent.
Grain land—about 25 years under cultivation (Caledon)	2·25 ,,
Grain land—virgin soil (Swellendam)	4·15 ,,
Maize land—(Ermelo)	0·75 ,,
'Turf' soil (Springbok Flats, Tvl.) Dr. J. J. Theron	1·93 ,,
Red-loam (Springbok Flats, Tvl.) Dr. J. J. Theron	2·20 ,,
Sandy loam (Ladybrand, O.F.S.)	0·74 ,,

CHAPTER IX

THE MECHANICAL COMPOSITION OF SOILS

IF we were to inspect the solid particles of an agricultural soil we would notice immediately that they vary in size. The soil contains coarse sand grains and sometimes small and large stones. However, a portion of the soil usually consists of particles that are so fine that they cannot be distinguished with the naked eye. The proportion of coarse to fine particles calculated on either the volume or the weight of soils will vary considerably in different soil types. By the *mechanical composition* of a soil is meant the relative quantities in which different-sized soil particles are present in the soil. The term *texture* is also used instead of mechanical composition. When sand particles preponderate in a soil (sandy soils) we say that the soil has a coarse texture. A clay soil again is said to have a fine texture on account of the fineness of clay particles. In between these two extremes are the loams.

From an agricultural point of view the mechanical composition of soils is a very important factor because on it all the physical properties such as temperature, aeration, and water-holding capacity will largely depend. With a little practice a fair idea of the texture of a soil may be obtained by rubbing a small amount of the moist soil between one's fingers. However, in order to estimate the proportions of particles of different sizes accurately it is necessary to analyse the soil mechanically.

THE MECHANICAL ANALYSIS OF SOILS

An ordinary agricultural soil consists of particles of diverse sizes varying from, say, a quarter of an inch in diameter to much less than one-millionth of an inch in diameter. In soil science the millimetre is used as unit when indicating the size of soil particles (25 millimetres = 1 inch). Soil scientists have also agreed that soil particles should be divided into certain groups of definite sizes. Such groups are called fractions. In the past there was little uniformity in this respect and different countries not only had their own methods of mechanical soil analysis, but they also adopted different groupings of fractions. Since 1924, however, an International Society of Soil Science exists and now there is greater uniformity. The following is the approved international classification of the soil fractions.

Name of fraction	*Maximum and minimum diameter of soil particles*
Gravel or stones . .	Larger than 2 mm.
Coarse sand . . .	2–0·2 mm.
Fine sand . . .	0·2–0·02 mm.
Silt	0·02–0·002 mm.
Clay	Smaller than 0·002 mm.

If we were to think of a method by which to divide soil particles into groups of different sizes our thoughts would probably turn immediately to

sieves. Actually sieves made of metal or cloth are used in the mechanical analysis of soils, but unfortunately even the finest sieve is still so coarse that it can only separate particles with a diameter of more than about 0·2 mm. That means that finer soil particles have to be separated by some other means, and sedimentation in water is very suitable for this purpose. The bigger and heavier the soil particles are, the quicker will they settle in a column of water of given height. There is a well-known mathematical relationship (Stokes's law) which expresses the relation between particle-size and weight on the one hand, and the velocity of fall through a column of liquid at rest, such as water, on the other. Actually this law only applies to spherical particles of the same specific gravity, and in the soil we have particles with diverse shapes and with different specific gravity. However, Stokes's law is also with a fair degree of accuracy applicable to a soil suspension in water.

There is still another difficulty which must be overcome if we wish to separate soil fractions accurately by means of sieves and water. Fine soil particles always adhere to one another and to bigger particles. It is easy to prove this to ourselves by sieving a certain amount of soil through a 1-mm. sieve, after having broken up all visible clods, until no more soil will pass through the sieve. If we now allow water to trickle through the soil on the sieve and catch it up in a glass beaker it will be noticed that the water is turbid and that fine sand settles on the bottom of the beaker. These bigger aggregates consisting of groups of small particles are called *soil crumbs* or granules (not clods!). Naturally, these crumbs are small: most of them pass through a 2-mm. sieve. For the fertility, or rather productivity, of a soil these granules are of paramount importance as will be discussed later. For the purpose of a mechanical analysis, however, these crumbs should obviously be broken up. There are many reliable ways in which a soil sample may be dispersed into its individual or ultimate particles. It may be boiled in water or mixed with water in a porcelain dish and rubbed with the fingers or with a rubber pestle or with a small hard brush against the sides of the dish. A better method than these is to take a quantity of soil, say 10 gm., and to stir it into water containing a small amount of ammonia or sodium carbonate.

There are many methods (and new ones are constantly being suggested) by which the sample, prepared as shown above, can be analysed mechanically, but because most of these methods require special apparatus we will only describe a simple decantation method here. However, we would first like to discuss briefly how soil samples should be taken in a field, orchard, or garden.

HOW SOIL SAMPLES SHOULD BE TAKEN AND PREPARED

It is of the utmost importance that a soil sample to be analysed, either mechanically or chemically, should be representative of the field from which it was taken. To the casual observer it might not be so noticeable but, nevertheless, soils differ considerably even at short distances apart,

especially if they are alluvial or situated on sloping ground. Thus it would usually be wrong to take a sample at one spot (one hole) only.

For an average agricultural soil 6–12 holes or pits, 2–3 feet in depth, are usually made at spots spread evenly over the field to be sampled. The holes are about 2 feet square and the faces are spaded down vertically. There are several reasons why it is better to make the holes when the soil is moist than when it is completely dry. The difference in colour, for example, between the topsoil and subsoil is much more noticeable in a moist soil than in a dry one. On account of its higher humus content the topsoil will usually be darker in colour than the subsoil. While the holes are open and before samples are taken, observations should be made in connexion with the soil profile (the vertical section). One should notice whether the soil profile is the same in all the holes, whether there is a sharp distinction between topsoil and subsoil, how deep the dark-coloured topsoil is, and, if possible, how deep below the surface the parent rock is. In the case of alluvial soils the texture of the different layers at different holes will often vary considerably.

If the soil profile is approximately the same at all the holes, the topsoil sample is first taken as follows: Loose leaves and litter are scraped away from the surface of the soil. A spade is then dug straight down as deep as the topsoil (6–9 inches) and a sod removed and placed on a clean bag or wheelbarrow. Similarly sods are taken from the topsoil at all the other holes, mixed well on the bag or wheelbarrow, and the clods, if any, broken with a spade. A few big handfuls (2–6 lb.) of this mixed topsoil are put into a clean linen or paper bag and labelled. Such a sample is also called a composite sample and it should be representative of the whole piece of ground. Where there are hillocks (*heuweltjies*) on a piece of ground or where there are wide variations in soil type on one and the same land, a drawing of the land should be made on a piece of paper indicating the areas where the different types occur and then a separate composite sample should be taken of each type.

The subsoil sample is taken in a similar way after the topsoil has been removed somewhat and the hole cleaned out. The depth to which a subsoil sample should be taken, and whether different samples should be taken at different depths, will depend on the nature of the subsoil and on other considerations. When the ordinary field crops are grown it is sufficient to take the subsoil sample to a depth of 1 foot in the subsoil and then a note should be made on the nature of the subsoil farther down. In orchards and especially in alkali (brak) soils it is necessary that the composition of the subsoil should be known to a depth of some 6 feet.

Samples can also be taken with a soil auger or a soil tube of which several types are in use. In stony and also in dry soils most types are unsatisfactory and in any case a much better view of the soil profile is obtained if a pit is made with a spade.

The composite sample is spread out on a firm piece of paper in a laboratory or any other clean room, or even outside if there is no wind, in order to

become air-dry. While a moist clayey soil is drying all clods should be broken because when quite dry they may be very hard and cause unnecessary trouble.

The air-dry soil is mixed well once more and 1 kilogram (about 2 lb.) of it is weighed off and passed through a 2-mm. round-hole sieve. The pebbles and coarse sand grains (together called stones or gravel) that remain behind on the sieve are then (still on the sieve) washed under a tap until the water runs through clear. They are then transferred to a piece of paper to dry. When dry they are again sieved on a 2-mm. sieve and then weighed. From this weight the percentage of gravel in the original soil may be calculated. Often it is possible to decide what the parent rock of the soil concerned is, by determining what rock fragments and minerals are present in the gravel fraction. Naturally, this is only applicable to residual soils.

The rest of the soil sample may now also be passed through the 2-mm. sieve and the coarse residue discarded. The soil particles that are smaller than 2 mm. in diameter are known as the 'true' soil or fine earth, and after mixing them well once again they may be placed in a clean glass container or tin and labelled. All subsequent analyses are made on this soil.

The beaker or decantation method of mechanical soil analysis: 10 (or 20) gm. of air-dry, 'true' soil are weighed into a porcelain dish and mixed to a paste with water. The paste is worked with the finger or with a rubber pestle for a few minutes and then it is washed into a clean glass beaker. The soil from the finger and the pestle should also be washed carefully into the beaker. The glass beaker should be approximately 10 cm. in diameter and 12 cm. deep. A piece of gummed paper is then stuck on the outside of the beaker, 10 cm. from the bottom. About 10 c.cm. of dilute ammonia is added to the water and soil in the beaker and the mixture is stirred for a short while. Now fill the beaker with ordinary clean water up to the 10-cm. mark, stir it well with a glass rod, and leave the suspension standing for exactly 4 minutes 48 seconds. The turbid suspension is now decanted or poured off with a steady movement without disturbing the sediment unduly. Enough water should be poured off to leave about $\frac{1}{2}$ cm. in the beaker. Fill the beaker again up to the mark, stir, and leave again for exactly the same time, after which the turbid suspension is again decanted. Repeat this performance until the water is quite clear after having stood for 4 minutes 48 seconds, i.e. until no mineral soil particles remain in suspension after 4 minutes 48 seconds. In the case of a sample containing comparatively fresh organic matter fine particles of crushed roots, &c., will still be in suspension at the end, but they need not be taken into consideration because they are eventually burnt away. In order to ensure that all the crumbs disintegrate, it is advisable to add a small amount of ammonia again after having poured off the suspension, say, four times.

By this process of sedimentation and decantation all particles with a diameter of less than 0·02 mm. are removed. The remaining sediment is washed back into a porcelain basin and after a few minutes almost all the

water can be poured off and the soil is now carefully dried on a sand bath or over a slow flame. Then the basin with soil is heated over a stronger flame in order to burn away any organic matter that may be present. Allow the soil to cool and place it on a sieve with meshes of about 0·2 mm. square.

If no such sieve is available the cloth of a very fine flour sieve may be stretched over a tin from which the bottom has been removed.

Sieve all the fine sand through as thoroughly as possible on to a smooth sheet of paper and weigh it. The coarse sand on the sieve is now weighed. We have thus separated the true soil into the following three fractions:

1. Coarse sand: 2–0·2 mm. in diameter.
2. Fine sand: 0·2–0·02 mm. in diameter.
3. Silt and clay: less than 0·02 mm. in diameter.

The percentages of coarse and fine sand are calculated. By subtracting this sum from 100 we obtain the percentage of silt and clay. However, this latter figure includes the organic matter and hygroscopic moisture that are present in the true soil. In order to determine the combined silt and clay fraction accurately, it is necessary to heat, say, 10 gm. of the original soil strongly. After cooling and weighing, the combined percentage of organic matter and hygroscopic moisture may be calculated and hence also the actual percentage of silt and clay.

If the silt and clay fractions are to be separately determined the method is somewhat more cumbersome because now the original suspension may only be decanted off after 8 hours. By this the clay fraction, i.e. particles with a diameter of less than 0·002 mm., is removed. Only if the suspension is clear after having stood for 8 hours is the time changed to 4 minutes 48 seconds. The turbid decantations must now be collected in a large glass beaker or dish so that the percentage of silt can be determined directly after settling, drying, ignition, and weighing. The percentage of clay is again calculated indirectly.

If sieves with openings of 1 and 0·5 mm. are available, the dry sand sediment may be passed through these and the 0·2-mm. sieve and thus it will be separated into coarse sand, medium sand, fine sand, and very fine sand. However, the most important distinction seems to be the 0·2-mm. size limit, and therefore separation of sand into two fractions, as shown above, should be sufficient for practical purposes.

The inclusion of the hygroscopic moisture in the percentage composition is a small inaccuracy in the method described above. This may be avoided by first determining the percentage of hygroscopic moisture in the air-dry soil (see later) and then taking a quantity of soil, which is equal to 10 gm. of over-dry soil, for the mechanical analysis. The above-mentioned inaccuracy is only of practical importance in the case of peaty soils and clay soils.

The following examples show the results of mechanical soil analyses as determined by the above simplified beaker method. The gravel-percentage was calculated on the original soil but all the other figures are based on the 'true' soil.

TABLE 8

Mechanical Composition of Air-dry Soils

Soil type	*Gravel content* >2·0 *mm.*	*Hygroscopic moisture and organic matter*	*Coarse sand* 2–0·2 *mm.*	*Fine sand* 0·2–0 02 *mm.*	*Silt and clay* <0·02 *mm.*
	%	%	%	%	%
Coarse sandy soil .	5·5	1·4	57·7	36·6	4·3
Fine sandy soil .	0·0	1·7	7·4	87·9	3·0
Sandy loam . .	2·5	4·0	30·4	45·7	19·0
Clayey loam . .	0·0	9·5	20·6	24·5	45·4

CHAPTER X

THE IMPORTANCE OF THE SOIL TEXTURE

A KNOWLEDGE of the exact texture or mechanical composition of soils enables us to classify them and to gather valuable information in connexion with their agricultural possibilities and weaknesses.

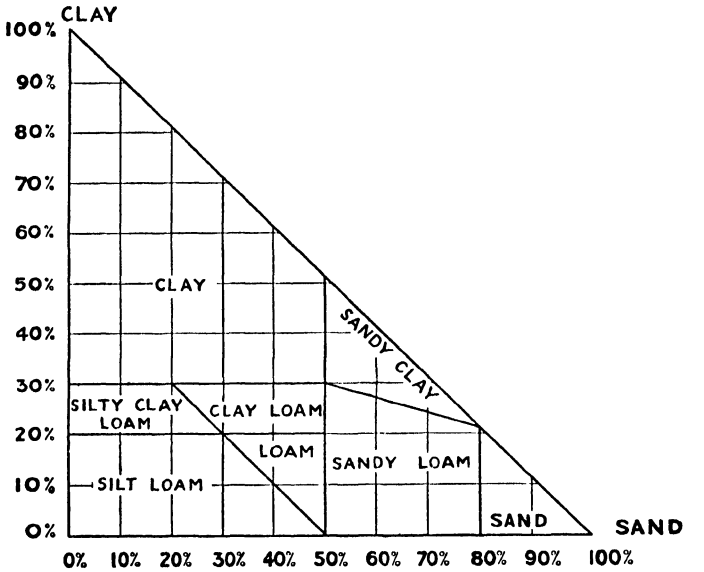


FIG. 3. Diagram from which the texture of soils can be deduced.

Soils may be classified from various aspects. In previous chapters we have already classified them according to their origin into primary and secondary soils, and according to their humus content into mineral soils and peaty soils. For scientific purposes, the classification according to the chemical composition of the soil profile, which is the result of parent rock, climate, vegetation, and topography, is considered to be the most useful. However, for practical agriculture the classification of soils according to their texture is one of the oldest and also the most useful. Texture can be used as a basis for soil classification because it cannot be altered by ordinary methods of soil cultivation and improvement. Usually that can only be done on a small scale and at great expense, e.g. the changing of a sandy soil to a sandy loam by heavy applications of silt or clay, and the application of a large amount of sand to a clay soil in order to render it more open and friable.

We can differentiate between many different types according to the relative proportions of the four chief soil fractions—coarse sand, fine sand, silt,

and clay. If we consider the coarse and fine sand as one fraction we have three main fractions and then we can make use of the foregoing diagram in order to determine to which class any particular soil belongs. The diagram is a modification (by the Soil Division, Pretoria) of the original representation by Whitney (America).

We can differentiate between four main soil classes and every class can again be subdivided so that we have a total of ten soil types (if the gravel content is not taken into consideration).

I. *Sandy soils* (more than 80 per cent. sand).
   1. Coarse sandy soil (more than 50 per cent. of the sand is coarse sand).
   2. Fine sandy soil (more than 50 per cent. of the sand is fine sand).

II. *Sandy loams* (50–80 per cent. sand).
   3. Coarse sandy loam (more than 50 per cent. of the sand is coarse sand).
   4. Fine sandy loam (more than 50 per cent. of the sand is fine sand).

III. *Loams* (up to 50 per cent. sand and less than 30 per cent. clay).
   5. Ordinary loam (30–50 per cent. sand and less than 20 per cent. clay).
   6. Silt loam (up to 50 per cent. sand and less than 20 per cent. clay).
   7. Clay loam (20–30 per cent. clay and 20–50 per cent sand).
   8. Silty clay loam (up to 30 per cent. sand and 20–30 per cent. clay).

IV. *Clays.*
   9. Ordinary clay soil (more than 30 per cent. clay and less than 50 per cent. sand).
   10. Sandy clay soil (20–30 per cent. clay and more than 50 per cent. sand).

When the total sand fraction in a soil rises above 50 per cent. it is important to know whether the sand is mainly coarse or fine. Hence the subdivision of the sandy soils on this basis. If the fine sand fraction predominates, cultivated soil has a tendency to form a hard crust on the surface on drying after rain or if the soil has been irrigated. This is especially liable to happen if the soil has a low humus (and lime) content.

This classification is only arbitrary and far from perfect. The different proportions in which the four fractions can be grouped in nature are so infinite that we are forced to adopt only a few for practical purposes. Even in this limited number we often find cases where soils have almost the same physical properties and yet, according to our scheme, they are grouped under different types. It is only when one of the four main fractions absolutely predominates that a soil has distinctive properties.

In this scheme the content of stones or gravel is not taken into consideration. Many of our soils, especially in the coastal regions of the Cape Province, contain a high percentage of such constituents, and thus the gravel must be taken into consideration when describing such soils.

Thus we have gravelly sands, gravelly loams, gravelly silt loams, and also true gravel or stony soils with over 70–80 per cent. gravel or stones. Especially the more or less colluvial soils on mountain slopes belong to this class.

A further difficulty which upsets strict adherence to the triangular diagram is the fact that organic matter and the hygroscopic moisture usually constitute a portion of the sum of the percentages in the mechanical analysis.

The following table gives a complete mechanical composition of some South African soils (according to an older grouping of fractions).

TABLE 9

Mechanical Composition of Some South African Soils

	No. 1	*No. 2*	*No. 3*	*No. 4*	*No. 5*	*No. 6*
	%	%	%	%	%	%
Stones (>2 mm.)	41·1	1·4	35·0	2·5	2·5	1·2
Hygroscopic moisture	0·5	0·6	1·5	0·6	4·3	7·7
Loss on ignition (organic matter)	1·5	3·2	3·5	3·1	10·9	7·3
Coarse sand (2–0·2 mm.)	15·0	8·1	22·0	61·6	5·2	19·7
Fine sand (0·2–0·04 mm.)	65·2	49·5	24·5	19·1	10·1	15·0
Silt (0·04–0·01 mm.)	4·7	10·9	11·0	3·0	9·1	6·3
Fine silt (0·01–0·002 mm.)	3·6	7·9	19·2	2·9	14·6	6·8
Clay (<0·002 mm.)	9·5	19·8	18·3	9·7	45·8	37·2

Locality from which sample was taken:

No. 1 is from a grain land in the Moorreesburg district.
No. 2 is from a tobacco and grain land in the Stellenbosch district.
No. 3 is from a grain land in the Caledon district.
No. 4 is from the Ermelo district, Transvaal.
No. 5 is a red-clay soil, Koedoespoort, Transvaal.
No. 6 is a turf soil, Transvaal.

SOIL TEXTURE AND PHYSICAL PROPERTIES

The results of mechanical soil analyses enable us to gather valuable information in connexion with the physical properties of soils. The most important of these physical properties will be discussed later in more detail. Here we shall show how different properties vary in degree in the case of the four usual soil fractions. Gravel and stones will exhibit the physical properties of coarse sand to a greater extent.

	Degree in which the soil fraction concerned exhibits the property			
Physical property	*Coarse sand*	*Fine sand*	*Silt*	*Clay*
Water capacity	Very low	Medium	High	Very high
Capillarity	Very low	Good	Great	Very great
Rate of water movement	Very fast down	Fast down and up	Slowly down and up	Very slowly down and up
Absorption capacity (for gases, water, and plant nutrients)	Very slight	Slight	Good	Very high
Cohesion and plasticity	None	Slight	High	Very high
Relative temperature	Warm	Fairly warm	Cold	Very cold
Aeration	Very good	Fairly good	Poor	Very poor

This summary shows clearly why a soil consisting mainly of one or even two closely related fractions would be less suitable for plant growth than a soil that contains moderate quantities of all the different fractions. As the proportion of any fraction increases such a soil becomes more suitable for plant growth in some respects and less suitable in other respects. For example, if a soil contains a large proportion of sand it heats up quickly, it is well aerated, excessive moisture drains away easily, and the soil is easy to cultivate. However, such a soil retains too little moisture and plants quickly suffer from a lack of moisture. Plant nutrients also leach out of such a soil very easily. If a soil has a high clay content it retains moisture and plant nutrients well but, on the other hand, such a soil is cold, badly aerated, easily becomes waterlogged, and is difficult to cultivate.

The intensity of the physical properties of fine sand and silt lies between those of coarse sand and clay—as may be seen from the summary. Thus it is easy to understand why sandy loams (that contain all the soil fractions in favourable proportions) are considered the most productive agricultural soils.

Finally, the soil texture also enables one to draw certain conclusions with regard to chemical composition of soils. Generally speaking, the sand fractions contain very little plant food such as potash, lime, magnesia, and phosphate, while the silt and clay fractions are considerably richer in these nutrients. Of course, the reason for this is that sand consists mainly of quartz and other minerals that have undergone little if any chemical weathering. Thus sandy soils are usually poor soils. The nitrogenous food of a soil depends on its humus content and not on its texture.

Investigation in South Africa has shown that in regions with a fairly high rainfall, say 25 inches or more per annum, sandy soils are more acid than loams and clay soils so that there is also a relationship between acidity and soil texture.

Because different agricultural crops need different quantities of water and plant food and because the root system of every plant species is typical as far as development and respiration are concerned, we find that a certain crop will give the highest yield on soils with a certain texture. Thus experience has taught us that wheat and barley grow best on the 'heavier' soils, while oats and rye prefer sandy soils. Potatoes also prefer sandy soils; maize prefers sandy loams; peaches and oranges do best in good loams; pears also grow best in loams, but also grow very well in clay soils. Apricots, plums, and even apples grow well in sandy and gravelly soils. Vines also generally prefer an 'open' soil such as gravelly granite or shale soils.

From this discussion it is evident that the mechanical analysis of soils enables us to come to important conclusions in connexion with their agricultural possibilities. Enough stress can hardly be laid on the necessity for taking into consideration the nature of the subsoil as well as that of the topsoil. For reasons which will be easier to understand later, it is necessary that we should not only have a knowledge of the mechanical composition of soils, but also of their humus and lime content, in order to draw the correct conclusions in connexion with the physical behaviour of soils.

The next paragraph is a summary of the characteristic properties of sandy and clay soils—the two extremes in soil texture. In the case of the different types of loams the following properties will vary between those for sand and clay.

Sandy soils are well aerated, easy to cultivate, well drained, and they are warm soils, but they have a low water-holding capacity and as a rule they are poor in all the different plant foods. With even a moderately high rainfall sandy soils can also be very acid especially if they are dark in colour, i.e. if they have a high humus content. Sandy soils also have a very low cohesion with the result that soil particles lie loosely against one another. Thus prevailing winds easily blow such particles from one place to another (wind-blown soils) unless the soil is covered with plant growth or protected by wind breaks. If satisfactory crops are to be reaped on sandy soils they should be watered regularly, receive medium applications of all three of the essential plant food elements, and, where necessary, lime should be applied regularly but with caution. Applications of organic matter to sandy soils give them body, in this way increasing their capacity for retaining water and plant nutrients. Thus it is important that farm manure or green manure should form the basis of manuring in such soils.

Clay soils retain water and plant nutrients well. The soil particles have a relatively high cohesion, and such soils are comparatively rich in plant nutrients (except phosphates). On the other hand, clay soils usually drain very slowly with the result that they are apt to become waterlogged, thus being badly aerated. Clay soils expand when moistened and shrink to the same extent on drying, with the result that often during a dry season large cracks appear in this type of soil. They should only be cultivated when they have the correct moisture content. If cultivated when too moist they puddle and afterwards form hard clods and big cracks. If cultivated when too dry they break up into large clods and the ploughed soil is quite unsuitable for a seedbed. Under the same rainfall conditions they are not as acid as sandy soils and yet, under intensive cultivation, they require more lime than sandy soils. In this case the lime also renders the clay more open, more friable, and easier to cultivate. For the same reason regular applications of organic matter (farm manure, straw, green manure) are advisable in the case of clay soils.

CHAPTER XI

SOIL COLLOIDS AND THEIR PROPERTIES

IN order to understand many of the characteristic properties of different soil types it is necessary that we should have a sound, albeit an elementary, conception of what is meant by soil colloids and their properties.

In connexion with the mechanical analysis of soils we have seen that if a soil sample is prepared for mechanical analysis, as outlined, and then shaken up in water, it forms a 'soil suspension', i.e. a dispersion of the soil particles in water. The larger soil particles (the sand) quickly settle on the bottom of the beaker, but the water remains turbid as a result of the finer particles that do not settle immediately. With most soil types we will find that the suspension is still turbid after days or even weeks or months. It is to-day a well-known fact that there are particles in our soils that are so small that they will remain in suspension almost indefinitely and that the force of gravity of the earth which tends to pull 'everything' down has no effect on them. These extremely fine soil particles are called *colloids*. Literally colloids would mean glutinous substances (Gr. *kolla* = glue), but we should rather forget this derivation because it is only when they are in a certain condition that they act like glue or gelatinous substances.

Thus the sub-microscopic size or fineness of matter characterizes the 'colloidal condition' of substances and any chemical substance may become a colloid if its particles could only be reduced to the desirable size. What, then, is the most important physical property characterizing a substance that is in such an extremely dispersed condition? If a piece of chalk, or any mineral that does not dissolve in water, is taken and a cube with edges 1 cm. in length cut from it, the cube will have a total outside area of 6 sq. cm. If it is suspended in water 6 sq. cm. of the cube will come into contact with water.

If the cube is now broken up and ground in a mortar and the fine particles are then suspended in water, the substance will still have a total volume of 1 c.cm. but the *surface area* of this substance coming into contact with water will now be considerably greater than 6 sq. cm. The total surface of a substance divided by its total volume will give us its specific surface. Because substances which are in colloidal state have such a minute particle size they have a large specific surface and this is their most important physical characteristic. When such a substance is suspended in water it has properties that it never had when its size was still such that it could be seen with the naked eye. Thus its particles may remain suspended in water and, practically speaking, they do not settle out at all; they show a peculiar (Brownian) movement when seen under a good microscope and the 'solution' may have a colour that the substance did not have in its coarse state. However, for us the most important property of colloids is

that they may have an electric charge which can either be positive or negative depending on the chemical nature of the substance and on the reaction (acidity or alkalinity) of the liquid.

At what degree of fineness does a substance exhibit these and other colloidal properties? The answer is that there is no definite size at which the particles suddenly begin showing these properties. In soil science we consider the clay fraction, i.e. particles smaller than 0·002 mm., to be colloidal although the finer portion of the silt also has colloidal properties but not to a very marked degree. Similarly the coarser clay particles, i.e. those with a particle size not much smaller than 0·002 mm., show colloidal properties to a lesser degree. In colloid chemistry particles are actually only classified as true colloids when they have a diameter of less than 0·0001 mm. (about 1/250,000 of an inch). Such particles pass through the finest filter paper. Thus there can be different kinds of clay, not only chemically, but also as far as the fineness of the particles is concerned.

The word molecule is used in science to indicate the smallest portion of a substance that still exhibits the chemical properties of that substance. If a molecule were further divided we would get the atoms of the substance and in the case of all substances consisting of two or more elements the atoms would be totally different chemically from the original substance. If a small amount of cane-sugar is stirred in water the sugar particles dissolve in the water and we get a true or *molecular solution* with the sugar molecules distributed evenly throughout the water. The sugar particles are then split up into their separate molecules. One property of true solutions is that they are absolutely clear even if they are coloured.

With substances in the colloidal state the splitting (dispersion) does not go as far as the molecular stage, but every particle still consists of a group (aggregate) of molecules. This is the fundamental difference between a true and a 'colloidal solution'; the latter also always exhibits a slight turbidity.

Until now we have assumed that the small colloidal particles that float about in the water are solid particles. However, certain liquids can also exist in the colloidal state when shaken up with another liquid such as water. Good examples of this are the oil sprays including ordinary paraffin. We call such a solution an *emulsion* and the term *suspension* is used when the suspended particles are solid. In science the terms suspension and emulsion are only used when the particles or droplets (liquid) are fairly large (more than 0·0001 mm.) and are still microscopically visible. Examples would be silt and coarse clay in water (suspension) and milk (emulsion, fat globules in water). If the particles have the true colloidal size, the 'solutions' are called suspensoids and emulsoids. In this last classification it does not really matter whether the colloidal particles are solids or liquids because this can hardly be differentiated, but it is of importance whether water molecules attach themselves to their surface or not. Emulsoids have a large affinity for water and suspensoids have none. True soil colloids fall largely under emulsoids. For our purpose we will, in future, only use the term suspension to designate a fine dispersion of soil colloids in water.

The substances that we find in the soil in the colloidal state are hydrated aluminium silicates which, collectively, we usually call 'clay', and also silicic acid, humus, iron hydrate, and aluminium hydrate. They originate in the soil from the weathering of minerals and, in the case of humus, from the decomposition and other changes which organic matter undergoes.

Of the many properties of colloidal substances there are two that are important for the behaviour of soils.

1. *Flocculation.* If we take a turbid clay suspension that has been standing in a glass beaker for a few days and add a knife point of slaked lime and stir it up in the suspension, we will notice after a few hours that the clay particles have settled on the bottom of the beaker in the form of visible flakes or 'crumbs' and that the water is now absolutely clear. This settling of suspended particles is called *flocculation.* The same thing will happen if we add a small quantity of any salt (e.g. common salt or gypsum) or of acid (e.g. hydrochloric acid) to the turbid clay suspension and stir it up. In nature this process takes place on a large scale when muddy river-waters mix with sea-water. This flocculation of silt and clay causes the formation of delta soils at the mouth of large rivers, e.g. the Nile.

Flocculation may be explained as follows: We have already mentioned that colloidal particles suspended in water are electrically charged. In the case of a clay suspension all the particles are negatively charged and, as is well known in electricity, the particles will repel one another when they come into contact with one another. Chemistry teaches us that if one of the above chemicals (electrolytes), such as table salt, is dissolved in water the molecules of such a substance split up (dissociate) into two parts. The one part (the cation) is positively charged and the other part (the anion) is negatively charged. The change may be represented as follows:

$$NaCl \rightarrow Na^{+} + Cl^{-}.$$

The common salt molecule splits up into sodium cation and chlorine anion. If a small quantity of the salt solution is added to the turbid clay suspension, the cations with their positive charges are attracted (absorbed)[1] by the clay particles with their negative charges. The charges on the clay particles are thus neutralized and if the clay particles now come into contact with one another (because they continually move about in the liquid) they adhere to one another. In this way more and more particles combine to form groups (aggregates) and eventually they become so large and heavy that they settle on the bottom of the beaker.

If a colloid exists in this flocculated or coagulated condition we call it a *gel* and in the suspended or deflocculated condition it is called a *sol.* This phenomenon is illustrated in Fig. 4 overleaf (the particles are drawn very large in proportion to the dimensions of the glass beaker).

The colloid may again be changed from the gel to the sol condition. If the clay gel is poured on to a paper filter and the clay granules separated from the liquid (they are too big to pass through the filter paper) and the

[1] To-day this explanation is slightly different and more complicated.

gel is now washed on the filter with a dilute ammonia solution, we shall find that the clay particles will again pass through the filter and if caught up in a beaker we will again have a turbid clay suspension (sol). Thus alkaline solutions (except lime) have a deflocculating or dispersive effect on

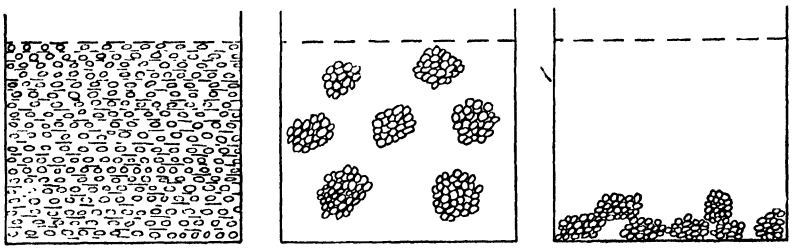


FIG. 4. Flocculation of soil suspension.

the ordinary soil colloids. (Compare the preparation of a soil sample for mechanical analysis.)

In agricultural soils we want the colloids always to be in the gel condition. The reason for this will be discussed in the next chapter. Here we shall only mention a few properties of gels. They are usually jelly-like, voluminous, elastic, and sticky and can retain a large amount of water when fully saturated. When such a gel dries out it shrinks immensely and has a tough appearance as if covered with a 'skin'. A small amount of gelatine or agar-agar, of which a jelly has been made, shows these properties very well. This behaviour of gels is responsible for the expansion of ordinary clay soils (that contain much clay gel) on moistening and their shrinkage and cracking on drying. This property also explains why clay soils are plastic and mouldable when wet and why they form hard clods when dry.

2. *Absorption and exchange of cations.* It has been known for a long time that pigments and certain salt constituents are retained by soils when solutions containing such substances are filtered through soil. For example, dark beer or liquid manure or brackish water may be filtered through a column of soil in a glass tube and the filtered solution inspected afterwards. To-day we know that the colloidal gels are responsible for retaining or absorbing the said substances. For soil fertility the absorption of basic constituents or cations of salts is very important. It is called *cation absorption.*

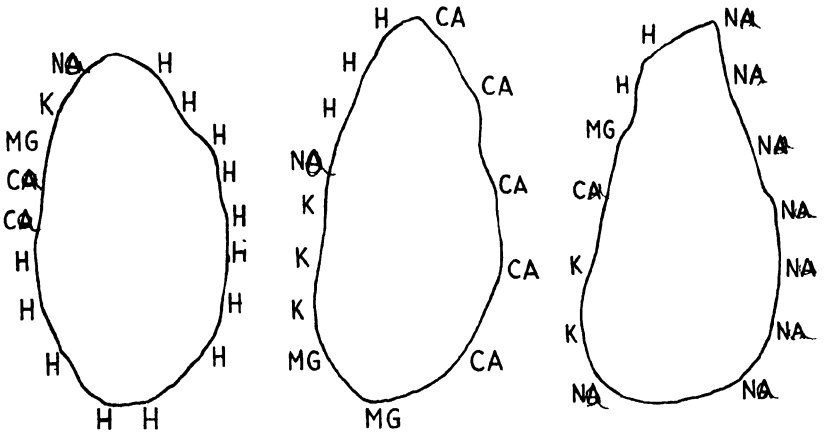
We have already said that colloids flocculate because they absorb cations. In an ordinary soil the colloids are in the gel condition and thus they are saturated with cations. Usually we find that the following five cations are present: hydrogen, calcium, magnesium, potassium, and sodium. In con-

nexion with the behaviour of soils it is essential to know which of these cations predominate in the *colloidal complex* as it is called. From this point of view agricultural soils may be divided into three classes:

(*a*) *Acid soils* in which absorbed hydrogen ions predominate.

(*b*) More or less neutral or *sweet soils* in which calcium (and magnesium) predominates, i.e. divalent cations.

(*c*) *Brackish soils* in which absorbed sodium (and potassium) predominates, i.e. univalent metallic cations.



Sour soil (*a*). Sweet soil (*b*). Brak soil (*c*).

FIG. 5. Absorbed cations.

Figuratively the state of affairs may be represented as above; every colloidal particle of the soil concerned has these cations predominantly attached to its surface (see Fig. 5).

We will discuss the properties of the three soil types afterwards and here we shall only mention some facts in connexion with this phenomenon of absorption. In ordinary slightly acid agricultural soils all five cations are present and the calcium and hydrogen ions predominate more or less as shown in the *b* diagram. If such a soil is fertilized with potassic fertilizers we find that potash (potassium) is retained by the soil (actually the soil colloids), but an equivalent amount of a previously absorbed cation, usually calcium, has been released in the soil solution. Thus an exchange or release of one cation takes place simultaneously with the absorption of another cation (in this case potassium). This exchange of cations is of great agricultural importance. Previously the term 'base exchange' was used but it is more correct to say 'cation exchange'. As in the case of potassic fertilizers the ammonium portion (NH_4) of ammonium-containing nitrogenous fertilizers is retained by soils. This shows that actually we fertilize the colloids. In other words we are augmenting the reserve supply of the nutrient concerned, when we apply soluble plant nutrients to the

soil. Thus there is no danger of such nutrients being leached out of the soil provided it contains sufficient colloids, i.e. provided the soil contains sufficient clay and humus. However, the nutrient absorbed in this way remains available to the plant because at any given moment a small amount of the nutrient will always be dissolved in the soil solution—again the result of this exchange phenomenon. The general rule is that the more the colloidal complex is saturated with a specific basic plant nutrient, the more of it there will be in the soil moisture or solution, and hence the larger the available supply to plants.

When lime is added to an acid soil the absorbed hydrogen, which is the cause of soil acidity, is exchanged by calcium and rendered harmless.

The main thing for us to realize is that the colloidal gel is, figuratively speaking, the soul of the soil and that it regulates (buffers) the concentration of dissolved chemical substances in soils in a marvellous way. Not only the chemical but also the physical properties of soils depend on the amount of gel and the kinds of cations that are attached to or absorbed on its surface. Humus and clay are the two most important substances that are present in the soil in the colloidal state. Their behaviour is not exactly similar and both are essential for a good soil. However, too much of either or both is also undesirable because then certain properties such as stickiness and immense water absorption come to the fore and the soil becomes too difficult to cultivate, badly aerated, and cold during wet periods. Sand, as the inactive or inert skeletal portion of a soil, is therefore also absolutely essential as a diluent, for a productive agricultural soil.

CHAPTER XII

THE STRUCTURE OF SOILS

SOIL texture refers to the size of the soil particles, but soil structure refers to the arrangement of the particles, especially the finer soil particles. There are two extremes in soil structure with intermediate conditions between them. The one extreme is a so-called *single-grain structure* of which the best example is, perhaps, a pure sand containing very little clay and humus. As a result of the relatively high weight of every sand grain such a soil settles and becomes very compact. Another example is a loam or a clay soil of which the colloidal particles are in the deflocculated or sol condition. Here also we find that the soil becomes very compact and because the fine particles form such an important part in these soils, they block the bigger openings or pores in between the larger particles with the result that the remaining pores are very small (see B in Fig. 6, p. 84). The disadvantages of these two types of single-grain structure in agriculture are different and we will discuss them presently.

The other extreme in the arrangement of soil particles is a *crumb structure*. In this case groups of the soil colloids are united with other finer soil particles into small granules, aggregates, or crumbs. The result is that such a soil has both very small and relatively large openings or pores. This is the ideal condition for an arable soil. The crumb condition of soils may be likened to that of freshly baked bread. The dough has risen well and in the bread there are hundreds of air spaces. This very desirable condition of an arable soil is known as good tilth:[1] 'soil tilth has often been defined as something every farmer can recognize but no scientist can describe' (E. W. Russell).

The diagram on p. 84 illustrates these structures.

A sandy soil with little humus naturally has a single-grain structure or, rather, it is structureless. As we will see later in this chapter its total pore volume or space in between the particles is relatively small but the individual pores are relatively large. The disadvantage to agriculture of this class of structureless soils is that water and plant nutrients pass through them and leach out of them too easily. The result is that they are poor soils with a very low water-holding capacity. Applications of large amounts of organic matter to add humus colloids to the soil, which will aid to build up a crumb structure, are essential.

If loams or clayey soils tend to have a single-grain structure, rain and irrigation water do not penetrate readily. The result is that run-off is relatively high and hence such soils erode easily. Because the soil particles settle so closely together, individual air spaces—the soil pores—are very small with the result that excess water cannot percolate through the soil

[1] Good tilth must not be confused with 'good heart'. A soil in good heart is one which, in addition to possessing good tilth, is well supplied with organic matter and plant nutrients.

rapidly enough during wet weather. All the soil pores are then filled with water and the soil contains no air, i.e. it is waterlogged. Seeds do not germinate in such a soil and the roots of growing and dormant plants, such as fruit-trees, die because they cannot breathe normally. Beneficial soil microbes also cannot function properly in such soils with the result that there is a deficiency in nitrates. Thus we have all the disadvantages of soils that are too wet including the fact that they puddle when tilled.

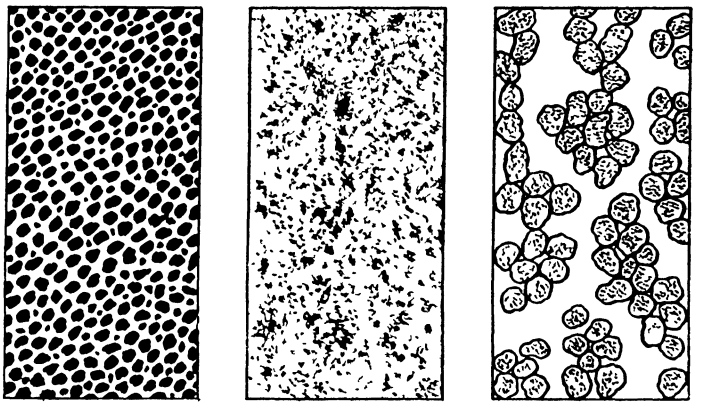


FIG 6 (After Stebutt)

A = Coarse sandy soil with single-grain structure.
B = Clayey loam with single-grain structure
C = Clayey loam with crumb structure

If such soils dry out to such an extent that plants can grow in them, roots encounter great resistance in their downward development because the soil is so compact. The result is that the plants are compelled to have a shallow root system with all its disadvantages.

Of course, soils can also become waterlogged as a result of an almost impervious stratum in the subsoil such as a layer of potclay, compact ironstone, or a hardpan. One should always determine whether the waterlogging is due to an impervious layer or a bad structure. This may be done by digging holes.

If the heavier types of soils are cultivated when either too dry or too wet the existing crumbs are partially destroyed. If a clayey soil is ploughed when too wet it puddles; the soil crumbs are compressed and the structure is destroyed in very much the same way as when a piece of freshly baked bread is pressed together between the fingers. If the soil is ploughed when too dry, hard clods and an unsuitable seedbed are produced and the fine dust that is formed is later washed in between the soil particles with the first rain so that the soil becomes very compact.

The crumb structure at the surface of soils, of which colloids are apt to be in a deflocculated condition, is chiefly destroyed by rain and irrigation

water. Also cultivated sandy soils that contain a high percentage of fine sand very often acquire a hard crust on the surface when they dry after rain or irrigation. It is a common phenomenon that rain-drops and, the more so, hail falling on a bare soil destroy the exposed soil crumbs purely by their mechanical pelting effect. Only a vegetal covering or a layer of trash, straw, manure, or a similar 'mulch' can protect the surface soil layer against such destruction of the crumb structure. Otherwise the hard crust should be loosened with suitable implements in order to re-establish a granular soil mulch.

Brak (alkali) soils may acquire a very poor structure, or rather, they may become structureless if they are heavily irrigated with pure water and drained afterwards. The reason for this is that the sodium clay deflocculates or changes to the sol condition as soon as the soluble sodium salts are washed out. However, the clay colloids need not be saturated with sodium in order to possess this disadvantage. Even soils in which more than 10–20 per cent. of the cations, absorbed by the clay, consist of sodium tend to become structureless and compact. Some of our arable soils belong to this class by nature and others can be brought into this condition by wrong fertilizing. Chilean saltpetre (sodium nitrate), karoo manure, and karoo ash are fertilizers that contain a high percentage of sodium and therefore they should not be applied in large quantities to soils that are clayey and apt to become very compact.

CRUMB STRUCTURE—ITS IMPORTANCE AND FORMATION

Since about 1930 the study of soil structure has received much attention, especially in Russia and America. This interest in soil structure is partially due to the fact that erodibility is related to structure and that measures which tend to improve soil structure also counteract soil erosion. Absorption of rain and irrigation water by the surface layer of soil and the percolation of this water into deeper layers is greatly enhanced if the soil has a good crumb structure. A crumb structure is also very advantageous to our field crops. Thus we find that for any given texture, moisture, air, and temperature relationships in a soil are the most favourable for plant growth if that soil has a crumb structure. Microbial life, which is so important in soil fertility, flourishes under the above-mentioned conditions and roots spend the least amount of energy in order to penetrate into the soil.

In spite of a great deal of research work since 1930, our scientific knowledge of many aspects of the granulation of soils is still very limited as may be gathered from the following discussion. As already indicated, a soil granule[1] is a small porous mass of soil particles of many different sizes, including humus particles. The more organic matter a soil crumb contains, the more porous and the lighter it is. *How big are these soil crumbs?* Russian research workers consider a diameter of 1–3 mm. ($\frac{1}{25}$–$\frac{1}{8}$ inch) to be the optimum aggregate size for aeration and movement of water.

[1] Soil granule, aggregate, and crumb are all designations for one and the same soil condition.

Others are of the opinion that soil crumbs should be as small as $\frac{1}{4}$ mm. in diameter while others again fix the minimum size at 0·05, i.e. $\frac{1}{20}$ mm.

This uncertainty in connexion with the size of soil crumbs is due to the fact that all the methods of aggregate analysis are still very arbitrary and hence inaccurate. A very important property of the crumb is its stability when subjected to rain or irrigation water and under cultivation. This stability of the soil crumbs is not constant for any specific soil but varies according to climatic and other conditions. A still greater variation in stability is, naturally, found in crumbs of different types of soils. The quantitative ratio and the nature and mutual relationship between the clay and humus colloids that are present in the different crumbs undoubtedly play a very important role in connexion with their stability. However, we do not wish to discuss this theoretical side any further. We would rather discuss the methods which the practical farmer can adopt in order to bring about this favourable structure in his soil. There are at least four measures:

(1) The first measure (and the most important in intensively cultivated soils) that aims at the improvement of soil structure is the addition of lime or lime-containing fertilizers. In this way a predominantly calcium-containing clay is obtained which is more or less a guarantee that the soil will have a crumb structure. Because of our uncertain rainfall crop production is usually of an extensive nature in South Africa with the result that lime applications to improve structure are exceptional. The reason for this is that lime costs money and that yields generally depend to a greater extent on factors other than the improvement of the structure of the soil by applications of lime. Thus only the other measures are usually adopted because they are, in any case, necessary in soil management. Phosphates are usually applied in the form of calcium salts and sometimes they contain a small amount of free lime, as in the case of basic slag and basic superphosphate, and this already helps to a certain extent to enrich soil colloids with calcium. In the case of nitrogenous fertilizers hardly any calcium compounds are used in South Africa. Where soils are apt to deflocculate and become compact, Chilean saltpetre should not be used.

It is nowadays maintained that even if the colloids are in the gel condition that does not necessarily mean that the soil would have a crumb structure. A hydrogen clay can be in a flocculated condition like a calcium clay but it has not the granulating effect of a calcium clay. Hence some research workers are of the opinion that it is the microbiological influence of lime which is responsible for structural improvements.

(2) The application of organic matter (farm manure, green manure, chaff, &c.) is the second procedure by which soil structure may be improved. The influence on soil of organic matter and the humus formed from it is far-reaching and diverse; but in this connexion only the net result will be stressed. Clay soils become more granular, friable, and easier to cultivate and sandy soils become firmer, i.e. they acquire body and a greater water-holding capacity. The structure-improving action of lime on clay takes place sooner and to a greater extent if there is also a quantity of decaying

organic matter in the soil which aids in rendering the lime more soluble, thus accelerating its flocculating effect on soil colloids. On the other hand, the humus formed from the organic matter should also contain enough calcium for the humus to have the desirable effect on the physical condition of the soil. Thus we see that humus and lime act in conjunction with one another in the improvement of soil structure. If coarse plant material such as straw, chaff, shrubs, and green manure is ploughed into clay soil, it temporarily loosens the soil mechanically so that excessive water drains away more easily and the penetration of air into the soil is facilitated. These effects also promote gel formation. However, it should be remembered that such a soil can only be planted to a crop after the rapid stage of decomposition is over and the soil has acquired a normal structure.

Concerning structure improvement by organic matter, the present contention is that viscous and slimy products of microbes as well as fungous mycelium largely aid in uniting fine mineral soil particles to crumbs. Laboratory experiments with different organic substances proved that the sooner the substances decompose in the soil, the sooner is the structure improved but the less lasting is the residual effect. Substances that decompose slowly also act more slowly but they have a more lasting beneficial effect on the structure of the soil, e.g. grain straw.

(3) Tillage will also enhance a crumb structure in the heavier soil types provided the soil has a favourable moisture content. Apparently each soil has a moisture content at which optimum granulation is obtained. On first thought it would appear that tillage must necessarily improve the structure of the soil because the soil is loosened when it is tilled, i.e. ploughed, harrowed, and cultivated. In other words, a certain weight of soil is made to occupy a larger volume than before. However, this effect is transitory because after the first rain the soil reverts to its original condition unless the colloids have, in the meantime, become more stable. Of course, soils are tilled especially to kill weeds, incorporate fertilizers and manure with the soil, and to prepare a good seedbed. If cultivation is carried out at the right time, i.e. when the soil is neither too wet nor too dry, better aeration and an increased microbial activity will be among the results. With applications of manure and green manure this will facilitate the formation of the crumb structure which is actually invisible. Thus soils are not only loosened and a visible, though merely temporary, granulation effected. As yet we have no simple explanation for any direct granulation by implements.

(4) Growing crops can also influence soil structure in a marked degree. It has been known for a long time that in more or less humid regions the soil acquires a very good crumb structure if it is left under grass for several years. Even if it is then ploughed and planted to field crops it retains this structure for a number of years. Recently this effect of growing crops on soil structure has been scientifically investigated and it appears that perennial grasses as well as legumes seem to have the most beneficial influence. Observations in South Africa strengthen this opinion. As yet

we cannot explain definitely why grasses and legumes should have such a beneficial influence on soil structure, but undoubtedly the nature and distribution of the root system, the production of carbon dioxide and probably other secretions of the roots, including the products of decomposition of the dying rootlets, are all factors that play some role in this connexion.

We shall see later when we discuss green manuring and the application of farm manures that in South Africa it is practically impossible to maintain thereby the humus content of arable soils. The only solution is to turn these into perennial pastures for some years. Thus they are 'rested', i.e. not cultivated. In those areas in which maize and winter cereals are grown a rotation system of grass- or dry-land lucerne for 3–4 years, followed by grain or other crops for 4–8 years, should be followed. In other words, annual field crops are rotated with pasture. This practice, together with compulsory contour tillage on all sloping lands, will be of the utmost benefit to soil fertility in South Africa.

PORE SPACE AND WEIGHT OF SOILS

In its natural condition a soil appears to be so compact that even the most observant agriculturalist will find it difficult to believe that only about half, i.e. 50 per cent., of the space occupied by a given amount of soil is filled by solid particles. The remaining half of the soil space is filled by air and water or only air in a very dry soil (see Fig. 1, p. 36). These openings, i.e. the total space in between the solid particles, constitute the pore volume. The soil pores provide passage and 'working space' to water, air, soil microbes, and plant roots and as such the pore space is a very important factor in soil productivity.

From the previous discussion it will be clear that pore space depends, in the first instance, on the structure of the soil. The looser and more granular the structure, the greater will be the pore volume because the space occupied by a certain weight of soil will have increased. Hence the fact that pore space usually decreases as one penetrates deeper into the soil.

The second fact, viz. that the pore volume of a soil increases with an increase in the fineness of the texture, is not so obvious. A clay soil or, even more so, a peaty soil has a much greater pore volume than a sandy soil. In order to realize this we must again refer to Fig. 6, A and C, p. 84. We distinguish between two types of pores in soils: the comparatively large openings, found in between coarse sand grains and true soil crumbs, that are called *non-capillary pores* and the very small *capillary pores* that are only found between individual particles of the soil crumbs and also between very fine soil particles. The second type of pore is almost completely absent in a sandy soil.[1]

It follows, therefore, that a clay soil with a good crumb structure has a

[1] According to v. Nitzsch the following are the sizes and quantitative relations of the pores in a clayey loam:

Non-capillary pores >0·15 mm. = about 10 per cent. of the pore volume.
Capillary pores 0·15–0·008 (?) mm. = about 85 per cent. of the pore volume.
Molecular pores <0·008 (?) mm. = about 5 per cent. of the pore volume.

greater total pore volume than a sandy soil. Of course, the individual pores in a sandy soil are usually larger than even the comparatively large spaces in between the separate crumbs of a clay soil. That is why water and air pass more slowly through a clay soil than through a sandy soil in spite of the greater pore volume of the clay soil, i.e. a clay soil is not as well drained and aerated as a sandy soil. The larger pores are the passages for the rapid movement and removal of water and air and the capillary pores retain water, air, dissolved nutrients, and microbes longer, so that they are actually the seat of chemical and biochemical reactions. The fine capillary roots and the root-hairs of plants also penetrate the capillary pores in order to absorb water and nutrients.

Sandy soils and sandy loams usually have a pore volume of 30–50 per cent. and peaty soils 80–5 per cent. Of course, the pore volume is calculated as a percentage of the total soil volume. The pore volume of one and the same arable soil varies, and although there are scientific methods by which it can be determined in the laboratory the most reliable results are obtained if the pore volume of the soil is determined in its natural condition.

Unfortunately there is no simple direct method by which the pore space of a soil can be determined. Thus the volume (V) of a sample of soil of known dimensions and still having its natural structure is determined and then the volume (v), of the soil particles only, is determined. The difference in volumes should then give us the volume of the space (S) in between the solid particles, i.e. the pore volume.

Thus $S = V - v$.

THE SPECIFIC GRAVITY OF THE SOLID SOIL CONSTITUENTS

In order to calculate the volume of the solid portion of a soil accurately, it is necessary that the specific gravity (S.G.) of the solid particles should be calculated first. This is done as follows:

A pycnometer of known volume, say 50 or 100 c.cm. at 15·5° C., is dried and weighed accurately—weight x, say (a pycnometer is a S.G. bottle). If we wish to determine the volume of the bottle ourselves, it is filled with boiled and cooled distilled water at 15·5° C. (or room temperature) and weighed. The difference in weight between the empty and full bottle also gives its volume because 1 gm. of water = 1 c.cm. The hygroscopic moisture content of an air-dry sample of the soil concerned is determined and a quantity of soil equal to, say, 10 gm. of absolutely dry soil is weighed off. This soil is transferred to the bottle without any loss and the bottle is half filled with distilled water. The pycnometer, without its glass stopper, is now heated gently on wire gauze over a flame in order to expel the air bubbles between the soil particles. Then allow it to cool down to room temperature and fill the bottle up to the neck with boiled and cooled distilled water. The glass stopper is now put on so that a small amount of water runs through the capillary tube in

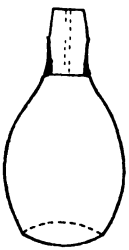


FIG. 7.
Pycnometer.

the stopper. Dry the outside of the pycnometer well with a cloth and weigh it immediately. The weight of the filled pycnometer (P) will consist of the weight of the empty bottle (x), the weight of the soil (10 gm.), and the weight of the water (y). The weights of the empty bottle, the full bottle, and the soil are now known:

$$y = P - (x + 10 \text{ gm.}).$$

The weight of the water (y) in grammes is also equal to the volume of the water in cubic centimetres. This volume deducted from the volume of the pycnometer gives us the volume of 10 gm. of soil. Let us assume this to be 4 c.cm.; then the specific gravity of the solid soil particles

$$= \frac{\text{Weight}}{\text{Volume}} = \frac{10}{4} = 2{\cdot}5.$$

Humus has a specific gravity of about 1·3 and the main mineral constituents of the soil have a specific gravity of about 2·65. Ferruginous minerals are considerably heavier, S.G. 3–5. Ordinary mineral soils containing little humus and iron minerals have a specific gravity of about 2·6. The specific gravity of ferruginous (red) soils will be about 2·8. Peaty soils, on the other hand, have a specific gravity of 1·5–2·0. The specific gravity of humus-deficient mineral soils can also be determined approximately by the following method:

Take a measuring cylinder of, say, 100 c.cm. and fill it with water to, say, 70 c.cm. Weigh off 20 gm. of air-dry soil and pour it slowly into the cylinder. The water rises in the cylinder, let us say, to the 78 c.cm. mark. Thus 20 gm. of soil has a volume of 8 c.cm. (78−70). Thus its specific gravity = 20÷8 = 2·5.

THE VOLUME WEIGHT OF SOILS

Because the solid soil particles only occupy about 50 per cent. of the volume of a soil in its natural state, it follows that the weight of a particular volume of soil (in its dry state) will only be about half of the specific gravity of the solid soil particles. This soil weight, which is much more important for practical purposes than the specific gravity, is called the *volume weight* or, also, the 'apparent specific gravity' of a soil. It may be determined as follows:

A metal cylinder, open at both ends, with a sharp cutting edge at the bottom end and of known volume and length (say 1,000 c.cm. and 15 cm. = 6 inches in length), is carefully driven into the soil until the surface of the soil is level with the top edge of the cylinder. The cylinder is now dug out carefully and with a table knife the soil is cut off level with both ends of the cylinder. The soil from the cylinder is now carefully transferred to a small clean bag and spread out in the laboratory to become air-dry. It is then weighed and mixed well, after which the hygroscopic moisture in a small sample of this soil is determined. The absolute dry weight of the whole sample can now be determined. Assume it to be 1,300 gm. and the

volume of the cylinder to be 1,000 c.cm. The volume weight of the soil will then be $1{,}300 \div 1{,}000 = 1{\cdot}3$.

In stony soil it is very difficult to determine the volume weight. In the case of a pure sand the approximate volume weight can be determined by weighing off, say, 100 gm. of air-dry sand (that contains extremely little hygroscopic moisture), pouring it into a clean dry measuring cylinder, and reading off the volume after having tapped the cylinder slightly on the table to enable the sand to settle.

Ordinary mineral soils have a volume weight of about 1·2–1·5, while true peaty soils have a volume weight of about 0·40. Apart from the specific gravity of the solid particles the structure or pore space of a soil is the most important factor affecting its volume weight. Because clay soils usually have a larger pore space than sandy soils, clay soils are (when dry) lighter than sandy soils.

In practice we use the terms 'heavy' clay soils and 'light' sandy soils but they refer to the ease of cultivation of the soils or the draught that is required when cultivating these soils and not to the actual weight of the soils.

If we know the average volume weight of a soil we can calculate what 1 morgen of soil, 6 or 12 inches deep, will weigh *when it is dry*. One cubic foot of water weighs 62·42 lb. If a soil has a volume weight of 1·40, then a cubic foot of the dry soil will weigh $62{\cdot}42 \times 1{\cdot}40 = 87{\cdot}4$ lb. One morgen of soil, 6 inches deep, has a volume of $300 \times 300 \times 0{\cdot}5 = 45{,}000$ cubic feet. Thus the weight of 1 morgen[1] of soil 6 inches deep would be $45{,}000 \times 87{\cdot}4 = 3{,}933{,}000$ lb. or roughly 4 million lb., i.e. 2,000 tons. A sandy soil will weigh more than 4 million lb. and a clay soil will weigh less, but for an ordinary sandy loam the above-mentioned figure will probably be very close to the actual weight. In any case, it is a figure which we may use if we wish to have a better idea of the amount of plant food or water that a morgen of soil, 6 inches deep, contains. Let us assume that a soil contains 0·005 per cent. of available phosphoric oxide. To the ordinary farmer this figure has no meaning. In actual weight for a morgen 6 inches deep, this comes to 200 lb. of phosphoric oxide, which gives us a much better indication of the fertility of the soil. If a soil contains 10 per cent. of moisture it means that a morgen of soil, 6 inches deep, contains 400,000 lb. or 40,000 gallons of water which is equal to about 1 morgen inch of rain.

Finally, to return to the calculation of the *pore volume* of soils. If we know the volume weight of a certain soil as well as the specific gravity of its solid particles, the pore volume of the soil may be calculated with the help of the following equation:

$$\text{Percentage pore volume} = 100 - \left(\frac{\text{Volume weight}}{\text{Specific gravity}} \times \frac{100}{1}\right).$$

Thus, if a soil has a volume weight of 1·4 and a specific gravity of 2·6, its pore volume works out to 46·2 per cent.

[1] An acre of soil 6⅔ inches deep is considered to weigh about 2 million lb.

CHAPTER XIII

WATER RELATIONSHIPS OF SOILS

THE behaviour of water in soils is not a very simple matter because there are so many varying factors that influence it. For a long time it has been customary to distinguish between *three forms* of soil water, and to begin with we shall abide by this classification.

If we spread out some soil in the laboratory or in any dry place and allow it to become 'air-dry', i.e. until its weight remains constant, we shall find that the sample still contains moisture. This moisture which is still present in a soil sample that is apparently perfectly dry is called *hygroscopic moisture.* Its presence may be proved in the following manner:

Take a long test-tube and put a teaspoonful of air-dry soil in it. Heat the soil gently over a weak flame. Drops of moisture will condense on the cold top part of the test-tube. The hygroscopic moisture can be calculated accurately by heating about 10 gm. of air-dry soil in a suitable crucible or glass bottle in an air oven, at 105° C., for about 6 hours. After cooling in a desiccator the soil is weighed again and from the loss in weight the hygroscopic moisture can be determined. A substance is usually called hygroscopic if it absorbs water vapour from the air and thereby becomes moist. Chilean saltpetre and especially calcium nitrate are hygroscopic, with the result that these fertilizers become moist and form lumps when the air is moist. Any substance that is comparatively fine absorbs moisture from the air or, rather, vapour condenses on its surface. The finer the particles are, the larger is the specific surface of the substance and the greater is the amount of moisture that can condense on its surface although the substance itself may appear to remain 'bone-dry'. Because colloids have an enormous specific surface (see p. 77), soils that contain a high percentage of colloidal material such as clay and humus usually contain a considerable amount of hygroscopic moisture. Sandy soils contain less than 1 per cent. of hygroscopic moisture, loams and clay soils 1–5 per cent., and peaty soils may contain as much as 20 per cent. of hygroscopic moisture when they are 'perfectly' dry.

As can readily be understood, this form of soil moisture is valueless to plants because it exists in an exceedingly thin film round the soil particles and they retain it with a force that exceeds the force which roots can exert in an attempt to remove this moisture from the particles.

If we add about 20 c.cm. of water slowly to about 20 gm. of air-dry soil in a funnel with filter-paper, or plugged with a piece of cotton-wool, the soil will naturally become wet, and it will not be able to retain all the moisture. A portion of the water will percolate through and may be caught up in a glass beaker. The same thing happens during continuous rains. The water retained by the moist soil is called *capillary water* and the excess water which the soil cannot retain and which percolates into the deeper soil layers is called *gravitational water* or free water. Gravitational water

is influenced by the force of gravity of the earth and capillary water is retained in the network of interstices or pores against the pull of gravity. Thus the capillary moisture is retained by, and moves in, the capillary pores of the soil while the gravitational water moves downwards and laterally in non-capillary pores and passages (compare p. 89 and diagram on p. 84). A sandy soil has relatively few capillary pores and thus it also has a low water-holding capacity. Loams and clay soils with a granular structure have innumerable capillary pores in the soil crumbs—as well as larger pores in between the soil crumbs. Capillary water is mostly found in these capillary pores and the larger non-capillary pores provide channels through which gravitational water can percolate downwards.

When rain falls on a dry soil the water moves downwards through the larger pores, whence it is absorbed into the smaller pores just as a sponge absorbs water. Thus gravitational water very soon changes to capillary water in such a soil.

In wet areas and in marshy places we find standing water in the deeper soil layers. This water is called *ground water*, and below the *water table* all soil pores and passages, whether large or small, are filled with water. In such a soil layer capillary water and gravitational water exist together for the time being.

In connexion with the capillary water we differentiate between two zones in which it may occur. Firstly, there is the capillary water in a well-drained moist soil in which the water table may be 10–20 or more feet below the surface of the soil. This is the usual state of affairs in most of the arable soils in South Africa, in any case during the largest part of the year. Although it is not a very good name we shall call this capillary water, which is in no way connected with a possible water table, the *apparent capillary water*. Research workers subdivide this water and give the subdivisions names such as funicular, pendular, and film moisture.

If we press the convex sides of two watch glasses against one another and pour water over them, a small amount of water will remain around the point of contact. Similarly pendular or 'hanging' water remains suspended from the points of contact of soil particles. If we press two or more glass rods against one another and submerge them in (coloured) water we will find that a thin 'cord' of water remains along the edges, where the rods touch one another, when the rods are removed from the water; hence the name funicular water. When the soil receives more moisture than is necessary to form only pendular water, the interstitial water between the different soil particles joins and funicular water is formed although it is not in 'straight cords' as is the case between the glass rods. It may twist in all directions. Finally, the very fine capillary pores in the soil may be completely filled with water, in which condition the moisture is truly 'capillary'.

In soils there is such a diverse arrangement of large and small particles, i.e. there is such a network of pores of all sizes linked together by larger openings, that it is easily understood that capillary water may exist in many

different forms. The moisture is retained by surface forces, mainly surface tension. The stronger the surface tension, the greater is the force with which the water is retained and the stronger the suction pressure for other moisture in the immediate vicinity.

An important point in connexion with a moist soil that is saturated with 'apparent' capillary water is that the larger soil pores and channels are filled with air so that the capillary moisture and the hygroscopic moisture would occupy, say, 75 per cent. of the total pore space of the soil, and air the remaining 25 per cent.

The second zone in which capillary moisture is found is the few feet of soil immediately above a water table. Thus, where free water is met with a few feet below the soil surface we have a zone of *true capillary water* somewhat similar to that demonstrated in physics by standing capillary tubes on their ends in a basin of water. We then find that the water rises in the capillary tubes. The thinner the tube, the higher will the water rise. With soil this phenomenon may be demonstrated by a similar experiment. Place a quantity of air-dry soil in a long glass tube about three-quarters of an inch in diameter. Cover the end with a piece of linen, and suspend the tube with this end in a shallow basin of water. The water will then rise in the dry soil. The finer the soil the higher will the capillary moisture rise, but the slower will be the upward movement of the moisture.

In the soil there are no long thin tubes—this is an obsolete idea—but actually a series of connected interstices or pores. Immediately above the water table all the soil pores are filled with water and only the larger spaces and passages contain air. The farther the distance from the water table the greater the percentage of air in the larger pores, with the result that the total moisture content decreases until, finally, only pendular and film water exist and only the very smallest soil pores are filled with 'capillary' water. This true capillary water should be able to rise a considerable distance above the water table, especially in clayey soils, but in practice the distance is not far. According to Keen (England) the actual capillary zone in soils is only a few feet above the water table, viz. about 14 inches in the case of coarse sand, in the case of fine sand about 28 inches, and in a clayey loam about 32 inches. Above this height movement takes place so slowly that it is of no practical importance.

THE WATER CAPACITY OF SOILS

By the term water capacity or water-holding capacity of a soil is meant that amount of moisture (apart from the hygroscopic moisture) which a specific weight or volume of soil can retain against the force of gravity. In other words it means the amount of capillary moisture that a soil can retain if sufficient provision exists for the drainage of any gravitational water.

The water capacity of a soil may be determined in the laboratory by the following method:

Take a wide metal cylinder with a perforated bottom—a round cigarette

tin with holes in the bottom will also do—and place a piece of cheese-cloth across the perforated bottom inside the tin. Now weigh the cylinder. Then fill it almost to the top with air-dry soil. Tap it gently on the table so that the soil can settle somewhat. Now weigh again. The weight of the soil is thus known and its volume can also be calculated if necessary.

One may then proceed according to either of the following methods:

(1) Pour water carefully on the soil until it begins to trickle through the perforations. Then place the cylinder on a suitable rest under a bell-jar or in any other confined space that is saturated with water vapour, i.e. where there is a little free water present on the bottom. The gravitational water, still contained in the soil, will now percolate through the gauze and after about 24 hours the cylinder may be removed and weighed. The percentage of moisture retained by the soil, i.e. its water capacity, is calculated from the increase in weight.

(2) Place the cylinder containing the air-dry soil in a shallow basin with about half an inch of water. The water will rise in the soil through the perforated end. As soon as the surface of the soil is moist, pour out nearly all the water from the basin. Cover the cylinder with a bell-jar and leave for 24 hours. Then weigh and calculate the amount of capillary moisture. In spite of all precautions, the lower portion of the soil in the cylinder always contains more moisture than the upper portion.

This shows that the determination of the water capacity of a soil in the laboratory does not give us an accurate indication of the amount of moisture that the same soil in the field will retain in its natural structure. The artificial determination is always higher than the actual water capacity that is to-day known as the *field water capacity*—or just *field capacity*. For example, the second method described above gives the water capacity of the soil in a certain orchard at Stellenbosch as 28 per cent., and yet repeated determinations in the orchard itself after good rains show it to be 16–17 per cent.

The field water capacity can be determined on the piece of ground concerned two to three days after a soaking rain of a few inches or a heavy irrigation. It is preferable that there should be no plant growth on the soil. Different samples of the moist soil are taken to a certain depth and weighed and dried in an air oven at 105° C., or the soil can first be spread out until it is air-dry, weighed, and the hygroscopic moisture then determined in a sample of the air-dry soil. In this way the average water-holding capacity under field conditions can be determined. Because the first few inches of soil quickly lose water by evaporation, the first 3 inches or even the first 6 inches in the case of orchard soils may be discarded, and the water-holding capacity of the pervious layers below 3 or 6 inches determined.

The water capacity may be calculated on the weight of absolutely dry soil or, better still, on the volume of soil. For the latter calculation it is necessary that we should know the volume weight of the soil unless the samples were so taken that they constituted a certain known volume. Assume the water capacity calculated on the weight to be 16 per cent. and

the volume weight of the soil to be 1·5. Then the water capacity calculated on the volume will be $16 \times 1{\cdot}5 = 24$ per cent.

The first and most important factor determining the water capacity of a soil is its texture, including its humus content. The more of the finer particles such as silt, clay, and humus a soil contains, the higher will be its water capacity. The reason for this is clear because with fine soil particles there are innumerable points of contact and capillary pores with the result that the soil can retain a large quantity of capillary water. Sandy soils contain relatively few capillary pores so that a high humus content in such soils is very important, because humus supplies the fine material with beneficial effects on water capacity.

A second, but less important, factor also influencing water capacity is the soil structure. With an increase in the pore volume of a soil the water capacity also increases up to a certain point, after which it decreases with an increase in pore volume because the soil then contains too high a percentage of non-capillary pores. Because a soil with a crumb structure has a greater pore volume than the same weight of soil with a single-grain structure, the soil with the crumb structure will have a higher water capacity. In a soil with a single-grain structure, gravitational water moves very slowly because there are so few of the larger soil pores. Thus it may appear as if such a soil has a higher water capacity. However, on account of its waterlogged condition such a soil is unsuitable for plant roots because they cannot breathe normally.

The water capacity of a soil is not a constant figure because the soil structure is subject to changes, and this also affects the water capacity. Apart from this, a portion of the capillary moisture is still subject to the pull of gravity, with the result that the water content of a particular soil layer (from which no water is lost through evaporation or used by plant roots) will decrease *slowly* when the downward movement of water can take place unhindered.

THE MOVEMENT OF SOIL MOISTURE

Hygroscopic moisture in soils can only move in the vapour form, viz. when a soil is subjected to temperature changes and changes in the humidity of the atmosphere. Gravitational water moves in the liquid form and normally this only takes place downwards or sidewards through the larger soil pores and channels under the force of gravity and under pressure from water in the upper soil layers.

The movement of capillary moisture is considerably more complicated and here it is necessary to treat separately the two soil zones in which capillary moisture may occur, as explained on pp. 93–9. The capillary moisture found in well-drained soils with a very deep water table moves in liquid form but so slowly that it can be neglected for practical purposes. The movement can theoretically take place in all directions from moist to drier zones, but in practice movement is chiefly downwards and where irrigation in furrows is practised it also takes place sidewards to a lesser extent.

A few days after a soaking rain has fallen or after a soil has been heavily irrigated the soil is usually saturated (to a certain depth) to its field capacity with capillary water. If the soil had previously been dry to a great depth as a result of water consumption by plants and rain moistened the soil, say, to a depth of 15 inches to its field capacity, then the soil layers below 15 inches would, practically speaking, remain dry. According to Rotmistroff (Russia) capillary moisture moves downwards in a dry soil with a speed of only 4–6 inches per month in the case of loamy soils.

With fine weather the surface soil will begin to dry out immediately after wetting, because capillary water will evaporate into the atmosphere which has a lower vapour pressure. As the moisture content of the surface soil decreases, the surface tension and thus the suction pressure of the remaining capillary moisture increases, and in order to establish an equilibrium water is drawn from the deeper layers where the moisture content is higher, and at the surface further evaporation would take place. Thus, it is said, the deeper soil layers become drier and drier. Actually such an upward movement of capillary moisture in *liquid form* hardly occurs at all. The first half-inch or so of the soil quickly loses its water by evaporation because it is directly in contact with the drier air. But the loss of moisture from the deeper soil layers also takes place as a result of evaporation because the moist soil air is constantly exchanged for the atmospheric air, mainly as a result of variation in temperature and air pressure and on account of diffusion (see next chapter). In this way capillary moisture is continually evaporating if the air in the soil pores is not 100 per cent. saturated with moisture. In the top 4–6 inches this exchange of water vapour takes place comparatively rapidly so that this layer of soil can lose all its capillary moisture within a week or so if warm, windy, dry weather prevails. Deeper down in the soil exchange of air is slower so that it takes considerably longer before the second 6 inches of soil is dried out, and in the case of soil layers below 12 inches hardly any moisture is lost through evaporation provided the soil does not crack on drying out.

The second cause for the decrease of capillary moisture is its absorption by plant roots. Formerly the view prevailed that when plant roots absorbed moisture from their immediate surroundings, then moisture would move from more moist areas to the root zone where the water was being used up, on account of the higher surface tension of the remaining moisture. This movement of capillary moisture from moist to less moist areas is at the best of times so slow that it may practically be discarded. That it does take place to a limited extent is proved by the fact that plants that were temporarily wilted during the day-time recover at night when transpiration is lower and time has been allowed for capillary water to move to the roots. However, the general opinion to-day is that plant roots must grow to the moister areas in order to get enough moisture and that movement of capillary moisture is of little practical value. In other words, the plant roots must 'graze' the soil in search of water.

Capillary moisture which is in contact with the water table moves much

faster in the capillary zone than the apparent capillary water, and in the supply of water to plants it can be of great importance under certain circumstances. However, here also the speed with which the water moves depends on the position of the moisture in the capillary zone. The shorter the distance from the water table, the faster will the movement of the water be to a spot from which it is being removed by plant roots and vice versa. The reason for this is that the nearer the soil layer concerned is to the ground water, the larger are the pores that are still filled with water, with the result that the capillary water in its movement encounters little resistance from friction. In the top layer of the capillary zone there is almost only pendular water and that moves very slowly.

Therefore as long as the water table does not sink too low, and as long as a considerable portion of the roots is in the capillary zone and fairly close to the water table, plants will be well supplied with water as stated above. Keen found that the capillary zone in which water moves fast enough is only a few feet in depth. Thus the water table has to be fairly near the surface to be of any value. This condition is typical of the pastures of Holland where the ground water is only a few feet from the surface. Also in some low-lying orchards in the Western Province, e.g. in Banhoek, the water table is only 3–6 feet below the surface during the summer months. In such soils fruit-trees can easily stand the dry summers. Naturally such soils should be well drained to prevent the root system from dying on account of a too high water table in the rainy season. In our arable soils the water table is, as a rule, so deep down that it is of no practical value in supplying water to agricultural crops.

THE AVAILABLE SOIL MOISTURE

Plants cannot absorb hygroscopic moisture. They can make use of gravitational water, but there are two reasons why gravitational water as such is not the direct source of water for agricultural crops. In well-drained soils gravitational water moves downwards comparatively rapidly through the larger soil pores and channels so that it does not exist for long after rain or irrigation. It either changes very quickly to capillary water or it drains beyond the reach of the plant roots. In badly drained soils, roots may find themselves temporarily in gravitational water and then, of course, they will absorb it. As a result of respiration of living roots the oxygen dissolved in the water will soon be used up and the roots will die unless the gravitational water drains away. In other words, agricultural crops cannot tolerate stagnant water for long and such water is as effective a barrier to the elongation of roots as is a compact rock formation.

There remains the capillary moisture which may occur in the two zones that have already been described. Actually it is the only form of soil water that plants normally absorb. We have just discussed the availability of the moisture in the capillary zone immediately above the water table and we also mentioned that this condition is exceptional in the agricultural soils of South Africa. Of much greater importance is the absorption of soil moisture

that has no contact with the free ground water and this we shall now discuss.

We find that agricultural crops wilt permanently when the soil layer in the root zone usually still contains considerably more than only hygroscopic moisture. In other words, all the so-called capillary moisture is not available to plants. The name 'dead water' has been given to this unavailable moisture which consists of the hygroscopic moisture and a portion of the capillary moisture. It is not yet possible to define the capillary portion of the dead water accurately, but undoubtedly a part of the pendular water and the capillary moisture that is found in the very minute soil pores belong to it. Such moisture is subject to a very high surface tension and the minutest soil pores have a much smaller diameter than the finest roots and root-hairs so that these roots cannot reach the water. It also appears as if the larger portion of the unavailable capillary moisture belongs to the so-called water of imbibition. We saw that colloidal gels absorb water and expand when moistened and that they lose water and shrink on drying out. It has been ascertained that in ordinary soils (saline soils excluded) the amount of water that is necessary for the 'softening' and expansion of the dried-out colloids corresponds more or less with the amount of capillary moisture that the soil still contains when the plants wilt permanently.

The separate colloids do not all need the same amount of imbibition water. Humus colloids need the most, then follows the 'clay' of the silicate complex, while colloids of iron and aluminium hydrates hardly need any water of imbibition. Furthermore, the amount of imbibition water (and also the amount of hygroscopic moisture) depends on the kind of cations with which the colloids are chiefly saturated. In this respect sodium is undesirable from an agricultural point of view. When the clay portion of a brak soil is saturated with sodium cations it needs an excessive amount of imbibition water. If, in addition to this, the brak soil contains a quantity of soluble sodium salts, the situation is aggravated, and the amount of dead water may rise to 40 per cent. of the weight of the soil. True peaty soils may contain up to 100 per cent. unavailable moisture. Naturally, ordinary sandy soils need very little imbibition water and therefore practically all their capillary moisture is available to plants.

The reason why 'dead' water is not available to plants is because the force with which soil particles retain it is greater than the suction pressure exerted by roots. However, the suction pressure of the roots of different crops varies (neither is it constant for one and the same crop) and is equal to 5–15 atmospheres. Usually the suction pressure is close to the former figure. The hygroscopic moisture in ordinary air-dry soils is retained with a force that is equal to about 100 atmospheres.

For practical purposes it is necessary to know the approximate critical percentage or, as it is usually called, the *wilting-point* in the root zone of the soil type concerned. Secondly we must know the field water capacity of that root zone. The amount of water between these two percentages would then be the amount of moisture that is available to plants.

The determination of the field capacity has already been discussed on p. 95. The wilting-point of a soil may be determined in the field when, in the later stages of its vegetative growth, the crop covers the soil and when the plants show distinct signs of wilting also in the morning (with no dew!).

Various soil samples are then taken from the zone in which most of the roots grow. In the case of annual crops this will most likely be the soil layer from 4 to 18 inches, and in the case of perennial crops (e.g. fruit-trees) from 7 to 24 inches. The soil samples are taken to a laboratory without any loss of moisture and the total moisture content is determined in an air oven at 105–110° C. The average figure is then taken to be the wilting-point of that soil. Provided the roots are well spread throughout that soil layer it will be found that the wilting-point determined in this way will be fairly constant for that soil irrespective of the kind of crop that is grown in it. So American research workers maintain. Rotmistroff, who did very accurate soil moisture research work since 1887, on the experimental fields at Odessa, Russia, but whose findings remained rather unknown in Western Europe and America, found, for example, that potatoes do not use the moisture in their root zone to the same extent as maize and winter cereals. After a potato crop the first few feet of soil still have about 2 per cent. more moisture than after these cereals. His explanation is that potatoes have not as dense a root system as the cereals. This observation again stresses the fact that plant roots must grow towards the moist soil and that the capillary moisture does not move easily to the roots where the soil is drier.

The depth of the root system and the amount of fibrous roots per unit volume of soil (the root density) mainly decide the wilting-point in the soil layer concerned, and that is the reason why the wilting-point of a certain crop does not necessarily coincide with the amount of 'dead' water in that layer. Thus unavailable soil moisture and 'dead' water need not be identical. The moisture may be unavailable for the simple reason that there are no roots in contact with it. Thus we must imagine wet and dry spots to exist in that part of the root zone where the roots are not very dense, with the result that plants wilt because transpiration is faster than the growth of roots to the moist areas and the movement of capillary moisture from moist to dry areas. Because soil is taken from the dry as well as the moist spots when taking samples to determine the wilting-point we find that the moisture content, when permanent wilting has set in, is actually higher than the amount of 'dead' water.

The cereals utilize soil water best on account of their dense root system while dicotyledonous plants, such as potatoes and fruit-trees, have a higher wilting-point on the same soil for the reason mentioned previously. The density of the root system, especially in the case of the latter plants, also decreases as the roots penetrate deeper into the soil. The result is that the wilting-point increases deeper down in the soil provided the soil texture remains the same throughout the whole root zone.

A second factor influencing the wilting-point is the rate of transpiration.

In the case of prevailing dry, warm, windy weather the wilting-point in the same soil under the same crop will be higher than on cool windless days. Because water consumption per day is so much less in the latter case, the fibrous roots have a better opportunity for utilizing the moisture and possibly the movement of capillary moisture towards drier areas also has some effect.

Thus the moisture content of a certain soil type at wilting-point is not a constant figure. Therefore the artificial determination of the wilting-point by growing plants in a confined space, e.g. in glass jars, in pots, or in iron drums, until they wilt permanently can only give us an approximate figure. The determination for a certain crop is best done with the soil in its natural structure and the root system in its natural distribution, and even then the determination will be affected by weather conditions. Soil sampling for the determination of the wilting-point as well as the field capacity is best done with the Veihmeyer soil-tubes.

The wilting-point (moisture equivalent) can also be determined approximately by laboratory methods, without plants, but because school laboratories do not possess the necessary apparatus, we will not discuss it here.

An approximate figure for the wilting-point as well as the field capacity of a particular soil to a certain depth is of great practical value in dry land, as well as in irrigation farming. The available moisture may be calculated from this, and if we possess more accurate data about the water consumption of different crops under different conditions, it would be possible to tell approximately for what period the water-supply will be sufficient. The amount of rain or irrigation water in inches that is necessary to moisten a soil effectively to a certain depth can also be calculated. If the soil layers are not quite as dry as the wilting-point about 1 *inch of rain or irrigation water* is required to moisten a soil layer 1 *foot deep* to its field water capacity. In the case of clayey soils this figure is slightly higher and in the case of sandy soils it is less than 1 inch. In the chapters on dry-land farming and on irrigation the above critical moisture margins will be discussed further. See also water relations in orchard soils, p. 274.

Another point of importance is whether the moisture content between the wilting-point and the field capacity is equally available to plants. In the past it was believed that every soil has an optimum moisture content at which agricultural crops grow best. This was supposed to be at a moisture content representing about 75 per cent. of the maximum water capacity. According to Veihmeyer, plants transpire the same amount of water whether the soil is saturated to its field capacity or whether the moisture content is near the wilting-point, in other words, the soil moisture is equally available at any point between these two margins. However, there seem to be sufficient observations for this statement to appear doubtful. In soils that are continually saturated to their field capacity the exchange of soil air is not very satisfactory and some plants, at least, are very sensitive to a high concentration of carbon dioxide in the soil air. Other research

workers, again, found that in such soils plants use water extravagantly; in other words, transpiration is higher.

When soils are dried out almost to the wilting-point, say 2 per cent. above it in the case of sandy loams, the position is more serious. Under such conditions plants no longer obtain enough moisture and on hot days they may become temporarily wilted which causes a decrease in plant production. From the data of different research workers it appears that after 80 per cent. of the available moisture has been used, plants suffer as a result of water deficiency unless the weather is cool and windless. Therefore, where irrigation is possible one should not wait until plants are permanently wilted before irrigating but soils should be irrigated at the first signs of temporary wilting. With practice it becomes easy to notice such changes. The following table gives the mechanical composition and the critical margins of moisture content as they have been determined in practice.

TABLE 10

	No. 1 Sandy loam, Pear Orchard, Stellenbosch	*No. 2 Sandy soil, Vineyard, Paarl*	*No. 3 Sandy loam, Orange Grove, Nelspruit, Tvl.*	*No. 4 Loamy sand, Orange Grove, Nelspruit, Tvl.*
	%	%	%	%
Coarse sand	44·6	62·2	37·7	62·0
Fine sand	26·5	34·4	25·4	21·0
Silt	10·3	4·4	2·9	3·9
Clay	18 0		30 6	11·2
Hygroscopic moisture	1·33	..	1·0	0·5
Loss on ignition	3·24	0·04	4·8	1·9
Field water capacity	14·56	4 1	18·0	11·0
Wilting-point	5·30	2·2	11·25	4·25
Available moisture calculated on weight	9·26	1 9	6·75	6·75
Available moisture calculated on volume	14·44	2 85	9 24	9·85

From the table it is evident how the field capacity is in the first instance influenced by the soil texture. Soil no. 3 with the highest clay content also has the highest water capacity, while no. 2 with very little clay (and humus) has a very low water capacity. On the other hand, however, soil no. 3 has not the highest amount of available moisture. Soil no. 1 has the most available moisture and even no. 4 slightly exceeds no. 3 because the moisture content calculated on the volume is a truer reflection of water-supply. The above soils all represent the second foot of soil where the roots are well distributed and where the available moisture content (in orchards) can be determined most accurately.

LOSS OF WATER FROM SOILS

Apart from the consumption of soil moisture by growing plants, water can only be lost from the root zones of soils in two ways, viz. by evaporation at the surface and by drainage to deeper levels.

Evaporation of water from the soil depends in the first instance on the prevailing climate, especially on the humidity of the air, on temperature, and on winds. The drier the air, the higher the average temperatures, and the more windy the locality, the more moisture will be lost from soils through evaporation. These are general factors which we cannot influence to any great extent except that drying out of soil by wind can in some cases be minimized somewhat by wind breaks, either high or low. More water also evaporates from bare surfaces than from soils that are covered with plant growth. Plants protect soil from the desiccating effect of winds and lower the maximum soil temperatures. Finally, the aspect of the land is also important. Level fields and fields with a northern, north-eastern, or north-western aspect heat up readily and will lose more moisture through evaporation than soils on southern slopes (Southern Hemisphere).

The effect of a loose surface layer of soil, i.e. a *soil mulch*, on the rate of evaporation from deeper soil layers will be discussed in detail in the chapter on dry-land farming (p. 128).

The second way in which moisture can be lost from the topsoil is by percolation of gravitational water to deeper layers. Naturally this only happens during continuous rains or after heavy irrigations on well-drained soils when the water-supply is in excess of the amount of water the soil can retain. Sandy soils have the lowest water capacity and by application of organic matter (farm manure, green manure, and other plant residues) one should constantly endeavour to improve it. Apart from the fact that we can ill afford to let any water go to waste in a country like South Africa with its dry seasons, a further disadvantage of this percolation is that plant nutrients are usually leached out of the soil and the soil becomes more acid. In acid, sandy soils the humus can also be leached out as the dark-brown river-waters of George, Knysna, Elgin, &c., so clearly prove.

Generally speaking, only slight leaching occurs in South African soils on account of the low rainfall. Even in areas with a high rainfall only the sandy soil types are particularly subject to leaching. The percolation and the accompanying loss in plant nutrients can be determined with lysimeters. Accurate data in connexion with this have thus far been obtained only on the University farm, Pretoria. The lysimeters are 4–4½ feet deep and contain the typical red loam which is fairly common in the summer rainfall area. The experiments have been going on since 1932, and it has been found that if a crop is growing on the soil absolutely no water percolates through it during the (summer) rainy season. Only at one time, from November 1933 to January 1934, when an exceptionally high rainfall of 26·42 inches was registered, 2·2 inches of the water percolated through, and even this might not have happened had the plants been in a more

advanced stage. However, when the soil lies fallow during the rainy season and has no plant growth on it, percolation is considerable, viz. 4·03 inches in 1934/5 and 4·31 inches in 1935/6. The annual rainfall was 19·07 and 32·5 inches respectively. The loss of nitrates from the 4½-foot soil layer calculated per morgen, in terms of sodium nitrate, was 1,667 and 1,806 lb. respectively; a terrific amount. The nitrate is of course not leached out as sodium nitrate but chiefly as calcium nitrate and magnesium nitrate. There was only a very small amount of potash and no phosphate in the drainage.

CHAPTER XIV

SOIL AIR

AIR is a normal and essential constituent of arable soil. In Chapter XII we have already pointed out that only about 50 per cent. of a certain volume of soil consists of solid particles. The remainder, the so-called pore volume, is filled with water and air. The wetter a soil, the smaller the amount of air it contains and vice versa. Thus air space = pore volume—space occupied by soil moisture. As long as the soil is not waterlogged, i.e. as long as the larger soil pores are not filled with water, there will usually be no shortage of air in the soil. Ordinary moist soil still contains more than 10 per cent. of free air (calculated on the total soil volume).

COMPOSITION OF SOIL AIR

The following figures give the average composition of dry soil air and of dry atmospheric air, expressed in volume percentages:

	Soil air	*Atmospheric air*
	%	%
Oxygen	20·0	20·95
Nitrogen (and Argon) . .	79·1	79·02
Carbon dioxide . . .	0·3–1·0	0·03

Thus there is no great difference between the two except that the soil air contains at least ten times as much carbon dioxide as the atmospheric air. However, the content of carbon dioxide in the soil air is not nearly as constant as in the atmosphere. In soils that are very dry it can be almost as low as in the free atmosphere and in moist soils to which farm manure or green manure have been added shortly before, the carbon dioxide content may possibly rise to 10 per cent.

The carbon dioxide in the soil air is the product of respiration of living organisms, viz. soil micro-organisms and plant roots. In a fertile soil the soil microbes are more important producers of carbon dioxide than the roots of agricultural crops. The tremendous amount of carbon dioxide that soil microbes can produce can be realized if we consider, by way of comparison, that the root system of a wheat crop on a morgen of land may exhale up to 10,000 lb. of carbon dioxide during its period of growth.

The various conditions affecting the activity of the soil microbes are indirectly the cause of the fluctuating content of carbon dioxide in soil air in so far as such microbes are responsible for its production. Such conditions are, especially, the moisture content (and sometimes also the air content) of soils, the amount of organic matter that provides the energy (fuel) for the microbes and the soil reaction, i.e. the acidity or alkalinity of the soil. In general, the greater the production of carbon dioxide in the soil, within a certain time-limit, the greater also is the fertility of the soil.

There is a second difference between the soil air and the atmospheric air. The soil air is usually more or less saturated with water vapour unless the soil is dried out to a very great depth. As a result of the very high humidity

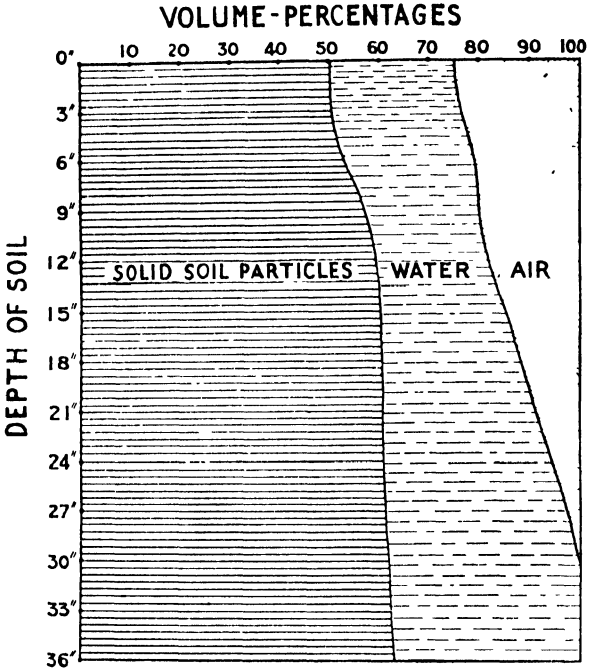


FIG. 8. Diagrammatic representation of the ratios of water and air at increasing soil depths. It is assumed that ground water occurs at a depth of 30 inches.

of the soil air, plant roots can remain alive even in a fairly dry soil. However, the air in the first 3–6-inch layer of soil, which is especially subject to exchange with atmospheric air, can become so dry during the dry summer months (Western Cape Province) that the sensitive roots of fruit-trees and the microbes in that soil layer die off or turn into a passive state respectively.

THE IMPORTANCE OF THE SOIL GASES

The nitrogen in the soil air has the same main function as the nitrogen in the atmosphere, viz. to act as a diluent for the other gases. It is only of direct importance as regards plant nutrition in that certain soil bacteria—the so-called nitrogen-fixing bacteria—can utilize the free nitrogen and manufacture nitrogen compounds from it which later become available to higher plants. Because these bacteria live in the soil moisture or in the roots, it is the dissolved nitrogen that they use. The gases, oxygen and carbon dioxide, are also partly soluble in water. One litre (1,000 c.cm.) of water at normal atmospheric pressure and at about 18° C. will dissolve

about 12·7 c.cm. (0·0147 gm.) of nitrogen and 6·6 c.cm. (0·0087 gm.) of oxygen from the air. The amount of carbon dioxide that will dissolve in water is in direct proportion to the carbon dioxide concentration in the air and, as we have seen, there are wide variations in the concentration of carbon dioxide in the soil air. If the soil air contains 0·3 per cent. of carbon dioxide, 1 litre of soil moisture at 18° C. will dissolve 2·99 c.cm. (0·0054 gm.) of carbon dioxide.

The oxygen in the soil is especially necessary for the respiration of plant roots and of those soil microbes (aerobic) that cannot live without oxygen. The formation of root-hairs is said to be largely dependent on the presence of sufficient oxygen. If the soil did not contain oxygen (water-logged soils) the organic matter would acidify and turn into peaty substances and the mineral nutrients would not be in a suitable form for agricultural crops. In this way, for example, sulphides will be formed from sulphates, and they are toxic to plants. Finally, salt absorption by plants is not possible without root respiration.

The carbon dioxide which is always, like the other gases, partially dissolved in the soil moisture can combine with water to form the chemical compound carbonic acid:

$$CO_2 + H_2O = H_2CO_3.$$

Carbon dioxide and Water give Carbonic acid.

Although carbonic acid is a very weak acid it renders the insoluble mineral plant food reserves more soluble and hence more available to plants. In this way the phosphate reserve becomes more available and calcium compounds are changed to soluble bicarbonates which keep the soil colloids in the gel condition, thus aiding the maintenance of a crumb structure in the soil. However, most of the carbon dioxide that is formed in the soil escapes from it and may be important in the carbon assimilation of our agricultural crops (compare p. 14).

SOIL AERATION

Winds bring about a continual mixing of the air above the soil. In the soil there are no air currents and yet the soil air is continually replaced by fresh air. How does this happen?

Previously soil workers were of the opinion that variations in atmospheric pressure and temperature, the movement of free water in soils (after rain or irrigation), and gusts of wind were chiefly responsible for the interchanging of soil air and atmospheric air. However, to-day it is considered that the aeration of soils is mainly due to diffusion.

What do we understand by the diffusion of gases? Any gas has the characteristic property that its molecules are in constant movement (kinetic movement) and if a small amount of gas is released in a confined space the gas molecules will soon be distributed evenly throughout that space. To express it differently, the gas concentration in that space will soon be the same throughout. If we were to cut out the bottom of a paraffin-tin and

solder it on to another similar tin with a number of small holes in the bottom so that the common bottom is perforated, and release some carbon dioxide in one tin, through a hole which is closed again, and leave the 'apparatus' to itself, the carbon dioxide would not only spread evenly throughout the tin in which it was released but it would also spread into the next tin through the perforated partition. This phenomenon can easily be proved by suitable experiments. This movement of gases through small openings or pores is called diffusion. The primary cause for this movement of a gas from one locality to another is the tendency of any gas to fill evenly the space at its disposal so that the *concentration will be the same throughout.*

Because the soil air usually contains considerably more carbon dioxide than the atmosphere there will be a continual flow or diffusion of carbon dioxide from the soil to the free atmosphere. On the other hand, the atmosphere contains slightly more oxygen than the soil air, where it is used by living organisms, and thus oxygen will continually penetrate into the soil. The exchange takes place through the larger soil pores. In this way, then, the aeration or ventilation of soils takes place. A very good expression for the exchange of soil gases is 'soil respiration', because it immediately calls to mind the fact that the soil is really a living organism by virtue of the innumerable soil microbes that it harbours. Research has shown that for an average fertile soil about 8 litres of carbon dioxide escape from every square metre of soil during 24 hours, and within 1 hour the soil air is replaced with fresh air to a depth of 8 inches.

Free water in soils is the most important factor hindering soil aeration because it blocks the larger soil pores. If we see to it that drainage is sufficient and that the soil has and retains a crumb structure, aeration will remain good. Some agricultural crops, such as potatoes, are more sensitive to insufficient aeration than others, and some weeds again can even grow normally in a soil that is completely waterlogged.

At the beginning of the chapter we said that the soil air also differs from the atmosphere in that it is more or less saturated with water vapour. The water vapour can also escape from the soil air by diffusion because the air above the soil contains less water vapour. As the water vapour diffuses from the soil air, fresh vapour is formed from the soil moisture and in this way the deeper soil layers also become drier and drier, if it does not rain for a long time. That is the chief reason why a soil mulch cannot prevent the drying out of deeper soil. At the most it can only delay the desiccation.

CHAPTER XV

SOIL TEMPERATURE

THE temperature of soils is an important factor in plant growth. Provided the soil contains sufficient moisture and air the speed with which agricultural seeds germinate is directly proportional to the soil temperature. It is a well-known fact that beans germinate much more slowly at the end of the winter than when they are planted during the warm summer months. The optimum temperature for the germination of most agricultural crops is about 25° C. (almost 80° F.). The growth of the crop also depends to a large extent on the soil temperature. This is easy to realize if we consider that a large part of the plant, viz. the root system, is in the soil. The optimum soil temperature for the growth of most agricultural crops in the temperate zone is also in the neighbourhood of 25° C. In South Africa the soil temperature may often become too high for plant growth and then we must endeavour to reduce it. The soil temperature is also indirectly important to plant growth because microbial activity and purely chemical reactions that render plant foods in the soil more available take place faster in a comparatively warm soil than in one that is cold.

Soils derive practically all their heat from the sun; the heat that reaches the earth's surface by conduction from the hot interior of the earth is negligible. A very small but vitally important fraction of the heat radiated by the sun reaches the atmosphere surrounding our globe and about a quarter of this heat reaches the surface of the earth where it is partially retained or absorbed.

THE HEATING OF SOILS

The heating of soils is the result of the absorption of heat-rays from the sun by the surface of the soil and the flow of this heat to the deeper soil layers by conduction. The following factors influence the heating of soils:

The *colour* of the soil is important in that objects that are dark or brown in colour absorb heat-rays more readily and reflect less of them than light-coloured objects. Thus soils that are rich in humus or iron compounds will absorb more heat than light-grey or whitish soils. On account of this, considerable differences in temperature may be noticed between dark and light soils if they are comparatively dry. However, in the case of moist soils the colour is of little practical importance because dark-coloured soils usually have a higher water-holding capacity than light-coloured soils (provided their texture is the same) and water has a high specific heat.

For any given climate the land relief or *slope*, especially in undulating or mountainous country, which is so characteristic of our coastal districts, has a very important effect on soil temperature. In this connexion there are two points that should be taken into consideration. Firstly, whether the land is level or sloping, and, secondly, the aspect of the slope. The more

perpendicular the direction at which the rays of the sun strike a surface, the more heat they will impart because then the heat from a particular sunbeam is limited to a smaller area. The accompanying diagram will illustrate this.

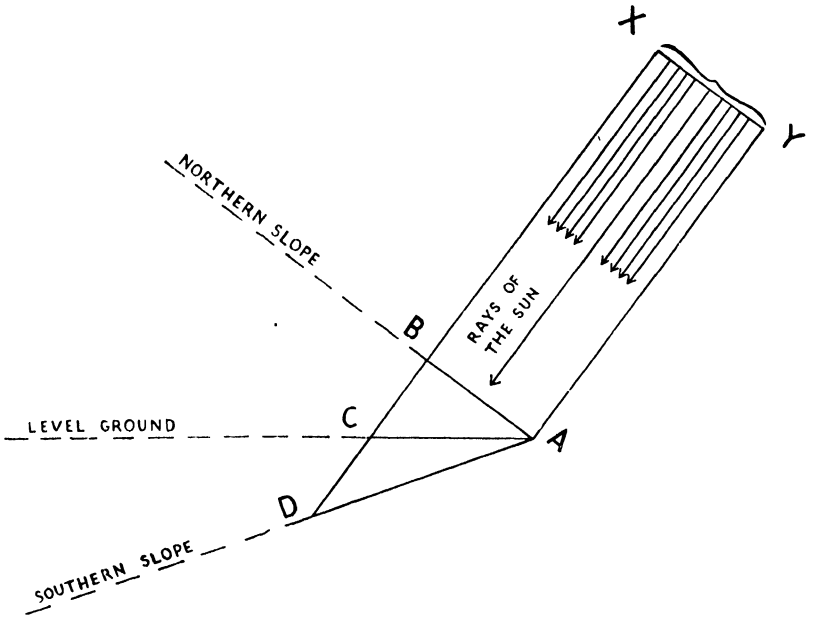


FIG. 9.

In this diagram it is assumed that a sunbeam, XY, strikes the surface of the earth on land with a northern aspect, on level land, and on land with a southern aspect. It is clear that the distance AB is smaller than AC and that this again is smaller than AD. In other words, the same amount of heat is distributed over a smaller area on a northern slope than on level ground or on a southern slope respectively. Because the position of the sun is north of us in the Southern Hemisphere, South African soils with a northern slope will become the warmest. Then come soils on western aspects, followed by eastern slopes, and, finally, soils on southern slopes will remain the coldest. Temperature recordings 2 inches below the surface of the soil, carried out by Aitken at Signal Hill, Pietermaritzburg, showed that at one o'clock p.m. soil on the northern side of a hill was about 12° F. warmer than soil on the southern side, with the same slope. For the early development and ripening of crops such as fruit it appears as if the morning sun is of the greatest importance, and thus fruit ripens first on soils with an eastern aspect.

Because the days are much longer in summer than in winter in our latitude more heat is radiated to the earth during a summer's day than during

a winter's day so that average soil temperatures are much higher than in winter. Apart from this, the sun is higher during summer with the result that its rays pass through a thinner stratum of air, and on level land, at least, rays fall more perpendicularly during the middle of the day.

Finally, the heating of soils situated in the same latitude and having the same aspect will depend on the *heat capacity* or *specific heat* of the soil. By the heat capacity of an object we understand the amount of heat, expressed in calories, which is required to raise the temperature of a given mass of the object 1° C. One calorie is the unit of heat and it is the amount of heat required to heat 1 gm. of water (which also has a volume of more or less 1 c.cm.) from 15° C. to 16° C. Hence the specific heat of water is taken as unity. The soil normally consists of solid particles, water, and air, and each of these constituents has a different specific heat.

Water has by far the highest specific heat of the three so that it needs the most heat in order to attain a certain temperature. Calculated on a volume basis, the different solid constituents (mineral substances and humus) have more or less the same specific heat and, on the average, this is only about one-fourth of that of water. In other words, a certain volume of solid soil particles only needs a quarter of the amount of heat needed by the same volume of water in order to attain a certain temperature. The air has a comparatively low specific heat so that it requires little heat to warm up. Consequently the moisture content of the soil is the factor that decides to what extent the temperature of a soil will rise on being exposed to a certain amount of the sun's radiation. Soils which are rich in humus and clayey soils are able to retain much water with the result that they are usually colder than sandy soils which have a low water capacity.

During the day-time the soil surface receives the heat of the sun and by conduction this heat is distributed to the deeper soil layers. Conduction of heat is the movement or flow of heat from one particle to the other. In this way one end of an iron rod will become very warm if the other end is held in the fire. Mineral particles that lie close together conduct heat faster than soil moisture, and soil moisture again conducts it about twenty times as fast as air. Thus a moist soil through the improved thermal contact between the soil particles conducts heat better than a dry soil. If a soil, saturated with moisture, is compared with an air-dry soil the ratio is about 10 to 1. On the other hand, however, a wet soil needs far more calories to be heated to a certain temperature than does an air-dry soil. For the warming of the subsoil it is more favourable if the soil is moderately moist, but not too wet.

THE COOLING OF SOILS

The soil as a whole loses heat and so cools down for two reasons. During the night the air above the soil becomes considerably colder than the soil because it radiates heat to the outer atmosphere. In this way the surface soil also loses heat by radiation to the cooler air. The more intense the cooling of the air above the soil, the colder will the surface soil become.

Thus the deeper soil is warmer than the surface layer during the latter part of the night and heat flows from here to the topsoil. In other words, in the topsoil the flow of heat during the night takes place in a direction opposite to that taken during the day. This shows that any factor which would reduce the cooling of the air above the ground during the night would also reduce the loss of heat from the soil. A cloudy sky, mist, and smoke reduce the radiation of heat to the atmosphere. Plant growth also decreases the radiation of heat from the topsoil because heat-rays from the ground are reflected back on to it. A soil that is covered with plant growth naturally also receives less heat by direct radiation from the sun; in other words, such a soil does not become as warm as a bare piece of ground but it will also not cool down to the same extent. A dry soil mulch becomes very warm during the day-time and very cold at night. Since the dry soil is a bad conductor of heat, its effect on the temperature of the deeper soil is approximately the same as a vegetal cover (see p. 129).

The second reason for the cooling of a soil is the evaporation of water. A large amount of heat is necessary for water to change from a liquid to a vapour. This heat is called the latent heat of vaporization and for every gramme of water at ordinary temperature it is about 600 calories. If water evaporates from the soil the necessary heat is taken from the soil, with the result that the soil cools down. Thus a wet soil is cold for two reasons. Firstly, it heats up more slowly on account of its higher specific heat and, secondly, it loses more heat through the evaporation of water than is the case with a comparatively dry soil.

TEMPERATURE FLUCTUATIONS IN SOILS

Up to now we have discussed the different factors influencing the heating and cooling of soils. It is clear that the soil temperature which depends upon many varying influences at any given time can never remain constant. Moreover, actually we cannot speak of the temperature of, say, the first foot of soil as a whole, because at any given time *the temperature will vary from inch to inch.* Systematic temperature recordings in different soil depths in an orchard in Stellenbosch gave the following results over a period of several years:

(1) The daily variations in temperature (amplitudes) are greater the nearer the recordings are made to the soil surface.

(2) The temperature of soil layers below a depth of about 2 feet remains almost constant over a short period of time.

(3) The times at which the maximum and minimum temperatures at a certain soil depth, say at 6 inches, are reached during 24 hours are not the same as the times when the air above the soil is warmest or coldest. It is always later. The deeper the soil in which the temperature is recorded, the longer is the lag. The diagram opposite explains this point very well.

(4) The lag in the maxima and minima that is noticed in the daily temperature curves also takes place to a lesser extent in the seasonal

curves that give the average temperature at a certain depth in the soil, with the same difference that the lag increases with an increase in depth in the soil.

Thus it was found at a depth of 2 feet in a level orchard soil at Stellenbosch that the highest average temperature (about 76° F.) remained fairly constant during January, February, and March, while the lowest average temperature at a depth of 2 feet (about 55° F.) remained fairly constant during July, August, and the first half of September.

The accompanying diagram gives the temperature curves in four different soil depths in a level orchard at Stellenbosch during 24 hours. The

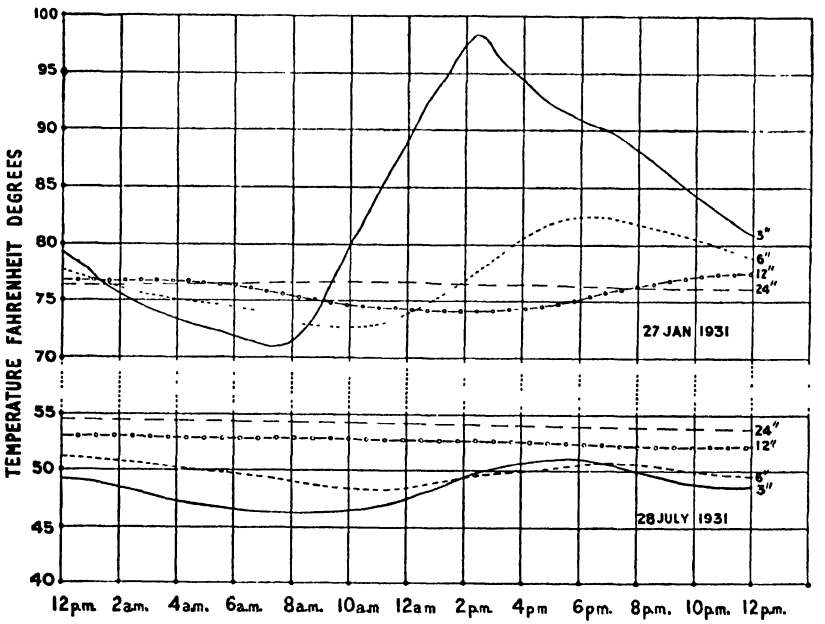


FIG. 10. Daily temperature curves in different soil depths.

temperatures were registered by self-recording soil thermometers. The first four curves are characteristic of the variations in soil temperatures during a warm summer day and night in a clean-cultivated orchard. The lower four, however, show the variations during a cold though sunny winter day in the same orchard that was then covered with *gousblom* (marigold).

As far as the daily fluctuations in temperature are concerned one can deduce from the figure that at a depth of 3 inches the soil is warmest at about 2.30 p.m. and coldest at about 7.30 a.m. during January and the difference in temperature (amplitude) is also very great, viz. about 25° F. (14° C.). At a depth of 6 inches the maximum temperature only occurs at 6.30 p.m. and the minimum at 9.30 a.m. At a depth of 12 inches the soil

is warmest at midnight and coldest at about 1.30 p.m. At a depth of 24 inches the daily fluctuations in temperature are very small (up to about 0·5° F.) and in the afternoons the soil is slightly warmer than at night, but this afternoon maximum has been delayed exactly 24 hours. In other words, this rise in temperature is the result of a previous warm day and the flow of heat takes 24 hours to reach the 2-foot depth. During and shortly after rain all the soil layers as deep down as the moisture penetrated have the same temperature.

During the winter months the subsoil has a higher average temperature than the topsoil. The daily lag in temperature during winter is considerably greater than during the summer months, especially if the soil is covered with plant growth. Of course, the lag is also greater during the summer months in soils that are covered with plant growth than in soils that are bare. J. F. V. Phillips gathered a lot of data in this connexion in the forest soils at Knysna. Unfortunately he did not have self-recording soil thermometers at his disposal with the result that the temperature curves cannot be plotted with great accuracy.

In practical agriculture the farmer cannot do much to influence the soil temperature. The locality and aspect of the land and the soil texture are the most important factors to be considered, and in growing early crops slopes which face north-east should receive preference. Secondly, the water relations in the soil should be as favourable as possible for plant growth and then the temperature will also be as favourable as the climate permits. Wet soils should be drained and all the measures effecting a granular structure should be applied. In this way excess water drains away more quickly and the soil will warm up sooner.

Finally, a soil mulch aids in giving the deeper soil a more uniform and actually a lower temperature. This can be of great importance during summer to soil microbes and the absorbing roots of plants, apart from the fact that the soil mulch possibly also slightly decreases loss of water from the soil by evaporation. Any object that shades the soil, such as straw, paper, or even stones, will naturally have the same effect, and actually to a greater degree than a soil mulch.

CHAPTER XVI

THE CONTROL OF SOIL MOISTURE

IN a previous chapter we discussed the scientific aspects in connexion with water relationships in soils. We now wish to discuss practical measures which aim at providing an optimum amount of soil moisture for crops. We need hardly stress the importance of this subject to South African agriculture.

We wish to discuss it from a wider angle than indicated by the heading. The following subjects will be treated consecutively:

(*a*) Absorption of Water by Soils and Soil Erosion.
(*b*) Dry-land Farming.
(*c*) Irrigation.
(*d*) Drainage.

(*a*) ABSORPTION OF WATER BY SOILS AND SOIL EROSION

The water that reaches the surface of the earth in the form of rain may undergo one of the following:

(1) It may wet the aerial parts of plants and evaporate without reaching the soil.
(2) It may reach the soil but may run off to lower-lying land and rivers and a portion or all of the run-off may evaporate or penetrate into the soil before it reaches a dam, lake, or sea.
(3) A portion immediately penetrates the soil raising its moisture content for a shorter or longer period of time. This water may partially evaporate from the soil again and plants may utilize it for their growth.
(4) During continuous rains a portion of the water may drain through the soil into deeper layers where it replenishes ground water or seeps through to rivers, &c.

Thus the soil is effectively moistened by a portion of the rain only. How large this portion is in relation to the total rainfall depends on a number of factors, the most important of which will be briefly discussed here.

The aerial parts of plants retain a certain portion of the precipitation, and the greater the plant surface, the greater the quantity of water that is retained and evaporates into the atmosphere without reaching the soil. According to European data, forest trees may retain as much as 40 per cent. of the total annual precipitation which thereafter evaporates again. Naturally, much depends on the nature and duration of the rain. Light mists and drizzles do not provide any moisture to arable soils although they are of agricultural importance in that they cause plants temporarily to use less soil moisture. This disadvantage that plants possess, viz. that they retain a portion of the rain causing it to evaporate without reaching the

soil, is more than offset by the fact that that portion of the rain which does reach the soil is better absorbed by a soil covered with plants because the vegetal cover increases the infiltration of water.

Surface run-off and soil erosion

Run-off of rain-water and the transportation of soil constituents, which almost always accompanies it and appears in an accentuated form as soil erosion, is closely connected with soil fertility. Run-off does not only mean a reduction in that factor of plant production which is in South Africa almost always in the minimum, but even in a very mild degree the removal of soil constituents by run-off means the loss of the most valuable soil constituents, viz. humus and clay particles.

For the whole of the Union and Basutoland the loss of rain-water by run-off has been estimated to be about $6\frac{1}{2}$ per cent. of the total annual rainfall, i.e. about $32\frac{1}{3}$ million acre feet. The Drought Commission of 1923 reports that run-off varies from almost nothing to 60 per cent. of the rainfall in the case of very steep catchments. This statement is vague and is not based on accurate measurements. The only published figures on run-off and soil erosion in South Africa of scientific value are embodied in a publication of the University of Pretoria,[1] where accurate observations on this subject have been made since 1931. The results of the first four to five years are of such importance that they are here given briefly.

Ten differently treated plots, 6 feet wide by 90 feet long, were partitioned on a reddish-brown sandy loam with a slope of 3·75 feet in 100 feet. The following table gives the treatment each plot received together with the average run-off as a percentage of the total rainfall and also the quantity of eroded soil. (The figures are for the rainy season, October to March.)

There are at least five factors that influence the percentage of run-off of rainfall and the quantity of eroded soil and we will discuss them in the light of the results given in Table 11 and of similar data.

1. *Slope* (topography). It is easy to realize that the velocity of water, its capacity to carry soil particles in suspension, and its erosive action on soils will increase with an increase in the gradient of a slope. The following mathematical relationship exists between gradient and the velocity of water and its erosive power:

(*a*) If the slope of the land is increased four times the velocity of water flowing over it is about doubled.

(*b*) If the velocity of water is doubled its erosive power is increased about four times.

(*c*) Moreover, if the velocity of the water is doubled its capacity for carrying soil material is increased about thirty-two times while the size of particles that can be transported by pushing or rolling is increased about sixty-four times.

[1] W. R. Thompson, *Rainfall, Soil Erosion and Run-off in South Africa*, University of Pretoria, 1936. See also W. R. Thompson, *Moisture and Farming in South Africa*, Central News Agency, Johannesburg, 1937.

TABLE II

No. of plot	*Soil treatment*	*Average run-off as a percentage of the total rainfall 1931–6*	*Average quantity of eroded soil per morgen per season in tons 1931–6*
		%	
1	*Maize annually*: 10 tons of kraal manure every third year and 200 lb. of superphosphate per acre annually . .	12·5	11·87
2	*Maize annually*: 200 lb. of superphosphate, 30 lb. of ammonium sulphate, and 15 lb. of potassium chloride per acre annually	23 4	15·17
3	*Cowpeas annually*: fertilization same as plot no. 2, harvested when pods have matured	19 9	11·88
4	*Teff Grass annually*: fertilization same as plot no. 2, two hay crops annually	16 7	2 61
5	*Rhodes Grass as permanent crop*: fertilization same as plot no. 2, two hay crops annually	5 3	1 87
6	*Bare plot, cultivated*: soil ploughed and cultivated as for maize, kept free from weeds.	40 6	36·49
7	*Bare plot, uncultivated*: all plant growth removed by cutting on appearing .	25·8	17 44
8	*Veld intact*: no grazing, burning, or cutting	0·48	0·05
9	*Veld grazed and burned*: rotative close grazing in spring and summer, autumn growth left and burned in August	10·82	1·09
10	*Veld closely grazed*: rotative close grazing during spring, summer, and autumn	5·6	0·21

Actual observations in America showed that the percentage run-off increases rapidly as the slope increases from nil to 2 per cent. As the gradient was increased to 3 and 4 per cent. the increase in run-off was proportionately more gradual and with steeper slopes the increase was very much slower. However, the effect of the slope on erosion was entirely different. As the slope was increased to 3 or 4 per cent. the increase in eroded soil was very slow, but a further increase in the gradient produced a rapid rise in eroded soil. This may be attributed to the increased carrying capacity of faster running water. In the Pretoria experiment the gradient of the soil is $3\frac{3}{4}$ per cent. In 1936 a new range of plots with a gradient of 7 per cent. was laid out.

It is common knowledge that a hilly and mountainous country, such as Basutoland or the Transkei, is very susceptible to erosion, especially when the vegetation is abused and rains are torrential.

In the winter rainfall region winter cereals are often grown on slopes up to 10–20 per cent., especially in the very undulating section of Caledon-Bredasdorp, but also in many other areas. Sheet and rill erosion occur commonly and this gradually decreases the fertility of the soil and gully erosion also is frequently encountered.

2. *Soil type.* On different soil types the amount of run-off and the extent of erosion may differ considerably even if other factors remain constant. In sandy soil types rain-water penetrates readily, and if they are deep, run-off and soil erosion will not be serious. However, sandy soils have a low water-holding capacity and if they are shallow and rest on a layer of potclay there may be a serious danger of run-off and hence soil erosion. Humus increases the water-holding capacity of sandy soils and improves the structure of all types. Improvement of structure increases the absorptive capacity of soils and thus the humus content is an important factor limiting run-off and soil erosion. The great difference in this respect, between plots no. 1 and 2 in Table 11, may probably be attributed largely to the kraal manure that was applied to plot no. 1.

The structure[1] and hence also the porosity of the soil are furthermore influenced by the clay fraction and its composition. Clay increases the water-holding capacity of the soil and is desirable in this respect, but, on the other hand, if the clay is partially or completely deflocculated, e.g. in black alkali (brak) soils, or if the soil contains too much clay, the soil may contain too few of the larger non-capillary pores (see p. 88), and thus water absorption and drainage of water into deeper layers will be too slow. Thus the intensity of the precipitation plays a big role, particularly in clay soils, as far as run-off and soil erosion are concerned.

In general, more water runs off on clay soils and erosion is worse than on sandy soils. The red clayey loams of the Transvaal and other regions have a very good crumb structure and seldom erode, but other clayey soil types are usually very susceptible to erosion.

3. *Cultivation and soil management.* It is true that a ploughed soil is better able to absorb rain-water quickly, but if, in a limited period of time, the rain exceeds the water-holding capacity of a ploughed soil it may erode exceedingly on sloping ground. The difference in run-off and erosion between cultivated and uncultivated soil may clearly be seen in Table 11, plots no. 6 and 7. Moreover, rain usually destroys the structure of the top layer of a ploughed soil with the result that it becomes more or less compact, a surface crust forming to a greater or lesser extent when the soil dries out. If a heavy rain falls before the surface soil has been loosened, the ploughed soil no longer possesses an improved absorptive capacity and run-off and erosion will be worse than on uncultivated soil.

Therefore, where ploughed soil lies fallow during a considerable part of the rainy season, e.g. the fallow grain lands of the winter-rainfall area or where the crop is still very young when seasonal rains set in (winter cereals, maize, &c.), it is essential that due consideration be paid to soil manage-

[1] See also the chapter on soil structure.

ment. In the long run it is advisable that contour ridges should be constructed on all cultivated lands with a slope of more than, say, 2 per cent. Meanwhile, ploughing should in any case never be up and down, as is so often still the case, but across the slope. We have already mentioned under (2) how the application of organic matter counteracts run-off and soil erosion. Finally, when heavy soil types are tilled, the moisture content of the soil should be taken into consideration with the object of maintaining and promoting a crumb structure and not destroying it.

4. *Character of the rainfall.* Three points are important in connexion with rainfall: the intensity, i.e. the quantity, that falls during one period, the seasonal distribution, and the total annual precipitation. The first point is infinitely more important than the other two in connexion with run-off and soil erosion. It is the intensity of the rainfall which is mainly responsible for the fact that run-off and soil erosion are more common in the summer-rainfall than in the winter-rainfall area. In the summer-rainfall area the major portion of the precipitation is torrential and a downpour of 1 or more inches within an hour, and sometimes some 6 inches within 24 hours, is common. No soil type can absorb this amount of water within such a short period, with the result that a high percentage runs off, causing soil erosion unless dense vegetation covers and binds the soil. The intensity of the rainfall was analysed in connexion with the Pretoria experiments and it was found that during the experimental years more than 67 per cent. of the rain occurred in the form of showers of half an inch or more, 33·3 per cent. in showers of 1–2 inches, and 9·5 per cent. was in the form of showers of more than 2 inches. These downpours occurred especially in the years 1930 and 1933 and in these years the total precipitation also was high. The relation between the intensity of the rainfall and run-off and soil erosion is well illustrated by the above observations which also reveal the effectiveness of a vegetal cover. Plots no. 5 (Rhodes grass) and no. 6 (bare, cultivated soil) may be contrasted. During a downpour of 1·68 inches that fell within 20 minutes, 330 gallons of water (70·2 per cent. of the shower) ran off plot no. 6 while on plot no. 5 the run-off was only 2·5 gallons (0·053 per cent. of the shower).

In connexion with the intensity of the rainfall in the winter-rainfall area, Dr. G. B. D. de Villiers, meteorologist to the Western Province Fruit Research Station at Bien Donné, Groot Drakenstein, has kindly furnished the following data for the period 1941–5.

The five years (1941–5) for which the data in the tables are given were all comparatively wet years, i.e. in all of them the total rainfall was above normal except 1943 which was more or less normal. During the period 1941–5 there was an average of 106 rainy days per year and if we take the whole year into consideration, showers of ½ inch or more were registered on an average of 27 days per year; i.e. 25 per cent. in comparison with 67 per cent. in Pretoria. Furthermore, we can see from Table 13 that on an average it occurs twice per year only that more than 1½ inches of rain falls during 24 hours. During the five years it occurred only once that a

TABLE 12

Year	*Number of days on which more than ½ in. of rain fell during 24 hours*				*Total annual rainfall (inches)*
	May	*June*	*July*	*August*	
1941	6	8	2	3	46·66
1942	5	9	2	5	34·05
1943	2	2	2	4	30·24
1944	5	7	4	4	39·32
1945	6	9	8	2	37·22
Monthly average .	4·8	7	3·6	3·6	

TABLE 13

Precipitation in 24 hours (inches)	*Average number of days during 4 months (May–August)*
½+	19
¾+	13
1+	7
1½+	2

shower of more than 2 inches fell on one day; on 26 June 1942, 4·70 inches fell.

The records show that as far as the heaviest shower in *one hour* is concerned, it only occurred *three times* during the five years that half an inch and more was recorded and then it was 0·70 inches only. So-called cloudbursts do occur in the winter-rainfall area but they are purely local, and no counter-measures, except perhaps a dense perennial pasture, can prevent soil erosion under such abnormal conditions.

The above figures are typical of that portion of the winter-rainfall region which is situated west of Sir Lowry's Pass. They show clearly that the intensity is *much lower* than that of the summer-rainfall region. In the real grain area of the Western Cape Province the average total rainfall is considerably lower (15–25 inches) than that at Groot Drakenstein and probably the day-intensities will also be lower. That accounts for the fact that grain lands on very steep slopes are not more *visibly* eroded. The figures in Table 12 also substantiate the general opinion that the rainy season of 1945 was especially disastrous as far as soil erosion is concerned, because the day-intensity of half an inch and more occurred more often than the average in three successive months, but especially in July. A knowledge of the intensity of the rainfall is very important in planning control measures against erosion for any particular region.

Another disadvantage of the South African rainfall is its seasonal distribution. Except for a small area in the Southern Cape Province the annual rainfall is largely limited either to the summer or winter months,

and the remaining half of the year is characteristically dry. The result is that vegetation, especially in the summer-rainfall area, is also decidedly seasonal so that it is sparse at the beginning of the rainy season and the ground may have bare patches. This condition is aggravated by man through injudicious grazing and veld-burning. Not only is extensive wind erosion possible on account of the fact that the surface soil is powdered and exposed by trampling of stock and veld-burning, but run-off and soil erosion are greatly increased during the rainy season. (Compare plots 7, 8, 9, and 10 in Table 11.)

Finally, the amount of run-off and eroded soil will naturally also vary according to the total rainfall if all other factors remain more or less constant. This fact is also illustrated well in the Pretoria experiments. The quantity of soil removed from plot no. 6 by erosion, during a relatively dry year, was 23·49 tons per morgen (11·16 inches in 1932–3), while the quantity in the ensuing wet season was 59·33 tons (31·34 inches of rain in 1933–4).

5. *Vegetation* is by far the most important single factor influencing run-off and soil erosion. The striking difference in run-off and erosion on different plots, as given in Table 11, is almost always due to the difference in vegetal cover of the ground. We need not discuss this here in detail, but a careful study of the data in the table will prove very instructive. The results obtained on plot 8 on the one hand and plots 6 and 7 on the other clearly reveal how a plant cover checks run-off and erosion.

Vegetation binds the soil, protects the surface layer against the harmful effects of rain on its structure, increases the humus content of the soil, and thus increases the penetrability of the surface soil for water. In this way run-off is either decreased or checked completely and soil erosion is likewise prevented or limited to a minimum. On the other hand, climatic factors and agricultural practices which result in temporary or permanent denudation of the soil will definitely increase run-off and soil erosion. Of these, the most important are injudicious cropping, overstocking and consequent overgrazing of veld, deforestation in regions with natural forests, and mountain- and veld-burning. The burning of mountain slopes should in any case be prohibited and provision made for fire-belts. Mountains are there to provide a regular supply of clear water to our rivers and not to send down flood-waters laden with soil constituents which silt up expensive reservoirs, destroy dams, cause extensive soil erosion, and indirectly contribute towards the desiccation of the country. Much has been said and written on veld-burning[1] and evidently it is a necessary evil under certain conditions, especially on the grasslands and in the rhenoster bush regions. From the point of view of soil fertility and soil and water conservation, however, it directly and indirectly leads to a depletion in the humus content of the soil and to increased soil erosion and run-off.

Having discussed in detail the five general factors in connexion with run-off we wish now to discuss briefly the process of soil erosion itself. We

[1] W. R. Thompson, *Veld-burning: Its History and Importance in South Africa*, Pretoria University, 1936.

differentiate between two[1] types of soil erosion: sheet erosion and gully erosion. Both result in a loss of valuable soil. The first type is less noticeable than the latter and, therefore, probably more insidious. It is the gradual removal of the fertile surface soil, or only the finer particles thereof, from higher- to lower-lying ground. Thus undulating ground, and sloping ground in general, steadily becomes shallower and less productive, especially because the removal of humus and finer soil particles causes a gradual decrease in the water-holding capacity of these soils. Sheet erosion occurs more commonly on cultivated lands, especially during the period when the soil is not yet covered with plant growth. This type of erosion also occurs at the commencement of the rainy season on veld that has been trampled excessively by stock, overgrazed, and burnt. Sheet erosion may develop into gully erosion although the latter usually develops 'on its own'.

In the case of gully erosion there is not only a loss of valuable soil but run-off is much higher than in the case of sheet erosion. Furthermore, water that has actually been absorbed by soil in the vicinity of gullies or dongas evaporates and drains away more readily. The result is that soils in an eroded area are drier than soils which are not eroded in an area with the same rainfall. Similarly, in the latter soils ground water is replenished to a greater extent. In the vicinity and especially on the banks of large dongas there is usually little or no vegetation on account of lack of moisture, and thus dongas readily increase in size by the action of flood-water and new dongas are formed laterally.

We must always bear in mind that the most important primary cause of soil erosion is the denudation of the soil. Veld- and mountain-burning, indiscriminate destruction of trees and shrubs, sledge-paths along mountain-sides, animal paths, overstocking, badly constructed and ill-maintained roads, inefficient tillage, and the cropping of too sloping land are all primary causes of soil erosion because thereby the one safeguard against erosion, viz. a dense vegetal cover, is destroyed for a shorter or longer period.

Soil conservation

Before giving a short summary of the practical measures to be taken in order to prevent soil erosion and to reclaim eroded land, we wish to give a short historical survey[2] of the steps taken by the Government, with this in mind. In this connexion the pioneering work done by the Drought Investigation Commission under the late Col. Heinrich du Toit is important. Their classic report (Blue Book) was published in 1923. It is still to-day an important reference work. Col. du Toit is not to blame for the fact that for several years the Government did little constructive work in order to combat soil erosion because he was well aware of its danger but received little support.

[1] An intermediate type between the two extremes is known as 'rill' erosion which is a visible, intensified form of sheet erosion.

[2] See lecture by Dr. J. C. Ross, Chief, Division of Soil Conservation and Extension, on 20 June 1945.

In 1929 a Soil Erosion Conference was held at Pretoria and all the government departments concerned were represented. As usual, important resolutions were passed. An advisory council for soil erosion was appointed and they were responsible for the introduction of the well-known *Soil Erosion Schemes* in 1933. According to these, farmers could obtain a government subsidy to cover a portion of the expenses incurred in anti-erosion work including the construction of dams for stock-watering purposes. Relatively few applications have in all these years been received for actual soil conservation. Up to 1945 about 10 per cent. of the farmers received subsidies under the above schemes amounting to £2,500,000, spent chiefly on the construction of dams. Since 1933 Pasture Research Stations have also been established in various parts of the Union and at the moment there are about sixteen of these and they conduct valuable research on pasture grasses and shrubs and on soil and veld conservation in general.

In 1939 the Division of Soil and Veld Conservation (now Soil Conservation and Extension) was founded as suggested at the Pretoria Conference in 1929. The next very important event was the Forest and Veld Conservation Act of 1941 according to which the Government may expropriate any land if necessary for the purpose of reclaiming wind-blown land, soil erosion control, or conservation of water sources. Certain areas may be proclaimed Conservation Areas. Thus there are the Vlekpoort Conservation Area (1941) of about 87,000 morgen and the Drakensberg Conservation Area (1944) of about one million morgen on the Natal side. In the meantime a private society was formed in 1943. It is known as the National Veld Trust and its main function is to bring the question of soil erosion to the notice of the general public and to keep the public informed. This is done by public lectures, films, and a monthly paper, *Veld Trust News*.

In August and September of 1944, Dr. H. H. Bennett of America, the well-known authority on soil conservation, visited the Union at the request of our Government. His radio talks and the pamphlet which he wrote at the end of his tour did much to awaken public interest. It is expected that in 1946 legislation[1] will be introduced in order to provide the necessary legal machinery to ensure farming systems that are in accordance with the soil-conservation policy of the Government.

The question of soil conservation is very comprehensive. Dr. Bennett describes it as follows in his pamphlet, *Soil Erosion and Land Use in South Africa* (1945):

'An engineer is not necessarily a soil conservationist. Neither is an agronomist, nor a forester. Soil conservation calls for the techniques of the crop specialist, the livestock specialist, engineers, foresters, soil scientists and other specialists—all working together as a single co-ordinated whole. That is soil conservation.

'Soil conservation calls for using the land properly and protecting it for permanent productivity. Irrigation and drainage; the use of crop rotations, lime, fertilizers and compost; wild life; hill-culture; climatological adjustments; these are all parts of soil conservation.'

[1] This has been accomplished.

The aim is that the Division of Soil Conservation will eventually have hundreds of trained soil erosion officers and instructors stationed over the whole of the Union so that they can advise and aid farmers in their battle against erosion and soil impoverishment.

From the above summary by Dr. Bennett it is clear that in this book we can only touch on certain aspects of this comprehensive subject. For this purpose we wish to divide all soils according to their utilization into: (1) *Pasture* and (2) *Arable land* (including all cultivated land, also that on which perennial pasture and field crops are rotated periodically).

Pastures constitute by far the greater area of the Union because in the greatest portion rainfall is too low and uncertain for crop production under dry-land conditions. The measures to be adopted in efficient veld conservation and management with the aim of maintaining and improving pasture grasses and shrubs and soil fertility are briefly as follows: The farm should be divided into camps (large paddocks) with suitable fences and every camp should be provided with water for stock. In this way trekking of stock to and from kraals and dams is obviated and thus unnecessary trampling of veld and formation of paths are prevented, both of which facilitate soil erosion. Camp boundaries (wire fences) should be selected with the aid of expert advice, lest anti-erosion works be hampered and soil erosion increased. Furthermore, grazing should be rotational and conservative in order to prevent overgrazing. In the real grass regions a system of deferred grazing should be followed. Every camp is rested in rotation for a growing season so that grasses can seed. At the commencement of the next growing season stock should still be kept off the grass until young grass has been properly established.

The number of stock on the farm should not exceed the carrying capacity of the veld. On sloping, deeper soil the effectiveness of contour furrows with a vertical fall of 12–18 inches between furrows should be tried out, not only to prevent run-off and soil erosion but also to give rain-water a better opportunity to penetrate into deeper layers. In the so-called mist belt of Natal the Cedara system may be followed, according to which high-producing grasses such as *Paspalum dilatatum* and kikuyu are grown and fertilized intensively. These grasses relatively quickly form a dense sward that will effectively prevent soil erosion even without contour furrows.

It is probable that within a number of years the Union will be divided into several regions, each with its own Pasture Research Station which will lay down a system of veld conservation and management based on research carried out in that area. Division into regions will be according to climate, topography, vegetation, and, possibly, the nature of the soil. It will be the duty of these research stations to test out the above and other measures, such as the necessity for veld-burning, the ratio of cattle to sheep in order to ensure maximum utilization of the veld, e.g. in the south-western districts of the Cape, maintenance and improvement of pasture grasses and shrubs, the nature of anti-erosion work, &c.

On *arable land* the following are some of the most important measures to prevent soil erosion. On all sloping land with a gradient of more than 2–3 per cent., one of at least two methods should be followed in order to check run-off and prevent soil erosion: (*a*) Contour ridges and furrows and (*b*) Strip-cropping.

There are mainly two types of *contour ridges or terraces*:[1] (1) Broad, flat terraces with a width of 20–24 feet; above the ridge there is a furrow, 10–12 feet wide and 15–18 inches deep in the centre. (2) Steep ridges and deep furrows. On ground with a fall of up to 10 per cent. and on deep soil, even up to 15 per cent., according to some, the broad-based terrace has the following advantages over the steep ridge. Although it is more expensive to construct there is no loss of arable ground because both furrow and embankment can be tilled and planted. Broad-based ridges are safer against run-off and easier to maintain than the steep ridges. Not only do broad-based terraces not hinder tillage, but farm implements, vehicles, &c., can easily cross them. Apart from the gradient there is one other condition when constructing broad-based embankments and that is that the soil should have a good depth.

The distance between one horizontal embankment and the next is mainly decided by the type of soil, the slope, and the intensity of the rainfall. It goes without saying that tillage and planting should, as far as possible, be parallel to the contour ridges. Farmers will require technical assistance especially in the way in which embankments should be ploughed because their height should be maintained.

The contour furrows should have very little fall lest they erode, and run-off should be afforded an opportunity to sink into the ground. On the other hand, superfluous water must be removed and for this purpose the furrows should not be longer than about 500 yards, or otherwise they should be very deep. The actual fall in the furrows, and also their length, will depend on the nature of the soil and the rainfall; the fall should increase steadily from about 3 to 9 inches in every 100 yards.

It is very important that the run-off should be well regulated where it is discharged from contour furrows, lest deep gullies be formed here. There are different ways of controlling the run-off but probably the best is to discharge this water on to meadow strips covered with a permanent grass such as *kweek* (couch grass) and kikuyu. Furthermore, dams and reservoirs may be constructed at suitable places if warranted by the amount of run-off and the requirements of the farm. This question of run-off shows how vital it is that in contour farming *all the farmers* of a certain area should co-operate because it will often happen that run-off from one farm is carried on to the neighbour's farm.

It is *essential* for successful conservation farming that the most suitable farming methods should be adopted especially in connexion with the

[1] Details of the construction of contour ridges may be obtained from soil-erosion engineers. (See also *The Farmer's Weekly*, 7–28 November 1945, for broad-based contour ridges.)

maintenance and increase of soil fertility; in other words, the regular application of as much farm manure and compost as possible, supplemented with fertilizers, especially phosphates. On very acid soils the application of agricultural lime must not be neglected, especially if lucerne or Rhodes grass is included in the rotation.

That brings us to the question of crop rotation. As discussed under 'Soil Structure', and as we will see again when discussing fertilizer practices, it is a practical impossibility in South Africa to maintain, let alone to increase, the humus content of cultivated soils if, year after year, winter cereals or maize only are grown, even with regular applications of farm manure or green manure. The only practical solution is to follow a humus-conserving cropping system by which the soil is periodically 'rested' under a perennial crop such as grass or lucerne.

Strip-cropping is also a type of crop rotation according to which strips of different crops are grown *on the same land* during *the same year*. These strips follow the contour and one of these crops *must* be a dense grass, lucerne, or other perennial crop because it must check run-off and prevent soil erosion, thus fulfilling the function of a contour ridge. After four to six years these strips are ploughed again and the annual crop(s) rotated with the 'permanent' crop. The future will teach us in how far strip-cropping is practicable in South Africa.

Reclaiming land with deep furrows and dongas is much more difficult and expensive. The aim should be to prevent strong flood-waters and where these do occur and carry soil with them, they should be checked, diverted, and distributed over a large area of land. This gives the water a better opportunity of sinking into the soil. We cannot give details of measures by which such dongas can be silted up again and covered with vegetation but merely wish to touch on certain points.

Where the topography permits, extension of the dongas at their top ends should be prevented by diverting flood-waters in a furrow. Where this is impossible and dongas at times contain much flood-water, the dongas should be dammed. The dams or walls may be constructed in different ways, e.g. with stones and wire netting which, together with sediment and debris, will eventually form a firm wall. Actual dam walls may also be constructed in the first instance. They should be higher than the surrounding soil surface. Care should then be taken that the discharge from the furrow is diverted and distributed lest a new donga be formed. In time the donga will silt up above the dam. The donga, or any badly eroded piece of land, should furthermore be fenced in so that vegetation and dam walls cannot be destroyed by livestock.

CHAPTER XVII

THE CONTROL OF SOIL MOISTURE (*cont.*)

(*b*) DRY-LAND FARMING

BY dry-land farming or dry farming one understands a certain system of soil cultivation which enables one to grow agricultural crops without artificial irrigation in areas with a limited rainfall. Actually the term 'dry-land farming' is a misnomer because literally it would mean the growing of crops on dry land, which is impossible. The system of dry-land farming aims at *retaining* and *conserving* as much moisture in the soil as possible. The word 'dry' refers to the climate because the system is especially practised in areas with a very limited and erratic rainfall, from about 10 to 20 inches per year.

In South Africa the methods of soil cultivation that are applicable to dry farming have to be applied to a greater or lesser extent wherever agricultural crops are grown, even on irrigated lands. The following are the chief points to be considered in the system:

1. *The nature and the depth of the soil.* From what we have already said about the water requirements of plants, the water capacity of soils, and the amount of available moisture in soils it is clear why a deep soil containing a large amount of available moisture is the first and most important requirement if crops are to be grown successfully where the rainfall is insufficient and where artificial irrigation is not possible. The depth of soil required is the same as the depth to which the root system of the crop in question will normally develop. For any special crop the water below the root zone does not help to meet the water requirements of the plants because under dry-land conditions the water table is usually too far down in the soil. Capillary water can only move upwards in liquid form for a very short distance above the water table.

The normal depths of the root systems of our agricultural crops are as follows:

Winter cereals .	2½ feet (oats) to 4 feet (wheat).
Maize . .	5–6 feet.
Sorghums . .	3–4 feet.
Potatoes . .	2–3 feet.
Lucerne . .	5–6 feet (1st year), 10–20 feet (2nd year).

Thus the first requirement for dry-land production of the ordinary annual crops is a soil 5–6 feet in depth. Lucerne can be grown successfully for pasturage under dry-land conditions in many parts of the Union, but, of course, as good yields as are obtained under irrigation can never be obtained on 'dry' land.

Furthermore, the nature of the first 6 feet of soil is important. It is obvious that if the soil is very sandy throughout it will not be able to retain enough moisture for good yields. This 6 feet of soil should also be free

from layers that are impervious to plant roots such as *ouklip* or other ferruginous hardpans or a very compact layer of potclay. If crops are grown under limited rainfall conditions, the amount of available moisture when the soil is saturated to its field capacity is decisive and, as we have already seen in a previous chapter, sandy loams, loams, and clay soils do not differ much in this respect. Thus they are all suitable for dry-land farming provided they have the required depth.

2. *Efficient tillage.* Former writers have stressed the importance of deep tillage in connexion with dry-land farming. It was thought that the soil should be ploughed to a depth of 10–12 inches at the beginning of the season. It is now known that it is the moisture in the 2–4-foot layer or the 2–6-foot layer (depending on the root system of the crop concerned) that supplies the major part of the water required by plants. Deep tillage is, therefore, no longer essential from the point of view of water conservation. In fact, the mouldboard plough is seldom used in American dry farming to-day. The depth to which the soil should be tilled will depend, in the first instance, on the nature of the soil layer, say, 6–20 inches deep in the soil. If there is no essential difference between the texture and structure of this soil layer and that of the soil as a whole there is no necessity, from a *water-conservation point of view*, to plough or otherwise loosen it. If, however, it contains a fairly hard layer that prevents the penetration of water and roots to the subsoil, this should be loosened. If the layer is not too hard, a strong plough will suffice but otherwise a subsoil plough, such as the 'Kilifer', should be used. The latter type of plough is already often used in orchards and widely spaced vineyards in the Western Cape Province to break and crumble hard strata in the subsoil. After such an operation performed on the dry soil, rain penetrates into the soil surprisingly quickly and even on fairly steep slopes there is hardly any run-off during the rainy season.

In ordinary soils, ploughing of the soil accelerates the penetration of rain-water to deeper layers where it is comparatively safe from evaporation. The nature of the rain as well as the nature of this upper soil layer must therefore be taken into consideration when deciding on the depth of ploughing.

Further, soils are ploughed in order to incorporate any plant growth on them and also manures. In South Africa it is almost always necessary to give at least a medium application of phosphate and in order to render it as available as possible to plant roots it should be ploughed deeply into the soil. Thus the soil should be ploughed deeply under dry-land conditions for the sake of the fertilizer even though deep tillage is not necessary to increase the water-supply available to plants. For practical reasons and also from the point of view of economy an average ploughing depth of 6–8 inches is probably sufficient.

The soil mulch

The loosening of the top layer of ploughed soil with harrows, cultivators, spring tooth harrows, &c., was formerly thought to be of great importance

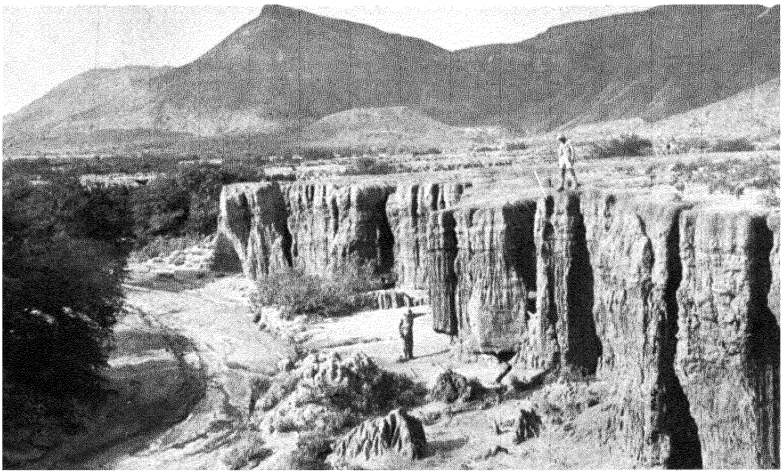


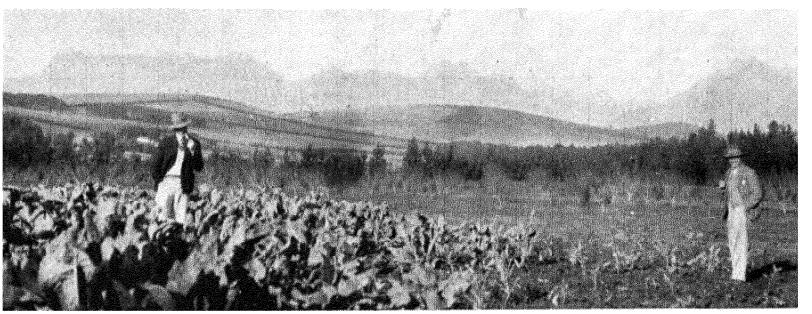
Photo C. J. J. van Rensburg

a Donga formed by soil erosion, Vlekpoort Reclamation Area, C.P.

Photo: Reg. M. Nicholson

b. Broad-based terrace on grain land. Elsenburg Experimental Farm

a A well-constructed ditch to receive seepage water from underdrains, Languedoc, Groot-Drakenstein, C P The openings of the drains on the left side of ditch are not visible on photograph



b On the right where the cauliflower crop is a total failure the soil is four times as acid as on the left where cauliflower grows well Both sections had the same manurial treatment Stellenbosch district.

in water conservation. In the light of what we said in Chapter XIII in connexion with the movement of soil moisture, viz. that it only moves in vapour form to the soil surface, it is clear that this movement cannot be prevented by a soil mulch. Only where the water table is no farther than 2–3 feet from the surface of the soil will a loose, dry-soil mulch reduce evaporation, because in this case water can move fast enough in liquid form to the surface to evaporate there. If, in this case, the top few inches of soil are loosened, the topsoil will dry quickly so that capillary moisture will no longer be able to rise to the surface in liquid form. Naturally evaporation from the moist layer will still take place, but the loss of moisture will be considerably less than when the capillary moisture is in direct contact with a dry, warm, windy atmosphere. Under conditions of dry-land farming the water table is usually very far down in the soil so that there can be no question of the upward movement of water in the liquid form, and thus a soil mulch will not be able to check loss of moisture by evaporation to any extent. Recent research in this direction proves this clearly. This was already the point of view of the Russian, Rotmistroff, at the beginning of this century.

However, the soil mulch has a marked influence on the temperature fluctuations of the soil mulch as well as of the layer of soil immediately below the mulch. The following results were obtained in an orchard on the Welgevallen experimental farm, Stellenbosch, with and without a 3-inch soil mulch. Self-recording soil thermometers were placed in the 6-inch soil layer.

TABLE 14

Temperature Recordings in an Orchard at 6-inch Soil Depth

Periods	*Average minimum temperatures*		*Average maximum temperatures*	
	With soil mulch	*Without soil mulch*	*With soil mulch*	*Without soil mulch*
Week 15.12.36–21.12.36	68·9° F.	68·7° F.	80·3° F.	86·3° F.
,, 22.12.36–28.12.36	71·0 ,,	71·5 ,,	81·5 ,,	88·3 ,,
,, 29.12.36–4.1.37	75·5 ,,	76·9 ,,	87·4 ,,	94·2 ,,
,, 5.1.37–11.1.37	75·0 ,,	75·3 ,,	85·1 ,,	91·4 ,,
,, 12.1.37–18.1.37	76·0 ,,	76·4 ,,	87 6 ,,	93·4 ,,
Averages for 5 weeks	73·3 ,,	73·7 ,,	84·4 ,,	90·7 ,,

During the five weeks that the temperature recordings were taken absolutely no rain fell. From the table it can be seen that at a depth of 6 inches the soil cools down to the same extent whether there is a soil mulch or not, but the maximum temperatures in the evening are on an average 6·3° F. higher in the soil that is not loosened on the top. The average daily temperature fluctuated 11·1° F. in the soil with the mulch and 17·0° F. in the soil without a mulch. On an average for the whole day and night, the soil at a depth of 6 inches was about 3·6° F. warmer in the compact soil than in the soil that had a loose layer of 3 inches on top.

Naturally, the higher temperature in the compact soil will result in a somewhat quicker exchange of air, and hence the loss of water by evaporation will take place somewhat faster than in the soil with a loose layer on top. Furthermore, the first few inches of the loosened soil are appreciably cooler in the morning than the surface layer of the compact soil so that more dew will condense on it than on the compact soil. This phenomenon can be observed with the naked eye. However, these effects of the soil mulch in conserving water are apparently of little practical importance.

The second and undoubtedly much more important function of the soil mulch as far as it affects the water economy of the soil, is that rain-water is absorbed so much more effectively and penetrates into deeper soil layers more readily where evaporation is less intensive. For this second function the soil mulch should not be too fine and dusty because a fine dusty layer of soil is apt to become very compact on being wetted. Thus the penetration of water will be retarded with the result that there will be an increase in run-off as well as a larger evaporation of soil moisture after the rain. The soil mulch should consist of small clods, but it should not be dusty. Thus the nature of the topsoil must be taken into consideration when the loose top layer is prepared and the most suitable implements should be used accordingly.

Apart from the preparation of the soil mulch, shallow cultivation also aims at the *destruction of all weeds* which use a considerable quantity of moisture in their growth. Hence also the necessity to plant all dry-land crops in rows, as far as possible, so that cultivation and the destruction of all weed growth can be carried out during the growing season of the crop. Some research workers even maintain that the destruction of weeds is the only useful effect of shallow cultivation on water economy in soils.

Under certain conditions other methods of protecting the soil, besides a soil mulch, may be applied. Farm manure, chaff, leaves, sawdust, &c., are materials that keep the soil cool and moist and some of them prevent the germination of weed seeds if they are spread out on cultivated soils. Under such a cover the soil surface remains loose and granular, and heavy rains sink into the soil easily without compacting the soil. On the Hawaiian islands, paper is spread out on cultivated lands on a large scale and pine-apples and other crops are grown successfully on such paper-covered lands. Loss of water by evaporation and weed growth are checked effectively on such soils without any further cultivation. In South Africa this practice has not yet been introduced. Another practice that has been very successful in tropical countries, especially in coffee plantations and orchards, is the cutting of a green-manure crop at the end of the rainy season and leaving it lying on the surface of the soil. This vegetal cover keeps the soil cool, moist, granular, and free from weeds. This method is also applicable in South Africa in the case of permanent crops, where strong winds are not prevalent.

3. *Time of sowing or planting.* By this we do not mean the time of year when the crop concerned should be sown or planted because this will

depend on the climatic requirements of the crop, but the time when enough moisture has been conserved in the soil so that a crop can be grown successfully even if very little additional rain falls. If we cannot depend upon a reliable rainfall, we must see to it before planting the crop that the necessary depth of soil (4–6 feet) is saturated to its field capacity with water. On account of the tendency towards overproduction of agricultural crops, prevalent before World War II, it was no longer considered economical to practise an extreme system of dry farming, i.e. to try to grow crops under conditions of such limited rainfall that two or more rainy seasons would be necessary in order to collect and conserve enough moisture for one good crop. The rainfall must at least be sufficient to saturate the soil layer to its field capacity if it has lain fallow for one rainy season.

The point to be stressed is that young plants develop a deep root system surprisingly rapidly (by the fourteenth day after germination the roots of winter cereals have penetrated a few feet into the soil) and if the soil, say from the 20-inch layer downwards, is still at the wilting-point the roots will only develop to a limited depth and the crop will very soon be dependent on rain. In case rain does not fall in time or is insufficient, such a crop will be either a complete or a partial failure. On the other hand, if the soil from the 7-inch layer down to the 3–6-foot depth is saturated to its field capacity, the crop can be sown at the normal time irrespective of whether the first rains fall in time or not. The crop will develop a normal root system and will be able to draw on the water-supply in the subsoil for a long time. Yields of winter cereals, maize, and other field crops are more certain in South Africa on lands that were left ploughed and received at least a certain amount of the rain of the previous season than on lands that were left in stubble after the previous crop had been removed.

4. *Choice of crops and methods of sowing or planting.* The shorter the growing period of a crop, the more suitable it is generally for dry-land conditions. Some grain and maize varieties have a much shorter growing period than others, and thus they are more suitable for dry-land farming. We call them drought-evading crops. On the other hand, a crop with a shorter growing period usually also has a shallower root system than one with a longer normal growing period. Thus the nature and water content of the deeper subsoil should also be considered in selecting the crop.

As far as the nature of the root system is concerned its normal depth is not the only point of importance. The density of the roots is also important because the denser the root system the better the crop will be able to utilize the available soil moisture. That is one reason why sorghums with their shallower root systems are more drought-resistant than maize with its deeper root system. Another reason is that the aerial portion of sorghums is smaller in proportion to its weight of roots than is the case with maize. In other words, sorghums have, in comparison with maize, a smaller transpiration surface and a more efficient root system.

A crop-rotation system in dry-land farming is not only necessary for the ordinary reasons for which crop rotation is advocated, but also in order to

make the best use of the available soil moisture in the first 6 feet of soil. Where possible a deep-rooted crop such as maize should be rotated with a shallow-rooted crop such as potatoes. After a crop of potatoes some available moisture may still remain in the first 2½ feet, but of more importance is the possible penetration of good rains during the season, and a portion of this water may percolate below the 2½-foot layer, and help to saturate the deeper subsoil. If maize is now planted after the potatoes the crop will have at its disposal a 3-foot layer of subsoil with moisture from the previous season that was not used by the potatoes. Water studies in arid and semi-humid areas of the Union have still to be carried out in order to prescribe the best rotation systems for any given area, bearing in mind the soil-water utilization.

Drought-resistance of crops is a complicated botanical question which we do not wish to discuss here. It is important to remember that the nature of the root system is closely related to *drought-resistance* which mainly depends on whether the crop can *endure periods of wilting without being injured.* Plants may wilt temporarily in a moist soil on exceptionally warm or windy days, because then transpiration is faster than the supply of moisture to the leaves through the root system. This phenomenon can be seen anywhere, although it is especially noticeable in garden crops (vegetables and flowers). Plants also wilt when the soil is so dry that the crop is no longer able to obtain any moisture from it. This wilting only ceases when the soil receives water from rain or irrigation. Plants that are sensitive to drought do not recover after rather lengthy periods of wilting, while drought-resistant plants can withstand such conditions without permanent damage. There are also critical stages in the growth period of plants when the water-supply is of more importance than at other times. By this we mean that a particular crop, measured by the yield which we shall ultimately obtain, has not the same resistance to drought conditions at different stages in its growth. Thus it has been found that the grain yield of winter cereals is most affected if they suffer from drought just before the piping stage.

The transpiration coefficient (see p. 17) is another factor that farmers in dry areas should consider when selecting a crop. Plants that use the available moisture more sparingly, i.e. that yield a bigger crop for a specific amount of moisture, naturally deserve preference over crops that yield less plant material for the same amount of water consumed.

Because a limited amount of soil moisture is the chief characteristic of dry farming, crops produced under this system should be sown and planted farther apart than crops grown in areas with an adequate rainfall.

Finally, the manuring is also important in connexion with the water consumption of plants. In a certain sense, crops use water more sparingly in a rich than in a poor soil. This means that for every unit of water consumed, more plant material is produced in a rich than in a poor soil. However, this does not mean that manuring will cause the total crop to use less moisture. When a soil is deficient in one or other plant nutrient and

we apply fertilizers containing this nutrient, the result will undoubtedly be not only a higher yield but also a higher water consumption. This point is often not considered when it is said that plants use water more economically if the soil is rich in available plant nutrients.

The effects of the different plant nutrients on the water requirement of crops are not all the same. In South Africa, wherever moisture conditions are such that crop yields are possible, a medium dressing of a phosphatic fertilizer may be safely applied. Phosphate stimulates root development, and this is important in connexion with the utilization of soil moisture in deeper soil layers. True dry-land soils are usually well supplied with potash so that applications of potassic fertilizers are, as a rule, not necessary, especially if farm manure is applied, as this also contains potash. On the other hand, it should be borne in mind that a sufficient supply of potash is essential because this plant nutrient has a beneficial influence on the water economy of plants.

Under real dry-land conditions we should be very careful in applying nitrogenous fertilizers (see also p. 23). Nitrogen stimulates luxuriant vegetative growth so that greater leaf development takes place and hence also a greater transpiration surface results. Thus plants suffer more from drought if they have had an excessive amount of available nitrogen during the early stages of their growth. Conditions may differ considerably but under dry farming it is generally safer to apply nitrogen, where necessary, in the form of slow-acting organic nitrogen. A moderate supply of farm manure is the most suitable and it should be applied in advance and worked well into the soil. All manures and fertilizers should be worked well into the soil under dry-land conditions in order to facilitate the development of a deep root system.

Degrees of dry-land farming

There are different degrees of dry-land farming, but it is impossible to discuss them in full here. However, we wish to explain the following briefly.

In the winter-rainfall area of the Cape Province, deciduous fruit-trees, vines, and Turkish tobacco, i.e. summer crops, are grown extensively without irrigation. Because the summer rains are insufficient the winter rains should be conserved as far as possible in the soil and in summer evaporation should be checked. In the case of Turkish tobacco the soil is usually ploughed a few times during winter, once very deep. After the plants have been transplanted in spring, the top layer of soil is kept loose and free from weeds by cultivation. In orchards the soil is usually tilled as deeply as possible towards the end of winter after a cover crop has grown in them for the greater part of the winter. In this way it is sought to maintain the humus content and the leaching of soluble nutrients, especially nitrates, is prevented. Furrows should be made on the contour in lands with a steep slope, in order to check run-off and soil erosion and to retain water from winter rains on the lands. During the summer months the top

layer of soil is kept loose and free from weeds. However, in the light of the latest knowledge, farmers should realize that it is an unnecessary expense to cultivate soils after a light rain.[1]

Even on the grain lands in the winter-rainfall area where winter cereals receive comparatively regular rain during their growing period, dry-land methods are applied to a certain extent. The soil is fallowed fairly deeply during winter, and in spring and sometimes also at the end of summer it is harrowed and cultivated well in order to break any hard crust that may have formed on the surface as a result of rain, and in order to combat weeds (such as *kweek* or couch grass). Rains that may still fall in October and November will then penetrate easily into the soil. If necessary such lands can be sown 'dry' in April or May if the first soaking autumn rains do not come in time.

In the summer-rainfall area of the Union, maize and potatoes are the two most important field crops that are grown without irrigation and the considerable fluctuations in the annual yields are a good indication of the erratic nature of the rainfall. A maize crop uses all the available moisture down to the 5–6-foot depth and if maize follows on a previous maize crop, its development is dependent entirely on sufficient rain, especially in the first half of the growing period. However, if the maize follows on another field crop that did not use the moisture in the deeper layers to the same extent, or, better still, if maize is planted on a land that lay fallow during the latter part of the previous rainy season, the yield would be far less dependent on the rainfall of the season during which it is grown. The annual fluctuations in yield would then be much smaller. Where wheat is grown without irrigation in the summer-rainfall area as in the Eastern Free State and the Eastern Province of the Cape, it is necessary that the soil should be tilled in time in late summer. Then the first 4 feet of soil is saturated to its field capacity when the wheat is sown in autumn. In the south-western districts of the Cape, Swellendam to Mossel Bay, the rainfall during the winter months is also too unreliable to sow wheat on stubble lands. This is still often done, usually with disastrous results.

It is the agricultural policy of the Union to-day to encourage animal husbandry in all semi-arid regions where irrigation is not possible. If the application of the principles of dry-land farming makes the production of a crop possible, food for animals should preferably be produced. This applies to all areas with an annual rainfall of less than 15–20 inches if this rain falls predominantly in summer in the form of heavy thunderstorms.

[1] See also Chapter XXXIII in connexion with water requirements of fruit-trees.

CHAPTER XVIII

THE CONTROL OF SOIL MOISTURE (*cont.*)

(*c*) IRRIGATION

IRRIGATION is the artificial application of water to soils and this measure is adopted in areas where the normal rainfall is insufficient or too erratic for profitable yields. In South Africa this practice almost always means the watering of soils by running water, but in Europe and America soils are also watered with huge sprays[1] on wheels (overhead sprays) that work on the same principle as lawn sprinklers.

As in the case of dry farming there are also different degrees of irrigation. Thus, summer crops in the winter-rainfall area of the Cape Province are sometimes irrigated once or a few times during the growing season. However, in the truly arid areas the precipitation is so low that the main supply of water for crops has to be provided in the form of irrigation.

Irrigation already plays an important role in South African agriculture and large sums of money are still being spent on *new irrigation schemes*. The area that was under irrigation in 1946 and that was under the control of water boards comprised about 300,000 morgen. Apart from this tens of thousands of morgen are also irrigated from private dams or reservoirs on farms and along rivers where the water is either diverted directly from the river or pumped up to higher ground. On account of the fact that the larger irrigation areas usually have fertile alluvial soils, a very intensive system of agriculture can be practised there and many families can make a good living on small holdings.

However, there is also another side to government-sponsored irrigation schemes. On account of the high initial capital expenditure and sometimes the high cost of maintenance, very few of them can exist unless a large portion of the capital expenditure is borne by the State. Viewed from a broad national point of view, however, irrigation schemes are essential, especially in a country like South Africa. Much can still be done by the Government as well as by farmers who have the means to make the waters of our rivers available for arable lands.

The history of irrigation dates from the earliest times. Countries such as Mesopotamia, Egypt, India, China, Mexico, Peru, &c., were irrigated on a large scale thousands of years before the Christian era.

Requirements in connexion with irrigation

Among the many factors that are necessary for any successful farming enterprise there are three that are of the utmost importance to the farmer who irrigates.

1. *Suitable soil.* Irrigable land is usually expensive and it should not only be able to produce high yields under systems of very intensive cropping,

[1] Sprays are also now in use in a few localities in South Africa.

but it should maintain its productivity even when irrigated injudiciously. The irrigation of soils is an art of which, it is true, the principles can be obtained in text-books but their application can only be learnt by actual practice. The two most important requirements for an irrigable soil are that it should be deep and permeable to water and plant roots and that it should be as free as possible from brak salts. Often a soil does not appear to be brak and yet saline layers may be present in the lower strata. This salt will be brought to the surface by irrigation, making the soil completely brak and useless for irrigation. Since about 1920 no start has been made on any irrigation scheme by the State before the Soils Section of the Division of Chemical Services has conducted a thorough survey of the soils in the area. After the soils have been inspected by borings and the sinking of holes, to a depth of 8 feet, and the soil samples analysed, they are classified as follows:[1]

Class I. Eight-foot-deep soil of medium texture, free from hardpans, stiff clay, coarse sand, or gravel layers.

Class II. At least a 4-foot depth of soil of Class I, resting on semi-permeable pans, coarse sand, gravel, &c.

Class III. At least a 4-foot depth of suitable soil of Class I resting on solid rock or impenetrable layers, or at least a 30-inch layer of soil of Class I resting on semi-permeable layers or gravel.

Class IV. Shallow soils that do not fall under the above classes.

According to their salinity[2] (brak content) soils are also divided into four classes:

Class I. Soils that contain less than 0·15 per cent. of brak salts throughout their total depth.

Class II. Soils containing from 0·16 to 0·35 per cent. of brak salts.

Class III. Soils containing 0·36 to 0·55 per cent. of brak salts.

Class IV. Soils containing more than 0·55 per cent. of brak salts.

The so-called 'Irrigable Value' or irrigability of the soil is then obtained by taking both classifications into consideration as follows (the roman figures indicate the classes given above):

Soil layers		*Brak content*		*Irrigable value*
I	+	I	=	1
II	+	I	=	2
I	+	II		
II	+	II	=	3
III	+	I		
I	+	IV		
Other combinations			=	4

This measure of irrigability or productivity under irrigation is fairly strict and some soils falling under classes III and IV can be made quite

[1] The Division is now using a revised, more complicated method of classification. Instead of four, six classes or Irrigable Values are used. Details may be obtained from the Division of Chemical Services, Pretoria.

[2] Here also the Division to-day uses a more comprehensive classification in which also the pH is taken into account.

productive if they are treated correctly. However, the Government must take the average ability and the usually limited financial means of the settlers into account. Thus it is a sound principle not to construct large irrigation works if a considerable portion of the soil that can be irrigated does not fall under classes I and II. The alluvial soils in and along old river-beds are usually comparatively free from brak salts and thus they are, from this point of view, very suitable for irrigation. The adjoining river-banks and higher ground may, however, be permeated with brak salts. If the main irrigation furrows pass through such formations that are permeated with brak salts and they are not cement-lined, lower-lying alluvial soils may become very brak as a result of leakage or percolation from the furrows. In the Olifants River irrigation settlement (C.P.) there are examples of this. The reclamation of brak soils will be discussed in a subsequent chapter.

The maintenance or increase of the fertility of soils under irrigation is very important. Not only should an adequate supply of the ordinary plant nutrients, especially phosphates and nitrogen, be ensured, but the humus content of such soils requires special attention. In order to maintain the physical properties of the soil, especially its structure, it is necessary that organic matter should be applied regularly in the form of green manure, farm manure, and compost.

2. *Suitable water.* Water from bore-holes, springs, dams, and rivers can be used for irrigation, but they contain varying degrees of impurities. Sometimes they contain silt as in the case of flood-waters of rivers, and if such turbid water is used on soils a considerable amount of plant nutrients, as well as water, are added to the soil. The classic example of such 'fertile' water is the River Nile when it is in flood. Another example of irrigation with water containing silt is the method followed in the valley of the Sak River, Calvinia. There, flood-waters which invariably contain silt are retained in special, shallow dams or basins to irrigate the soil. Such water is less suitable for permanent crops such as oranges, vines, or lucerne, unless the water can be regulated effectively, because there is the danger that crops can silt up. Sewage effluent from settling-tanks, filter-beds, &c., is another example of water that has manurial value.

Among the 'clear' irrigation waters, hard water, i.e. water containing dissolved calcium (and magnesium) salts, is the most suitable as a rule. Relatively pure, soft water is also good but water containing dissolved sodium salts is harmful in the long run because soils irrigated with such water eventually become brak. The water from South African rivers seldom contains sufficient brak salts to be unsuitable for irrigation. However, some dam waters in the Karoo and especially water from boreholes can be totally unsuitable for irrigation on account of their high brak content. Examples of this are well known. Therefore such waters should be analysed and expert advice obtained in connexion with their suitability before they are used for irrigation.

Often it is very difficult to tell beforehand whether a brackish water is

unsuitable for irrigation because its harmful effects will depend on the porosity of the soil and the sensitiveness of the crop to brak conditions. Thus brackish water may be used on deep, sandy soils but the same water on loams or clay soils will very soon harm the soil structure to such an extent that the growing of crops will become a difficult problem. If the water contains considerable calcium salts together with the sodium salts, or if the soil contains carbonate of lime or gypsum, a brak content that would otherwise be dangerous could be perfectly harmless.

In general, irrigation water should not contain more than 0·07 per cent. of brak salts, i.e. less than 70 parts of brak in 100,000 parts of water. If only the chlorine content is taken into consideration the critical point is about 0·02 per cent., i.e. irrigation water should not contain more than 20 parts of chlorine (as chloride) in 100,000 parts of water.

The water from boreholes may contain sulphuretted hydrogen and is then recognized by its characteristic smell. Such waters should not be used on lands on which crops are growing because the sulphuretted hydrogen is harmful to plants and such water contains too little oxygen. Such water should first be left standing in a dam or reservoir for a certain time until the harmful compound is oxidized or volatilized, i.e. until the water has lost its bad odour. Of course, soils can be irrigated with such water provided they are not seeded immediately.

3. *Suitable crops.* Because irrigation soils are limited and expensive only the most remunerative crops, generally speaking, should be produced, i.e. such crops as have a high market value per morgen-yield. Thus winter cereals and maize should, as a rule, not be grown on such soils in normal times. Where the climate permits it is advisable to grow permanent crops such as citrus fruits, deciduous fruits, and grapes (sultanas and table grapes). On brak soils olives and figs are suitable crops. A choice of the most suitable field crops and vegetables should be made and they should be chosen for their regular demand and because they fit well in a rotation system covering all the seasons. As a perennial crop lucerne does very well on deep, alluvial soils and it is also the crop that is usually grown very extensively on irrigation soils in South Africa. About six cuttings can be obtained in a year and the cost of producing lucerne is usually relatively low. On the other hand, the market value of lucerne is also often very low even if it is ground, and thus the growing of lucerne should go hand in hand with dairy farming in order to get the best profit from the soil.

According to the returns of the Director of Irrigation, the following were the percentages of cultivated areas under different crops, grown under irrigation, in 1935 (schemes under control of the State): winter cereals, especially wheat, 38·75 per cent.; lucerne, 22·43 per cent.; maize, 9·22 per cent.; vines, 5·42 per cent.; vegetables, 4·17 per cent.; citrus, 4·06 per cent.; tobacco, 2·19 per cent.; legumes (except lucerne), 2·67 per cent. Apart from this there were also pastures and flowers under irrigation.

How water is measured

Irrigation works are constructed under the supervision of engineers and the measuring and distribution of water at big irrigation schemes are also activities falling outside the work of the ordinary agriculturalist. We only wish to explain a few terms which the irrigation farmer will encounter, and will also elucidate a method by which the amount of water in a furrow can be calculated without the use of sluice gates.

The following units are often used:

1 morgen[1] is 100 × 100 yards = 10,000 square yards or 90,000 square feet.

1 gallon of water (South African and Imperial) = 277 cubic inches = 0·16 cubic feet = 10 lb.

1 cubic foot of water = $6\frac{1}{4}$ gallons = $62\frac{1}{2}$ lb.

1 morgen-inch of water = 46,875 gallons.

1 morgen-foot of water = 562,500 gallons.

1 cusec is one cubic foot of water per second.

1 cusec for an hour = 6·25 × 60 × 60 = 22,500 gallons.

1 cusec for a day = 24 × 22,500 = 540,000 gallons = approximately 1 morgen-foot.

By one morgen-inch of water we mean that quantity of water that would stand 1 inch deep on 1 morgen of soil.

In order to measure approximately the flow of water of a stream (i.e. the number of cusecs), the following rough method will give good results (Fig. 11).

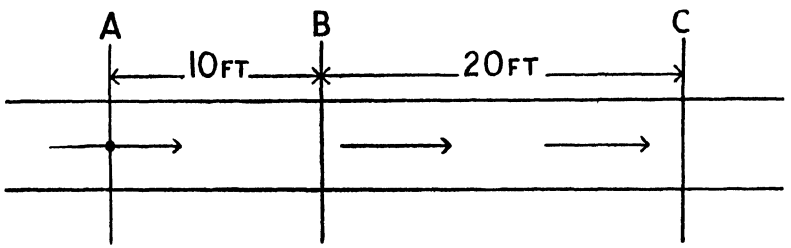


FIG. 11.

The speed of the stream is first measured. Find a distance along the furrow where the course is fairly straight, where the gradient is as regular as possible, where the bottom of the furrow is as symmetrical as possible, i.e. not deep on one side and shallow on the other, and where the furrow is free from plant growth for at least 40–50 feet.

Measure off a distance *BC*, that is exactly 20 feet, along the furrow, and drive in pegs at *B* and *C* on the bank. About 10 feet above *B*, at *A*, a piece of wood or cork is put in the *centre* of the stream. The time, in seconds, that

[1] Actually a Cape morgen is 10,244 square yards, i.e. about 101 × 101 yards, but for practical purposes the above measurements can be used.

it takes the object to float from *B* to *C* is measured accurately. Repeat this process six times and calculate the average time that it takes the object to float from *B* to *C*. If we assume that the time is 10 seconds, the surface speed of the water in the centre of the stream will be 20 ÷ 10 = 2 feet per second. In order to calculate the average speed of the whole stream of water this speed is multiplied by the factor 0·7. In our example the result is 1·4 feet per second.

The number of cusecs or the strength of the current is equal to the average speed multiplied by the area of the cross-section of the current, in square feet. This section is measured as follows:

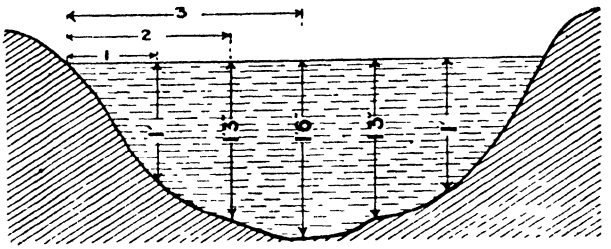


FIG. 12.

The depth of the stream is measured across at regular intervals. The area of the cross-section will be the total sum of the depths multiplied by the regular interval between. If we take the figures in the sketch as an example then:

The area of the cross-section =

$$1 \times (1 + 1{\cdot}25 + 1{\cdot}5 + 1{\cdot}25 + 1)$$
$$= 6 \text{ square feet.}$$

Then the strength of the current =

$$6 \times 1{\cdot}4 = 8{\cdot}4 \text{ cusecs.}$$

$$8{\cdot}4 \text{ cusecs for an hour} = 8{\cdot}4 \times 22{,}500 = 189{,}000 \text{ gallons.}$$

With such a stream of water we would, therefore, be able to give about 4 morgen 1 inch of water in an hour or we would be able to give 1 morgen a 4-inch irrigation in that time.

Where a relatively small stream of water runs through a pipe the flow can be measured by allowing the water to run into a bucket or paraffin-tin of, say, 4 gallons and measuring the time it takes for the bucket or tin to fill up. Here also it should be measured several times and the average taken. The flow of water is then expressed in so many gallons per minute or hour, or it may be calculated in cusecs.

Methods of applying water

The aim of the farmer who irrigates should be to derive as much benefit as possible from the water at his disposal. In other words, he should aim

at getting a high production of plant matter for every unit of irrigation water, say 1,000 gallons. In order to achieve this he must make sure that the irrigation water is brought into that soil layer where plant roots can make the best use of it, and he should guard against two ways in which water can be lost.

If the soil is not saturated to a considerable depth there is a proportionately heavy loss of water from the surface soil by evaporation into the atmosphere. This loss is especially marked in the case of clay soils that readily become compact. Apart from the fact that such a shallow moistening results in a great loss of water it also has the disadvantage of encouraging a shallow root system. Such a crop consequently cannot make use of all the available plant food and needs watering at frequent intervals.

Irrigation water (and soluble plant nutrients) is also lost when it drains beyond the reach of plant roots. This occurs particularly if sandy soils are irrigated too heavily. Also if, in the deeper soil, there is an impervious layer, the soil becomes waterlogged and plant roots die off. The leaves of orange-trees, for example, become mottled under such conditions and the tips of the branches die off. This is due to the so-called dry root-rot, a disease that often occurs and is caused by over-irrigation.

Many different methods of irrigation are in use and in the choice of a particular method the nature and gradient of the soil, the kind of crop, and the amount of available moisture should, among other things, be taken into consideration. We will describe the most important methods in outline, but it must be borne in mind that the efficient use of irrigation water is an art that must be learnt by practice.

1. *Furrow method.* This method is applicable in the case of all crops which are grown in rows, such as fruit-trees, vines, berry-fruits, potatoes, vegetables, &c., and on soils in which water penetrates easily. The soil should have a certain slope and even very steep slopes can be irrigated with furrows by making them diagonal to the direction of the slope. In the case of smaller crops where the rows are a foot or more apart every row, or, if need be, every other row, should be irrigated. In orchards at least two furrows, one on either side of every row of trees, should be made while the trees are still small. The number of furrows in the case of older trees will depend on the distance between the rows and on the permeability of the soil. Water running in the furrows moves chiefly downwards and the sideward penetration of water is very little as a rule. The nature of every soil will decide both the downward and sideward penetration of moisture. To ensure that the whole of the deeper soil layer receives sufficient moisture, it is essential that one should investigate for every soil type how distribution of the water takes place. Approximately two to three days after the water has run in the furrows a deep furrow is sunk at right angles to the irrigation furrows and the extent to which the water moved downwards and sidewards is determined. This investigation will enable us to decide whether more furrows are necessary or whether the water should run more slowly in the furrows.

The most important advantages of the furrow method are that a larger area can be irrigated with a given quantity of water than under the other systems and that the loss of moisture from the soil by evaporation is relatively low. The deeper and narrower the furrows are made the smaller is the loss of water by evaporation after irrigation, but the higher is the cost of constructing the furrows and the more difficult subsequent cultivation of the soil will be.

The furrow method also has certain disadvantages. In clayey and silt soils the water moves downwards so slowly that the soil is moistened to a shallow and insufficient depth by the furrow method. By allowing the water to run more slowly and for a longer period of time the soil is moistened to a greater depth and more effectively, but some soils still do not absorb enough moisture in spite of this treatment. The second disadvantage that is manifested on all soil types is the irregular moistening of the soil at the top end of the furrows in comparison with the bottom end. In the case of very permeable soils loss of water and plant nutrients and waterlogging of the soil at the top ends of the furrows may occur. Thus the length and the rate of fall in the furrows should be made such that as regular a moistening of the soil as possible and no waterlogging will result. Finally, if orchards are irrigated by the furrow method only a portion of the orchard soil is actually watered and the soil in between the trees, where there are no furrows, may remain absolutely dry. This is especially the case in older citrus orchards. Thus these spaces should either be watered by basins that are filled with water from the furrows, or by zigzag furrows that run laterally from the long furrows in order to ensure that the entire root system receives water.

2. *Hole method.* Some orchard and vineyard soils, such as are found at De Doorns and Robertson, absorb water so slowly that they cannot be irrigated by means of furrows. Sometimes the basin method (see later) cannot be used in these soils because the soils are too steep or because the water-supply is limited, &c. In such cases the hole method is used. It is a modification of the furrow method because here the water also runs in furrows, but at short intervals in or next to the furrows there are holes and they are filled with water. Sometimes it takes days before all the water has drained from the holes, but the deeper soil, at the holes at any rate, is thoroughly moistened in this way. The depth of the holes is approximately 1 foot and the area 2 feet square.

In vineyards the holes are made in squares in every other row, and in orchards two or more holes are made in the vicinity of each tree, about 6 feet from the trunk. In order to lessen evaporation from the holes they are sometimes filled with shrubs or prunings. After a year the holes with the rotted plant material are covered up and new holes are made. In this way the soil becomes richer in humus and looser in course of time so that the ordinary furrow method can sometimes be applied after a number of years.

3. *Flooding method.* By this method of irrigation the whole surface of

the soil is more or less put under water. Different systems of watering fall under this general heading, but we will only discuss a few that are often used in South Africa.

Firstly, there is the *'saaidam' method* that is especially used in the North-Western Cape Province and the Sak River valley. The most important requirement in this method is that the soil should be fairly level within a basin formation. The arable land is transformed into one or a whole series of 'dams' or basins by constructing long walls, 3–6 feet high, across the slope. If any rain falls all the run-off will run into the first dam or it may even be filled from irrigation water if there is sufficient. A large piece of land now stands under a few feet of water for several days or longer, depending on the rate at which the water sinks into the soil. As soon as the soil is wet to the required depth the wall is broken in the centre and the second dam is filled, &c.

After the topsoil has dried off sufficiently it is ploughed and seeded. In this way good grain yields may reach maturity with very little subsequent rain. Even vineyards can be watered in this way during the dormant period provided the soil is very deep, has a good water-holding capacity, and provided the water table is not too high after the dam has been emptied and the water has drained away. An additional advantage of this method is that any phylloxera insects that may exist are killed so that American stocks are not necessary.

There are several variations of the ordinary *basin method.* Thus there is the 'chess-board method' that is applied especially in orchards if the soil type does not absorb water readily. Low walls are made with plough or spade, in between and across the rows, so that every tree stands in a 'dam' or 'basin'. The furrows run in between every other row between two banks and the basins are filled from the furrows. In order to prevent collar rot in citrus trees and gummosis in stone-fruit, it is essential that the water should be prevented from coming in direct contact with the trunks of the trees by making ground walls about a foot from the trunks. On slopes the dams are only made above every row of trees.

Oblong basins of different sizes can also be constructed depending on the slope and nature of the soil. The method is applied especially in the case of lucerne and winter cereals. The basins are from an eighth to half a morgen in area and from the furrows, running alongside these blocks, an irrigation of 3 inches or more is given at a time. The soil in every basin should be levelled very carefully so that it receives the same amount of water all over.

Finally, we would like to stress a few rules that should always be borne in mind in connexion with irrigation. Where annual crops are grown the soil should be moistened well throughout the root zone, i.e. down to 3–6 feet, before it is ploughed and seeded or planted. The first watering after this should be delayed as long as possible until the plants show a need for water, i.e. until the water has been consumed almost to the wilting-point. In this way the young plant is forced to develop a deep root system. If the

soil is then watered again it should be irrigated thoroughly so that the entire root zone is saturated to the field capacity. Watering always impairs the structure of the soil, therefore the number of irrigations should be limited as far as possible. Fewer but heavier irrigations are better for several reasons than more but lighter irrigations. We have already seen that a light irrigation is nothing but a shallow irrigation and very wasteful as far as water utilization is concerned.

The more recent knowledge in connexion with the field water capacity, the movement of moisture in soils, and the evaporation of water from soils has markedly influenced the technique of irrigation. It is high time that agricultural advisers be appointed at our irrigation schemes and that technical knowledge be applied in practice. A great difficulty to-day is the fixed turns farmers or settlers have in using the water, and it would require a considerable amount of organization from the official to effect a more efficient use of the irrigation water. Where the State spends so much money in order to erect irrigation schemes it is in the interests of everyone that this important link, viz. the well-trained technical adviser, should also be appointed.

Thus the first and most important principle in irrigation is to saturate the total root zone to its field capacity. The number of morgen-inches that will be necessary for this purpose will depend on the soil type, i.e. its texture throughout the root zone, the depth of the root system of the crop concerned, the moisture content of the different soil layers before irrigation takes place, and the method of irrigation. In good orchard soils we can assume that the most important distribution of roots is found to a depth of 3 feet, but about two-thirds (by weight) of the roots is found in the 7–24-inch layer. The result is that the latter layer reaches the wilting-point before the third and fourth foot of soil. Although the trees will not yet suffer markedly from drought when the first 2 feet of soil have reached the wilting-point, it is advisable to irrigate then. In this way less water will be required to saturate the entire 3 feet of soil to its field capacity than when the deeper soil has also reached the wilting-point—probably 3 morgen-inches instead of 4.

The second principle with irrigation is not to irrigate a wet soil; in other words, to guard against over-irrigation. This mistake is made at least as often as under-irrigation. It means a wastage of water and thus a decrease in the *efficiency of irrigation*, by which is meant that percentage of irrigation water that is actually used by the crops for transpiration. An efficiency of 60 per cent. is considered good. The water that percolates through the root zone as a result of over-irrigation carries nutrients, especially nitrates, with it and thus the fertility of the soil is decreased and crops suffer as a result of it. Moreover, the deeper soil layers are usually subject to water-logging, hence to a lack of oxygen, if over-irrigation occurs, and thus root diseases may appear. The quality, and often also the quantity, of the crop may suffer as a result of over-irrigation.

The necessity for shallow cultivation (soil mulch) after irrigation will

depend on circumstances. Where irrigation water is limited all weeds should be destroyed by cultivation. Cultivation is also necessary in clayey soil types that are apt to form deep cracks on drying out. If these do not occur then shallow cultivation is not necessary after irrigation. Further details in connexion with the irrigation of orchards will be discussed in Chapter XXXIII.

CHAPTER XIX

THE CONTROL OF SOIL MOISTURE (*cont.*)

(*d*) DRAINAGE

BY land drainage we understand the removal of the superfluous or free water from the upper layers of the soil and thus a lowering of the water table. Free, stagnant water in the first 2–3 feet of soil is harmful to plant growth for several reasons. In such a case the soil pores are for the greater part, or sometimes wholly, filled with water, with the result that the soil contains little or no air. As a result plant roots and beneficial soil microbes cannot exist because they need oxygen for respiration. In orchard and vineyard soils which suffer from excess moisture during winter and spring the deeper roots of the crop die off. In the dry summer months such crops will be the first to suffer from drought because they cannot utilize the deeper soil moisture. Wet soils are also cold and difficult to till and undesirable weeds such as East Indian *kweek*, rushes, and reeds can be very troublesome. A second instance where drainage is necessary is in the reclamation of brak (alkali) soils when the excess of soluble salts must be removed from the root zone by flooding the soil. This aspect of drainage will be further discussed in Chapter XXII.

How excessive wetness originates

With our limited rainfall, a water table that is too high very seldom occurs in soils of the more or less level plateaux of the summer-rainfall area, so that drainage is here seldom necessary. Necessity for drainage occurs

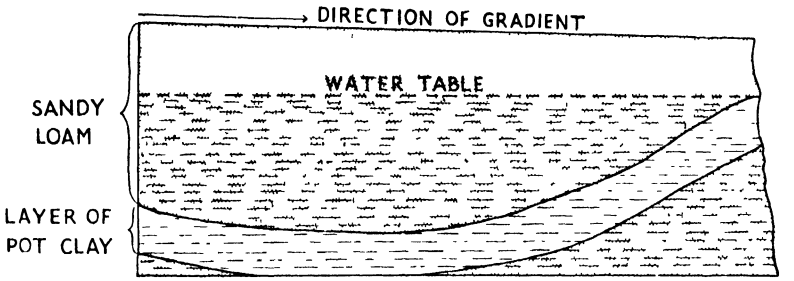


FIG. 13. Soil section indicating how a stratum of potclay prevents free water from draining away, thus giving a perched water table in a sandy loam in which drainage should be good.

much more commonly in the low-lying, more or less alluvial *vlei* soils of mountainous and hilly regions, especially in the coastal areas with a winter rainfall. In such cases a high water table is very often not so much the result of the actual rainfall on that particular soil, as it is the result of surface water and/or seepage from higher ground in the vicinity. Often springs and water veins are present in soils in marshy and level lands and

they are the cause of wet patches of soil. Sometimes a shallow stratum of potclay can be the cause of a temporary excess of water in the soil, especially if the potclay or some other impervious layer in the subsoil has the shape of a basin. Water will gather in such a basin and at its centre it will actually stand higher than the height of the potclay stratum.

In irrigated soils the water table may also often be too high on account of seepage of water from canals, or injudicious irrigation, or impervious layers as described above. Diverse soil conditions may be responsible for insufficient removal of rain and irrigation water from it and thus it is absolutely essential that the cause should be determined accurately before the soil can be drained efficiently. By sinking holes (pits) the nature and distribution of subsoil strata may not only be inspected, but the height of the groundwater table can also be determined accurately after heavy rains or irrigation.

Methods of soil drainage

There are two fundamentally different ways of removing superfluous water in and on soils: (*a*) open furrows or ditches and (*b*) closed or underground drains of which tile drains are the most important. Open ditches are necessary in cases where surface waters must be quickly removed. In South Africa open ditches always play an important role in the removal of superfluous water from wet soils because our heavy precipitation is usually limited to a certain time of the year. The chief aim, therefore, is to get rid of the excessive water quickly. On the other hand, however, cultivated soils should be well saturated with water during the rainy season because there is always a dry period in the year.

It has already been mentioned that a temporary excess in moisture may be due to run-off water from higher areas gathering in lower-lying areas. By diverting run-off and by constructing contour furrows on slopes, much can be done to regulate it. In this way lower-lying soil is not only prevented from becoming too wet, but higher-situated soil is moistened to a greater depth, thus becoming more productive.

The most important advantages of open ditches are that they are cheaper to construct, that they remove water on the surface faster, that they require less fall than underground drains (thus being almost the only type that can be used on very level soils), and that the soil itself is never excessively drained. The latter fact must be borne in mind, especially in a country like South Africa with its seasonal droughts. Open ditches, 3–6 feet deep, are common in the vineyards and orchards of the Western Cape Province.

Too many open ditches will, however, hamper efficient tillage, and weeds thrive in and along the banks of ditches so that they are a source of weed distribution. The result is that considerable sums have to be spent in keeping such ditches clean and in an efficient condition. Naturally open ditches usually also decrease the area of arable land. Finally, soils that are really wet cannot be drained effectively with open drains only. A certain minimum of open ditches is always essential in any drainage scheme, not only to cope immediately with flood-waters but also to receive the water from

underdrains. On a piece of land that is really marshy open ditches should first be constructed to remove a certain amount of the water because it is impossible to lay tiles properly in a soil that is very wet.

Underdrainage

The above-mentioned disadvantages of ditches do not exist in the case of underdrains, although the initial capital expenditure is much higher. Drainage by means of underdrains of some description or other is a very old practice in the improvement of agricultural soils. However, drainage by means of earthenware pipes or tiles only dates as far back as 1810 when James Graham applied it in England. To-day, especially in European countries, it is the most common method of land drainage. In South Africa tile drainage has only been applied widely since the beginning of this century. It was first used in the Western Cape Province.

Before we mention the different materials from which underdrains can be constructed it is necessary to note a few important points in connexion with underground drainage. Free water usually moves downwards, but in wet soils the deeper free water may be under considerable pressure so that it may also move sidewards and even upwards under certain conditions if it is given a way of escape. In drainage, use is made of these particular properties of free water in soils. Because the lateral movement of free water depends on pressure and because it is slower in clay soils than in sandy soils, the water table between two drains will never be on a level with the drains but will always have the appearance of an upward curve. The more clayey the soil is and the farther the drains are removed from one another, the higher will the curve be above the level of the drains.

The following diagrammatic representation of the vertical section of a soil layer between two drains illustrates the water table as well as the direction (arrows) in which water moves to the drains after the free water, immediately above the drains, has already been removed.

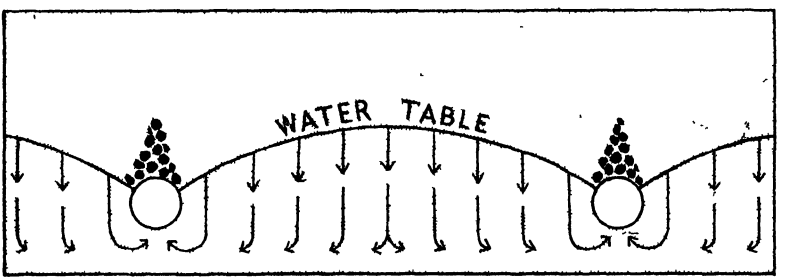


FIG. 14.

The depth of the drain below the surface of the soil will depend mainly on the kind of crop to be grown and on the nature or texture of the soil or soil layers. In the case of annual crops drainage to a depth of 3–4 feet is

usually sufficient, but the drains should be at least 5–6 feet below the surface for perennial crops such as fruit-trees, vines, and lucerne if the soil permits. The more sandy a soil is, the deeper the drains can be. The soil should be examined carefully for impervious strata. If a very thick layer of pot-

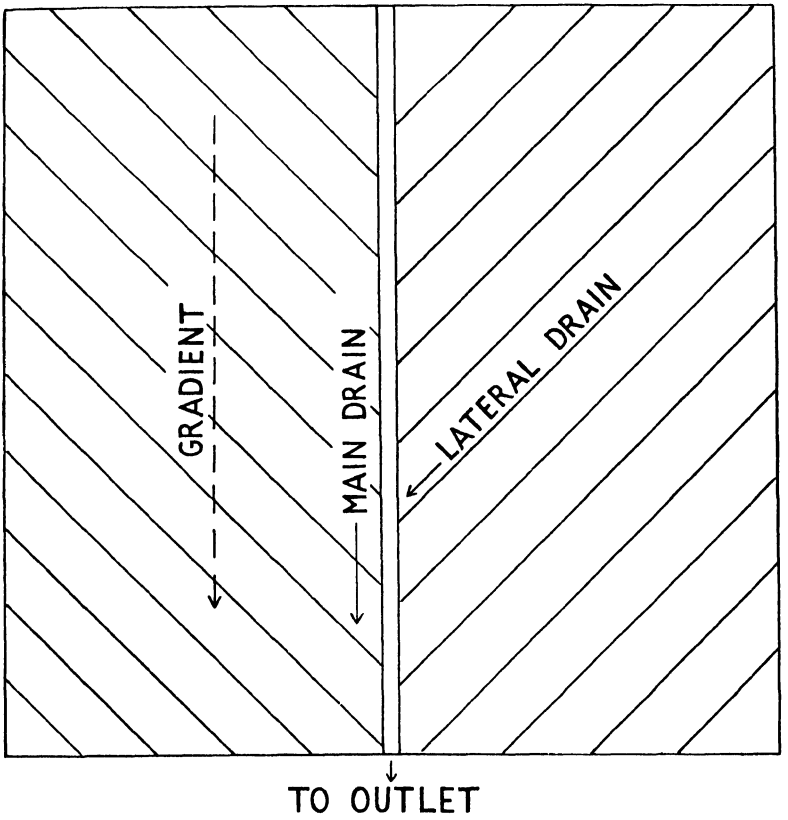


FIG. 15. Branched drainage system.

clay occurs it is almost impossible to drain such a soil effectively with tiles. If the layer of potclay is relatively thin, say 6 inches, and the soil below the clay is porous, the tiles may be placed below the layer of potclay or on a level with its lowest surface. In such a case care should be taken not to cover the tiles with the clay soil, but with a layer of coarse sand.

The distance between one row of tiles and the next will depend on different factors such as the texture of the soil, the depth of the drains, the amount of water to be withdrawn, the fall of the ground, and the kind of crop to be grown on the land. The soil texture and the nature of the clay are the two most important factors affecting the permeability of the soil to water. The distance at which drains should be placed apart at any

specific depth may be calculated by various, if somewhat complicated, formulae, but none of these is satisfactory. As a general indication the following figures may be used:

In sandy soils the drains may be 50–100 feet apart.

In ordinary loams the drains may be 30–50 feet apart.

In heavy loams the drains may be 15–30 feet apart.

In heavy clay soils the drains may be 12–15 feet apart.

In orchards the drains will usually be made in every other wide or diagonal row, unless the soil is very wet, in which case a drain in every row will be necessary. Orchards and vineyards are the most important plantations that are drained by means of underdrains in the Western Cape Province. The drains usually run parallel to one another and all run into an open ditch, across the bottom of the orchard or vineyard, which removes the seepage water. With other crops it is sometimes necessary to have a branched system of drainage consisting of a number of lateral drains or sub-drains that flow into a main drain. Many modifications of the branched system are possible, depending on the size of the land and the direction in which it slopes. The sketch on p. 149 indicates the usual form known as the 'herring-bone' system.

Materials that can be used in constructing underdrains

Faggots and brush are probably the materials that were first used for underdrains. A ditch is dug, a layer of branches, shrubs, &c., trampled into the bottom of the ditch, and the ditch is again covered with soil. At the lower end these drains run into open ditches. However, material of vegetable origin will rot relatively quickly in the soil unless it is constantly covered with water. Because drains in South Africa usually only function during the rainy season this system is not suited to our conditions. Nevertheless, *vine prunings* are often used in the Western Province in the drainage of vineyards. The shoots are placed either upright or flat, in ditches in the rows that are 4–6 feet deep and covered with soil. The more clayey a soil is the longer will such a drain be serviceable, but new drains must in any case be made periodically so that this system has almost the same disadvantages as open drains.

Wooden poles (Fig. 16 A) with a diameter of 3–8 inches and 1–2 feet in length can also be used for drains, but usually such drains do not last long

FIG. 16.

in South Africa. Even *pipe-calabash* has been used for drains in brak soils (Robertson) at a time when calabash pipes were in vogue. In ordinary soils they will not last long.

A very efficient drain can be made of *stones* provided the work is done with precision. When round stones are used the biggest are placed in the bottom of the ditch and the smaller ones on the top (Fig. 16 B). Still smaller stones and sand should then be placed on top of the previous stones before the ditch is covered up with soil. It is better still to use flat stones (Fig. 16 C and D), but the openings to the 'throat' should be closed with smaller stones which should be covered with a layer of coarse sand before the drain is filled with soil.

Cement pipes or tiles were, as far as is known, first used in South Africa (for land drainage) by the late Mr. F. J. Joubert, Paarl, in 1898. The tiles can be made on the farm by mixing $3\frac{1}{2}$–4 parts of sand with 1 part of cement, and it is maintained that their cost is about one-tenth of the cost of earthenware tiles.

One of two methods can be used in laying the drains. One of these is to make U-shaped tiles, about 1 foot in length. Two sections are then placed on top of one another, forming a circular opening of about 3–4 inches in diameter (Fig. 16 E). Another method is to make the bottom section of the cement tile directly in the ditch. The bottom of the ditch is first levelled and then a small furrow is made in the bottom of the ditch with an old shovel that has been bent into a spoon-shape. The furrow is now plastered out to a thickness of about half to three-quarters of an inch with cement mortar. After the cement furrow has set and dried the U-shaped section is inverted on it. This is done when the subsoil is still relatively dry, i.e. at the beginning of the rainy season. As a rule such a drain is more effective than one consisting of loose tiles because the bottom half cannot shift.

Laying of the cement tiles should be done with great precision. They should have a regular fall of at least 6 inches in 100 yards, i.e. 1 in 600, so that the flow of the water will be unchecked. Secondly, all the larger openings at the joints should be closed up with cement. Water filters through the smallest openings and if there are large openings, sediment will enter through them, clogging the drains. The last and, probably, the most important point is that a thick layer of coarse sand should be placed on the tiles before the ditch is filled up with soil. This will facilitate drainage, will prevent fine sediment from closing up the drains, and to a large extent it will also prevent plant roots from growing into the pipes and clogging them—a common occurrence especially with permanent crops. When drains do become clogged the dampness of the soil will indicate the position of the stoppage, and then the drain should be opened and the roots removed.

Earthenware tiles are made of burnt clay. They last the longest but are also the most expensive. The pipes or tiles are usually made in lengths of 12 inches with a diameter of 3, 4, 6, and 9 inches. In branch or lateral drains 4-inch tiles and in main drains 6-inch tiles are usually used. All the points mentioned in connexion with cement tiles are also applicable here except that the joints are not closed with cement because this is the chief

entrance for the water. With all tile drains it is further necessary that outlets in the open ditch be at least 1 foot above the high-water mark of the ditch and that a small concrete wall be built, through which the drain protrudes, so that the sides of the ditch cannot cave in. Sometimes it is essential that netting wire be placed over the outlets of the drains to prevent rats and mice from entering the drains and blocking them with their nests.

In conclusion it may be mentioned that the so-called mole-drainage, so commonly carried out in England in stiff clay, has, to our knowledge, nowhere been used in South Africa.

CHAPTER XX

THE CHEMICAL PROPERTIES OF SOILS

THE CHEMICAL ANALYSIS OF SOILS

In several of the previous chapters we have come across chemical compounds which occur in soil. The sum total of chemical substances in soils can be surprisingly large and in one and the same soil they may be subject to continual changes. Some of these substances influence, directly or indirectly, the nutrition of plants, and we now wish to pay special attention to these.

About 1840 the so-called mineral theory was expounded by Liebig, according to which plants absorb their raw nutrients from the soil in the form of mineral salts. Chemists then were of the opinion that the problem of soil fertility had been solved because in order to determine the fertility of any soil it would merely be necessary to analyse it chemically. It was soon realized, however, that the problem was far from simple and, in general, chemical analyses gave such unreliable results that this method was largely abandoned. In recent times, however, intensive research has again been made in this direction and to-day there are several methods that give more or less reliable information in connexion with the manurial requirements of soils. Field experiments still provide the standard measure or criterion by which the reliability of such analytical methods can be tested.

The greatest difficulty that the chemist has in analysing soils is that he cannot simulate accurately in the laboratory the method by which a plant extracts mineral nutrients from the soil. If we consider that the chemist aims at extracting or dissolving as much plant food from the soil within, say, one hour as the plant will absorb over a period of four to six months of growth under varying conditions of temperature, moisture, and air relationships in soils, we realize immediately that the problem is virtually beyond solution. In addition there are several other difficulties. The root systems of various crops are not identical and some are better able to utilize the plant foods in the soil than others. To what depth should the soil be analysed? What percentage of the total mineral food, absorbed from the soil by the plant, is taken from the topsoil, i.e. the depth to which the soil is ploughed? How would a high gravel content affect the analysis of the fine soil? These are a few of the many questions that we cannot answer definitely and in any case the answers would differ, depending on the depth and composition, both physical and chemical, of the soil.

It is no wonder that the scientist and the farmer resort to the piece of land in question and carry out careful fertilizer experiments on the land, under the prevailing climatic conditions, in order to determine the manurial requirements of the soil. Unfortunately difficulties are also encountered with such experiments, but they will be discussed later.

Chemical analyses have the advantage that they can be carried out relatively quickly and cheaply. The more such analyses are correlated

with the results obtained from fertilizer experiments, the more reliable will be the analyses of soils on which no experiments have been made. Chemical analyses are also very valuable in order to ascertain the general level of fertility of soils in new areas (soil surveys).

RESERVE PLANT FOOD

If a small amount of soil is shaken up in a flask with a large amount of water only about one ten-thousandth part will dissolve in the water. This is a fortunate circumstance, otherwise heavy rains would soon cause soils to lose their fertility. We therefore usually use stronger solvents than water when preparing soil solutions. The chemical analysis of soils can be carried out in many different ways, but all the methods can be divided into two main groups: (*a*) determination of the total or largest portion of the plant food present in soils, and (*b*) determination of only a small portion, the so-called 'available' plant food in soils.

Treatment of the soil with fairly concentrated, boiling *hydrochloric acid* and analysing the resultant solution or extract is an example of the first group. It is an old method which is still being used to-day, especially in the Union. It is easy to realize that the strong hydrochloric acid will dissolve far more plant food than a plant can absorb in one season or even in many years. The plant food determined in this way is called the 'reserve plant food'. A very small portion of this reserve can be absorbed by the crop during one growing season; unfortunately the analysis does not indicate how much this available portion is, with the result that usually we cannot tell with any certainty whether fertilizing is necessary or not. The chances are that if the reserve is high there will be sufficient available plant food for the crops for some years to come, and if the reserve is low there may not even be sufficient for one satisfactory crop. In the above-mentioned instances the hydrochloric acid method gives comparatively reliable information, although if the reserve is low we cannot say without further information what the quantitative manurial requirement is likely to be.

The actual nutrients determined in the hydrochloric acid extract are phosphoric oxide and potash and sometimes also lime and magnesia. However, it is desirable that the amounts of the other dissolved constituents should also be determined, especially the iron and aluminium, because that would give us some indication of the availability of the phosphate reserve.

The total nitrogen (in combined form) in a soil is not determined in the hydrochloric acid extract. It is determined by the Kjeldahl method whereby the soil is boiled with concentrated sulphuric acid.

Together with the chemical soil analysis, the percentage of hygroscopic moisture, the loss on ignition, and the soil reaction (degree of acidity or alkalinity) are usually also given.

In order to give an indication of the number of substances, &c., that are determined in such an analysis, the complete results of the following five types of soil are given:

No. 1 is a sandy soil derived from granite, Darling, C.P.

No. 2 is a gravelly, fine-sandy loam, formed out of Malmesbury Shale, Langgewens, Malmesbury, C.P.

No. 3 is a sandy loam that originated from Grotto-Sandstone (Stormberg-Series), Cambridge, Ladybrand, O.F.S.

No. 4 is (black) 'turf', formed from norite, Brits, Transvaal.

No. 5 is a reddish-brown clay loam, derived from dolerite, North Coast, Natal.

TABLE 15

Chemical Soil Analyses

	No. 1	*No. 2*	*No. 3*	*No. 4*	*No. 5*
Gravel (> 2 mm.)	2·0%	30 9%	5 0%	0%	1·2%
Hygroscopic moisture	0 37%	0·79%	1·05%	12·15%	4 00%
Loss on ignition	0 74 ,,	2·64 ,,	1·62 ,,	7 95 ,,	14·14 ,,
Insoluble matter	96·74 ,,	88·60 ,,	93 68 ,,	57·99 ,,	62·77 ,,
Dissolved Silica (SiO_2)	0·04 ,,	0·10 ,,	0 28 ,,	0 05 ,,	0·04 ,,
Dissolved Alumina (Al_2O_3)	1 05 ,,	2·72 ,,	1·82 ,,	13·49 ,,	10·19 ,,
Dissolved Iron oxide (Fe_2O_3)	0 69 ,,	4 03 ,,	2·36 ,,	9·55 ,,	13 19 ,,
Dissolved Lime (CaO)	0·06 ,,	0·18 ,,	0·30 ,,	1·97 ,,	0·42 ,,
Dissolved Magnesia (MgO)	0 14 ,,	0 45 ,,	0·12 ,,	0 45 ,,	0·24 ,,
Dissolved Potash (K_2O)	0 156%	0 331%	0·142%	0 248%	0·121%
Dissolved Phosphoric oxide (P_2O_5)	0·039 ,,	0·056 ,,	0·087 ,,	0·031 ,,	0·095 ,,
Total Nitrogen (N)	0·065 ,,	0·070 ,,	0·072 ,,	0·121 ,,	0 167 ,,
Soil reaction, pH	5·54	6·06	5·97	6·75	5·79

These soils are all slightly acid except the 'turf' soil (no. 4) which is almost neutral. It contains the largest percentage of lime (mostly absorbed by the clay colloids) but there is no free carbonate of lime.

The novice may be surprised at the high percentage of soil that is not soluble in strong hydrochloric acid. The insoluble residue consists of quartz, released silicic acid, and unweathered or semi-weathered silicates and other minerals. It will be noticed from the table that the two soils, nos. 4 and 5, which originated from basic igneous rocks, i.e. rocks that contain little free quartz, contain relatively low percentages of insoluble constituents.

The dissolved constituents, except the nitrogen, are, customarily, indicated as oxides, but it must be clearly realized that they do not occur as free oxides in the soil. They exist in other combinations, partially as salts, partially as hydroxides (iron and aluminium), and partially as absorbed cations (p. 80).

Experience has shown that potash, phosphoric oxide, and nitrogen are the three major plant foods that may be deficient in soils and hence may limit crop yields. As indicated previously the amounts of these substances which are soluble in concentrated acids bear no definite relation to the amounts available to plants, and hence no accurate deductions concerning the manurial requirements of the soil can be made. It is essential that we should make use of the results of fertilizer experiments on a similar soil

type, or at least of the practical experience of farmers who apply fertilizers to such soils. For South African conditions the following table may be used as a general guide in the case of analytical results obtained by boiling the soil in strong acids.

TABLE 16

Analytical Results as an Indication of Soil Fertility

Degrees of soil fertility	*Nitrogen*	*Phosphoric oxide*	*Potash*
I. Poor . .	Less than 0·05%	Less than 0 05%	Less than 0·075%
II. Medium .	0 05–0·10%	0 05–0·10%	0·075–0·15%
III. Fairly fertile .	0·10–0 20%	0 10–0·20%	0·15–0·30%
IV. Fertile . .	More than 0·20%	More than 0·20%	More than 0·30%

When the soil analysis indicates that the soil falls within the poor class (I) in relation to one or more of the major plant foods, it is almost always essential, even under extensive agriculture, to apply fertilizer containing the nutrient or nutrients in question.

When the soil is only of 'medium' fertility it is difficult to know, without further information, whether manuring will be worth while. The increase in yield or the improvement in quality may not be sufficient to warrant the additional expenditure. The closer the percentage figure of a particular plant food is to the next higher fertility grade (III), the less profitable will be the application of such a fertilizer to soils under extensive farming. On the other hand, the lower the percentage figure within the 'medium' range, the more likely it is that the crop will respond to such an application. Under intensive production, with favourable water relationships, soils of medium fertility will, as a rule, respond well to fertilizers. However, the manurial requirements of the crop concerned should also be taken into consideration; e.g. when a potato crop is grown on a soil with a medium quantity of potash, an application of a potassic fertilizer will pay, provided other growth requirements are satisfactory, whereas the soil would contain quite sufficient potash for winter cereals.

In general, soils which we classify as 'fairly fertile' will only respond to fertilizers if high yields of high quality are possible. For example, in the case of fruit-trees and vines it may pay to manure such soils with phosphate and potash in order to improve the keeping quality of fruit and grapes, thus procuring considerably higher prices for the products. Garden crops that can be irrigated, if the need arises, also require a very fertile soil so that high yields may be maintained. If the soil type falls in the 'fertile' class it is doubtful whether manuring will have any immediate beneficial effect on the yield.

Apart from the above views a few chemical and bacteriological aspects should also be taken into consideration in the interpretation of analyses.

Nitrogen in the soil is present almost exclusively in an organic form, viz. in the protein form, and as such it is not available to plants. A small and varying amount of this nitrogen will in time, say within a year, be changed to ammonium compounds and nitrates in which forms plants can use it.

Under favourable environmental conditions, such as sufficient moisture and air and a suitable temperature and soil reaction, the soil microbes may release in available form 2 or more per cent. of the soil organic nitrogen during the growth period of the crop, whereas, under very acid conditions, for example, the release of available nitrogen would be much slower.

Phosphoric oxide occurs in soils as phosphates (salts) of calcium, magnesium, iron, aluminium, &c., and also as organic compounds, e.g. in humus. If a soil is acid and is rich in iron and alumina and thus lacks calcium and magnesium, the phosphoric oxide is usually very unavailable to plants. Two soils may, therefore, have exactly the same phosphate reserve and yet differ greatly as far as the availability of their phosphate is concerned.

The texture of the soil is an important point to be considered in connexion with the *potash reserve*. If two soils have different textures but the same total potash content, a sandy soil will contain more available potash than a clayey one.

According to Table 16 the first three soils have a medium nitrogen content while the last two fall in the fertile class as far as the nitrogen is concerned. In fertilizer trials with winter cereals on soils 1 and 2 there was only a slight response to a nitrogenous dressing. The same applies for sugar-cane on soil no. 5, whereas potatoes showed a marked increase in yield on soil no. 3 as a result of an application of nitrogen. (The 'turf' soil was not taken from a field on which fertilizer trials had been carried out.)

According to our table, soils 1 and 4 would be poor in phosphate and the remaining three would be medium. These three, however, contain more iron and alumina than no. 1 and therefore it is probable that their phosphate reserve is rather unavailable. Fertilizer experiments actually showed that all four soils gave increased yields with phosphate applications. In comparison, no. 2 responded the least to applications of phosphate.

As far as the potash reserve is concerned, nos. 3 and 5 are medium, no. 1 fairly fertile, and nos. 2 and 4 fertile. On soils nos. 3 and 5 fertilizing with potash gave a good increase in yield with potatoes and sugar-cane respectively. Winter cereals did not respond to potash applications on soils nos. 1 and 2. In any case soils nos. 4 and 5 have a high clay content so that one can conclude that the potash reserve was relatively unavailable.

To sum up it may again be stated that to know the amount of reserve plant food in the soil does not help us to determine the amount available to the plant, nor to decide always whether fertilizer will be beneficial. This point may be illustrated by the following calculation:

Assume a soil sample taken from the top 6-inch layer of the soil to contain 0·04 per cent. of phosphoric oxide and the weight of 1 morgen of dry soil, 6 inches deep, to be 4,000,000 lb. The morgen of topsoil would then contain 1,600 lb. of phosphoric oxide as reserve supply. A good wheat crop of, say, 10 bags of grain per morgen will need about 24 lb. of phosphoric oxide for grain and straw. Yet we know from experience that if a soil contains 0·04 per cent. of phosphoric oxide an application of 400 lb. of superphosphate (containing about 70 lb. of phosphoric oxide) per morgen is

necessary, otherwise the yield will be about 4 bags of grain per morgen only. In other words, wheat plants are only able to utilize about 9 lb. of phosphoric oxide from the total quantity of 1,600 lb. In actual practice the state of affairs is still worse, because we may safely assume that the majority of the roots will penetrate deeper than 6 inches so that the phosphate reserve at the disposal of the crop will be still greater.

AVAILABLE PLANT FOOD

There are different ways to determine the so-called 'available' plant food in soils, but we will here discuss the citric acid method only because up to now it is the method that has been the most widely used. It was suggested in 1894 by Dyer (England). At that time botanists were of the opinion that plants secreted organic acids through their roots and that these acids dissolved mineral plant nutrients, rendering them available to plants. Dyer determined the acidity of the sap of roots of different families of plants, and found that the average acidity of the sap was more or less the same as that of a *1 per cent. citric acid solution.* He therefore concluded that the actual amount of mineral nutrients which can be absorbed by plants, can be determined by treating the soil with 1 per cent. citric acid solution. Usually this method is only used for the determination of phosphate and potash.

Although we no longer believe that organic acids, possibly secreted by plant roots, play any role in rendering plant nutrients available the method is still used. Experience has taught us that results obtained by extraction with citric acid give us at least a better indication of the immediate fertilizer requirements of the soil than, e.g., the hydrochloric acid method. Two soils may have the same phosphate reserve, and if one gives increased yields on applications of phosphate and the other not, we usually find that the former contains considerably less available phosphate (as determined by the citric acid method) than the latter.

The amount of available plant food, as determined by the citric acid method, is still appreciably greater than the amount that the plants can actually absorb during one growing season. This is mainly due to the fact that plant roots can never come into intimate contact with every soil particle during one season, whereas, if a small amount of soil is shaken up in a large amount of citric acid solution for a considerable time, every particle is subjected to the dissolving action of the acid. Evidently there is a fairly constant ratio, for every soil type, between the amounts of phosphate and potash that are available to plants and that are assimilable during one season. This ratio we may call the 'assimilable coefficient' and it is the amount of plant food that plants can absorb, divided by the amount of available plant food and multiplied by 100.

In Germany it is assumed that in sandy loams about 6 per cent. of the 'available' phosphate and 50 per cent. of the 'available' potash can be utilized by winter cereals during one growing season. As yet we have no reliable figures in South Africa. They would be of great practical value. If the assimilable coefficients for our most important soil types and crops

were known, more accurate deductions could be made from analyses indicating the amount of available plant food, and this would greatly aid us in our advice concerning the manurial requirements of soils. The five soils previously tabulated contained the following amounts of available phosphoric oxide and potash:

TABLE 17

	No. 1	*No. 2*	*No. 3*	*No. 4*	*No. 5*
	%	%	%	%	%
Available Phosphoric oxide (P_2O_5)	0·0018	0·0023	0·0019	0·0006	0·0005
Available Potash (K_2O) . .	0·0173	0·0175	0·0168	0·0079	0·0162

Because the assimilable coefficient of the available phosphate and potash supplies in our most important soil types is still unknown, it is difficult to give marginal figures for the available amounts above which manuring would be unnecessary, and below which fertilizers should be applied. In the case of winter cereals and maize the following provisional figures may be used as a probable margin: 0·0075 per cent. available phosphoric oxide and 0·0025 per cent. available potash. According to this criterion all five soils are very deficient in phosphate but they contain sufficient potash for grain crops. For potatoes, sugar-cane, and other crops requiring more potash, a considerably higher margin should be used for potash. The amounts of available phosphoric oxide and potash in these soils should, furthermore, be compared with the conclusions of our previous discussion.

In the case of nitrogen the question of availability is more complicated. It has already been mentioned that most of the nitrogen reserve in soils consists of proteins, a small portion of which (perhaps about 2–3 per cent. per annum) is annually changed by soil microbes to ammonium compounds and nitrates. In a certain sense the nitrates are the end-products of these microbial changes. They are soluble in water and hence are available to all plants. Thus if we determine the amount of nitrogen present as nitrates in a soil at any given time, we also know exactly how much available nitrogen the soil contains.

The trouble here is that the nitrate content of the soil can fluctuate almost from day to day because it is a product of the activities of soil micro-organisms, and their activities are influenced by so many varying conditions. Furthermore, nitrates are not retained in the soil, but can be leached from the topsoil during continuous rains. The result is that the available nitrogen content of soils is dependent on climatic conditions, soil types, and systems of rotation to a much greater extent than are the available phosphate and potash.

Generally, the available nitrogen in soils is not determined. The total amount only is determined. Climatic conditions, soil type, and the nitrogen requirement of the crop will determine the application of nitrogenous manures. Nitrification studies and fertilizer experiments will give us more definite information in connexion with such applications.

CHAPTER XXI

SOIL ACIDITY

ACIDS are defined by chemists as substances which produce hydrogen ions when dissolved in water. Hydrochloric acid molecules consist of hydrogen atoms (H) and chlorine atoms (Cl) in the ratio of 1 : 1 so that the formula for hydrochloric acid is HCl. When hydrochloric acid is dissolved in water, as is the case with ordinary hydrochloric acid, its molecules dissociate into ions and this change is written as follows:

$$HCl \rightarrow H^{+} + Cl^{-}$$

A Hydrochloric acid molecule dissociates into Hydrogen and Chlorine ions.

Every hydrogen ion is positively charged and every chlorine ion is negatively charged. Thus an ion differs from an atom in that it is electrically charged.

The number of hydrogen ions in a given volume of water, say 1 litre, determines its acidity. Thus, we say that the *hydrogen-ion concentration* is a measure of the active acidity of a substance when dissolved in water. The actual acidity, therefore, depends on the amount of hydrogen ions liberated by 'dissociation' of the molecules and not by the amount of hydrogen in the molecules. Strong acids such as hydrochloric acid, sulphuric acid, and nitric acid produce many hydrogen ions, whereas weak acids such as carbonic acid and many of the organic acids produce relatively few hydrogen ions in an aqueous solution.

An ordinary acid may be recognized by its taste, but the determination of the presence and quantity of hydrogen ions is an infinitely more accurate test. For example, a moist, acid soil will not have a sour taste—there are too few hydrogen ions for that test—but the concentration of such ions may be high enough to hamper seriously the development of plant roots and soil microbes.

To-day there are many accurate methods by which even a very low concentration of hydrogen ions can be measured. It can either be done with a weak electric current or with the aid of certain indicators which change colour at a certain degree of acidity. The best-known indicator that has been used for a considerable time in qualitative tests of this nature is litmus in the form of litmus-paper (the colouring matter is absorbed in porous paper). Such a strip of litmus-paper turns red when dipped into an acid liquid and blue when dipped into an alkaline liquid. In the case of soils the litmus test can be carried out as follows:

About a teaspoonful of soil is placed in a clean crucible (or saucer) and flattened slightly. A strip of blue litmus-paper and a strip of red litmus-paper are then placed next to one another on the soil. (Litmus-paper may be obtained from a chemist's shop.) Another teaspoonful of soil is put on top of the paper strips. Their ends should protrude. The soil is then moistened well with distilled water or clean rain-water. After half an hour

the strips are removed and washed with distilled water. They should now have more or less the same colour; either reddish-pink (an acid or sour soil) or bluish (an alkaline soil). If the litmus has a colour that is in between red and blue we say that the soil is neutral, i.e. it is neither markedly acid nor alkaline. The intensity of the colour indicates to a certain extent whether the soil is very acid or very alkaline. If the soil is found to be very acid or alkaline it is advisable to send representative samples to a well-equipped laboratory where the soil reaction can be determined accurately and cheaply within a very short time.

By 'soil reaction' is understood the condition of the soil in respect of its acidity or alkalinity. Alkalinity is the opposite to acidity. While acidity is characterized by an excess of hydrogen ions (H^+) in the liquid, the concentration of which decides the degree of acidity, alkalinity is characterized by an excess of hydroxyl ions (OH^-). Caustic soda is a typical example of a substance with an alkaline reaction. When caustic soda (sodium hydroxide) is dissolved in water the change that takes place can be written as follows:

$$NaOH \rightarrow Na^+ + OH^-$$

Sodium hydroxide dissociates into Sodium and Hydroxyl ions.

In an aqueous solution there are always hydrogen ions as well as hydroxyl ions and the 'reaction' is determined only by the excess of the one over the other. When the hydrogen ions predominate we have an acid reaction and when the hydroxyl ions predominate the liquid will be alkaline. Finally, if there are as many hydrogen ions as hydroxyl ions the liquid will be 'neutral'. These facts in connexion with reactions should be well remembered.

We have seen that an acid or sour soil contains an excess of hydrogen ions. How must we picture to ourselves their presence in soils and how does acidity originate in soils? These questions are not so easy to answer in simple language, but we shall try to explain the essential details.

There is always a certain amount of carbonic acid in soils because carbon dioxide is a product of the respiration of roots and soil microbes, and a certain amount of the carbon dioxide dissolves in and combines with water.

$$CO_2 + H_2O = H_2CO_3$$

Carbon dioxide and Water give Carbonic acid.

However, carbonic acid is a very weak acid. According to the above explanation that would mean that carbonic acid molecules only dissociate into ions to a small extent. Those molecules which actually do dissociate do it as follows:

$$H_2CO_3 \rightarrow H^+ + HCO^-_3$$

Carbonic acid dissociates into Hydrogen and Bicarbonate ions.

The concentration of the hydrogen ions formed in this way is never high enough to harm plant growth. Yet these hydrogen ions cause the *solid* soil particles also to become potentially acid, and then the matter is more serious.

In order to understand the cause of an acid condition in soils we must refer to what was said under cation absorption (p. 80). We saw that the soil colloids, consisting mainly of clay and humus, usually have five different major cations (i.e. ions with positive electric charges) absorbed on their surface: hydrogen, calcium, magnesium, potassium, and sodium. An acid soil is characterized by the fact that hydrogen predominates among the absorbed cations. The larger the proportion of hydrogen ions to the other four, the more acid is the soil. If the ions of calcium (and magnesium) predominate the soil will be slightly acid, neutral, or slightly alkaline. If the ions of sodium (and potassium) predominate, we usually have a very alkaline soil (black alkali soils).

The colloidal clay and humus particles (see diagram (*a*), Fig. 5, p. 81) can, therefore, be considered as complex acid molecules in the case of acid soils and for the sake of simplicity we will call them clay acids and humic acids. It should be borne in mind, however, that in the case of arable soils such colloids will always contain small amounts of calcium, potassium, &c., as well. We shall confine our discussion to clay. More or less the same phenomena are shown by humus.

As long as the hydrogen on the clay does not appear in the soil moisture, viz. as hydrogen ions, the clay acid does not exhibit its acidity. The peculiarity of clay acid is that it produces very few hydrogen ions in pure water, in other words, it is a very weak acid. However, soil water is never quite pure. It always contains a small amount of dissolved salts and that is where the trouble starts. We saw on p. 81 that the absorbed cations can be replaced by cations from the soil solution, and it is this replacement or exchange that can acidify the soil moisture. Imagine the soil moisture to contain potassium chloride which we may have applied to the soil as a fertilizer. The following exchange may then take place:

$$\text{Clay}-\text{H}+\text{K}^+ + \text{Cl}^- \rightleftharpoons \text{Clay}-\text{K}+\text{H}^+ + \text{Cl}^-$$

Clay acid and Potassium chloride give Potassium clay and Hydrochloric acid.

In an aqueous solution potassium chloride very easily dissociates into its ions, potassium (cation) and chlorine (anion), and similarly the hydrochloric acid molecules that are formed as a result of the exchange are dissociated into their ions, hydrogen and chlorine. In this way the soil moisture becomes markedly acid whereas the clay acid would not render pure water really acid.

The composition of the soil is very complex and this cation-exchange is constantly taking place. The most important point to remember is that if *the soil colloids are saturated mainly with hydrogen, the soil moisture* will also contain many hydrogen ions; in other words, it *will be acid.* If the nature of the climate and soil type are such that leaching occurs to any extent, the soil will gradually become more acid unless lime is applied periodically. This is because hydrogen ions are produced by the carbonic acid (and also other acids) that is present in the soil solution and the hydrogen ions replace absorbed metallic cations (bases), mainly calcium,

from the colloids. The liberated metallic cations can then be leached from the soil during heavy rains. The change can be represented by the following equation:

$$\text{Clay}-\text{Ca}+2\text{H}^{+}+2\text{HCO}^{-}_{3}\rightarrow\text{Clay}-\text{H}_2+\text{Ca}(\text{HCO}_3)_2$$

Calcium clay and Carbonic acid give Hydrogen clay and Calcium bicarbonate.

It has been known for a considerable time that seepage waters from soils contain relatively large amounts of calcium salts, especially bicarbonates and nitrates. Hydrogen is thus retained by the clay and it can again be replaced, rendering the soil moisture acid.

Thus soil particles (colloids) are deprived of their basic substances under high rainfall conditions, and these bases are replaced by hydrogen. In a humid climate the farmer should aim at putting back basic substances into the soil regularly—lime and basic fertilizers—in order to compensate for this loss of bases by leaching and plant nutrition. In this way the absorbed hydrogen is again replaced and rendered harmless.

WHERE ARE ACID SOILS FOUND?

It is clear that the chances for soils to become acid increase as the annual rainfall increases. Soils of humid areas are subject to leaching and as a rule they are sour. On the other hand, soils in arid regions are not only not acid, but an accumulation of salts may occur, thus rendering them brak. In South Africa the soils of the southern and eastern coastal areas, of the Eastern Free State, and also of a large part of Transvaal and Natal are moderately and, sometimes highly, acid.

Apart from the climate the soil texture is also important in this respect. It is easy to realize that under the same precipitation sandy soils will be subject to greater leaching than loams and clay soils which have a higher water-holding capacity. The result is that sandy soils are usually more acid than the heavier soil types under the same rainfall conditions. Finally, the farmer can either augment or check the acidification of his soil by his manurial practices and systems of crop rotation.

DEGREES OF SOIL ACIDITY

Scientifically it is not sufficient just to say that a soil is very acid or slightly acid. There must be an objective standard by which the acidity can be measured. From the previous discussion it is clear that we must differentiate between the hydrogen ions that are retained by the *solid soil particles* and those that are present in the *soil solution*. The actual or active acidity which primarily affects the development of plants and soil microbes depends on the hydrogen-ion concentration in the soil solution. This can be determined by different methods.

The degree of acidity of the soil solution is to-day commonly expressed in terms of 'pH'. According to this scale the hydrogen-ion concentration *in any solution* can vary from 1 to 14. These figures are totally misleading to the uninitiated in that they are negative powers of 10 so that 1 indicates the highest concentration and 14 the lowest.

A neutral solution is a solution containing equal quantities of hydrogen ions (H^+) and hydroxyl ions (OH^-) and its pH is 7; the more acid, the smaller will the figure be. An alkaline solution has a pH of more than 7; the more alkaline, the higher the figure. For soil reactions the pH scale may be interpreted as follows:

pH 3·0 – 4·5 = exceedingly acid.
„ 4·5 – 5·5 = markedly acid.
„ 5·5 – 6·5 = slightly acid.
„ 6·5 – 7·5 = more or less neutral.
„ 7·5 – 8·5 = slightly alkaline.
„ 8·5–10·0 = very alkaline.

Soils with an acidity of more than pH = 3 and an alkalinity of more than pH = 10 very seldom occur.

The amount of hydrogen held by the solid particles (clay and humus) can also be determined, and in a scientific investigation of the soil it is necessary to do so. The pH also gives us an indication of the so-called *lime requirement* of soils, provided we take the amount of clay and humus in the soil into consideration.

THE PRACTICAL IMPORTANCE OF THE SOIL REACTION

For practical agriculture it is important, for at least three reasons, that the soil reaction, i.e. the degree of acidity or alkalinity, should be known.

(1) The growth of agricultural crops is influenced to a large extent by the soil reaction. In the light of our present knowledge agricultural crops may be divided into two groups from this point of view:

(*a*) *Acid-tolerant crops*: oats, rye, maize, potatoes, sugar-cane, the most important fruit-trees, vines, tobacco, cotton, pine-apples, peanuts, cowpeas, water-melon, &c.

(*b*) *Acid-sensitive crops*: wheat, barley, mangels, sugar-beet, fig-trees, cabbage family, lucerne, clover, peas, beans, onions, musk melon (cantaloup), &c.

In the case of acid-sensitive crops the soil should have a pH that is higher than 5·5, or, better still, 6·0. With a pH lower than 5·5 the soil should be limed or, under a system of extensive farming, basic fertilizers should be used instead of acid or neutral fertilizers. Acid-tolerant crops still grow well on soils with a pH of about 5·0 and even less; but in general it is advisable, for other reasons, to lime any soil with a pH of less than 5·0.

As far as alkalinity is concerned our knowledge of the margin beyond which growth is adversely affected is limited. However, in general we can say that the acid-tolerant crops do not grow well on soils that are rich in calcium and very few agricultural crops will grow if the alkaline reaction is above pH = 8·5.

(2) Microbial activity is also influenced by the soil reaction. In general, bacteria are sensitive to acidity. For their maximum development they prefer a soil reaction which is similar to that for acid-sensitive crops. The activities of microbes will be discussed in a subsequent chapter.

(3) A knowledge of the soil reaction is also essential in order to be able to make the best choice of fertilizers. On soils with a high acidity we should use nitrate of soda, basic slag, basic superphosphate, and even raw rock phosphate instead of superphosphate and ammonium sulphate. The use of lime will later on be discussed in full. In general, it is not advisable to apply more than 1–2 tons of lime per morgen at a time. If the soil is very acid, applications should rather be repeated in subsequent years. A deficiency in any of the trace elements occurs commonly on an alkaline soil, especially if the humus content of the soil is low.

CHAPTER XXII

BRAK SOILS AND THEIR RECLAMATION

PROPERTIES AND CLASSIFICATION OF BRAK SOILS

THE characteristic property of nearly all brak (alkali) soils is that their clay portion is largely saturated with sodium ions. It is then called a 'sodium clay' although it may still contain considerable quantities of other cations (see diagram *c*, Fig. 5, p. 81). A second characteristic of brak soils is that they usually contain considerable quantities of water-soluble sodium salts such as sodium chloride (common salt), sodium sulphate (Glauber's salt), and sometimes also sodium carbonate (washing-soda). The harmful effects of these salts on plant growth are due to the fact that the soil solution may become too concentrated as a result of their presence, and agricultural crops are not adapted to such a high concentration. The protoplasm of the plant cells shrinks (plasmolysis) if the salt concentration of the plant food solution is too high, with the result that the plant dies.

When sodium carbonate (soda) is present two other very undesirable conditions obtain. Firstly, a soil solution containing a large amount of soda has a very alkaline reaction; the pH is usually higher than 8·5 and few plants can tolerate such a reaction. Secondly, the physical properties of the soil become very unfavourable for plant growth. The fine soil particles are in a deflocculated condition with the result that the soil is structureless. Such a soil is very compact, does not absorb water easily, and if it does become wet it remains wet for a long time; it is badly drained and hence also badly aerated. Apart from this, the soil expands considerably when it is wet and big cracks are formed when it dries out. These are all typical properties of a sodium clay which is in a deflocculated condition. However, if the soil contains much sodium chloride and sodium sulphate the clay will remain granular, i.e. flocculated, and in such cases it is mainly the high salt concentration that is harmful to plant growth.

We have already mentioned that *water relationships* and *aeration* may be very unfavourable for plant growth in brackish soils. However, it is necessary that this aspect of the brak question should receive special emphasis because usually it receives so little attention. Dr. J. J. Theron[1] (Pretoria University) has supplied some very interesting data in this connexion for some citrus orchards in the Sundays River valley (C.P.). As a result of saline irrigation water the soils of many of the groves have become considerably brak, and in the spring of 1931 the trees relatively rapidly started losing their leaves on a large scale. An intensive study of the trouble revealed that in many cases the brak content of the soil had reached a dangerous concentration, but that this, in itself, could not be adequate reason for the extensive defoliation of the trees. Briefly, the finding was

[1] J. J. Theron, *Alkali and Irrigation Studies with Citrus Trees in the Sundays River Valley*, University of Pretoria, Publication No. 40 (Agricultural Series), 1937.

that the salinity impaired the structure of the subsoil to such an extent that when the soils were irrigated they contained so little air that the roots of trees could hardly penetrate beyond a depth of about 24 inches. This shallow root system, especially in a brackish soil, meant that trees *soon suffered from drought* in spite of the fact that the subsoil had not by a long way reached the wilting-point. Furthermore, we must always bear in mind that a brak soil contains much more 'dead water' than a brak-free soil of the same texture.

Brak soils may be divided into two classes:

1. *Saline Brak* (formerly known as 'White Brak' or 'White Alkali'). This type of soil contains an excess of sodium chloride or sodium sulphate or both. The clay portion may consist mainly of a sodium clay, but the soils have a good structure and the high salt concentration is the most important impediment to plant growth. Gypsum soils and even calcareous soils may also be considered as types of saline brak, but most crops still grow well on them. Only magnesium-containing saline brak (which seldom occurs) is very harmful.

2. *Alkaline Brak* (formerly known as 'Black Brak' or 'Black Alkali'). As indicated by the name a high, harmful, alkaline reaction is one of the characteristics of this type of brak. The clay portion consists of deflocculated sodium clay which is responsible for the undesirable properties mentioned above. Furthermore, the soil always contains a larger or smaller quantity of sodium carbonate but never a large amount of the salts mentioned under 1. An alkaline brak soil is totally unsuitable for plant growth.

In connexion with saline brak soils, the extent to which they can be cropped will depend on their salt content and hence the tolerance of the crop concerned for such a high salt concentration in the soil solution. In connexion with the salt content the Division of Soils in Pretoria gives the following limits:[1]

A. Soils that contain on an average more than 0·55 per cent. of soluble salts to a depth of 8 feet are unsuitable for almost all crops.

B. Soils that contain 0·35–0·55 per cent. of soluble salts to a depth of 8 feet will only be suitable for the production of crops that are very tolerant of brak, such as mangels, barley, sorghums, sugar-beet, cotton, lucerne, fig-trees, and olives. It is desirable that these soils should be irrigated heavily before planting so that the salts may be washed into the deeper soil layers to some extent, because young plants are more sensitive to brak than older plants.

C. Soils that contain 0·15–0·35 per cent. of brak salts to a depth of 8 feet can be cropped profitably provided two points are taken into consideration. Crops that are very sensitive to brak, such as peach- and orange-trees, should not be planted, and, secondly, tillage and irrigation of the soil should be carried out judiciously. When the soil is irrigated this should be thorough, and immediately the top layer of the soil is somewhat

[1] Instead of four limits the Division to-day differentiates between eight soil types and, furthermore, the pH of the soil is taken into consideration.

dry it should be loosened. As a result of this, salts will remain more evenly distributed throughout the deeper soil layers and a dangerous accumulation of salts in the topsoil as a result of evaporation will be prevented.

D. Soils which contain on an average less than 0·15 per cent. of salts to a depth of 8 feet are suited to almost all crops, but here also irrigation and tillage should be carried out with judgement in order to forestall trouble. It is easy to realize that even such soils may still contain enormous amounts of salts if we consider that a salt content of 0·10 per cent. to a depth of 8 feet constitutes a total amount of about 32 tons per morgen.

One drawback in connexion with this classification is that salt-containing layers often occur in certain depths. The topsoil and deeper subsoil may be almost free from salts, but, at the 2-foot layer, say, a stratum of brak may occur. Such a soil can be very dangerous, although the total salt content calculated on the entire 8 feet may be less than 0·2 per cent. Thus, the classification should only be used as a general guide and every individual case should be treated according to its specific findings. In any case the composition of the clay fraction should always be determined.

ORIGIN AND OCCURRENCE OF BRAK SOILS

Brak salts in soils may originate from three sources:

1. *Sea winds*, blowing inland from the sea, always carry fine salt particles and these may settle on the land in a purely mechanical way or, dissolved in water, they may be brought to the soil by rain or mist. In general, the nearer to the sea the greater the supply of salt via the air. If such an area has a low rainfall and/or if the soils are not very permeable, the salt supply may be larger than its leaching from the soil and in the course of centuries the soil may become completely brak. Undoubtedly the brak salts that are present in the 'hardpan' and in other soils of the north-western coastal area of the Cape Province originated in this way, although in some cases near the coast it is also possible that the present dry land was once periodically flooded with sea-water.

2. *Products of the weathering of rocks.* Only sedimentary rocks may be so rich in soluble salts that on weathering to soil material they may cause an accumulation of salts under low rainfall conditions. The present surface of South Africa consists mainly of sedimentary rocks, some of which are fairly rich in soluble salts, such as the Dwyka Series, the Malmesbury shale, and the Enon conglomerate (Worcester–Robertson). On account of the low rainfall in many of the districts in which such rocks occur, the salts remained to a large extent in the original soils. However, usually the quantity of the salts is too low to render the whole area brak, but flood and seepage waters, during and after rains, transport these salts from higher- to lower-lying areas where the water evaporates and the salts remain behind. In this way brak soils originate in the ravines, valleys, and basins of such areas, and even salt pans may form in this way. In some localities, e.g. in the districts of Malmesbury and Piquetberg, the salts originated from the sea as well as from the weathering of the mother rock.

3. *Brak irrigation water.* Some geological formations such as the Dwyka, the Bokkeveld shale, the Uitenhage Series, and the Enon conglomerate contain brak subterranean waters. If water from boreholes in such formations is used for irrigation, the soils may eventually become completely brak. Brak water is responsible for the fact that many orchard and garden soils in Karoo towns and on farms have become brak. When main canals of big irrigation schemes run through saline soil layers and the canals are not rendered impervious with cement, lower-lying alluvial soils may be ruined by brak seepage waters. This has often occurred in South Africa, e.g. along the Olifants River (Van Rhynsdorp). The main canals cross hardpan which is impregnated with brak salts and, by seepage, lower-lying alluvial soils have become completely brak in certain patches.

Saline brak soils usually occur only in regions where the rainfall is very low and especially where the subsoil contains a layer of impervious clay. It is also in such areas that irrigation is practised on a large scale if enough irrigation water is available. Thus it is small wonder that most irrigation schemes are confronted with the brak problem. Sometimes brak patches appear on non-irrigated lands after a series of abnormally dry years, and then they disappear again when a series of wet years follows (south-western districts of the Cape Province). This brak no doubt originates from saline layers deep down in the soil.

As far as the alkaline brak is concerned it probably occurs in South Africa only when saline brak soils are reclaimed in the wrong way. It has been proved beyond doubt that, if a saline brak soil with a sodium clay is irrigated too heavily with pure water so that the bulk of the salts is eventually washed out, alkaline brak will result. The sodium clay is deflocculated and the soil exhibits all the undesirable properties which we mentioned under alkaline brak.

THE RECLAMATION OF BRAK SOILS

The policy of the Government since about 1920 has been to withhold approval of any state-sponsored scheme until the soils of such an irrigation area have been examined carefully. In the survey special attention is paid to the depth of the soil and the occurrence of brak. If the investigation reveals that there is a danger that the soil may become brak to any extent under irrigation, the scheme is not attempted. The reclamation of brak soils is a difficult and expensive matter. We shall only discuss the most important points in this connexion.

The first requirement in the reclamation of brak soils is to know the exact composition of the soil, the nature of the subsoil, and the origin of the brak. Thus holes must be sunk, drainage in the subsoil inspected, the brak content must be determined, and the clay fraction of the soil should be analysed. Soil analyses, therefore, are necessary. However, the following preliminary test may give us much information in connexion with the nature of the brak soil. Divide a representative sample of brak soil into two portions of, say, 50 gm. each. Add enough pulverized gypsum (calcium

sulphate) to cover the point of a knife to the one portion and mix well with the soil. Add 200 c.cm. of pure water to each soil sample in a glass beaker, stir and pour into a funnel with filter-paper. After the water has filtered through, the soil on the filter should be washed well with pure water several times. It will be noticed that the soil treated with gypsum gives a clear filtrate even if it is washed many times. With the untreated soil one of two things will happen. Either the water will run through turbid very soon or it will remain relatively clear after several washings. In the first case we have a sodium clay which begins to deflocculate and to run through turbid as soon as the free, soluble sodium salts have been removed by the water. This proves that the soil would not be improved by irrigation and drainage, because such a soil would thereby change into the alkaline brak type and hence become worse. If the water remains clear even though no gypsum was added, the experiment proves that the clay portion is mainly a calcium clay, and that such a soil can be freed of its brak salts by irrigation and drainage and thus be changed into a productive soil.

Our first object when improving brak soils containing a large proportion of sodium clay is to convert that clay into a calcium clay. This may be done by applying finely ground gypsum and working it into the soil before irrigation and drainage. The required amount of gypsum usually amounts to several tons per morgen. Because gypsum is only slightly soluble in water (about 1 in 400) some soils will acquire a hard cement-like top layer after irrigation and drying out. Recent research abroad has shown that in such a case it is better to use less gypsum, and some potassium sulphate instead. This potash fertilizer is readily soluble, and the deeper soil layers especially will improve much faster than when gypsum only is applied. Evidently the potassium clay acts somewhat differently from the sodium clay, and also brings about a granular structure in soils.

Instead of gypsum, ground limestone may also be used in improving brak soils, but it acts very slowly unless large amounts of farm manure are applied at the same time.

The application of fresh or semi-rotted organic materials such as chaff, rotted straw, and manure mixed with much straw is, in any case, very beneficial to brak soils, because the soil is loosened in this way so that brak salts can be washed down more easily. The carbonic acid formed from the rotting straw and manure also facilitates the chemical changes that should take place in such a soil.

Where farmers wish to improve brak patches in their orchards, vineyards, and other arable lands, a large amount of stable manure and rotted straw should be ploughed in, and immediately afterwards a few tons of gypsum or agricultural lime per morgen should be broadcast and worked into the soil. This should be done at the beginning of the rainy season, and also, if possible, a few deep ditches should be made to remove saline seepage water from the patches. During the dry season it is desirable that the soil should be covered with a layer of straw to minimize the evaporation of water and the consequent rising of salts.

Where irrigation is possible the same procedure is adopted. First gypsum and stable manure are added before the soil is leached. In any case, provision for the removal of brak salts should always be made, and this may be the most expensive item in the reclamation of brak soils and one that is the most difficult to carry out.

By growing brak-resistant fodder crops such as mangels, sugar-beet, and even salt bush (*Atriplex* species) many of the saline ravines and brak spots that are now useless can provide valuable fodder and pasture. In many cases it will even be possible, by deep tillage, gypsum applications, irrigation, and drainage, to change such places into profitable lucerne lands.

CHAPTER XXIII

SOIL MICRO-ORGANISMS AND THEIR ACTIVITIES

WE are all acquainted with a large number of inhabitants of the soil such as earthworms, ants, termites, snails, spiders, millipedes, as well as bigger animals such as moles, ant-bears (*erdvark*), and 'jumping hares'. They are organisms that are visible to the naked eye, and their effect on the soil is also more or less visible. Of infinitely greater importance to soil fertility, however, are the activities of microscopically small living organisms of which vast numbers are present in every thimbleful of moist soil. Because they are so small they are called micro-organisms or, briefly, microbes. When the word microbe is used one usually thinks of disease germs. But the vast majority of soil microbes are faithful assistants of the agriculturalist. Thus it is essential that he should have some knowledge of their activities. The study of soil microbes dates back as far as about 1880 only, but to-day it is a comprehensive section of soil science.

GROUPS OF MICRO-ORGANISMS

Four groups of micro-organisms are considered to be important in connexion with soil fertility.

1. *Bacteria* are unicellular plant organisms, about one-thousandth of a millimetre (1/25,000 of an inch) in size. They contain no chlorophyll. Soils contain dozens of different kinds of bacteria, but viewed through a microscope their appearance is so similar that one can only differentiate between about half a dozen forms. The two most important shapes are (1) more or less spherical (cocci) and (2) rod-shaped or oblong (see Fig. 17). A characteristic of many rod-shaped bacteria is the presence of a definite number of flagella (one or more) with which they propel themselves in a liquid. Propagation of bacteria takes place simply by fission by which one individual divides or splits into two. If we consider that, under favourable conditions, such division may occur every half an hour it is no wonder that millions of individuals may originate from a single bacterial cell within a period of twenty-four hours.

Bacteria may, for example in a very dry soil, exist in a passive condition brought about by a thickening of the cell walls, and in this condition they can survive unfavourable conditions for years. This property is important for the existence of bacteria. Some forms of bacteria form within the cell a small seed, as it were, called a 'spore', and such a spore surrounded by a thick wall is even better able to withstand unfavourable conditions. Spores can even remain alive in boiling water for several hours. When, after a dry period, the soil receives moisture again the spores germinate, and propagation by cell-division commences once more.

The importance of bacteria in soils is due to the fact that there are millions of them in every gramme of moist, fertile soil and that they are responsible for so many diverse chemical reactions. The most important

of these changes will be discussed presently. It should be borne in mind that bacteria, as a group, thrive best if the soil is neither too acid nor too alkaline.

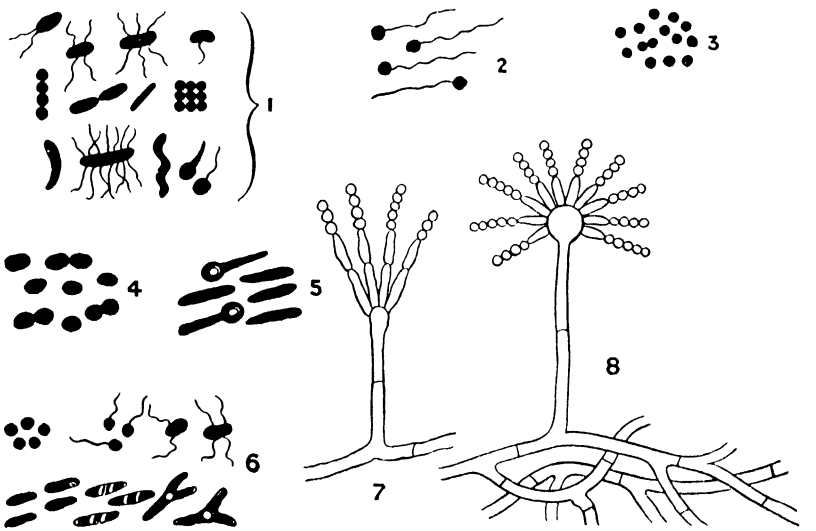


FIG 17 Soil microbes (magnified a few thousand times)

1 Different kinds of soil bacteria that decompose organic matter and are responsible for the formation of ammonia from proteins 2 Nitrite bacteria (*Nitrosomonas europea*) 3 Nitrate bacteria (*Nitrobacter*) 4 Nitrogen-fixing bacteria (*Azotobacter chroococcum*) 5 Nitrogen-fixing bacteria (*Clostridium pastorianum*) 6 Different morphological forms of nodule bacteria (*Bacterium radicicola*) 7 Penicillium fungus 8 Aspergillus fungus

2. *Fungi* are also plant organisms, but they differ from bacteria in that every individual is multicellular and is made up of a network of threads collectively called mycelium Every individual usually produces a large number of spores, and these develop into new individuals. The moulds are an important group of soil fungi. They are very common in everyday life, e.g. the moulds that appear on bread, cheese, jam, fruit, &c. The majority of soil fungi prefer an acid reaction, therefore they are the microbes that predominate in very sour soils. They contain no chlorophyll and live on dead vegetable matter and sometimes, unfortunately, also on living plants. Their activities affect soil fertility in many ways, but in the main they are responsible for decomposing coarse organic matter incorporated with the soil and for rendering albuminoid nitrogen available to higher plants.

Mycorrhiza. The German botanist, Frank, had observed as far back as 1885 that certain fungi grew on, and some even into, the tissue of the roots of higher plants without injury to the latter. On the contrary, the higher plants seem to benefit by their presence. Apparently the fungus breaks down the protein nitrogen in the soil into simpler compounds which

are then available to the roots of the higher plants. Other plant nutrients also may possibly be rendered more available by the fungus. Frank named this association mycorrhiza (literally, fungus-root).

Lately much attention is being devoted to this still rather obscure phenomenon. Whereas formerly this association was thought to be characteristic of the roots of coniferous trees, especially their seedlings, and of certain other 'wild' plants, some workers to-day maintain that most agricultural crops also have their specific mycorrhizal flora, provided the soil contains abundant humus which must be regularly augmented by heavy dressings of farm manure and compost. They further maintain that the health, vigour, and yield of the crop are directly dependent on this association. The future will show whether these claims can be substantiated scientifically.

3. The *Algae* are the third group of micro-organisms which belong to the vegetable kingdom. The green slime on stagnant water (dams) is known to many people, and this consists mainly of algae. Like the fungi, they are usually multicellular individuals, but they contain chlorophyll or some other pigment which enables them to assimilate carbon dioxide like higher plants. They occur in considerable numbers, mainly on and in very moist soils, where they may be considered to function as a 'green-manure' crop.

4. The *soil protozoa* are unicellular animal micro-organisms. In ordinary agricultural soils, as far as we know, they play a role of little importance, and hence we do not wish to discuss them any further.

CONDITIONS GOVERNING THE ACTIVITIES OF SOIL MICROBES

The following soil conditions influence the activity of bacteria and fungi, which are the most important soil micro-organisms:

1. *Soil moisture* is the first essential requirement for active microbial life. Actually microbes are aquatic and they revert to a dormant state (if they do not die) when soils dry out. Generally speaking it would be correct to say that in a soil containing enough moisture for the growth of our agricultural crops bacteria would also thrive well. Fungi can exist under slightly drier conditions than bacteria, but for best development they also require soils that are well moist. Thus soil microbes are inactive during the dry period of the year, e.g. during the summer months in the Western Cape Province and during the winter months in the summer-rainfall area.

As far as the *air supply* (aeration) of the soil is concerned it may be said that all fungi and almost all useful soil bacteria require oxygen for respiration. They are called aerobic microbes. There are also soil bacteria that can live without oxygen (anaerobic microbes), but some of them are directly harmful to soil fertility. Because microbes live in the soil moisture it is naturally the dissolved oxygen that they utilize. Provided the larger soil pores are filled with air, the soil moisture will always contain sufficient dissolved oxygen. Tillage operations which improve the aeration and moisture content of soils for our agricultural crops will, therefore, also increase the activity of soil microbes.

2. The *temperature* of the soil also influences the activity of soil microbes to a large extent, and their optimum or most suitable temperature is about 30° C. (86° F.). However, in South Africa soils very seldom become so cold that microbes cannot live actively in them. Apart from nutrition, the moisture content and the temperature of soils are the two most important growth requirements for soil microbes. In the winter-rainfall area these conditions are the most favourable during autumn and spring. In the summer-rainfall area the summer months are the most favourable, because both moisture content and soil temperature are then at their best.

3. *Organic food* is absolutely essential for fungi and for most of the bacteria. Therefore, it would be correct to say that, in general, soil microbes will increase in number with an increase in humus content of the soil provided other growth requirements are favourable. Thus applications of farm manure, compost, green manure, and other plant residues result in an enormous increase in the numbers of soil microbes. The organic or carbonaceous food is utilized as energy-material (food) and as building material (for new cells), just as any animal body would use such food. The only difference is that soil microbes can digest any possible carbon compound, which is not the case with animals. Naturally they also prefer easily digestible food. Thus sugars, starch, cellulose, and hemicellulose are decomposed rapidly, while lignin or woody tissue decomposes much more slowly. Carbon dioxide is the product of respiration or oxidation of the carbonaceous matter. Consequently the production of this gas in the soil is a good measure of the activity of microbes, if higher plants are not growing on the soil.

4. Being plant organisms, bacteria and fungi also require *mineral food*, and in South African soils the limited supply of phosphate may be a serious hindrance to their activity. Thus soil microbes are also provided with mineral plant food when fertilizers, phosphatic ones especially, are applied to soils. This is one important reason why the humus content of cultivated soils is depleted so rapidly when fertilizers are used year in and year out, and too little farm manure or green manure is ploughed into the soil.

5. The *soil reaction* also influences the activity of soil microbes. Bacteria, as a class, prefer a soil that is more or less 'sweet', whereas the fungi prefer an acid or sour soil. Consequently, when soils are limed, biochemical changes for which bacteria are responsible are speeded up. Of these, nitrification is one of the most important.

FUNCTIONS OF SOIL MICROBES

Carbon transformations

In Chapter VIII we gave a description of the decomposition of carbon compounds, thus a short summary here will suffice.

When organic matter in the form of farm manure, compost, green manure, straw and chaff, &c., is worked into the soil, and the soil contains sufficient moisture, a rapid decomposition of the major portion of organic constituents results. New microbe cells are formed as well as the products

of respiration (oxidation), carbon dioxide, and water. Sugars, starch, cellulose, and hemi-cellulose decompose relatively quickly in this way (within about six months), and the residue consists of the organic matter which we call humus and which is derived mainly from the lignin (woody tissue) of the original vegetable matter. The humus, which is of a complex nature and which also contains the constituents, mainly proteins, of dead microbe cells, undergoes a further, slower process of decomposition brought about by more generations of microbes. The non-nitrogenous carbon compounds of the original plant material and of humus[1] are finally completely decomposed, carbon dioxide and water being the end-products of this process. This process may be represented by the following diagram:

$$\text{Plant material} \xrightarrow{\text{rapidly}} \text{Humus} + CO_2 + H_2O$$

$$\text{Humus} \downarrow \text{slowly}$$

$$CO_2 + H_2O$$

The changes in the nitrogen compounds

Ammonification, or the formation of ammonia, is the process by which ammonia (NH_3) is released from organic nitrogen compounds as a result of the activity of soil microbes. The organic nitrogen in the soil exists, normally, in the form of protein nitrogen, and this is present mainly in humus. If the soil contains no fresh organic matter and conditions for microbes are favourable, they will gradually decompose the protein nitrogen into its components, which are called amino-acids. The amino-acids are immediately decomposed into ammonia, carbon dioxide, and water.

If sulphur and phosphorus compounds which are also products of the decomposition of albuminoid or proteins are disregarded, the process of ammonification may be schematically represented as follows:

$$\text{Protein} \xrightarrow{\text{slowly}} \text{Amino-acids} \xrightarrow{\text{rapidly}} NH_3 + CO_2 + H_2O$$

Ammonia and Carbon dioxide and Water.

In the soil moisture the ammonia combines with carbonic acid so that it exists in the form of dissolved ammonium carbonate.

The rate at which ammonia is formed in the soil depends on the rate at which proteins can split up (hydrolyse) into amino-acids. Humus protein is decomposed with relative difficulty, which is an advantage, for otherwise soils would very soon lose their reserve nitrogen and become infertile. Some proteins, applied to the soil in the form of fertilizers, decompose fairly rapidly, so that a large amount of ammonia is formed in the soil shortly after the application. Examples of these are dried blood, fish meal, crayfish meal, &c.

[1] Naturally, all the humus is never destroyed completely, new microbial substances being synthesized continually.

In decomposing farm manure, also, ammonia is constantly formed. It is mainly the easily decomposable nitrogen compounds of the urine that are so quickly transformed to ammonia. Hence the smell of ammonia that can always be noticed in stables. Old kraal manure such as 'karoo manure' has long since lost by volatilization and leaching all the nitrogen that the urine contained. Hence the slow but lasting effect of karoo manure in respect of the nitrogen nutrition of crops.

Many species of bacteria and fungi are capable of bringing about the process of ammonification. Thus it will take place in any arable soil provided the soil is moist and aerated.

Nitrification is the formation of nitrates from ammonia, or, rather, ammonium compounds, through the action of bacteria. Because agricultural crops absorb their nitrogen largely in the form of nitrates, this process has received much attention in the past, and the fertility of soils is often measured by their ability to form a large amount of nitrates.

Whereas many kinds of microbes can produce ammonia from organic nitrogen compounds, only a few genera of bacteria (and no fungi, as far as is known) can change the ammonia to nitrates. The process is completed in two steps and each step is brought about by a specific bacterium. Two forms of bacteria known as nitrite bacteria, viz. *Nitrosomonas* and *Nitrosococcus*, convert ammonium compounds to nitrous acid. This nitrous acid is then neutralized, purely chemically, to nitrites by the bases of the soil, e.g. carbonate of lime.

In the second biochemical change the nitrites are converted to nitrates by the genus *Nitrobacter*, which is also known as the nitrate bacterium. Chemically, both processes are so-called oxidations, i.e. the conversion of the original compounds is effected by combination with oxygen. The nitrifying bacteria, by which we mean both groups, must, therefore, have sufficient oxygen, i.e. the soil must be well aerated. These bacteria could not live in waterlogged soils, hence no nitrates can be formed in such soils. These changes may be represented by the following equations:

I. (*a*) $(NH_4)_2CO_3+3O_2 = 2HNO_2+CO_2+3H_2O.$

Ammonium carbonate and Oxygen give Nitrous acid and Carbon dioxide and Water.

(*b*) $2HNO_2+CaCO_3 = Ca(NO_2)_2+CO_2+H_2O.$

Nitrous acid and Carbonate of lime give Calcium nitrite and Carbon dioxide and Water.

II. $Ca(NO_2)_2+O_2 = Ca(NO_3)_2.$

Calcium nitrite and Oxygen give Calcium nitrate.

Theoretically, soils should not be too acid for active nitrification because, firstly, the nitrous acid has to be neutralized by a base and, secondly, these bacteria prefer 'sweet' soils. However, in practice it has been found that sufficient nitrates are formed even in fairly acid soils provided sufficient ammonia is produced. Generally speaking, liming acid soils will increase

the rate of ammonification and nitrification, but with an extensive system of agriculture, as is usual in South Africa, applications of lime very seldom pay apart from the fact that they would also bring about a faster depletion of the already low humus content of our soils. Thus nitrifying bacteria can evidently adapt themselves to moderately acid conditions, and the amount of nitrate which is formed in a given period of time will depend only on the amount of ammonia released by the soil microbes.

It is also of theoretical interest to know that nitrifying bacteria require no organic carbon compounds, because, like green plants, they are able to assimilate carbon dioxide with the aid in this case of the energy obtained from the above oxidations.

Because nitrates are readily absorbed by growing plants and because they leach out of the soil fairly easily during heavy rains, the amount of nitrates in a soil at any given time will depend on:

(1) the amount of nitrates formed in the soil during the period preceding the sampling;
(2) the absorption of nitrates by growing plants during the preceding period;
(3) the precipitation and hence the possible leaching in the preceding period.

In the winter-rainfall area the soil usually contains the largest amount of nitrates in the autumn after the first soaking rains, but before any leaching can have occurred. In the summer-rainfall area the soil also contains a maximum amount of nitrates after the first seasonal rains, i.e. November–December. In South Africa the nitrate-nitrogen content of ordinary arable soils during the peak period varies between 5 and 10 parts to every million parts of soil. If only the top 6 inches of soil is taken into account, i.e. the layer in which nitrification mainly occurs, it would mean that a morgen of soil, 6 inches deep, would contain 20–40 lb. of nitrate-nitrogen. Shortly after the beginning of the growing season (rainy season) the nitrate content of the soil is usually in the peak stage, but as the crop matures the nitrate content decreases to practically nothing.

Assimilation of ammonia and nitrates by soil microbes. Bacteria and fungi also require nitrogenous food for the synthesis of new cells. The conversion of simple nitrogenous compounds such as ammonium salts and nitrates to complicated microbial protein is called nitrogen assimilation. In other words, microbes utilize the available inorganic nitrogenous food in the soil in much the same way as do higher plants, and, therefore, they may be the cause of higher plants suffering a nitrogen shortage under certain conditions. When does this happen?

At this stage the reader no doubt realizes that soil microbes may be responsible for many different nitrogen changes. Fortunately we know to-day under which conditions each group of soil microbes is *specially* active in bringing about a certain change, and thus, knowing the conditions, we can predict when a specific change in nitrogenous compounds will predominate. This is what the practical farmer wishes to know.

The assimilation by soil microbes of nitrogenous compounds which are also available to higher plants will overshadow all other nitrogen changes after relatively fresh organic matter has been incorporated with the soil. This is the case when relatively fresh farm manure (especially when it contains much bedding material), cover crops, trash, grass, straw, and chaff are ploughed into the soil. The microbes then have so much available carbonaceous food that the increase in their numbers is enormous, with the result that they will need a large quantity of nitrogen for their body substances. Consequently they utilize all the nitrogen which may be present in the soil in the form of ammonium compounds and nitrates. Actually the rate at which such organic matter will decompose in the soil depends on the supply of available nitrogen, provided the soil contains sufficient moisture. Thus, wheat-straw or dry grass will rot more quickly in the soil if a nitrogenous fertilizer such as sulphate of ammonia or Government guano is broadcast over the material before it is ploughed under—a practice that will usually not pay in South Africa. In any case, there are no nitrates in the soil for some time afterwards and this should be taken into due consideration in crop production.

This period of rapid decomposition and lack of nitrates in the soil is sometimes called the 'negative period'. It is also, more appropriately, called a period of 'nitrogen starvation'. The length of the period will depend on the chemical composition and the quantity of the organic matter that is ploughed in. The richer the material is in nitrogen and the smaller the quantity of organic matter, the quicker will decomposition take place and the sooner will ammonium compounds and nitrates again appear in the soil. In the case of leguminous green-manure crops such as peas, cowpeas, and lupins this negative period will last for 2–4 weeks, depending on the temperature, aeration, and moisture content of the soil. In the case of other cover crops that are used as green manure, such as *gousblom*, rye, teff, &c., nitrates may only appear again after a period of 4–8 weeks. When much wheat-straw and chaff are ploughed in it may take some 6 months before the material has rotted completely and nitrifying bacteria come to the fore again. The younger the green-manure crop is at the time of ploughing under, the shorter will be the negative period.

Fixation of elementary nitrogen by bacteria

A limited number of bacteria are able to utilize the free nitrogen gas dissolved in the soil moisture as nitrogenous food, forming their proteins from it. This process is called *nitrogen fixation*. In this respect these few forms of bacteria differ from the rest of the vegetable kingdom which can only utilize combined nitrogen, i.e. compounds. The discovery of this peculiar characteristic of certain bacteria immediately clarified some well-known but inexplicable facts in connexion with soil fertility. The oldest agriculturalists in human history knew already that legumes apparently left the soil in a better state of fertility than was the case prior to planting.

In 1886 two German research workers, Hellriegel and Wilfarth, proved beyond doubt, with pot cultures, that legumes differ from other crops in that they normally have round or finger-like protuberances or nodules on their roots and that these harbour bacteria. These bacteria fix or assimilate the nitrogen gas that is dissolved in the soil moisture and convert it to proteins. After the bacterial cells die (which is constantly occurring with some of the bacteria throughout the growing period of the legume) the proteins decompose to simpler substances which can be absorbed by the legume and assimilated. Thus, legumes are independent of the nitrogen content of the soil (see also p. 24). These bacteria are called symbiotic nitrogen-fixing bacteria or, briefly, 'nodule bacteria'. The scientific name for these bacteria was formerly *Bacterium radicicola*. To-day the generic name is *Rhizobium*.

Research workers discovered that there is not just one species of nitrogen-fixing bacteria for all legumes, but that every legume, e.g. lucerne, needs a specific species of the bacterium that will live in symbiosis with it. Legumes which are grown as agricultural crops are to-day divided into seven classes according to the species of bacterium that occurs in their roots. Thus, lucerne, ordinary green peas, garden beans, soya-beans, and cow-peas each lives in symbiosis with a different species of bacterium. From this one would conclude that in growing legumes instances may arise where the desired bacteria are not present in the soil. It would then be necessary to inoculate the seed or the soil with the desired bacteria. Fortunately, practice has proved that this is seldom necessary in South Africa. It is only when a legume is grown for the first time on a virgin soil, especially soils with sclerophyllous shrubs in the winter-rainfall area, that inoculation is essential. When a legume is grown in an area where it has not previously been grown inoculation may also be advisable to ensure that the desired bacteria are present. By inspecting the roots the farmer should, in any case, satisfy himself that the bacteria are present in sufficient numbers.

Inoculation may be done in one of three ways. A few bags of topsoil from land on which the legume concerned has produced root nodules are broadcast over the new land, harrowed in, and the legume planted. The soil may also be mixed well with the legume seed and both sown together through a seed-drill. The disadvantages of this method are:

(1) undesirable weeds may be spread with the soil and
(2) the cost is high if the soil for inoculation has to be brought over a long distance.

The second method is the so-called 'glue' method which is generally used by the Stellenbosch-Elsenburg College of Agriculture. About 3 ounces of carpenter's glue is dissolved in a gallon of water. The legume seed, lying in a pile on a cement or wooden floor, is now watered with this glue-water with a watering-can while the seed is turned and mixed with a spade. Soil from a land on which the legume concerned has previously grown and produced nitrogen nodules is now sifted over the moist, sticky seed through a $\frac{1}{4}$-inch mesh sieve while the heap is still being turned. In this way a coat

of bacteria-containing soil will stick to every seed. The seed should then be sown immediately or otherwise it should be spread thinly on a (shaded) dry floor where it can quickly become air-dry, after which it can be put into bags and kept until planting time. Otherwise the moist seed will turn mouldy, losing its germinating power.

The third method of inoculation is to moisten the seed with an aqueous solution containing a pure culture of the desired species of bacterium. The bacteria are grown in laboratories on artificial media and sold to farmers in glass or metal containers, &c. This method is in general use in Europe and in America, and in South Africa it is also gaining ground. Nitrogen-fixing bacteria increase the fertility of the soil by adding to the nitrogen supply. This is especially the case where a leguminous crop has been ploughed in as green manure. This method of manuring is accompanied by certain grave difficulties in South Africa, as will be discussed later. Furthermore, it should be borne in mind that the quantity of nitrogen which a legume crop fixes from the 'air' depends on three things:

(1) the presence of the desired bacteria in the soil,
(2) the yield of the legume crop, and
(3) the amount of nitrates present in the soil during the growth of the legume.

Nitrates in the soil are absorbed by legumes as readily as by other plants, and the richer the soil is in nitrates the less free nitrogen is fixed, even though nodules may be present in large numbers on the roots. Because the yield of any crop in South Africa is mainly dependent on the phosphate content of the soil, apart from the moisture supply, a phosphatic fertilizer should always be applied when the legume is sown.

Finally, it is useful to know that the roots of agricultural crops, including legumes, often exhibit thickened protuberances which are in no way related to the above-mentioned nodules. Such thickenings of the roots are usually caused by nematodes (eelworms) and are very harmful to the crop concerned. They usually occur in crops growing on moist or irrigated soils (e.g. vegetable gardens and irrigation settlements). They may be distinguished from nitrogen nodules by the fact that the whole root lengths may be greatly thickened whereas nitrogen nodules appear more commonly as outgrowths on the roots.

Besides the symbiotic nitrogen-fixing bacteria there is a second group of bacteria that possesses the same ability and we call them 'free-living' nitrogen-fixing bacteria. The most important in this group is the aerobic bacterium, *Azotobacter*. These bacteria utilize some of the constituents of organic matter in the soil as a source of energy food which enables them to convert free nitrogen to protein compounds. Thus, applications of farm manure, green manure, straw, &c., to soils will supply them with the required 'fuel'. Furthermore, they have a high phosphate requirement and the soil should not be too acid—the pH should not be less than 6·0. *Clostridium* represents a second group of free-living nitrogen-fixing bacteria which differ mainly from the Azotobacter group in two respects: they

are anaerobic and are therefore active in badly aerated soils, and they are much more resistant to soil acidity than the Azotobacter group.

Although these free-living nitrogen-fixing bacteria are fairly common in soils, and although they undoubtedly aid in maintaining the nitrogen supply, our knowledge of the quantity of nitrogen which they are annually able to fix, say, per morgen, is still very limited. The more attention is paid to soil tillage and application of organic manures and fertilizers, the better will these bacteria be able to increase the nitrogen content.

There remains one important link in the nitrogen cycle, as effected by soil microbes, vis. *denitrification*. By this change is meant the liberation of

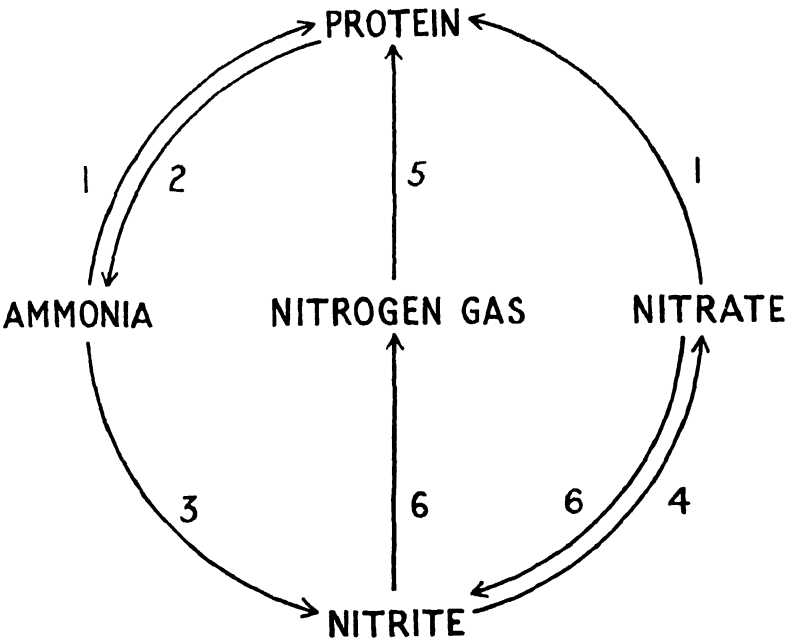


FIG. 18. The Nitrogen Cycle.

1 = Assimilation of ammonium compounds and nitrates (bacteria, fungi, higher plants).
2 = Ammonification (bacteria and fungi).
3 and 4 = Nitrification (bacteria).
5 = Nitrogen fixation (bacteria).
6 = Denitrification (bacteria).

nitrogen gas from nitrates. Chemists call it a reduction process which indicates that it occurs in the absence of air or oxygen. There are many kinds of bacteria that can live without free oxygen (anaerobic bacteria), but they also need oxygen to enable them to liberate the needed energy from the organic food substances and this oxygen they obtain from nitrates and nitrites. Nitrogen gas is given off during the process. Chemically, the

process may be written as follows in the case of potassium nitrate or ordinary saltpetre:

$$\text{Sugar} + KNO_3 \rightarrow K_2CO_3 + CO_2 + H_2O + N_2.$$

Sugar and Saltpetre give Potash, Carbon dioxide, Water, and Nitrogen.

Sugar represents the organic food.

This process, of course, is very harmful because it is responsible for a loss of combined nitrogen. Fortunately, it probably only occurs in water-logged soils. Thus, wet soils should be drained so that they will contain sufficient air, preventing denitrifying bacteria from carrying on their destructive functions. Denitrification also takes place in manure heaps and kraals when the manure is stored loosely or when the top layers have been allowed to dry out. Nitrates are formed in such layers and when it rains the nitrates are leached into deeper, badly aerated layers where they are denitrified. When discussing the storage of manure we will learn how such loss of nitrogen may be avoided.

In conclusion, a diagram illustrating the cycle of the most important nitrogen changes, as effected by microbes, is given on the opposite page.

PART THREE

FERTILIZERS AND MANURES, THEIR PREPARATION, PROPERTIES, AND USE

CHAPTER XXIV

INTRODUCTION

AT this stage it is necessary that we should pause for a moment and review briefly the most important facts with which we have dealt so far.

As explained at the outset, the central theme of this book is the capacity of soils to produce remunerative crops. To begin with, let us review the six growth requirements for plants, which we mentioned in Chapter II, somewhat more fully.

1. Plants must have sufficient *light*. This only applies to the aerial parts of the plant, especially the green leaves which cannot assimilate the raw carbon foodstuff, viz. carbon dioxide, in the absence of light. The importance of this is easily understood if we consider that approximately half the dry matter of plants consists of carbon. The growth factor, light, can be influenced favourably or otherwise by the spacement of the plants, i.e. the rate of seeding. The seasons with their variations in length of day are responsible, primarily, for the actual amount of light available to plants and this is a definite quantity for every locality, which is beyond our control. (See also Chapter III, Carbon Assimilation.)

2. Plants must have sufficient *air*. The aerial as well as the underground parts of plants constantly respire and for this process they require oxygen which they obtain from the air. The aerial parts of the plants always have sufficient air, but the root system may have an insufficient air supply. In the chapters on the Pore Space of Soils, Soil Air, and Drainage of Soils we discussed the factors which influence the aeration or ventilation of soils.

3. Plants must have sufficient *water*. Plants absorb water through their roots, from the soil, and utilize it for various functions. So diverse are the functions of water in normal plant growth, and so large is the total amount of moisture that a crop requires in order to mature, that water is by far the most important growth factor in a country like South Africa with its limited and erratic rainfall. Different chapters in this book, such as those on the Water Requirements of Plants, Water Relationships in Soils, and the Control of Soil Moisture, deal with this important aspect of plant growth.

4. The *temperature* of the air as well as the temperature of the soil is important to plant growth. The influence of temperature was discussed in the chapters on Carbon Assimilation and Heating and Cooling of Soils.

5. The soil should contain no *chemical ingredients* that are *injurious* to plants. In the chapter on Soil Acidity it was pointed out that too high

a degree of acidity or alkalinity, i.e. too high a hydrogen-ion concentration or hydroxyl-ion concentration, in the soil moisture may be harmful to agricultural crops. In the chapter on Brak Soils we saw how these soils are unsuitable in several respects for crop production. There are also other chemical substances which may sometimes occur in soils in excessive quantities and thus be harmful, such as manganese compounds, nitrites, and ferrous compounds, but they are exceptional.

6. Finally, soils should contain a sufficient quantity of each of the *essential mineral nutrients* (which include nitrogen) and these should be in an available form. Most of the previous chapters which do not touch directly on the growth requirements have a direct or indirect bearing on the question of available plant food or soil fertility in the narrow sense of the word; especially the chapters on Soil Nutrients, Chemical Soil Analysis, and the Activities of Soil Microbes.

The science and practice of manuring is based on facts that have been mentioned in previous chapters, but all the so-called physical properties of soils also influence manuring to a great extent. Practical experience, innumerable soil analyses, and fertilizer experiments have proved that soils are rarely deficient in plant foods other than the following three:[1] *nitrogen*, *phosphate*, and *potash*. Therefore they may be called the major food elements for plant growth and a manure or fertilizer may be defined as a substance containing one or more of these three ingredients.

The science and practice of manuring, therefore, deals with the preparation, properties, and application or use of these food substances. However, enriching soils in plant nutrients will be of no avail if other growth requirements, e.g. an adequate water-supply, are not favourable. Under such circumstances fertilizer applications may even be responsible for decreased yields and crop failures.

Manures or fertilizers are divided into two main groups:

1. Artificial fertilizers.
2. Natural or farm manures.

These terms are unsatisfactory, and should not be interpreted too literally, since the words fertilizer and manure are used rather indiscriminately in English. By fertilizers we usually understand such substances as are rich in one or more of the three major plant-food elements, but contain little, if any, organic matter (organic matter for the formation of humus). Farm manures, on the other hand, contain on a percentage basis a large amount of organic matter and relatively little actual plant food. However, manures do contain all the plant nutrients and, in that sense, they are designated as being 'complete'. But the plant food they contain may be unbalanced as far as the fertilizer requirement of the particular soil is concerned, and in South Africa farm manures should as a rule be supplemented with phosphatic fertilizers. Fertilizers usually contain only one of the three major nutrients. They are then said to be 'single', 'simple', or

[1] Cases where a deficiency of other plant nutrients, including the trace elements, occurs in South Africa have been discussed in Chapter IV.

'straight' fertilizers and they can be divided into the following three classes according to the plant-food element they contain:

1. *Nitrogenous fertilizers* such as Nitrate of Soda and Sulphate of Ammonia.
2. *Phosphatic fertilizers* such as Superphosphate and Basic Slag.
3. *Potassic fertilizers* such as Muriate of Potash (potassium chloride) and Sulphate of Potash.

Although not actually manures, it is customary to consider liming materials as a fourth class of fertilizers.

NITROGENOUS FERTILIZERS

When discussing the nitrogen nutrition of plants in Chapter IV, we pointed out that agricultural crops normally absorb their nitrogenous food in the form of nitrates. Any other nitrogen compound which is soluble in water is also available to plants, but bacteria very soon convert such compounds to nitrates. Thus nitrates are the only water-soluble nitrogen compounds that may exist in soils in considerable quantity for any length of time without being changed by microbes to other forms. Conditions under which they may change were discussed in Chapter XXIII. Apparently most agricultural crops prefer nitrogen in the form of nitrates, and since nitrate nitrogen is very water-soluble and is not 'fixed' by soil colloids it is the most available nitrogenous food.

To-day there are very many different nitrogenous fertilizers on the market but chemically and agriculturally they can be divided into three classes: (1) nitrates, (2) ammonium-containing fertilizers, and (3) organic or protein-containing fertilizers.

Nitrate fertilizers

Nitrate of soda or Chilean saltpetre (sodium nitrate, $NaNO_3$) is the oldest and best-known nitrate fertilizer. It occurs in large quantities as deposits in the rainless regions of Chile—hence the name. In the arid regions of Australia and South-west Africa, nitrate of soda is also found, but as yet these deposits have not been exploited. In Chile the saltpetre beds have been worked since 1830, and since 1890, especially, enormous quantities of the commercial salt (about 2 to 3 million tons annually) have been refined and used mainly as fertilizer. There are different theories in connexion with the origin of these saltpetre deposits in Chile and elsewhere but we do not intend discussing them here.

The saltpetre beds, which usually occur a few feet below the surface of the soil and are known as 'Caliche', are opened by trenching, drilled, and blasted by means of explosives. The caliche that is mined at present contains from 12 to 25 per cent. of sodium nitrate. The most important impurities are common salt (NaCl), Glauber's salt (Na_2SO_4), gypsum, iodates, borates, and earth. By dissolving the mined product in warm water (mother liquor), separating and cooling the solution to almost freezing-point, crystallization takes place. The commercial product obtained to-day

is almost chemically pure (98 per cent. sodium nitrate) and guaranteed to contain 16 per cent. nitrogen. It also contains traces of boron and iodine.

The fertilizer is a coarse or pellety whitish salt, with a bitter taste. Under humid conditions it attracts moisture (it is hygroscopic) with the result that larger lumps are formed.

Thus nitrate of soda should only be ordered shortly before it is to be used, otherwise it should be stored in a dry place. If it does become lumpy the lumps should be broken with spades on a cement floor prior to distribution.

Nitrate of soda is readily soluble in water, thus it rapidly dissolves in soil moisture with the result that its effect on plant growth is remarkably quick. The nitrate portion is not absorbed by the soil particles but moves downwards with the soil moisture. This property should be borne in mind when using nitrate of soda lest it be leached from the soil. It is used almost exclusively as a 'top dressing'. By this we mean that the fertilizer is broadcast when the crop is already growing and requires nitrogen. The root system of the crop will then be distributed more or less throughout the soil, so that the crop will be better able to utilize the nitrate nitrogen before leaching occurs, unless heavy continuous rains fall shortly after top dressing. In the case of winter cereals in the winter-rainfall area, nitrate of soda, if needed, is broadcast towards the end of winter (July–August). If it is applied in small quantities, say, 50–100 lb. per morgen, it should be mixed with sandy soil in order to facilitate even distribution on the land. In the case of orchards, vineyards, and Turkish tobacco it is broadcast during the first half of September. In the case of garden crops, potatoes, &c., the fertilizer should be applied with care so that none falls on the leaves because it may 'burn' them. In the case of nursery beds, vegetables, flowers, &c., it is safer to dissolve a handful of saltpetre in a watering-can full of water and to water the beds with it. This is followed by watering with pure water in order to wash the salt solution from the leaves.

Nitrate of soda may be harmful to the structure of some soil types if it is used year after year. This is because a sodium clay is eventually formed as a result of cation exchange and this type of clay tends to deflocculate and to form a hard crust after drying out.

Nitrate of lime ($Ca(NO_3)_2$) is in theory a much more suitable nitrate fertilizer than nitrate of soda, but unfortunately it is very hygroscopic and is not yet used in South Africa.

Nitrate of potash (KNO_3), or ordinary saltpetre, contains two of the major plant-food elements, viz. potash and nitrogen. One would think that this would be of great advantage, but unfortunately the fertilizer contains too much potash (45 per cent. K_2O) in proportion to nitrogen (about 14 per cent. N). Relatively few South African soils respond to potash, and even they do not, as a rule, require much potash. The farmer may therefore be wasting money on potash if he uses this fertilizer. Like all other nitrates, nitrate of potash is best used as a top dressing and on a small scale it may be recommended for flower and vegetable gardens.

Ammonium-containing fertilizers

Sulphate of ammonia ($(NH_4)_2SO_4$) is the most important fertilizer in this group. The chief sources of supply are:

(*a*) Coal which contains an average of about 1 per cent. of nitrogen. Ammonium sulphate has for years been a by-product of the coal industry. When coal is burnt the nitrogen escapes into the atmosphere and is lost; but when the coal is distilled in closed retorts—in the manufacture of coal-gas and coke—a portion of the nitrogen is volatilized as ammonia and ammonium salts, and retained in the 'wash-water'. Slaked lime is then added to this so-called ammoniacal liquor which is then distilled, and the ammonia absorbed in sulphuric acid. After the sulphuric acid has been neutralized, the solution is evaporated and the salt remains in the form of fine short white crystals. Sometimes the sulphate of ammonia has a yellowish or bluish colour. The colour is of no consequence as long as the fertilizer is dry, fine, and contains at least 20·5 per cent. nitrogen. The two reactions, (1) when distillation takes place after the addition of milk of lime, and (2) when the ammonia is absorbed by sulphuric acid, can be represented by the following chemical equations:

1. $$(NH_4)_2CO_3 + Ca(OH)_2 = 2NH_3 + 2H_2O + CaCO_3.$$

Ammonium carbonate and Slaked lime give Ammonia, Water, and Carbonate of lime.

2. $$2NH_3 + H_2SO_4 = (NH_4)_2SO_4.$$

Ammonia and Sulphuric acid give Ammonium sulphate.

The annual world production of sulphate of ammonia from coal, by this process, is about 2 million tons. In South Africa nothing is, as yet, being produced in this way.

(*b*) The inexhaustible supply of nitrogen gas in the atmosphere. About four-fifths of the atmospheric air is nitrogen gas and the air over one square mile of land surface contains about 20 million tons of nitrogen. The problem of combining the gases nitrogen and hydrogen on a large scale to form ammonia was solved in Germany shortly before World War I. To-day a much larger tonnage of nitrogenous fertilizers is manufactured from atmospheric nitrogen than is obtained from Chile and coal combined. All industrial countries, even South Africa (Modderfontein), have factories in which atmospheric nitrogen is fixed. The result is that the price of nitrogenous fertilizers in peace-time has dropped considerably.

Viewed superficially it would appear as if the manufacture of ammonium sulphate from atmospheric nitrogen is a very simple matter, but the difficulty is to obtain pure nitrogen and hydrogen and to construct the contact furnaces in such a way that they can resist very high pressures. Briefly, the process is as follows:

Very pure nitrogen and hydrogen gases in the volumetric proportion of one to three are passed, under very high pressure, over a heated catalyst. A portion of the gases then combines, forming ammonia. The gas mixture

is then cooled down and led through water which absorbs the ammonia and the residual gases are again dried and sent over the catalyst. The ammonia is passed through dilute sulphuric acid or treated with a suspension of gypsum, together with carbon dioxide. The above reactions may be represented as follows:

1. $$N_2+3H_2 = 2NH_3.$$

Nitrogen and Hydrogen give Ammonia.

2. (*a*) $$2NH_3+H_2SO_4 = (NH_4)_2SO_4.$$

Ammonia and Sulphuric acid give Ammonium sulphate.

(*b*) $$2NH_3+CO_2+CaSO_4+H_2O = (NH_4)_2SO_4+CaCO_3.$$

Ammonia, Carbon dioxide, Gypsum, and Water give Ammonium sulphate and Carbonate of lime.

Sulphate of ammonia is also a quick-acting fertilizer. It is only slightly slower than nitrate nitrogen. It is readily soluble in water but the ammonia part of the salt behaves in the soil in a way quite different from the nitrate part of nitrate fertilizers. It is absorbed by the soil colloids, clay and humus, and as a rule simultaneously replaces calcium, so that calcium sulphate is formed in the soil and it may even be leached out of the soil by heavy rains. A small amount of the ammonium portion remains in the soil solution and the absorbed portion is slowly released or exchanged as nitrifying bacteria convert the dissolved ammonium[1] portion to nitrates. Within about a month or so most of the ammonium nitrogen will have been changed to nitrates and will be available to growing plants.

Thus ammonium sulphate may be applied at planting or sowing time, and as the crop develops the nitrogen is absorbed in the nitrate form. This means that there is very little danger of leaching provided that the soil is not too sandy or poor in humus and that a crop is growing on the land. As a result of this property of ammonium sulphate it is safer for the ordinary farmer to use than nitrate of soda. Because it is changed to nitrate nitrogen relatively quickly, it may also be applied as a top dressing.

The second important feature of ammonium sulphate is that it acidifies the soil. The ammonium portion which is converted to nitrate as well as the sulphate portion requires a base, usually calcium, for neutralization. This calcium is obtained from the absorbed calcium supply in the soil, if the soil does not contain free carbonate of lime. The plant absorbs the nitrate of lime, and the calcium sulphate is also partially absorbed by plants, but during heavy rains it may be leached from the soil. Thus there is a loss of basic or calcareous material from the soil with the result that the soil becomes more acid. The intensity of this acidification will depend on the quantity of sulphate of ammonia that is applied annually, and on the nature of the soil and the rainfall. Generally speaking, this acidification process following the use of sulphate of ammonia is not very serious in

[1] According to Lees and Quastel (England) the absorbed ammonium is nitrified by bacteria *on the colloid surface* and *not* in exchanged form in the soil solution.

South Africa, but nevertheless farmers should bear this fact in mind, especially in the winter-rainfall area, and basic fertilizers such as basic slag and even agricultural lime should be used when acid soils are regularly fertilized with sulphate of ammonia.

In Europe and America various other ammonium-containing fertilizers are to-day manufactured, such as *Ammonium chloride* (25 per cent. nitrogen), Ammonium phosphate or *Ammophos* (11·0 per cent. nitrogen), *Leuna Saltpetre* (a mixture of ammonium nitrate and ammonium sulphate, with 26 per cent. nitrogen), and *Nitrochalk* (15·5 per cent. nitrogen). The first three are not very suitable for South African soil types, for various reasons, or are not imported into South Africa. We wish, however, to say something about nitrochalk. It is manufactured in England and elsewhere and consists of a mixture of ammonium nitrate and fine precipitated carbonate of lime ($NH_4NO_3 + CaCO_3$). Thus half of the nitrogen is in the ammonia form and the other half in the nitrate form. Consequently a portion of the nitrogen is immediately available and the rest becomes available a little later. It may be applied at planting time or, safer still, as a top dressing. Because it contains more than 40 per cent. of carbonate of lime it will not render soils more acid nor will it have the harmful effects on soil that are caused by nitrate of soda. Provided its price compares favourably with that of other nitrogenous fertilizers it may safely be used on any soil type and with any crop. It is a yellowish dry fertilizer.

During World War II some South African farmers became acquainted with a new nitrogenous fertilizer, *Ammonium nitrate*. Actually this is the same nitrogenous compound present in nitrochalk but in a much more concentrated form containing more than double the amount of nitrogen, viz. *33·0 per cent.* It has been manufactured in America since 1942 in the form of small granules, and the 'pills' are coated with an inert powder (kaolin?) so that its highly hygroscopic nature does not manifest itself and it does not cake in the bags. It is nevertheless shipped in moisture-proof bags and the fertilizer should be used soon after opening the bags. It is best used as a top dressing, always bearing in mind its high nitrogen content. Its continued use will cause the soil to become more acid, exactly as in the case of sulphate of ammonia.

There are a few fertilizers which, chemically, cannot be grouped under ammonium fertilizers, but, from the point of view of availability, i.e. agronomically, they belong to the same class.

Urea ($CO(NH_2)_2$), containing 46 per cent. nitrogen, is actually an organic compound which is also present in the urine of farm animals. In the soil it is very soon changed to ammonium carbonate which is then converted to nitrate nitrogen by nitrifying bacteria. Thus its behaviour in the soil and its effects on plant growth are almost the same as those of the ammonium fertilizers. On account of its very high nitrogen content and other undesirable properties it is not a very suitable fertilizer for general purposes. It is a white, fine-crystalline substance which to-day is also manufactured from atmospheric nitrogen.

Calcium cyanamide or Nitrolime ($CaCN_2$), containing 16–22 per cent. nitrogen, is another organic nitrogenous fertilizer with approximately the same nitrogen availability as the ammonium fertilizers. This was the first nitrogenous fertilizer ever to be manufactured from atmospheric nitrogen, viz. since 1895. The annual production is normally about a million tons. It is mostly manufactured in Europe and America. Pure nitrogen gas is passed over calcium carbide (or lime and coke) in electric furnaces at approximately 1,000° C., when the following reaction takes place:

$$CaC_2 + N_2 = CaCN_2 + C.$$

Calcium carbide and Nitrogen give Calcium cyanamide and Carbon.

The black carbon which is formed imparts to the fertilizer its black colour and dustiness. Apart from the two substances that are given on the right-hand side of the equation, the fertilizer contains also about 20 per cent. of free, burnt unslaked lime besides other ingredients of limestone.

Calcium cyanamide is very dusty when handled or when broadcast and this is one of its main drawbacks as a fertilizer. Therefore, when the fertilizer is to be broadcast by hand it is advisable to mix it beforehand with moist sand.

After it has been ploughed in the calcium cyanamide undergoes the following changes in the soil:

Calcium cyanamide → cyanamide → urea → ammonium carbonate → nitrite → nitrate.

Free cyanamide is harmful to plant growth and therefore it is very important that it should be worked into the soil in good time; about fourteen days before anything is sown or planted.

In Europe, calcium cyanamide is the cheapest nitrogenous fertilizer. In South Africa it may be used, especially in orchards and vineyards where it can safely be worked into the soil when this is tilled in late winter.

Government Guano or Bird Guano is the oldest fertilizer used in the winter-rainfall area of the Cape Province. It has been used since about 1880. It consists of the excrements of sea birds (penguin, gannet, cormorant) which occur in millions on the islands along the south and west coasts of the Union and South West Africa. Since 1891 the Government (first the Cape Government and now the Union Government) has had the sole right of collecting and selling the guano (a Spanish-Peruvian word meaning bird dung) and it is only supplied to bona-fide farmers. Thus it is not an ordinary commerical product although private companies sometimes still collect small quantities along the south-western coast, &c., or import it from Peru (Peru Guano) and other places.

The old deposits of by-gone ages have long since been shipped away with the result that now the annual deposit is all that is available. This amounts to about six to ten thousand tons. The islands are divided into two groups according to the time when the birds breed. On the southern group guano

is gathered from approximately the middle of January to April and sold to farmers who applied for it during April. On the northern group gathering takes place during March to June and is distributed to farmers during July. The price is fixed periodically by the Government and the guano is sold in 200-lb. bags.

Because these birds eat fish only, their droppings are very rich in nitrogen and phosphate but poor in potash. The composition of the guano is not constant but is approximately as follows:

10	per cent.		Nitrogen.
10	,,	,,	Phosphoric oxide.
2	,,	,,	Potash.
10	,,	,,	Lime (combined as phosphate).

Thus guano is not only a nitrogenous fertilizer, but it also contains a considerable quantity of phosphate and a small quantity of potash. The typical ammonia smell is an indication that some of the nitrogen, at least, must be present as ammonium carbonate. However, there are other ammonium compounds as well and usually 20–30 per cent. of the total nitrogen in ordinary guano consists of ammonium nitrogen. About 50 per cent. of the nitrogen is in the form of uric acid and in the soil this is converted to ammonium compounds probably within about a month. Thus we can say that about 70 per cent. of the nitrogen in Government guano will have the same manurial effect as ammonium sulphate and would therefore become available to plants during the first growing season. Consequently guano has a quick and a lasting effect on plant growth. For ordinary use it is a very safe nitrogenous fertilizer. The only point to be remembered is that it should be mixed well with the soil at the time of planting or sowing.

Phosphate is the second important ingredient of Government guano. It is practically as available to plants as the phosphate in superphosphate, provided the guano is evenly distributed throughout the soil. Because the phosphate requirement of South African soils is so high, a phosphatic fertilizer should, in most cases, be applied in conjunction with Government guano. The potash content of Government guano is very low and where soils require manuring with potash, it should be supplemented with a potassic fertilizer.

Bat guano is very similar to bird guano as far as its qualitative composition is concerned except that it varies to a greater extent and it is usually only half as rich in plant food as bird guano. All bat guano has already been removed from the best-known caves.

Organic fertilizers

When the farmer talks about organic nitrogen he always means nitrogenous compounds consisting of protein or albuminoid substances. A characteristic of such nitrogenous compounds is that soil microbes change them slowly to simple ammonium compounds and nitrates. The result is

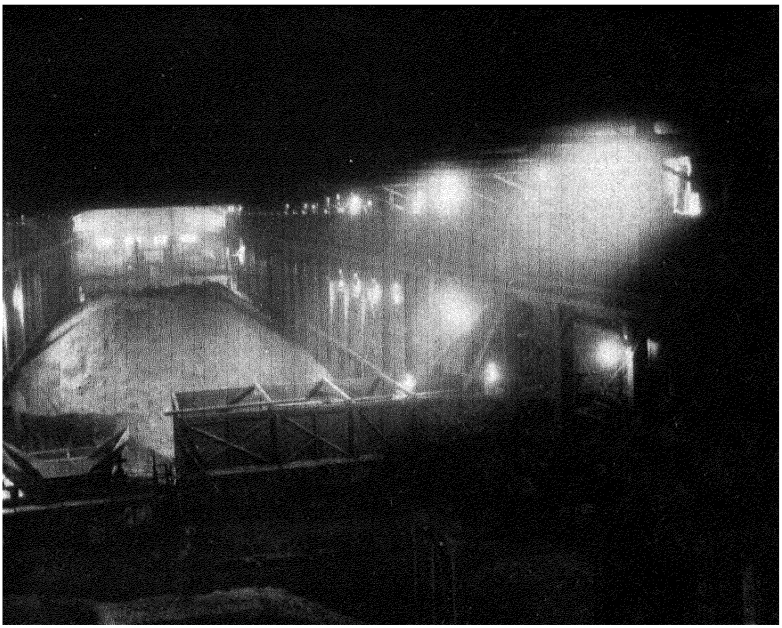


Photo Cape Explosives Works, Ltd

a Interior of Superphosphate factory, Somerset West, C P , looking over dens to superphosphate stockpile with batch mixer in the background

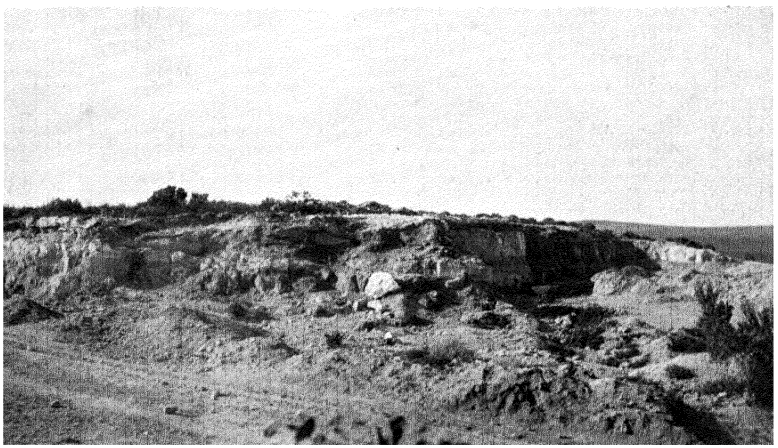
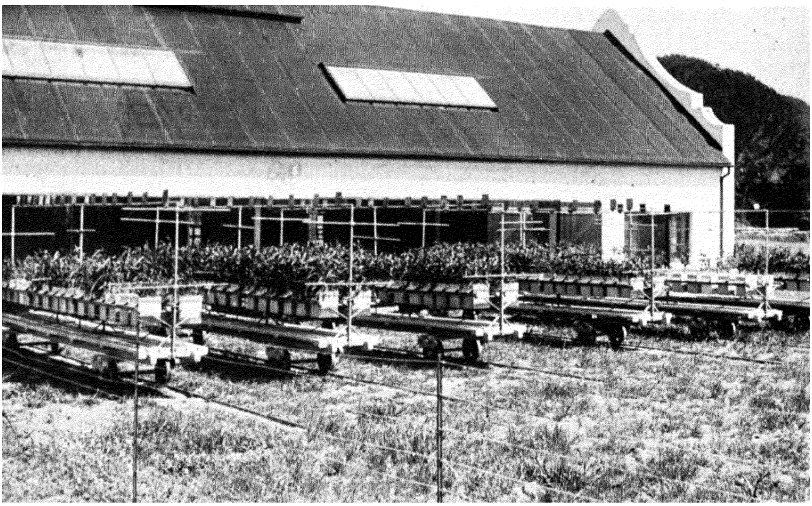
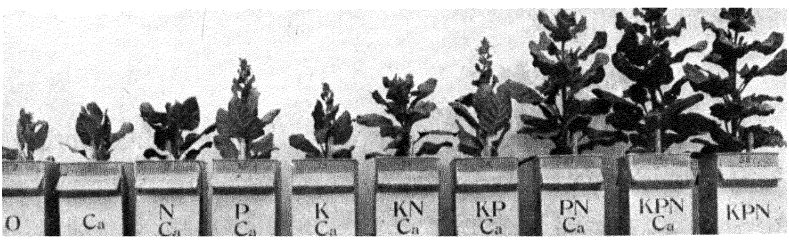


Photo Piquetberg Bredasdorp Limeworks, Ltd

b Limestone quarry for Agricultural Lime, Bredasdorp, C.P.



a Pothouse on the Experimental Farm, Stellenbosch



b Fertilizer experiment in pots, with nicotine tobacco (*Nicotiana rustica*) as experimental plant

that the effect of albuminoid nitrogen on plant growth is also slow. The advantage of this is that it has a much more lasting effect on successive crops than ammonium and nitrate nitrogen which rarely have any residual effect. Thus soil fertility is 'permanently' increased to a certain extent by protein nitrogen. This is of special importance in the case of perennial crops such as fruit-trees, vines, and sugar-cane. But even in the case of winter cereals such manures are beneficial because the stubble lands will provide good grazing.

Unfortunately organic nitrogen of animal origin is normally very expensive, and the difference in the price of such nitrogen and that of the quick-acting fertilizers will become even greater in future. This is because the sources of organic nitrogen, such as dried blood, fish meal, crayfish meal, whale meat (whale guano), and bone meal, are limited, and the products are increasingly being utilized as animal and poultry feeding-stuffs. On the other hand, the production of quick-acting nitrogenous fertilizers can be increased indefinitely with a corresponding decrease in cost of production.

The progressive farmer should produce more and more organic nitrogenous manures, mainly of vegetable origin, with the aid of cheap nitrogenous fertilizers. We have in mind, especially, a larger production of kraal manure or compost. Plant residues, chaff, and straw should be ploughed into the soil in larger amounts where the manufacture of manure and compost is not possible, and more cover crops or pasture leys should be included with the object of increasing the humus-content of the soil and consequently the organic nitrogen content.

Dried blood is still the most important organic fertilizer of animal origin. It is a by-product at municipal or other abattoirs where cattle and sheep are slaughtered on a large scale, e.g. for the export of meat. Fresh blood contains about 80 per cent. water and 20 per cent. albumen, i.e. about 3 per cent. nitrogen.

The collected blood is coagulated by steam, the serum is run off, and the coagulated clots of blood are dried under reduced pressure and then ground fine. It is a brown, powdery substance containing an average of about 12 per cent. nitrogen.

For an organic fertilizer dried blood acts relatively quickly, and in warm soils especially it becomes largely available to plants in the first growing season. It should always be worked well into the soil before sowing or planting.

Crayfish meal, without most of the shells, is sometimes also used as a fertilizer. It is a by-product of the crayfish-canning industry—an important industry in South Africa—and it contains about 6 per cent. nitrogen, 1–2 per cent. phosphoric oxide, and a small amount of free carbonate of lime.

As a nitrogenous fertilizer it acts as quickly as dried blood. It is, however, an excellent animal food, and farmers should beware of paying too high a price for it as a fertilizer.

Whale meat or whale guano is another valuable South African by-product. It contains approximately 10 per cent. nitrogen and 1–2 per cent. phosphoric oxide. Formerly it was used almost solely as a fertilizer, but at present it is used mainly as an animal food. It is a relatively expensive fertilizer and acts more slowly than the first two organic manures.

These and other forms of organic nitrogen are, to-day, found mainly in fertilizer mixtures put on the market by fertilizer firms. Their presence is one reason for the relatively high price of such fertilizers.

CHAPTER XXV

PHOSPHATIC FERTILIZERS

IT is customary in the case of fertilizer analyses, as in the case of soil analyses, to speak of the phosphorus nutrient as phosphoric acid or phosphoric oxide. Chemically these two terms do not mean the same thing but they are both indicated by the formula P_2O_5 (Phosphorus pentoxide). Actually, in manures the phosphorus food is normally present in the form of phosphates, i.e. salts of phosphoric acid, and it is in this form that plants absorb it.

In the choice and use of phosphatic fertilizers solubility plays an important part. The government regulations governing the sale of fertilizers mention *three grades of solubility* and according to this we can classify phosphatic fertilizers in three classes: (1) Water-soluble phosphates, (2) Phosphates soluble in 2 per cent. citric acid solution but not in water, and (3) Phosphates that are only soluble in strong mineral acids (sulphuric acid, nitric acid, hydrochloric acid). The solubility will depend largely on the chemical composition or formula of the phosphate, but the degree of fineness is also important; the finer the particles of a given weight of the substance, the more readily will they dissolve in a liquid with which they come in contact. This is of special importance in the case of water-insoluble phosphates.

The phosphates, or salts of phosphoric acid (H_3PO_4), which are sold as commercial fertilizers almost all fall in the class of calcium phosphates. In order to be conversant with the properties of different phosphatic fertilizers, it is necessary to say something about the possible composition of different calcium phosphates. We can differentiate between four types:

1. Monocalcium phosphate ($CaH_4(PO_4)_2$) is readily soluble in water and it is the most important compound in superphosphate.

2. Dicalcium phosphate ($Ca_2H_2(PO_4)_2$) is not soluble in water but it dissolves readily in weak, dilute acids such as 2 per cent. citric acid. Nowadays this compound does not occur in many fertilizers (Government guano and superphosphate contain a little of it), but it is one of the forms into which monocalcium phosphate changes, e.g. when superphosphate is incorporated with most soils. Basic superphosphate, which can be made on the farm from superphosphate, contains a fair amount of dicalcium phosphate.

3. Tricalcium phosphate ($Ca_3(PO_4)_2$) is neither readily soluble in water nor in weak acids, but it dissolves in strong mineral acids. If it is ground very finely a fair percentage of the phosphate will sometimes dissolve in weak citric acid. Tricalcium phosphate is the form in which calcium phosphates usually occur in nature, e.g. in phosphate rock and in bones.

4. Tetracalcium phosphate ($Ca_4P_2O_9$) is supposed to be the phosphate that is mainly found in basic slag, but other more complicated compounds

actually predominate in it. The basic slag phosphate is not soluble in water, but it does dissolve in weak acids such as 2 per cent. citric acid. In other words, it has approximately the same degree of solubility as dicalcium phosphate.

In general, we can say that among phosphates the water-soluble ones are the most valuable to the farmer because usually they are most available to growing plants. The citric acid-soluble phosphate acts slightly more slowly than the water-soluble, although it also will act quickly on acid soils. In such instances it is of even greater value than water-soluble phosphate, as we shall see later. Finally, phosphates which are only soluble in strong acids will become available very slowly, with the result that they are the least valuable to the farmer unless the soil is very acid and the price is relatively low. The following are the most important phosphatic fertilizers:

Superphosphate. This is the oldest artificially produced fertilizer and its manufacture as a fertilizer dates back to 1842 when Lawes in England prepared it from rock phosphate and sulphuric acid after the famous German chemist, Justus von Liebig, had suggested treating bones with sulphuric acid. Recent research has shown that others used this 'patent' at an earlier date to render insoluble phosphates more available to plants. It is by far the most important phosphatic fertilizer in present world trade, and about 20 million tons are manufactured annually.

The two substances from which superphosphate is prepared are finely ground phosphate rock and fairly concentrated sulphuric acid. The suitability of the phosphate rock for the preparation of superphosphate depends mainly on two requirements:

1. It must contain a high percentage of calcium phosphate (say, more than 60 per cent.).
2. It should not contain more than 2 per cent. of iron and alumina.

The rock phosphate which has thus far been discovered in South Africa does not meet these requirements, and therefore the rock phosphate for our superphosphate factories (Somerset West (Cape) and Umbogintwini (Natal)) has to be imported. The most important countries in which large amounts of phosphate rock occur are North America, North Africa, and some South Sea islands.

Superphosphate is prepared as follows: Approximately equal amounts of phosphate rock and concentrated sulphuric acid (approximately 70 per cent.) are weighed off separately and mixed for about one minute in a mixer with mechanical rotators. The warm mixture then falls through a flap into a huge den[1] where the chemical reactions continue. After the den has been filled and the mixture has been left for a further twelve hours to harden and to cool down somewhat, it is removed by a travelling crane and deposited in a pile in a large shed in order to mature. After some weeks it will be ready for use. Before bagging it is necessary to grind the fertilizer

[1] In South Africa a method of manufacture is now used which obviates the use of dens.

because during maturing it hardens into a compact mass. The most important chemical reactions that take place after mixing are the following:

1. $Ca_3(PO_4)_2+2H_2SO_4+5H_2O = CaH_4(PO_4)_2.H_2O+2CaSO_4.2H_2O.$

Tricalcium phosphate and Sulphuric acid and Water give Monocalcium phosphate and Gypsum.

Actually the reaction takes place in two stages and the above equation only gives the initial and end products.

2. $CaCO_3+H_2SO_4+H_2O = CaSO_4.2H_2O+CO_2.$

Carbonate of lime and Sulphuric acid and Water give Gypsum and Carbon dioxide.

Phosphate rock always contains carbonate of lime, and about 5 per cent. of carbonate of lime is advantageous in the rock, because in the reaction given above heat and carbon dioxide evolve, with the result that the mass becomes warm and porous and the first and most important reaction can take place more completely.

3. Constituents of phosphate rock, such as iron and aluminium compounds and calcium fluoride, also react to a certain extent with sulphuric acid, with the result that the completed fertilizer contains various different chemical compounds.

However, the two most important ingredients of superphosphate are *Monocalcium phosphate* and *Gypsum*. Besides this it sometimes contains a small amount of free phosphoric acid and also a small amount of dicalcium phosphate and unchanged tricalcium phosphate. A superphosphate analysis would, e.g., be as follows in terms of its phosphoric oxide content:

Water-soluble phosphoric oxide	18·0 per cent.
Citric acid-soluble phosphoric oxide . . .	18·5 ,, ,,
Total phosphoric oxide	19·0 ,, ,,

From such analysis one can see that the superphosphate in question contains 18 per cent. of phosphoric oxide mainly as monocalcium phosphate and free phosphoric acid (H_3PO_4), 0·5 per cent. (18·5 minus 18·0) of phosphoric oxide probably as dicalcium phosphate, and 0·5 per cent. (19·0 minus 18·5) phosphoric oxide in the form of tricalcium phosphate and possibly iron phosphate.

In the superphosphate trade only the water-soluble phosphoric oxide is taken into account. According to government regulations a high-grade superphosphate should contain at least 18 per cent. and a low-grade superphosphate at least 15 per cent. water-soluble phosphoric oxide. Practically all the superphosphate that is sold on the South African market is of the high-grade class.

Superphosphate[1] is a greyish-white granular fertilizer. Sometimes it is slightly moist (with an acid odour), but it should be as dry as possible and contain no lumps so that it can easily be distributed by hand or by a fertilizer drill.

[1] 'Ultrasuper' is an imported Netherlands product which has been dried artificially and is granular.

When superphosphate is applied to a moist soil the monocalcium phosphate dissolves in the soil moisture, but within a very short period (a few hours) it is precipitated in the soil pores as fine, solid particles. The result is that the phosphate is no longer readily soluble in water and thus it is no longer liable to be leached from the soil by rain. It is important to know which new phosphate compounds have been formed.

In slightly acid, neutral, and calcareous (alkaline) soils the precipitate will consist mainly, or exclusively, of dicalcium and tricalcium phosphate, i.e. the monocalcium phosphate reacts with dissolved carbonate of lime or other calcium compounds.

1. $CaH_4(PO_4)_2 + Ca(HCO_3)_2 = Ca_2H_2(PO_4)_2 + 2H_2CO_3.$

Monocalcium phosphate and Calcium bicarbonate give Dicalcium phosphate and Carbonic acid.

2. $CaH_4(PO_4)_2 + 2Ca(HCO_3)_2 = Ca_3(PO_4)_2 + 4H_2CO_3.$

Monocalcium phosphate and Calcium bicarbonate give Tricalcium phosphate and Carbonic acid.

Although the precipitated calcium phosphates are not readily soluble in pure water, a small amount does dissolve in soil water containing carbonic acid. Thus, it becomes available to plants.

In the case of markedly acid soils the soil solution contains very little dissolved calcium compounds and iron and aluminium become more active. The result is that the dissolved monocalcium phosphate reacts with iron and aluminium compounds. In such a case many reactions are possible but for the sake of simplicity the following only is given:

$$2CaH_4(PO_4)_2 + Fe_2O_3 = 2FePO_4 + Ca_2H_2(PO_4)_2 + 3H_2O.$$

Monocalcium phosphate and Iron oxide give Iron phosphate, Dicalcium phosphate, and Water.

Thus, half, or even more, of the water-soluble phosphate is changed to iron (and aluminium) phosphates, and in a short time these phosphates become so insoluble that plants can make very little use of them. In practice it is said that superphosphate does not do well on acid soils, reverting soon to very insoluble forms.

These complicated chemical[1] changes that occur in respect of the water-soluble phosphatic food lead us to draw the following conclusions about superphosphate as a fertilizer:

1. Although the phosphorus nutrient in the fertilizer is water-soluble, no leaching (practically speaking) occurs in soils as a result of heavy rains, because the monocalcium phosphate is very soon changed to forms which are insoluble in water. Therefore, applications of superphosphate are given at planting or sowing time or even earlier if farming activities permit.

2. In contrast with nitrogenous food the phosphatic plant food hardly moves in the soil at all. It remains in the zone in which it was incorporated. This also applies to the water-soluble monocalcium phosphate which will,

[1] It is also possible that some of the phosphate ions are adsorbed by the soil colloids.

at the best of times, move in the soil for a few inches only before it is completely precipitated. Naturally, it will go slightly deeper in sandy soils than in loams and clayey soils. Therefore, where possible, superphosphate should be worked well into the soil. It is of special importance that orchards and vineyards should receive stripwise a deep cultivation at periodic intervals in order to work the phosphate, which usually remains in the topsoil layer, more deeply into the soil. All phosphatic fertilizers are unsuitable as top dressing if the soil cannot be cultivated after broadcasting.

3. Superphosphate should not be used on acid soils with a pH of less than about 5·5, because the availability of the phosphate on such soils is too low, and its residual effect too short. Such soils should be limed prior to applying superphosphate. The alternative is to use phosphatic fertilizers such as basic superphosphate, basic slag, and even rock phosphate which are all insoluble in water. Formerly it was thought that superphosphate increased the acidity of acid soils and that this was the cause of its poor effect on such soils. To-day we know that superphosphate does definitely not increase the acidity of soils, but that owing to its quick reversion to very insoluble forms it is not economical to use ordinary superphosphate on markedly acid soils.

4. Under favourable conditions about 10–20 per cent. of the phosphatic food in superphosphate is absorbed by plants during the first growing season. The reason for this low availability is the inefficient distribution of the phosphatic fertilizer in the soil and the relative insolubility of the newly-formed precipitates. Therefore, an application of superphosphate should usually contain at least five times as much phosphoric oxide per unit area, over and above the amount of available phosphate in the soil, as would be required by a good crop on that area.

The question arises: How much of the phosphatic nutrient that was not used during the first growing season becomes available to plants during the second and subsequent seasons? To express it differently: What is the residual effect of superphosphate?

This question can only be answered satisfactorily by a fertilizer trial on the soil type, with the crop-rotation system in question and under the prevailing climatic conditions. In general we can say that the residual effect of an application of superphosphate on a calcareous and more or less neutral soil will last for several years. In acid, ferruginous (red) soils the residual effect in the second season will be very small and during subsequent seasons it need not be taken into account at all. The majority of South African arable soils fall in the latter class. The result is that the farmer cannot depend on the residual effect of the previous year's application, and therefore phosphatic fertilizers should, as a rule, be applied every year. This is especially the case when the dressings are relatively small.

Finally, the following question in connexion with superphosphate may be asked: What is the advantage of treating phosphate rock with sulphuric acid, rendering it water-soluble, if, in the soil, it reverts to an insoluble

form? Firstly, the freshly precipitated phosphate is more soluble in soil water and hence available to the plant than the original ground phosphate. Secondly, although the monocalcium phosphate only moves slightly in the topsoil before it is precipitated, the distribution in the smaller pores of the soil crumbs is far better than in the case of phosphates that are insoluble in water. When, in the case of pot cultures, finely ground rock phosphate is thoroughly mixed with the soil it may in certain cases be almost as available to plants as superphosphate. However, under field conditions it is never possible to mix the fertilizer so thoroughly with the soil, and for this reason higher yields are usually obtained with superphosphate which does spread itself in the soil to a certain extent.

Sometimes the opinion is expressed that fertilizing with superphosphate depletes the soil. It is said that in the beginning superphosphate produces high yields but that gradually yields tend to decrease with subsequent applications and that stubble lands no longer produce much grazing. This is only the case where superphosphate is applied *exclusive of all other fertilizers and manures* and where a system of monoculture without any crop rotation is in vogue. Because even virgin soils in South Africa contain so little available phosphates an initial application of superphosphate will give a tremendous increase in yield with the result that farmers are apt to apply superphosphate exclusively. It is not borne in mind that the superphosphate also provides excellent food for the soil microbes and they, in increased numbers, decompose humus at a much faster rate. This means that large amounts of nitrate nitrogen are produced on account of increased microbial activity as a result of soil cultivation and the application of the phosphate, and consequently high yields are obtained. Because the humus content of the soil is depleted its structural condition is impaired; it becomes more compact especially after rains and thus moisture and air conditions become less favourable for plant growth. Moreover, the nitrogen content of the soil, and sometimes also the potash content, may become dangerously low. An insufficient supply of the latter nutrients along with a less favourable moisture supply and limited root distribution may then be the limiting factors in crop yields and not the phosphate content of the soil.

Therefore, an application of superphosphate should be accompanied by applications of organic matter (farm manure, compost, green manure, straw, and grass). If this is not possible the lands should be 'rested' periodically under leys of grass or legumes (lucerne). Fertilizing with phosphatic fertilizers exclusively and continually is very dangerous in South Africa, and every farmer should guard against it in order to maintain the productivity of the land. In European countries it was formerly said that lime makes for rich fathers but poor sons. Let this not be said of superphosphate in South Africa!

We have discussed the use of superphosphate in great detail because superphosphate constitutes over 60 per cent. of the fertilizer consumption in South Africa (at present the superphosphate requirement is more than

a million tons annually), and therefore a sound knowledge concerning the correct use of superphosphate is essential to every South African farmer.

Basic slag ranks second in importance in the world consumption of phosphatic fertilizers and especially in the Western Cape Province it is also well known. It is a by-product of the steel industry where the original iron ores contain appreciable phosphorus. The phosphorus is removed from the pig-iron by charging lime into the converter, turning on the blast, and running the molten pig-iron into the converter. The phosphorus is oxidized to phosphoric pentoxide which combines with the lime and appears on the surface of the molten, refined iron which is now called steel, together with silicic acid and other impurities. The slag is removed and after cooling the big hard lumps are pulverized in ball mills.

Nowadays, in England, phosphorus is removed from the pig-iron by a new method (open-hearth process) yielding an inferior quality slag which may not be imported into the Union. The importation of basic slag into the Union has dropped considerably since World War I and this fertilizer now comes exclusively from the continent of Europe (Germany, Belgium, France). The annual production of basic slag is normally about 5 million tons and the annual imports into South Africa are about 15,000–20,000 tons. The South African Steel Industry does not produce any basic slag.

Basic slag is a greyish-black powder with a very high specific weight. It is evaluated on the basis of its solubility in 2 per cent. citric acid solution. According to government regulations, high-grade basic slag should contain at least 17·0 per cent. phosphoric oxide, soluble in citric acid. Fertilizer experiments have proved that the phosphate in basic slag which is soluble in 2 per cent. citric acid is also readily available to plants. Furthermore, the regulations demand that the basic slag should be so fine that at least 80 per cent. will pass through a 90-mesh sieve.

Besides phosphate, basic slag contains a considerable quantity of free unslaked lime (CaO). Thus, this fertilizer is very suitable for acid soils. In the first place, it reduces the acidity to a certain extent and, secondly, the phosphate in basic slag is more available to plants in acid than in sweet soils. Because the phosphate is not water-soluble it is not changed to unavailable iron and aluminium phosphates in acid soils. In contrast to superphosphate it has a lasting residual effect even in acid soils. Thus, it is very suitable for incorporating with the deeper soil, especially before planting young fruit-trees and vines.

The most important point to be borne in mind when using basic slag is that it should be mixed thoroughly with the soil because it hardly moves at all in the soil. On fallow grain lands in the Western Cape Province it is usually harrowed into the braaked soil some months before planting or sowing. The reason for this is not, as farmers say, that it gives the basic slag time to dissolve in the soil solution, but because the soil is cultivated at least twice after the fertilizer application and prior to sowing.

Basic superphosphate. Because importation of basic slag after World War I decreased considerably, and because its price is high in comparison

with that of ordinary superphosphate, a substitute for basic slag was called for since ordinary superphosphate is unsuitable for use on markedly acid soils. Basic superphosphate is a name given to two different mixtures: (1) superphosphate mixed with carbonate of lime (ground limestone) and (2) superphosphate mixed with rock phosphate. Strictly speaking the name may, in trade, only be used for the first mixture, although farmers are free to make up either mixture.

When superphosphate is mixed with ground limestone the free phosphoric acid is converted to tricalcium phosphate and a portion of the monocalcium phosphate is changed to di- or tricalcium phosphate.

1. $$2H_3PO_4+3CaCO_3 = Ca_3(PO_4)_2+3CO_2+3H_2O.$$

Phosphoric acid and Carbonate of lime give Tricalcium phosphate, Carbon dioxide, and Water.

2. $$CaH_4(PO_4)_2+CaCO_3 = Ca_2H_2(PO_4)_2+CO_2+H_2O.$$

Monocalcium phosphate and Carbonate of lime give Dicalcium phosphate, Carbon dioxide, and Water.

The word 'basic' refers to the excess of lime which the superphosphate contains after treatment. It is clear that the superphosphate 'loses' a large amount of its water-soluble phosphate depending on the amount of lime that is added and the amount of free phosphoric acid in the superphosphate. However, the di- and tricalcium phosphates that are formed in this way are readily soluble in 2 per cent. citric acid and hence readily available to plants. According to government regulations the commercial product is sold on the basis of 2 per cent. citric acid solubility and naturally this includes the remaining water-soluble phosphoric oxide.

When superphosphate is mixed with finely ground rock phosphate the reactions that take place are approximately the same as those given above. The rock phosphate also contains a certain amount of carbonate of lime which reacts with the free phosphoric acid and monocalcium phosphate, forming di- and tricalcium phosphate. Furthermore, the tricalcium phosphate of the rock phosphate may gradually react with a portion of the monocalcium phosphate of the superphosphate, forming dicalcium phosphate.

$$CaH_4(PO_4)_2+Ca_3(PO_4)_2 = 2Ca_2H_2(PO_4)_2.$$

Monocalcium phosphate and Tricalcium phosphate give Dicalcium phosphate.

Thus the preparation of a basic superphosphate aims at changing a portion[1] of the water-soluble phosphoric oxide in the superphosphate to a form in which it is not soluble in water, but in such a way that it remains a calcium phosphate. Naturally this is only an advantage where there is a danger that the water-soluble phosphoric oxide of the superphosphate will revert to insoluble iron and aluminium phosphate, e.g. in very acid soils. With the second method there is a secondary aim, viz. the conversion of

[1] Analyses showed that only a small portion, about 20 per cent., of the water-soluble phosphoric oxide in the mixture underwent the above change.

part of the tricalcium phosphate of the rock phosphate to a form in which it is more available to plants. The method for the farmer to follow will depend on the prices of agricultural lime and rock phosphate. In general, the second type of basic superphosphate is more suitable for very acid soils or the warm soils of the summer-rainfall area, and the first type (mixed with lime) is more economical on soils of medium acidity.

The proportions in which superphosphate and lime or superphosphate and rock phosphate are mixed will depend on certain conditions. A good mixture is one consisting of two bags (400 lb.) of superphosphate and one bag of limestone (150–200 lb.), or one bag (200 lb.) of rock phosphate. Naturally the rate of application will be higher with the first mixture than with the second. Mixing should be done thoroughly on a hard floor. If the superphosphate contains much free phosphoric acid the mixture will temporarily become warm, but this is of no importance.

Basic superphosphate is a dry, granular fertilizer. Like basic slag it should be well worked into, and mixed with, the soil. It may be used to increase the phosphate reserve, e.g. when establishing orchards or vineyards.

Rock phosphate is mined on a very large scale in certain countries (especially in North Africa and the United States of America). It is used mainly for the manufacture of superphosphate, but under certain conditions it may be used as a fertilizer for arable soils. These conditions are:

1. It must be very finely ground.
2. The unit value of the phosphoric oxide in rock phosphate should be much lower than that of water-soluble phosphoric oxide in superphosphate.
3. The soil should preferably be under a permanent crop such as fruit-trees.
4. The soil should be acid and should have a high humus content.
5. The rock phosphate should, chemically, not be too insoluble.

Most of these conditions are quite apparent and show clearly that the use of pure rock phosphate in South Africa is very limited. The last two conditions will be discussed in greater detail. Our arable soils generally have a very low humus content and therefore it is essential that an application of rock phosphate should be accompanied by an application of farm manure, compost, or by green manuring—practices which are not always easy to carry out in South Africa. The organic matter produces carbonic acid and other acids during decomposition and they convert the rock phosphate to a more soluble form.

In connexion with the last condition we can differentiate between three kinds of rock phosphates:

(*a*) *Phosphorites* (lime phosphates) in which practically all the phosphoric oxide is in combination with calcium. Phosphorite originated from old guano deposits or from accumulated remains of marine life. It contains free carbonate of lime and is usually a relatively soft rock. 'Langfos' (Langebaan phosphate, Cape) belongs to this class.

(*b*) *Apatite* also consists of calcium phosphate, but it contains no free carbonate of lime. It is very hard and crystalline and occurs as bands in igneous rocks.

(*c*) *Iron* and *Aluminium* phosphates are, like phosphorites, of organic origin, but they contain little calcium and are usually very hard rocks.

For fertilizing the phosphorites are by far the most suitable rock phosphates. Apatite-phosphate is usually much less soluble in soils than is phosphorite. 'Phosmeal' falls in this class and was at one time mined in the Eastern Transvaal. Finally, the iron and aluminium phosphates are the least available of all to plants. Unfortunately much of the rock phosphate that has thus far been discovered in South Africa is iron or aluminium phosphate or a mixture of (*a*) and (*c*) (Saldanha Bay).

Lime phosphates may, as shown under basic superphosphate, be used to advantage, together with superphosphate, on acid, ferruginous soils, provided their price is low enough.

Untreated bone-meal (ground bones) is the oldest phosphatic fertilizer, and since the beginning of the previous century it has been used in increasing quantities. At the beginning the difficulty was to grind the bones sufficiently fine because coarse particles of bone can lie in the soil for years without decomposing. Nowadays the bones are sterilized with steam or otherwise—government regulations require that this should be done—and then they are dried in warm, rotating ovens. After this process the bones are brittle and are fairly easily ground. According to our regulations bone products may be sold in three grades, depending on their fineness:

1. *Bone-meal.* This is the coarsest product but it should, nevertheless, be so fine that at least 85 per cent. will pass through a standard sieve with round holes of 2 millimetres in diameter.
2. *Bone-dust.* This product should be so fine that 85 per cent. of the material will pass through a sieve having holes of 1 millimetre in diameter.
3. *Bone-flour.* This is the finest bone fertilizer and 100 per cent. thereof must pass through a 1 millimetre sieve and at least 50 per cent. through a one-half millimetre sieve.

Green, dry bones contain approximately (main constituents):

10 per cent. moisture.
10 per cent. fat.
18 per cent. nitrogenous matter (= about 3 per cent. nitrogen).
44 per cent. lime phosphate (= about 20 per cent. phosphoric oxide).
5 per cent. carbonate of lime.

By sterilizing with steam nearly all the fat is removed, with the result that the percentages of nitrogen and phosphoric acid are higher in steamed bone-meal than in the untreated product. Usually such a bone-meal contains about 3–4 per cent. of nitrogen and 24–26 per cent. of phosphoric oxide. Ordinary bone-meal contains, in addition to the bones, the hooves and horns of the animals, with the result that the composition is not constant.

Bone-meal is now fed extensively to farm animals in order to supplement the shortage of phosphates in the grazing. In the preparation of such a bone-meal the hooves and horns (which are rich in nitrogen) are removed in order that the product should have as high a phosphate content as possible with as little unnecessary odour as possible. The bone-meal that is sold as fertilizer contains the horns and hooves as well, thus it is darker in colour and richer in nitrogen.

Steamed bone-meal is used mainly as a phosphatic fertilizer, but it also contains a considerable amount of organic nitrogen (as indicated by the above analysis). This nitrogen should be considered when comparing the manurial value and price of bone-meal with that of, say, superphosphate. Its nitrogen acts more slowly than the nitrogen of dried blood.

The phosphate in bone-meal is usually appreciably more available to plants than that of rock phosphate (phosphorite). It is sold on a basis of total phosphoric oxide, i.e. phosphoric oxide that is soluble in strong mineral acids. However, the citric acid-soluble phosphoric oxide is usually also given. It is more available in acid soils than in 'sweet' soils, and can be profitably used on intensively farmed soils such as orchards and vineyards.

In comparison with the other phosphatic fertilizers, bone-meal is to-day very expensive because its production is limited (whale-bone meal is an important source in South Africa), and the demand as a mineral feed for animals is very great. Therefore, the wise farmer would hardly use it as a fertilizer. It is an ingredient of many mixed fertilizers on the market. Sometimes farmers mix bone-meal with superphosphate in order to obtain a dry granular fertilizer that will run easily through the seed drill and that will contain some nitrogen. However, rock phosphate or ground limestone and a small amount of sulphate of ammonia, mixed with superphosphate, will also produce such a fertilizer at a considerably lower price.

Abroad, bones are sometimes degelatinized in order to obtain the valuable by-product, glue or gelatine. The bone-meal which is obtained in this way contains very little nitrogen (about 0·7 per cent.) but the phosphoric oxide content is higher, usually about 30 per cent. This bone-meal is sold in South Africa as Degelatinized Bone-dust or Degelatinized Bone-flour. It is very fine, acts more quickly than ordinary bone-meal as a phosphatic fertilizer, but it is also very expensive.

Unsteamed bones are very difficult to grind. Farmers who have large quantities of bones on their farms and wish to use them as fertilizer may leave them to dry in the sun and then burn them with wood. The bone ash that is obtained in this way is a good phosphatic fertilizer. Naturally it contains no nitrogen.

Finally, we may mention another water-soluble phosphatic fertilizer that contains no calcium (lime), viz. *Ammonium phosphate* or, as it is known commercially, *Ammophos*, $NH_4H_2PO_4$. This is prepared by combining (synthetic) ammonia with phosphoric acid. It is a white, fine-crystalline salt that is readily soluble in water and contains 11 per cent. of nitrogen

and about 56 per cent. water-soluble phosphoric oxide, i.e. about three times as much phosphoric oxide as high-grade superphosphate. It is very suitable for all slightly acid, neutral, and alkaline soils, i.e. soils with a pH of more than 6·0. On very acid soils it is not advisable to use it, because the phosphoric acid will precipitate with iron and alumina, soon becoming unavailable. In any case, the ammonium portion will acidify such soils still further. The nitrogen acts like the nitrogen in ammonium sulphate. It is ploughed or cultivated well into the soil at planting time, and it should be borne in mind that (*a*) only a third of the amount usually applied in the case of superphosphate, should be applied, and (*b*) it should be used on soils which also respond to nitrogen.

CHAPTER XXVI

POTASSIC FERTILIZERS

USUALLY, plant ash contains much actual potash (potassium carbonate, K_2CO_3). The presence of a carbonate can easily be proved by the effervescence (evolution of carbon dioxide) when an acid is added to the ash. Sometimes plants such as tobacco, sunflower, seaweeds, and their ash are used as potassic fertilizers. Ordinary stove ash (when wood or animal dung is burnt) contains from 6 to 10 per cent. of pure potash (K_2O). Karoo ash is the ash obtained when Karoo or kraal manure is burnt and it contains, on an average, 10 per cent. potash (K_2O), 15 per cent. lime (CaO), and 2·5 per cent. phosphoric oxide (P_2O_5). But kraal manure should not be purposely burnt because all the organic matter and nitrogen are lost during combustion.

As ash from these sources contains potash (potassium carbonate) and because this compound is alkaline, its possibly harmful effects should be taken into consideration when using it as a fertilizer. Ash should never be applied in too large a quantity, nor should it be used continually on the same soil because it may be responsible for excessive alkalinity in soils, which may be harmful to plant growth. Karoo ash contains considerable amounts of soda also and this may damage the soil structure, causing soils to become compact and form a hard crust. Ash should only be applied on acid, coarse-sandy soils, and some time before sowing or planting. Ash serves a good purpose when preparing farm compost (see later) and it should be limited to that use if possible.

The potash content of soils and manures is always indicated as potassium oxide (K_2O), and not as K_2CO_3 as would be chemically more correct when the term potash is used.

The subterranean potash salt-mines in Central Germany and in Alsace, and in other parts of the world, e.g. Poland, Russia, Spain, Texas, are the main source of potassic fertilizers. The potash salt deposits also contain huge quantities of rock salt (common salt); therefore the salt deposits are clearly of marine origin, the sea-water having evaporated in former geological ages. For example, the water of the Dead Sea is so concentrated already that a company is busy manufacturing table salt, potash salts, and other chemicals from it.

Potash salts have been mined in Germany (originally at Stassfurt only) since 1861, and prior to World War II annual production of crude potash salts in Germany and Alsace (France) was about 15 million tons. The crude potash salts contain large quantities of magnesium and sodium salts and as low-grade fertilizers they are used almost exclusively in Germany, where they are marketed under the name Kainite (containing about 12 per cent. potash). The bulk of the crude salts is refined for the purpose of

producing higher-grade potassic fertilizers. There are three concentrated potassic fertilizers on the market:

1. *Muriate of potash* (or potassium chloride, KCl) is a coarse or a fine salt closely resembling ordinary stock salt (but with a bitter taste). The fertilizer contains from 80 to 96 per cent. potassium chloride. The remainder is mainly sodium chloride (common salt). It is customary to sell also this fertilizer on its pure potash content (K_2O)—although it contains no oxygen—and the above limits represent about 50–60 per cent. of potash. According to government regulations high-grade muriate of potash should contain at least 60 per cent. pure potash and the low-grade fertilizer must contain at least 50 per cent. pure potash.

The high-grade product is used almost exclusively in South Africa. In European countries large amounts of potassium chloride are sold, containing 20, 30, and 40 per cent. pure potash.

2. *Sulphate of potash* (or potassium sulphate, K_2SO_4) is a fine, yellowish salt. The fertilizer contains 75 90 per cent. potassium sulphate, which means that its pure potash content varies approximately from 40–48 per cent. According to the regulations the high-grade sulphate of potash should contain at least 48 per cent. and the low-grade 40 per cent. water-soluble potash, i.e. K_2O.

3. *Potash-magnesia* (or potassium magnesium sulphate) is a mixture of potassium sulphate (K_2SO_4) and magnesium sulphate ($MgSO_4$). The fertilizer is usually sold on a basis of a pure potash content of about 28 per cent. and 10–12 per cent. magnesia (MgO). It is also a fine, yellowish salt for which there is, as yet, no demand in South Africa. In some countries, e.g. Holland, it is used especially on peaty and sandy soils for crops such as potatoes which require a large amount of potash as well as magnesia.

From the point of view of nutrition all the potassic fertilizers are equally available to plants because all of them are readily soluble in water. As in the case of ammonium salts the potash or basic portion of the salt is retained by the clay and humus particles of the soil. Thus, there is little danger of leaching as a result of heavy rains although the potash nutrient is, in the first instance, water-soluble. Consequently potassic fertilizers may safely be applied before or at planting or sowing. In the case of deep-rooted crops, such as fruit-trees, it is essential to plough the potassic fertilizer deep into the soil because it moves downward very slightly on its own accord, except in very sandy soils. Although it is retained by the soil colloids, most of the potash is nevertheless available to plants since a small amount of potash will always be found in the soil solution on account of cation exchange.

The question arises: Which one of the two potassic fertilizers offered for sale in South Africa should the farmer buy? The potash plant food in sulphate of potash is more expensive than that in muriate of potash. Consequently one should always use muriate of potash unless the chlorine portion is harmful to the soil or the quality of the crop concerned.

The quality of potatoes and tobacco is affected by considerable amounts of chlorine in the soil with the result that sulphate of potash is always used with these crops. In the case of bearing fruit-trees and vines and possibly also sugar-cane, it is customary to apply sulphate of potash, but a lot depends on the rainfall and soil type. If the precipitation and soil type are such that leaching of the soil can occur, muriate of potash may safely be applied regularly or alternatively. Winter cereals, maize, vegetables, legumes, cotton, pine-apples, &c., are always fertilized with muriate of potash on ordinary soil types.

In the case of brak soils, sulphate of potash should always be applied. Recent research has shown that sulphate of potash can improve the structure of brak soils.

South African soils, especially in the drier regions, are on the whole well supplied with potash. On sandy soils in coastal areas and in the case of crops that make a big demand on the potash supply, application of potassic fertilizers should, however, always be considered.

These fertilizers have practically no influence on the soil reaction, i.e. the soils do not become more acid.

LIMING MATERIALS

Why is lime applied to soils?

Fertilizers are applied to remedy any deficiency of plant food. Lime is applied with a different object. It renders the soil a more favourable medium for the growth of roots, and makes the nutrients more available to the plant. It is, therefore, an indirect fertilizer or, as it is more appropriately termed, a soil improver.

The diverse effects of lime on soils may be discussed under three headings:

1. *Lime improves the chemical properties of soils.* In this connexion there are two particular effects of lime in which we are interested. The first is the neutralization or 'sweetening' of acid soils. Many agricultural crops cannot tolerate soil acidity and the majority of the useful soil microbes do not prefer such a condition. In Chapter XXI we pointed out that soil acidity is due to the fact that the clay and humus particles contain too many absorbed hydrogen ions, and that the acidity is decreased and eventually removed completely if the hydrogen ions are replaced by calcium or other metallic cations. Therefore, when an acid soil is limed, the absorbed hydrogen is replaced by the dissolved calcium and *rendered harmless.* It is important that the released hydrogen ions as such should disappear, otherwise the soil solution (soil moisture) would become very acid. Thus, an application of gypsum does not reduce soil acidity because the hydrogen ions remain in the soil moisture, and, in any case, they are not exchanged to the same extent as when lime is used. The following equations explain the effect of lime, carbonate of lime, and gypsum (calcium sulphate). For the sake of simplicity we assume that the clay portion

of an acid soil is saturated with hydrogen only which, of course, is hardly ever the case.

1. $$\text{Clay}{-}H_2 + Ca(OH)_2 \rightarrow \text{Clay}{-}Ca + 2H_2O.$$

'Clay acid' and Slaked lime give Calcium clay and Water.

2. (*a*) $$\text{Clay}{-}H_2 + Ca(HCO_3)_2 \rightarrow \text{Clay}{-}Ca + 2H_2CO_3.$$

'Clay acid' and dissolved Carbonate of lime give Calcium clay and Carbonic acid.

(*b*) $$2H_2CO_3 \rightleftharpoons 2H_2O + 2CO_2.$$

Carbonic acid may split into Water and Carbon dioxide.

3. $$\text{Clay}{-}H + CaSO_4 \rightleftharpoons \text{Clay}{-}Ca + H_2SO_4.$$

'Clay acid' and Gypsum may give Calcium clay and Sulphuric acid.

The so-called 'lime requirement' of a soil depends on the amount of absorbed hydrogen ions in, say, a pound of soil. There are different methods by which this requirement may be determined either accurately or approximately, but in practice the rate of application depends on other aspects also.

Secondly, lime has the chemical effect that, theoretically, certain nutrients become more available to plants. Apart from its effect on the availability of nitrogen, which will be discussed under the bacteriological effects of lime, the effect of lime on the phosphorus food is, perhaps, the most important. After an application of lime to acid soils there is the possibility that the mineral phosphate reserve in the soil will be changed partially to a lime phosphate form which can be more readily absorbed by plants than iron and aluminium phosphate. Furthermore, phosphatic fertilizers will, for the same reason, have a longer residual effect on acid soils after liming. This has already been discussed in connexion with the application of superphosphate on acid soils. Because our soils generally have such a low phosphate reserve and because crop production is usually extensive, it will seldom pay to apply lime with the object of increasing the availability of the phosphate reserve or to increase the residual effect of phosphatic fertilizers. In such cases it is more economical to use a basic phosphatic fertilizer instead.

Whether the potash supply in soils will become more available as a result of liming is doubtful, and, in any case, it is not sufficient reason for an application of lime.

Another chemical effect of lime is that plants will have an increased supply of lime. This direct manurial effect of lime is very seldom important enough to warrant liming. However, if valuable animals are kept on a 'sour' farm, it may pay to apply lime to the soil in order to obtain healthier livestock.

Finally, excessive liming may be chemically harmful to the soil. It can decrease considerably the availability of the trace elements, especially iron

and manganese, with the result that a deficiency in these occurs. Therefore, the pH should preferably not be raised above 6·0, especially in soils with a low humus content.

2. *Lime improves the physical properties of soils.* The primary reason for the beneficial effect lime has on soil structure is that lime changes the colloidal clay and humus substances to 'calcium compounds'. This was explained in the paragraphs dealing with the neutralization of acid soils. The calcium clay has the property of being granular and such a soil usually has a crumb structure. The result of this, again, is that the soil has relatively large pores which enable free water to drain away easily. Thus, clay soils which have received an application of lime have improved drainage, are well aerated, they heat up more readily, a hard crust is not formed so easily, and the clods, in any case, break up easily. It is clear that such an improvement in the tilth of clay soils is important and it pays to lime intensively cropped soils of this description. If the soil tends to become water-logged because it has an impervious layer of potclay in the subsoil, liming will be of no avail unless provision is first made for the removal of the superfluous water.

3. *The bacteriological effects of liming.* Most forms of bacteria are sensitive to excessive acidity. This is especially the case with the bacteria that are responsible for ammonification and nitrification and those that fix elementary nitrogen. The improved aeration brought about by liming on clay soil also increases microbial activity. Thus, when acid or clayey soils which are rich in nitrogen are limed, the application of lime has more or less the same effect as an application of a nitrogenous fertilizer would have because the nitrogen reserve becomes available to plants more rapidly. Naturally this means that the nitrogen reserve in the soil is utilized to a greater extent and it is this effect of lime, especially, that is responsible for the old adage used in European countries:

> Lime and lime without manure,
> Will make both farm and farmer poor.

This is the result of any one-sided system of manuring as we pointed out when discussing superphosphate.

Sometimes it pays well to lime acid soils to which different fertilizers have been applied for years, in order to render the accumulated plant food reserve more available. In orchards and vineyards especially, it is economically sound to lime the soil at periodic intervals. It should, however, be done within limits and the soil should receive applications of organic matter (farm manure, compost, green manure, &c.) regularly to compensate for the more rapid depletion of the humus content. One should also guard against raising the pH above 6·0.

Apart from the above aspect we may say, by way of a summary, that soils should be limed for two reasons:

1. To decrease soil acidity which may be harmful to certain crops and soil microbes.

2. To improve the tilth and friability of heavy clay soils which are difficult to till.

Forms of lime

In South Africa two forms of lime are exclusively used to ameliorate soils.

1. *Finely ground limestone* or agricultural lime ($CaCO_3$). This is prepared simply by grinding the original limestone. The softer forms of limestone receive preference because they are easier to grind and also act faster in neutralizing acidity. The materials offered for sale in South Africa usually contain about 80–90 per cent. of carbonate of lime ($CaCO_3$) and the remainder is fine quartz sand. However, sometimes pure limestone, containing up to 96 per cent. of carbonate of lime, is also used.

Because it is so cheap it does not pay to spend too much money on grinding. However, the product is usually fine enough for over 80 per cent. to pass through a 1-millimetre sieve.

The word 'marl' is used to designate a clay that contains a variable percentage (40–60) of carbonate of lime. In places such as Robertson and Montagu such marl deposits occur, which can be used as agricultural lime on sandy soils if the expense of transport is low enough.

2. *Slaked lime* ($Ca(OH)_2$). When limestone is heated in a kiln at a temperature of more or less 1,000° C., carbon-dioxide gas is given off by the carbonate, and quicklime or stone (lump) lime is left behind. If, after cooling, a certain amount of water is added to the lime, slaked lime is obtained, i.e. a chemical change takes place, heat is evolved, and the lumps of lime crumble down to a powder.

(*a*) $$CaCO_3 = CaO + CO_2.$$

Carbonate of lime gives Calcium oxide (quicklime) and Carbon dioxide.

(*b*) $$CaO + H_2O = Ca(OH)_2.$$

Quicklime and Water give Slaked lime (Calcium hydroxide).

In South Africa a certain type of lime, which is not ground limestone but a mixture of carbonate of lime and slaked lime, is sometimes marketed as agricultural lime. So-called air-slaked lime is slaked lime ($Ca(OH)_2$) which has been exposed to the air for a long time, combined with carbon dioxide from the air and changed partially to carbonate of lime ($CaCO_3$) again. Or the lime may be only partially burnt so that it contains a certain amount of carbonate of lime. In either case, such a lime is unsuitable for building purposes, &c., and then it is sold as agricultural lime.

Which of the two principal forms of lime is most suitable will depend on the unit value of the active agent, namely, calcium oxide (see Chapter XXVII), delivered at the farm and, to a lesser extent, on the type of soil. In general, agricultural lime is used to neutralize soil acidity and slaked lime to improve the physical properties of heavy clay soils. Because slaked lime is much more soluble in water than carbonate of lime, it acts more

quickly on soils and also spreads more easily throughout the soil. However, the carbon dioxide and carbonic acid that are always in the soil air and soil moisture respectively will change slaked lime to carbonate of lime within a relatively short period of time.

1. $$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O.$$

Slaked lime and Carbon dioxide give Carbonate of lime and Water.

2. $$Ca(OH)_2 + H_2CO_3 = CaCO_3 + 2H_2O.$$

Slaked lime and Carbonic acid give Carbonate of lime and Water.

Usually ground limestone is so much cheaper than slaked lime that preference is given to the former in spite of the fact that it does not act so quickly. Both forms of lime should always be mixed well with the soil. The best way is first to plough the soil and then to broadcast the lime, preferably through a fertilizer distributor. The soil is then harrowed thoroughly or the lime worked into the soil with a cultivator or disk harrow. When the soil is ploughed in winter the lime is further mixed with it.

The best time to apply the lime is at the beginning of the rainy season so that the lime can dissolve slowly and the chemical reactions can take place. However, at the time of application the soil should be well dried off. If agricultural lime is applied the land may be planted immediately if necessary. If slaked lime is used it is advisable to wait a few weeks before bringing seed into the soil.

As far as the quantity is concerned, one to two tons per morgen are a good average. If the soil is very acid it is better to repeat the treatment after a year or so than to give too much at a time. In the case of sandy soils there is the danger of over-liming, with the result that the top layer of soil becomes too alkaline and thus unsuitable for the growth of certain plants. On clay soils, heavier applications are less likely to do damage.

Finally, it should be borne in mind that lime is no substitute for fertilizers and that farmers should use it with discretion. When in doubt, it is always safest to seek advice from the Agricultural College serving the area in question.

CHAPTER XXVII

FERTILIZER MIXTURES

THERE are many firms and municipalities in South Africa that manufacture fertilizers or trade in them and many of them sell, apart from the ordinary straight fertilizers, fertilizer mixtures. These mixtures are sold under various trade names such as Capex, Safco, Fison, &c. Usually every firm has a whole range of separate mixtures,[1] each meant for a certain crop such as wheat, maize, potatoes, &c. To the uninitiated these mixtures often present difficulties. Generally the mixture with the lowest price per ton is bought, and actually it may not be as cheap as it appears to be or it may be unsuitable for the soil on which it is to be used.

Commercial fertilizer mixtures present advantages as well as disadvantages to the farmer. Usually the fertilizer is dry, fine, and well mixed and can be distributed by hand as well as through a fertilizer drill. It will not form lumps or deteriorate in any other way if not used immediately. The mixtures always contain the major plant food elements so that there is no danger of one-sided fertilization. To the farmer who does not know how the ordinary straight fertilizers should be used and does not know how to make his own mixtures, commercial mixtures are safe to use.

The first disadvantage of such mixtures is that they cost considerably more than the total price of their constituents, if bought separately. Naturally, the manufacturer is entitled to an extra charge to cover mixing expenses, interest, and redemption charges on machinery, storage, &c. Where fertilizer expenses constitute only a small part of the cost of production, e.g. in fruit production, the higher cost of mixtures is not very important.

A second disadvantage of mixtures is the possibility that they may be unsuitable for the crop or soil type on which they are to be used. For example, the soil may have a high potash and a low nitrogen content, with the result that the potash in the mixture may be redundant but the proportion of nitrogen far too small to satisfy the requirements of a heavy crop. All mixtures are usually high in phosphate because our soils contain so little of this plant nutrient.

Thus, it is clear that the progressive farmer who is familiar with the fertility and manurial requirements of his soil, and who knows the properties of different fertilizers, will buy single or straight fertilizers only, and if he wishes to apply mixtures he will mix them himself. Where Government guano is used it should always be mixed at least with a phosphatic fertilizer, or some phosphatic fertilizer should be applied in conjunction with it. Besides the proportion in which fertilizers should be mixed, the following two points should be taken into consideration:

1. Mixing should be thorough and preferably on a hard cement floor. The ingredients are placed in layers, one on top of the other; that which

[1] At the time of going to press only the dozen or so standard mixtures allowed by the Government during World War II are still on the market.

constitutes the bulk of the mixture comes first, and the others are arranged according to the quantities used. They are then mixed thoroughly by turning the heap over several times with spades, from one side to the other. Just prior to turning it finally it is advisable to screen the mixture through a quarter-inch sieve in order to break up any lumps. Naturally, if one of the fertilizers was lumpy before mixing, these lumps should first have been broken up. In the case of Government guano it is advisable to sift or screen it before mixing.

2. Care should be taken that certain fertilizers are not mixed, because either some of the plant nutrient may volatilize or become less available or the mixture may become hard and lumpy. A diagram is sometimes used to indicate which fertilizers may or may not be mixed. However, there are to-day so many fertilizers on the market that such a diagram is confusing to most people, and there are only a few rules to be observed in connexion with mixtures.

Ammonium-containing fertilizers may not be mixed with fertilizers containing lime (calcium hydroxide or calcium oxide) because ammonia gas would be released, causing a loss of nitrogen. Thus, Government guano, ammonium sulphate, ammonium nitrate, and animal and poultry manures may not be mixed with basic slag or slaked lime. It would be perfectly safe to mix these fertilizers with superphosphate or basic superphosphate. However, if superphosphate and ammonium sulphate (and a potassic fertilizer) are mixed, the mixture becomes very hard if left for a time so that it is advisable to use such an inorganic mixture immediately.

Theoretically superphosphate should not be mixed with carbonate of lime or fertilizers containing this constituent, such as bone-meal and rock phosphate, because the water-soluble phosphate reverts partly to an insoluble form. However, such mixtures are used on purpose in South Africa where superphosphate is relatively much cheaper than other phosphatic fertilizers and it has to be used on acid, ferruginous soils.

THE EVALUATION OF FERTILIZERS

The market value of fertilizers naturally indicates the price they would fetch on the open market. As in the case of any other commercial commodity, this price depends on the cost of production and is also influenced by supply and demand.

The agricultural value of a fertilizer is something quite different, and this depends on the increased crop yield for which such a fertilizer is responsible when applied to a soil. Let us assume that two farmers buy a fertilizer at the same price. The one farmer uses it in the right way and at the right time on his soil which has a definite deficiency of that particular plant food. The application may double his yield. In such a case we could say that the fertilizer has a high agricultural value to him. The other farmer uses the fertilizer in the wrong way and at the wrong time or on a soil that does not really need it. For him that fertilizer has little, if any, agricultural value during that year. This shows that the agricultural value

of the fertilizer depends on the way in which it is used and in many cases also, unfortunately, on the rainfall during the ensuing season.

Because a certain fertilizer such as superphosphate may be sold in different grades, and because different fertilizers may contain the same plant nutrient in different forms and in different quantities, it is essential that we should have some common basis or unit by which to calculate and compare the commercial value of fertilizers. As unit we could use, for example, 1 lb. of the pure plant food as expressed or determined by the analysis. Thus, the percentage nitrogen (N) is determined in the case of nitrogenous fertilizers, the percentage phosphoric oxide (P_2O_5) for phosphatic fertilizers, and the percentage pure potash (K_2O) in the case of potassic fertilizers.

Instead of using 1 lb. of the plant food concerned it is customary, in South Africa, to take as unit *one per cent. per ton* of the nutrient, i.e. 20 lb. The so-called *unit value* then would be the price of 20 lb. of the plant nutrient concerned, and this is obtained by dividing the price of a ton of fertilizer containing that nutrient only by the percentage composition of the plant nutrient in that fertilizer. Let us assume that we wish to buy a water-soluble phosphate and that we have the following quotations:

	Percentage phosphoric oxide			
	Water-soluble	*Citric acid-soluble*	*Total*	*Price per ton*
				£ s. d.
(*a*) No. 1 high-grade superphosphate	19·0	19 3	20 0	3 7 6
(*b*) No. 2 high-grade superphosphate[1]	17·1	17·5	17·9	3 2 6
(*c*) Medium-grade superphosphate	16·0	16·5	17·0	2 17 0

Superphosphates are evaluated and sold on their water-soluble phosphoric oxide content. Thus, the percentages in the second and third columns do not interest us as far as calculating the unit value is concerned. The unit values for the water-soluble phosphoric oxide would, therefore, be the following:

(*a*) $\frac{£3.\ 7s.\ 6d.}{19{\cdot}0} = 3{\cdot}55$ shillings or about 3*s.* 6*d.*

(*b*) $\frac{£3.\ 2s.\ 6d.}{17{\cdot}1} = 3{\cdot}65$ shillings or about 3*s.* 7*d.*

(*c*) $\frac{£2.\ 17s.\ 0d.}{16{\cdot}0} = 3{\cdot}56$ shillings or about 3*s.* 6*d.*

Thus, the unit value of the medium-grade fertilizer is the same as that of the highest grade fertilizer at the factory, and the second one is slightly more expensive. For the farmer who stays near the factory it will make little difference whether he buys (*a*) or (*c*), but if railage is to be taken into consideration it will definitely be better to buy the highest grade, because

[1] According to the new Government Regulations a high-grade superphosphate should contain at least 18 per cent. water-soluble phosphoric oxide.

ten bags of the medium-grade superphosphate will still contain even a little less water-soluble P_2O_5 than eight and a half bags of the highest grade.

In a similar way the unit values of nitrate nitrogen, ammonium nitrogen, organic nitrogen, potash, lime, &c., can be calculated and the farmer can make his choice accordingly.

It is not so easy to calculate the commercial value of fertilizer mixtures, but even this can be done if the unit values of the different fertilizers are known. However, the analysis of an ordinary mixture usually does not supply sufficient information in connexion with the fertilizers that were used in making up the mixture. This is especially the case with nitrogen where there may be a wide difference between the unit values of the different forms of nitrogen.

The Fertilizer Act

Since 1917[1] there exists in the Union an Act governing the trade in fertilizers and animal feeding-stuffs, and according to it certain regulations in connexion with the sale of fertilizers have been formulated. All fertilizers (except lime, in its different forms) must be registered annually with the Department of Agriculture, with a statement of the guaranteed analyses of these fertilizers, and this information is then published. There are also certain conditions to which certain fertilizers must conform and according to which they are divided into grades, but these were mentioned when the different fertilizers were discussed. There are three other points, in connexion with the regulations, which are important:

1. Certain margins[2] of error in the registered analyses are permissible, namely:

0·5 per cent. water-soluble phosphoric oxide in superphosphate and fertilizer mixtures.

1·0 per cent. citric-soluble phosphoric oxide in basic slag, rock phosphate, and guanos.

1·0 per cent. total phosphoric oxide in fish guano, bat guano, whale guano, meat-meal, bone-meal, and rock phosphate.

0·5 per cent. nitrogen in all fertilizers except bird guano in which the permissible error is 1 per cent.

2·0 per cent. potash in potassic fertilizers containing more than 15 per cent. potash, and 0·5 per cent. potash in fertilizer mixtures and guano.

Therefore, if a fertilizer firm sells, say, superphosphate with a guaranteed analysis of 19 per cent. water-soluble phosphoric oxide and it happens that the fertilizer contains only 18·5 per cent. water-soluble phosphoric oxide, the seller is still within the law and cannot be prosecuted.

2. When phosphatic fertilizers are registered the percentage water-soluble, 2 per cent. citric acid-soluble, and total phosphoric oxide should be given separately. In the case of nitrogenous fertilizers the total nitrogen percentage should be given and it should be mentioned in which form or

[1] This Act has been amended and new Regulations promulgated in June 1948.

[2] The margins of error are discounted under the new Regulations.

forms the nitrogen is present, i.e. whether in the form of nitrate, ammonium compound, or organic compound. The amount of each form of nitrogen, where more than one occurs, need not be given. This is a shortcoming in the regulations. In the case of potassic fertilizers it should also be stated whether the potash is present as chloride, sulphate, nitrate, &c. This information is usually given in price lists and sales accounts of fertilizer merchants.

3. Any person who contravenes or fails to comply with any provision or requirement of the Regulations shall be guilty of an offence and liable to a fine not exceeding fifty pounds, or imprisonment for a period not exceeding six months, or to both such fine and such imprisonment.

CHAPTER XXVIII

FARM MANURES

STABLE and kraal manure or, as we usually call it, farm or farm-yard[1] manure, are very important to the producer of agricultural crops, for two reasons.

Firstly, farm manure contains practically all the plant nutrients that were contained in the animal feed and in the pasturage. The more animal products and the fewer plant products the farmer sells off his farm, the better will he be able to maintain the fertility of his soil. However, he should take care to accumulate and store the manure in the correct way and to incorporate it with the soil by the best method, lest great losses occur necessitating the use of extra fertilizers.

Secondly, farm manure provides the soil with the necessary organic matter to replenish the ever-decreasing humus content of the soil. It is for this reason that fertilizers can never take the place of farm manure in a long-term production system, unless perhaps the farming system and the climate are such that the soil can be green-manured every year. A statistical survey shows that annually about 1½ million tons of farm manure is applied to soils in South Africa. The district of Malmesbury heads the list with approximately 100,000 tons per annum. However, if we consider how many farm animals there are in the Union—excluding the purely pastoral areas where manure is no longer gathered in kraals on account of the new camp system—and see how much manure is 'made' on farms, we come to the conclusion that far more farm manure could be produced in our arable areas. The available farm manure is also often used very injudiciously.

THE COMPOSITION OF FARM MANURES

Naturally the composition of farm manures is not as constant as that of most of the fertilizers. There are four groups of factors which may influence the composition and hence also the value of, say, a ton of rotted manure.

1. The composition of the fresh faeces and urine of farm animals may fluctuate widely. Firstly, the composition of the fresh excreta will differ according to the kind of animal, its age, and its function on the farm. The four most important farm animals are horses (and mules and donkeys), cattle, sheep, and pigs and we find that the excreta of horses and sheep are considerably richer in plant nutrients than that of cattle and pigs. Table 18 (following page) gives the average composition (according to German data) of 1,000 lb. fresh excreta of cattle, horses, sheep, and pigs respectively.

From the table it can be seen that the bulk of the phosphate is excreted in the faeces and that the nitrogen and potash again occur largely in the urine. This shows how important it is to retain all the urine in the kraal and not to let any black liquid drain out of the kraals on account of heavy

[1] We have few farm-yards in South Africa.

TABLE 18

	Cow		*Horse*		*Sheep*		*Pig*	
	Faeces	*Urine*	*Faeces*	*Urine*	*Faeces*	*Urine*	*Faeces*	*Urine*
	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.
Water	800	925	750	890	680	875	820	940
Organic matter	180	30	230	70	290	80	160	25
Nitrogen	3·0	10	5 5	12·0	6·0	15 0	6 0	5·0
Phosphoric oxide	2 0	1·0	3·0	0·5	3 0	1 0	5·0	0·5
Potash	1 0	15 0	3·3	15·0	2 0	18 0	4 0	10·0
Lime	1 0	3·0	2 3	1 5	4 0	3 0	0 5	0 2
Daily excretion	52	20	35 5	8 0	2·5	1 5	6 0	3·5

rains. In stables with cement or cobbled floors the urine should also be caught up in pits and utilized. Besides, the plant nutrients in the urine are dissolved in water and hence readily available to plants.

Horse and sheep dung is relatively dry and warm and cattle and pig dung contains more water and is cold. Where possible the excreta of the different animals should be mixed for storage and rotting

Because young growing animals use more nitrogen and phosphate (and lime) for body-building, the dung of these animals is not as rich in these substances as is the dung of full-grown animals. In the case of the latter all the plant nutrients in the food are present again in the excreta, unless the animals are in milk in which case a certain amount of the substances goes into the milk. According to American data every 100 parts of the following nutrients in the animal feed are distributed as follows:

TABLE 19

	Faeces	*Urine*	*Milk*
Nitrogen	31	52	17
Phosphoric oxide	75·5	1·5	23
Potash	15	75	10

Naturally the quantities will depend on the milk yield of the animal, but it shows that dairy farmers who produce their own food sell considerable quantities of plant nutrients off their farms.

The composition of the fresh excreta depends largely on the chemical composition of the feed. This fact is easy to understand if we consider that all the nitrogen and mineral constituents of the foodstuffs are voided in the excreta of full-grown animals unless the animals are in milk. Thus, the richer the feed is in the ordinary plant nutrients the more valuable will be the manure. In other countries this is borne in mind and much attention is paid especially to the protein content and hence the nitrogen content of feeding-stuffs. Farmers who feed a large amount of 'concentrates' to their animals will also obtain nitrogen-rich manure. In South Africa the question

of phosphates is especially important. Because our soils, and consequently the fodder plants, are relatively poor in phosphorus, the farm manure is also particularly poor in this constituent.

2. The second factor influencing the composition of the ultimate manure is its age or stage of decomposition. Moist manure teems with living microbes and they consume the remaining energy-containing constituents of the faeces along with the organic matter added in the form of bedding material. Therefore, the older the manure the greater is the loss of organic constituents. A manure heap may lose at least half its weight (dry matter) during a period of decomposition or rotting lasting three to six months. Thus, if no plant nutrients are lost through volatilization or leaching the manure should contain twice as high a percentage of plant nutrients as it did before rotting commenced. In practice we find that older manure usually does contain a higher percentage of plant nutrients than fresh manure. Unfortunately rotting of manure is always accompanied by a loss of plant nutrients. Rotted manure will always contain less nitrogen, in absolute figures, than fresh manure. This loss is due to volatilization of ammonia and elementary nitrogen during storage. If leaching by rain is not prevented and if black water is allowed to run from the kraal or manure heap, older manure may even have a lower percentage of the three major plant nutrients than fresh manure. This will be discussed under section four.

3. The amount and nature (including the composition) of the bedding material which is put into the stables and kraals will directly and indirectly influence the composition of the farm manure, which is usually a mixture of faeces, urine, and bedding. There are three requirements for good bedding material: it must have a high absorptive capacity for liquids (urine and rain-water); it should, if possible, contain a high percentage of plant nutrients; it should rot easily, becoming fine and mixing well with the dung. Wheat and oat straw and chaff, *vlei* grass and ordinary veld grass make very good bedding. Ferns, bulrush, shrubs, and vine prunings are less suitable because they do not rot easily and manure containing such material is coarse. On fruit and wine farms where bedding is scarce such material is used, and such a coarse manure has its advantages when used on heavy clay soils. Sawdust contains very little plant nutrients but it has a high absorptive capacity for liquids and when other bedding is scarce it may be used in moderate amounts. Manure containing much sawdust should undergo a longer rotting period than other manure before it is used on land that is to be seeded immediately. Pine needles also make good bedding provided they are old enough, dry, and no longer contain any volatile oil.

4. The method by which manure is stored and its treatment during storage may greatly affect its composition and value. There exists a tremendous literature on this aspect of the subject and much research has been conducted thereon. To-day it is fairly well known what changes the plant nutrients undergo during the process of decomposition, and what losses can occur as a result of volatilization and leaching. The practical

question arises: How can a farmer produce as large an amount of high-quality manure as possible with as little extra expenditure as possible? Many storage systems have been advocated, but the system giving the most economic results in any specific region will depend on the farming system, rainy season, &c.

It is essential that we should know what changes and what losses of plant nutrients may occur in rotting manure before we can suggest a practical method by which manure may be stored. One method which is sometimes adopted in other countries, viz. removing the fresh dung every week throughout the year and working it into the soil immediately, is not practicable in South Africa. The distribution of our rainfall does not permit the production of different crops throughout the year. Furthermore, it should always be borne in mind that lands may not be planted or sown to a crop immediately after fresh dung has been applied to the soil, because the crops would then suffer from a lack of nitrogen during the first half of the growing season (see p. 178).

ROTTING OR DECOMPOSITION OF FARM MANURE

The faeces of animals teems with intestinal bacteria and, furthermore, the dung is 'inoculated' from the air, &c., with different bacteria and fungi. The moist mixture of faeces, urine, and bedding is excellent for many kinds of microbes especially because it contains a large amount of food (energy-containing material) for them.

The substances which undergo changes during the process of decomposition may be divided into two groups: (*a*) nitrogen-free organic substances and (*b*) nitrogenous substances. The nitrogen-free substances constitute the bulk of the solids in dung and bedding and they consist largely of carbohydrates, mainly cellulose and lignin. With the exception of lignin or woody tissue, nitrogen-free substances, with the exception of that portion used by microbes in building new cells, may practically all be broken down into gases (carbon dioxide and methane) and water, if storage lasts long enough. Therefore, their destruction would mean a large decrease in the quantity of the manure. We should aim at retarding this destruction of organic matter during rotting because it is far more advantageous if decomposition takes place partially in the soil and not in the manure heap. How can we influence the process?

The microbes that we find in a manure heap may be divided into two groups according to their oxygen requirements: aerobic micro-organisms which require air or free oxygen, and anaerobic bacteria which can decompose carbohydrates or other substances in the absence of air. The former would be responsible for far greater decomposition of organic matter within a given time than the latter. Thus, it follows that manure should not be well aerated and this condition may be brought about by keeping the heap moist and as compact as possible. Under such conditions the available oxygen is quickly used up by microbes and replaced by carbon dioxide and methane. Once this condition exists the aerobic fungi

and bacteria cease to function and only the anaerobic bacteria will remain active, causing slow decomposition. The dung and bedding will eventually become fine and dark in colour; in other words, a certain amount of 'humus' is formed. When manure is kept moist it will also remain relatively cold and this is another reason for slower decomposition.

Manure which is stored in stables will be trodden down by the animals and kept moist, provided bedding is added with discretion. Difficulties arise in open kraals and other places in the open where manure is stored. During the rainy season the manure remains sufficiently moist. Leaching of plant nutrients may even occur if enough bedding is not added. During the dry season, on the other hand, the top layer of manure may become very dry, allowing air to penetrate into the manure, thus facilitating rapid decomposition. If the kraal contains a large amount of manure during the dry season, some arrangement should be made to moisten it occasionally in order that it may remain moist, compact, and cool.

The nitrogenous substances of fresh dung consist of two groups of compounds. The faeces and the bedding contain practically only albuminoid nitrogen, and this is changed very slowly during the rotting process. Positive loss of nitrogen from this source will always be low and may be prevented completely by treating the manure heap in the correct way. The trouble lies with the nitrogenous compounds of the urine which amount to at least 50 per cent. of the total nitrogenous excreta of animals. Microbes change these nitrogenous compounds (consisting mainly of hippuric acid and urea) almost completely to ammonium compounds within a few days of excretion. Because decomposing dung always contains a large amount of carbonic acid, the ammonium compounds consist mainly of ammonium carbonate. Unless there is an abundance of moisture this compound volatilizes very easily (in stables there is usually a strong smell of ammonia).

It is essential that we should know what may happen to the ammonium compounds because then we can devise means of preventing loss of nitrogen or of limiting it as far as possible.

1. The ammonium carbonate may volatilize if the manure gets dry. Therefore it should be kept moist during the dry season of the year and trees may be planted round the kraal to reduce desiccation by sun and wind to a minimum. The manure in the kraal should not be turned over unless it is done in rainy weather, because it would result in volatilization of much available ammonia.

2. Ammonium compounds may be converted into nitrates by nitrifying bacteria. For this process air is essential in the manure heap because only aerobic bacteria can bring about nitrification. This, then, is another important reason why manure should be kept moist and compact because the formation of nitrates in the manure heap is definitely undesirable, even though this process is so important in the soil. The reason for this is that nitrates may be denitrified. Nitrogen gas is then given off and lost because nitrates are easily washed from the upper aerated layers into the deeper layers where denitrification can take place. Thus manure always

contains very little nitrate nitrogen. The only kind of manure in South Africa that may contain a fair amount of nitrate nitrogen is old, dry karoo manure that has had no rain on it for months.

3. Seepage water from wet kraals may contain water-soluble nitrogen compounds and also potash, phosphate, and humus. Naturally the more the manure is subject to leaching the higher will be the loss of plant nutrients in this way. Leaching of manure may be prevented in two ways. If the place in which the manure is stored, which is usually a kraal, is under a roof, little leaching can occur. However, few farmers with many animals will incur the extra expense of covering their kraals. The second way to prevent leaching is by providing sufficient bedding to absorb all the rain-water. This method could easily be carried out on the grain farms of the Western Cape Province, for example. If neither a roof over the kraal nor sufficient bedding is possible there remains one method only of saving the leached nutrients. The floor of the kraal should be made impermeable to water, with stones and cement, and it should have a slight fall to one corner. From this corner all the seepage water should be led through a pipe into a cement pit outside the kraal. This seepage water will be rich in nutrients. It may be used to keep the manure moist during the dry months or, better still, it may be pumped or poured on to the manure shortly before it is transferred to the lands.

4. The ammonium nitrogen may undergo one other change. The microbes that are responsible for the decomposition may use it as nitrogenous food, thus converting it to albuminoid nitrogen. This always occurs to a certain extent. To favour this process large amounts of bedding should be added to the faeces and urine, preferably bedding that will provide the microbes with energy-giving food that they can assimilate readily. Grain straw, chaff, and dry *vlei* and veld grass are excellent for this purpose. There are three advantages attached to adding large amounts of bedding to the manure. It increases the amount of manure; it prevents leaching of plant nutrients by rain; and it retains nearly all the nitrogen in the manure. The only disadvantage of such a manure is that the nitrogen it contains is in a rather unavailable form when the manure is ploughed in. Therefore such a manure should be ploughed into the soil at least a few months before the land is to be seeded. On the other hand, there is a big advantage attached to a manure containing only traces of ammonia. It can be carted to the land, broadcast, and even left for some time before it is ploughed in, and there will be little, if any, deterioration.

TREATMENT OF MANURE

The method of adding much bedding to the dung and storing the manure in open kraals where the animals keep it compact is by far the cheapest and best method under present South African conditions. It should be used on all farms where farmers have large amounts of bedding at their disposal, especially on grain-producing farms in the Western Cape Province and in the Eastern Free State. In the Western Cape the manure is

ploughed into the soil towards the end of winter on lands that are braaked (fallow), which gives it sufficient time to rot. By the time the next wheat crop is to be grown the straw which such manure always contains will have decomposed and the manure will have taken full effect. Where this method is not practicable a modified method of storing the manure should be followed, but it should always be remembered that the manure should be kept moist and as compact as possible.

It is not advisable to add gypsum or superphosphate to the manure to prevent nitrogen losses by volatilization or, in the case of superphosphate, to balance the plant nutrients in the manure. It is doubtful whether the loss in nitrogen is actually prevented to any appreciable extent, and if applied separately superphosphate can be applied much more evenly to the land.

After this discussion of the different factors that affect the composition of rotted farm manure, it is clear that the composition may vary widely. In South Africa we can differentiate between at least *three kinds of farm manure* and in each kind there would be fluctuations in composition:

(*a*) Stable manure or kraal manure in the preparation of which relatively large amounts of bedding are used, and which is never older than a year.

(*b*) Karoo manure or dung which is found in kraals in the arid sheep (or goat) areas is usually fairly old and contains no bedding material.

(*c*) Kraal manure (cattle manure) which contains little if any bedding and has accumulated over a period of a year or slightly longer.

The first type of manure is found mainly in the winter-rainfall region of the Cape Province and in stables in municipal areas, and the third kind is found mostly in the kraals in the summer-rainfall region of the Union.

Tables 20 and 21 (page 226) give average compositions of the above three kinds of farm manure. By way of comparison we also give the composition of farm-yard manure mixed with bedding, as it is usually prepared in Central European countries. In the case of the two types of kraal manure[1] every analysis represents the average composition of about twelve different samples taken from twelve different farms. In the case of karoo manure the analysis represents the average composition of about two dozen samples, procured from different districts in the Eastern Karoo.

When the composition of the different kinds of kraal manure is calculated on the moisture-free material there are no big differences between the figures. South African kraal manure differs from European farm-yard manure in one important respect. It contains a high percentage of insoluble 'ash' which is nothing but very fine earth (dust, &c.). To a certain extent, also, it is due to this foreign matter that the potash content is so much higher than that of European manure. Analyses showed that about 20–25 per cent. of the total potash, as given in the analyses, is water-insoluble.

[1] The analysis of manure from the summer-rainfall areas was kindly supplied by Mr. H. H. Cornell, formerly Lecturer in Chemistry, Agricultural College, Grootfontein, Middelburg, C.P.

TABLE 20

Chemical Composition of Farm Manures

Percentages calculated on *dry matter*

	Organic matter	*Total ash*	*Insoluble ash*	*Nitrogen*	*Phosphoric oxide*	*Potash*
	%	%	%	%	%	%
Kraal manure (grain farms, W.P.) .	55·58	44·42	33·36	2·20	0·90	3·16
Karoo manure .	50 00	50 00	27 00	1·66	1·28	5·74
Kraal manure (summer-rainfall area) .	53·00	47·00	..	1·66	0·70	3·24
Mixed farm-yard manure (Germany)	84 80	15·20	..	2·00	1·00	2·80

TABLE 21

Chemical Composition of Farm Manures

Percentages calculated on *moist manure*

	Moisture	*Organic matter*	*Total ash*	*Insoluble ash*	*Nitrogen*	*Phosphoric oxide*	*Potash*
	%	%	%	%	%	%	%
Kraal manure (grain farms, W.P.) .	50·0	27 79	22 21	16·68	1 10	0·45	1·58
	66·6	18 53	14·81	11·12	0·73	0·30	1·05
Karoo manure	20 0	40·00	40·00	21 61	1·33	1·00	4·60
Kraal manure (summer-rainfall area) .	30·0	37·10	32·90	..	1·16	0·50	2·26
Mixed farm-yard manure (Germany) .	75·0	21 20	3·80	..	0·50	0·25	0·70

In other words, it comes from the soil that is present in the sample and should not be shown in the analysis of the manure. Because of the high percentage of mineral 'impurities' in South African kraal manure it contains relatively little organic matter in comparison with European manure, when calculated on the dry matter.

The amount of plant nutrients and organic matter which a given weight of manure brings into a morgen of soil will depend largely on the moisture content of the manure. Unfortunately the moisture content can vary widely and thus it is difficult to know exactly how much plant nutrient a certain dressing of manure will have supplied to the soil. Table 21 may be used for general guidance. Usually karoo manure is fairly dry and 20 per cent. moisture is a good average. Kraal manure from Transvaal, Free State, &c., is slightly more moist and in this case we can take 30 per cent. moisture as an average. The kraal manure from the Western Cape

Province is usually transferred to the fields, orchards, &c., after the first autumn rains have fallen. Its moisture content would probably fluctuate around 50 per cent. However, if the winter rains set in earlier than usual 66·6 per cent. may be taken as an average moisture content.

As far as the availability of the plant nutrients in farm manures is concerned, we can assume that the phosphate and potash in well-rotted manure is approximately as available to plants as these nutrients would be, for example, in superphosphate and muriate of potash respectively. It has already been mentioned that a portion of the potash comes from the admixture of soil and naturally its availability will be very low. The availability of the nitrogen in farm manure varies widely and is usually very low. The most one can expect is about 10–15 per cent. availability during the first growing season. Farm manure usually has a fairly good residual effect, and therefore some of the nitrogen in the manure will still become available during the second and third years after application.

It is not possible to attach to farm manure any general commercial value unless its composition is known. All transport and handling costs up to the time that it is distributed on the soil must also be taken into consideration. The value may vary from 5*s*. to 15*s*. per ton according to its moisture content.

KAROO MANURE

During 1944 the Division of Chemical Services analysed a great number of samples of kraal manure from various districts in the Karoo, also determining the brak content. The Division kindly furnished the analyses of thirty samples from the Eastern Cape Province. In addition to the average analysis, as already given in Tables 20 and 21, Table 22 gives us the brak content and the fluctuations. *All data are calculated on manure with 20 per cent. moisture.* This was approximately the average moisture content, although it varied from 12 to 55 per cent. calculated on the moist manure as basis.

TABLE 22

Composition of Karoo Manure (with 20 per cent. moisture)

	Average composition	*Highest figures*	*Lowest figures*
	%	%	%
Organic matter	40·00	53·70	30·60
Ash	40 00	49·40	26·30
Nitrogen (N)	1·33	2·00	0·72
Phosphoric oxide (P_2O_5)	1·00	1·57	0·46
Potash (K_2O)	4·60	6·28	3·20
Sodium (Na)	1·78	4·65	0·17
Chlorine (Cl)	2·60	6·36	1·44

In the Stellenbosch-Elsenburg laboratories we have a record of about 100 analyses of karoo manure, but unfortunately the moisture and brak

content were usually not determined. Our data differ from the Pretoria data in one important respect. The average phosphoric oxide content is considerably lower, viz. 0·70 per cent. instead of 1·00 per cent. The average potash content is also about 1 per cent. lower.

In connexion with the brak content the table shows that, on an average, it consists of about 4 per cent. sodium chloride, although this figure may rise to 10 per cent. It follows that 5 tons of karoo manure per morgen may add 400–1,000 lb. of common salt to a morgen of soil. Thus the climate and nature of the soil should also be taken into consideration when deciding on the quantity of manure to be applied per morgen, lest the soil become brackish as a result of karoo manure.

The availability of the nitrogen in karoo manure is relatively low, and according to manurial trials it would seem as if only about *5 per cent.* of the nitrogen is available during the first growing season (winter crops). Probably the availability will be slightly higher in the case of summer crops in the summer-rainfall area, although it will hardly be above 10 per cent. The nitrogen in karoo manure has a good residual effect.

THE EFFECT OF FARM MANURE ON SOILS

The effect of farm manure on soils is threefold:

1. It has a direct nutritive effect on plant growth just as any other fertilizer has. Because it originated from plants farm manure will naturally contain, besides nitrogen, all the mineral constituents, including the trace elements, which plants absorb. However, it contains too little phosphate for our soils, and therefore it is essential to apply some phosphatic fertilizer along with the farm manure. Besides the fact that it contains all the plant nutrients a large quantity of carbon dioxide is evolved in the soil during the process of decomposition. The major portion of this gas escapes from the soil and leafy low-growing crops such as potatoes may utilize it in their process of carbon assimilation. A smaller portion of the gas dissolves in the soil moisture, forming carbonic acid, which, although only a weak acid, dissolves the reserve mineral substances in the soil more readily than pure water. Thus farm manure also has an indirect manurial effect in that it mobilizes the reserves.

2. Farm manure improves the physical properties of soils. This effect is very important in the case of most of our arable soils. Farm manure increases the humus content of soils at least temporarily, and consequently the water-holding capacity of sandy soils, with the result that they are also better able to retain plant nutrients. In the case of clayey soils and soils which become compact very easily the structure-improving effect of the manure is its most important physical effect. The organic matter (coarse and fine) of the farm manure, as well as the carbonic acid which is a result of the process of decomposition, has a loosening and flocculating effect on heavy soils. The result is that the soil becomes granular, absorbs rainwater more readily, and free water drains away more readily during continuous, heavy rains. Consequently the soils are better aerated, with the

result that seeds germinate more quickly, plant roots penetrate more deeply into the soil, and soil microbes are better able to fulfil their useful functions.

3. The micro-biological effect. Not only does farm manure improve the physical soil conditions for higher plants and microbes, but it also provides the latter with a large amount of energy-giving food (organic matter). Trenched or otherwise unproductive topsoils are inoculated with large numbers of living microbes by an application of farm manure. In good arable soil this inoculation is not considered to be important because these soils already possess their typical microflora. However, an application of farm manure will cause a rapid rise in their numbers. The decomposition of farm manure in soils takes place differently from that in a moist, compact heap of manure. In the soil it is mainly the aerobic microbes that are responsible for decomposition and thus the final products of oxidation, viz. carbon dioxide, water, nitrates, sulphates, phosphates, &c., are formed.

Experiments abroad and in South Africa have proved that when winter cereals and/or maize only are grown, annual dressings of up to 10 tons of farm-yard manure per morgen fail to maintain the humus content of the soil. In other words, under such a cropping system the destruction of organic matter is more rapid than the said addition. Under such conditions, therefore, there is no question of permanently improving the physical properties of the soil. The humus content can only be maintained and increased if annual applications of farm manure are considerably higher, say 20–40 tons per morgen. Sometimes such heavy annual dressings are given where vegetables are grown.

THE USE OF FARM MANURE

Ordinary farm manure should not be handled when dry, and if possible it should be carted during cool weather from the stables or kraals to the lands. Karoo manure and semi-rotted kraal manure, mixed with a large amount of bedding, need not be treated so carefully because they contain little, if any, ammonium carbonate that can volatilize. When ploughing manure into the soil the same difference applies. Well-rotted manure should be broadcast and ploughed in immediately after it has been removed from the kraal. There are two disadvantages attached to the practice of carting the manure on to the lands a few weeks or even months before it is to be ploughed in and leaving it in little heaps, exposed to wind, sun, and rain: the ammonia nitrogen may volatilize and the manure will go mouldy, which means that the available nitrogen has been converted into fungoid protein. The result is that such a manure has no available nitrogen for some time after it has been ploughed under. Secondly, if it rains while the heaps are on the land the soluble nutrients will be washed into the soil in those spots where the heaps were. In this way rank spots are caused resulting in an uneven stand and ripening of the crop. If such heaps are covered with soil leaching may be prevented, but this incurs extra expense and mould will in any case occur, unless the manure is very wet and anaerobic.

Karoo manure and semi-rotted manure containing a large amount of straw need not be ploughed into the soil immediately after distribution unless the land is on a steep slope and there is danger that the manure may be washed away by rain. Even well-rotted manure need not be ploughed under immediately after broadcasting if this is followed by rain and the weather remains cool. Soluble plant nutrients are washed into the soil evenly and after that there is no danger that ammonia may volatilize.

The time when the manure should be incorporated with the soil, and the procedure to be adopted, will depend on the nature of the crop and the most suitable time for soil tillage. In the winter-rainfall area, for example, the manure is worked into the soil in orchards and vineyards at the beginning of winter. In the case of grain lands the manure is carted on to the fallow lands during the dry period of late summer and the heaps are broadcast and ploughed in at sowing-time. A much better system for grain lands of the Western Cape Province is to make a large quantity of semi-rotted kraal manure, using grain straw and chaff. Production commences when the first autumn rains fall, and about the beginning of August the moist manure is carted on to those lands that are to be braaked (fallowed) for the next wheat crop.

As far as the dressing of farm manure is concerned, 5–10 tons (4–8 wagon loads) per morgen is a good average application for most crops. However, in the case of potatoes and garden crops, twice as much may be used to advantage. Because karoo manure is drier and considerably more concentrated than ordinary farm manure, it is used in quantities of a third to a half of these dressings. Finally, it must be remembered that if good results are to be obtained in South Africa, any application of farm manure should be supplemented with some phosphatic fertilizer or other.

COMPOST

The name compost indicates that we have to do with a 'combination' of different substances and in Europe the name dates back to very long ago, when it was used to indicate the manurial mixture which the farmer made out of all the waste material around the homestead. In China also this practice is thousands of years old. Fallen tree leaves, garden weeds, waste vegetables, kitchen ash, intestines and blood of slaughtered animals, &c., are stacked, together with lime and some earth, in a heap 6–8 feet high and kept moist. Sometimes bedroom slops are also used to keep the heap well moist. After several months the heap is 'turned' with a fork and this operation is repeated several times until, after six months to a year, it is suitable for use as manure, usually in gardens.

Since about 1920 rapid advance has been made in connexion with the production of compost. This was mainly stimulated by the results of two groups of research workers. At Rothamsted, England, Richards and Hutchinson investigated the rotting of moist grain straw that had been treated with chemicals. The outcome of this was the ADCO-process for

the manufacture of synthetic or artificial farm manure. In South Africa experiments with grain straw, maize stalks, sugar-cane residues, &c., have also been conducted according to this process and excellent compost has been made, but the patented mixture of chemicals is too expensive. In 1931 Sir Albert Howard and Wad published their book *The Waste Products of Agriculture*, and in it they describe the Indore-process which they developed in India and which aroused great interest.

Since about 1936 much interest has been shown in South Africa and considerable experimental work in connexion with the making of compost has been carried out. The following points[1] should be taken into consideration when preparing compost:

1. The plant material should be air-dry or wilted otherwise it becomes too compact in the heap and air is excluded.

2. Extra nitrogenous food should be supplied for the microbes, because in composting the aim, as in the rotting of farm manure, is to get rid of the excess of carbohydrates in the plant material and to convert this material to a fine, humaceous mixture. Scientifically we say that the carbon-nitrogen ratio should be narrowed down. Microbes require considerable nitrogen for their development with the result that decomposition is speeded up, the compost heap heats up sooner and remains warm longer as more nitrogenous material is added. This may be in the form of animal dung, poultry manure, Government guano, sulphate of ammonia, &c.

3. The compost heap should be fairly moist because bacteria live in a moist medium, but it should not be dripping wet or sodden.

4. There should be sufficient air in the heap and this is impossible if it is too wet. Thus it becomes clear that the preparation of compost differs in an important respect from the storage of ordinary farm manure. Not only must the compost heap not be too wet but it should also not be trampled down. A test for active decomposition and, thus, for sufficient air (and nitrogen) is that the inside of the heap should heat up considerably (50°–60° C.) within a few days. An iron rod may be stuck into the heap for this purpose. If the temperature suddenly drops or if the heap does not heat up the material should be turned again and thoroughly mixed.

5. A final condition which is also not necessary when storing manure is the application of basic material such as wood ash, agricultural lime, or (less desirable) 'sweet' agricultural soil. This is done to neutralize the organic acids, thus enabling the bacteria to play the major role in the process of decomposition.

Roughly we can differentiate between two types of compost:

Farm compost. On farms and small holdings where a relatively large acreage is cultivated in comparison with the number of animals kept, or where animals are not kraaled or stabled for long periods, where vegetables are produced, and in urban gardens this method of 'making' manure can profitably be followed. Any waste plant material such as grain straw, maize

[1] See Dr. E. R. Orchard, 'Compost: its preparation and use', *Scientific Bulletin*, no. 201, Government Printer, Pretoria, 1939. Price 3*d*.

stalks, fallen tree leaves, weeds, waste vegetables, lawn cuttings, shrubs, &c., is built up in layers 1 foot deep and 6–12 feet wide. On every layer about an inch of animal manure or (less) poultry manure, a mixture of sulphate of ammonia and superphosphate or, also, Government guano, is spread thinly. On this again a thin layer of wood ash, kitchen ash, or agricultural lime is spread. The layer is now watered thoroughly. If the plant material does not absorb water readily, e.g. grain straw, it should previously have been watered thoroughly or even soaked in water before the manure and basic material is added. Repeat the above procedure until the heap is about 3–3½ feet high. The top may be covered with a thin layer of soil or vegetable matter and this is worked into the heap at the first turning. During dry weather the heap should be watered periodically. After 3–4 weeks the heap will have settled and cooled down considerably and it is now turned with forks from one end. If necessary it is made slightly narrower. The heap is turned every 3–4 weeks until, in 3–5 months' time, the material has rotted to a comparatively fine, dark-coloured manure. It will cost anything from 5*s*. to 15*s*. to prepare a ton of well-rotted compost.

Municipal compost. In this connexion Mr. J. P. J. van Vuren, an extension officer in the Department of Agriculture, is the pioneer in South Africa. In 1939 he adapted the Watson method—tried out near Calcutta, India—of preparing compost from municipal refuse, at Ficksburg. Since 1942 other agricultural officers have received instructions to propagate the method throughout South Africa. In the Western Cape twenty-seven municipalities are at present manufacturing about 8,000 tons of compost annually. Altogether there are now (1946) about a hundred municipalities, especially of our smaller towns, that adopt this method. All the vegetable refuse in cities and towns is composted with night soil or (less effective) sewage sludge in aerated, shallow pits. Details in connexion with the method may be obtained from the agricultural colleges.

The following table gives the composition of compost samples which have been analysed in our laboratories during recent years. They represent about a dozen typical samples of farm compost and a dozen of municipal

TABLE 23

Composition of Compost

	Farm compost (*40 per cent moisture*)			*Municipal compost* (*20 per cent. moisture*)		
	Average	*Highest figures*	*Lowest figures*	**Average**	*Highest figures*	*Lowest figures*
	%	%	%	%	%	%
Organic matter	..	..	..	40·0	67·7	26·7
Ash	..	..	..	40·0	53·3	12·3
Nitrogen	**0·54**	0·96	0·31	**1·35**	2·33	0·62
Phosphoric oxide	**0·25**	0·44	0·14	**0·96**	1·24	0·53
Potash	**0·66**	1·06	0·32	**0·75**	0·87	0·61

compost from farms and towns in the winter-rainfall area. The pamphlet by Dr. Orchard, mentioned earlier, contains compost analyses from other parts of Southern Africa, England, and India.

The figures (Table 23) show that the ratio of major plant goods in *farm compost* is approximately the same as in ordinary farm manure; in other words the nitrogen and potash contents are about twice as high as the phosphoric oxide content. However, they show that the absolute average figures (percentages) are considerably lower than in ordinary farm manure. Probably the percentage of organic matter is also considerably lower, i.e. farm compost contains a relatively large proportion of soil. Therefore farmers are advised to add as little soil as possible to the compost heaps, otherwise handling and haulage costs are too high in proportion to the amount of plant food and organic matter incorporated with the soil.

In respect of *municipal compost* the average composition is strikingly similar to that of karoo manure as far as the moisture content, organic matter (loss on ignition), nitrogen, and phosphate are concerned. However, it contains much less potash and, naturally, is not as brackish as karoo manure. This shows that, as a rule, municipal compost is a more valuable manure than farm compost but, on the other hand, its composition varies more than that of farm compost. The compost of a few towns is very inferior.

As a result of good aeration during the process of decomposition, all types of compost usually contain a certain amount of nitrate nitrogen and that accounts for the relatively quick effect of compost on plant growth in comparison with ordinary farm manure. Our experiments seem to indicate that during the second half of the growing season the nitrogen in ordinary farm manure is more available than that in compost. Furthermore, the residual effect of organic nitrogen in municipal compost seems to be very low during the growth of the second crop. Thus municipalities are advised to fix the price of their compost strictly according to its manurial value or otherwise its use may fall into disfavour.

POULTRY MANURE

Poultry manure is practically always synonymous with fowl or hen manure. Its composition may vary widely according to food, storage, age, and especially moisture content. Fresh fowl droppings contain more than 70 per cent. moisture. Air-dry fowl manure containing little soil has approximately the following composition: 10 per cent. moisture, 4·0 per cent. nitrogen, 3·0 per cent. phosphoric oxide, and 1·0 per cent. potash. Relatively fresh, moist fowl manure with 60 per cent. moisture will contain a percentage of slightly less than half of these nutrients. Thus, in comparison with ordinary farm manures, fowl manure is rich in nitrogen and phosphate, but has a low potash content.

Poultry manure is a very important source of plant nutrients and farmers should value it much higher. If only the night droppings of fowls (i.e. in the houses only) are taken into consideration we may roughly assume that

1,000 hens will produce about 20 tons of fresh manure or 5 tons of air-dry manure per annum. According to this the night droppings of the 7½ million fowls in the Western Cape Province annually amount to about 150,000 tons of fresh manure or 40,000 tons of air-dry manure with 10 per cent. moisture.

On farms where animals are kraaled at night a minimum loss will occur if the poultry manure is also stored in the kraal. The poultry manure is periodically gathered, broadcast in the kraal, and immediately covered with a layer of straw or litter. On purely poultry farms, droppings of the previous night can, during the dry season, be gathered every morning and spread out thinly on a hard cement floor, quickly to become air-dry. The dry manure is then stored in a heap under a roof and is a suitable commercial article if the quantity exceeds the farmer's own requirements. Dry fowl manure can be used at the rate of 2–4 tons per morgen, especially for vegetables which require much nitrogen. The availability of the nitrogen is considerably higher than that of ordinary farm manure, probably at least 25 per cent. during the first year. Where there is sufficient vegetable matter for the preparation of *compost*, fresh or dry fowl manure may be used most profitably for this.

CHAPTER XXIX

GREEN MANURING

THE AIM OF GREEN MANURING

BY green manuring is meant the ploughing under of a crop when in the full flowering stage, with the object of incorporating a mass of plant material with the soil. Such a crop may be grown specially for the purpose or the natural weed growth may be ploughed under as green manure. With green manuring we aim chiefly at obtaining the following two effects on the soil:

1. We wish to incorporate a large amount of organic matter with the soil in order to maintain its humus content or increase it, if possible.
2. We wish to retain the soluble plant nutrients that may be leached from the soil and, if possible, we wish to increase the nitrogen reserve in the soil.

Other subsidiary aims will be mentioned presently.

It is well known that the humus content of cultivated soils, especially in South Africa, undergo a rapid decrease unless organic matter is regularly applied or the soil rested. There are only three ways in which much organic matter can be rapidly incorporated with the soil:

1. Application of large quantities of farm manure and compost.
2. Green manuring in some form or other.
3. The ploughing under of much straw, chaff, trash, and similar plant residues.

Where such practices are not possible or are uneconomical a crop-rotation system should be followed which aims at replenishing the humus content of the soil.

The effect of green manuring on the nitrogen content of the soil is rather a complicated question. It has already been mentioned (p. 24) that bacteria normally occur in the roots of legumes. These bacteria are able to fix elementary nitrogen gas and convert it to nitrogen compounds. Legumes, therefore, need not be dependent on any other source for their nitrogen supply. Thus we find that legumes will grow well on soils that are deficient in nitrogen provided the soil contains the other plant nutrients in sufficient amounts. When a green-manure crop is ploughed into such a soil, the latter is enriched in organic nitrogen. If the legume crop is grazed down on the land and the stubble and dung are subsequently ploughed into the ground, or if the crop is used as silage and the dung is afterwards returned to the land and ploughed under, the increase in the nitrogen content of the soil will still be considerable. Naturally, much less organic matter will in this way be incorporated with the soil than when the complete green crop is ploughed under. Even when the legume crop is removed from the land and the dung of the animals that feed on the crop is not returned to the land, the soil will still be richer in nitrogen than before the crop was grown because the soil has the benefit of the nitrogen in the stubble and roots.

In the above instances the soil will only be enriched in nitrogen if the soil was poor in available nitrogen during the growing period of the leguminous crop, and if a good crop was obtained. Good growth of the green-manure crop will depend on favourable growing conditions. If the soil already is relatively rich in available nitrogen, i.e. nitrate nitrogen, the legume will not effect a remunerative increase in the nitrogen content (if there is any increase at all) because the legume, like any other plant, will utilize the available nitrogen in the soil. This will be the case in spite of the presence of bacteria on the roots.

Thus, from the point of view of increasing the nitrogen content of the soil, green manuring is only profitable when the soil is poor in available nitrogen. If the soil is relatively rich in available nitrogen any other crop, yielding a large quantity of plant material, will be equally suitable for green manuring. In such a case the crop may also be called a *cover crop* because it covers the soil during the rainy season and retains all the soluble plant nutrients, especially nitrogen, and prevents them from being leached from the soil.

In the case of orchards and vineyards in the winter-rainfall area, we have a good example of this. If such soils are manured regularly but not irrigated during the dry summer months, they contain a large amount of soluble plant food, especially nitrate nitrogen, after the first rains in autumn. A non-leguminous crop which will grow well during the cold, wet winter months will be as effective in maintaining the humus and nitrogen content of the soil as a legume, such as peas. The ordinary winter weeds such as 'Cape weed' (*gousblom*), &c., are a very good cover and green-manure crop, or a cereal such as rye can be grown where there are no weeds. On the other hand, however, it is better to grow a legume such as peas or lupins on a soil that has been newly trenched and on poor orchard soils which have a low humus content and, hence, a low nitrogen content. On trenched soil the legume seed should be inoculated to ensure that the nitrogen supply will be increased.

In the summer-rainfall region green-manure crops may also be divided into two groups, the use of a crop from either group depending on the fertility of the soil. On the one hand we have natural grasses or teff, buckwheat, &c., and legumes such as cowpeas, velvet beans, mung beans, sunn hemp, &c., on the other.

Apart from maintaining the humus and nitrogen content of the soil, a green-manure crop has other advantages. On steep slopes a cover crop will aid in preventing erosion of fertile soil during the rainy season. The roots bind the topsoil and the vegetative cover reduces the pelting force of rain and hail, not only preventing erosion, but also facilitating penetration of rain-water into the deeper soil layers. The plough-sole and other compact layers in the subsoil will allow water and air to penetrate them more easily on account of channels formed in the subsoil by dead and decayed plant roots. Plants such as lupins, with tap-roots, will be better in this respect than those with relatively shallow, fibrous root systems.

REQUIREMENTS FOR SUCCESSFUL GREEN MANURING

The most important requirement for green manuring is a reliable rainfall or sufficient irrigation water. The unreliable water-supply in most of our crop-producing areas is one reason why green manuring is so seldom practised in South Africa. If the green-manure crop grows well the farmer hesitates to plough it under and either grazes or ensiles it or allows it to mature as any other crop. If the farmer has no reasonable certainty that there will be sufficient moisture in the subsequent season, from rain or irrigation, for a satisfactory main crop following on the green-manure crop, he will be quite entitled not to plough under the green-manure crop. If the following season happens to be dry and no irrigation is available to augment the rain, the green-manured land will not only show no adequate returns, but it may aggravate matters considerably. For example, if the green-manure crop is a legume it may increase the nitrogen content of the soil to such an extent that the main crop is affected more by the water shortage than if there had been no green-manure crop (see p. 23). The green-manure crop will also dry out the soil considerably if there is no rain and it may not be well rotted by the time the main crop is planted.

Other requirements for successful green manuring are that the crop should be sown and ploughed under in good time, that it should receive the necessary mineral fertilizer, that it should not become a weed on the lands, and that the main crop should follow as soon as possible on the green-manure crop. Thus, in the winter-rainfall region, peas should be planted during April, or at the latest, during the first half of May, to obtain a satisfactory crop by August when it should be ploughed under. A green-manure crop should always be ploughed under in good time so that the ground gets a few good rains on it before the end of the rainy season. Good rains are necessary for efficient decomposition and also aid in bringing about that continuity in soil structure which is so essential in preventing excessive loss of moisture.

In South Africa it is always necessary to apply a phosphatic fertilizer when the green-manure crop is sown and this may suffice also for the main crop, or a small additional dressing only of phosphate need be given. On very acid soils such crops as peas require an application of lime as well. Potash may also be applied to the green-manure crop if the soil and the main crop require it. If these nutrients are applied a good green-manure crop will be ensured and the plant foods remain in the soil for the main crop.

There are two points to be considered in connexion with the period which should elapse between green manuring and planting of the main crop. Firstly, one should wait at least three to six weeks (the period is longer for non-leguminous than for leguminous crops) before planting or sowing anything on a soil that has been green manured. The reason for this is that much carbon dioxide is given off during decomposition, the soil is loose, and there is an absence of nitrate nitrogen. Consequently, seeds will not

germinate well and young plants will suffer from nitrogen shortage and grow poorly. On the other hand, the main crop will benefit most from the soil-improving effects of green manuring if it is sown or planted immediately after this short, unfavourable period. In South Africa, water shortage usually prevents immediate cultivation and seeding of green-manured soil, and usually a period of six months or more has to elapse before the main crop can be grown. Orchards and vineyards in the winter-rainfall region are two of the few exceptions in this respect, and it is for this reason that green manuring is, and should be, such a common practice in orchards and vineyards. The tree or vine starts its new growth shortly after the green-manure crop has been ploughed under. On land under irrigation the system of rotation can also be such that the green-manure crop is soon followed by another crop. Irrigated soils require, as previously pointed out, regular applications of organic matter.

THE IMPORTANCE OF HUMUS

At this stage it is necessary that we should give a summary of the effects of humus on cultivated soils and stress the necessity of maintaining a certain humus content in the soil.

The effects of humus, or rather organic matter, on soils are diverse and most aspects of it have already been discussed in previous chapters of this book. The results may be summarized under three headings.

1. Humus improves a soil *chemically*. Usually only the nitrogen supply is considered in connexion with the chemical effect of humus because the nitrogen reserve in the soil occurs almost entirely in the humus. The organic nitrogen exists in the form of proteins which do not decompose easily. Probably most of it is microbial protein and, as such, it is not readily available to plants, but if there is a good supply of humus in the soil there will be a steady flow of available nitrogen, depending on microbial activity, and this is very important in connexion with the permanent fertility of the soil. Apart from the fact that humus is a 'reserve' bank of nitrogen it also contains other plant nutrients such as phosphate, potash, lime, magnesia, &c., which become available to plants on decomposition or mineralization. Usually this is considered to be of secondary importance because mineral fertilizers can be applied to soils without great expenditure. However, there are exceptional cases where, on account of an unfavourable pH or for some other reason, plants suffer from a deficiency in available iron or other trace elements, in soils containing little humus. If, in such cases, organic matter is added to the soil the symptoms attributed to a deficiency in the above substances often disappear.

2. Humus improves the *physical* properties of soils. Of special importance in this connexion is the increase in the water-holding capacity of sandy soil types and the improvement in the structure of all soils, especially clay soils that do not belong to the class of red loams. An improved structure means that the soil absorbs water more readily and that there are bigger soil pores through which superfluous, gravitational water may

drain away. This also improves soil aeration. This physical improvement which is especially brought about by 'young' humus is difficult to measure. Improved yields are the only really practical criterion to apply.

It has been clearly shown in the winter-rainfall area that on soils into which kraal manure or straw and chaff have been ploughed at braaking (fallowing) time, wheat crops are able to tolerate considerably higher fertilizer applications, especially nitrogen, with a corresponding increase in yield, than on soils to which no organic matter has been applied. This increase in productivity can only be attributed to the improved water economy in the soil. It has also been proved that soils having a high humus content are less likely to be eroded either by wind or water (see p. 118).

3. Organic matter influences, to a large extent, the *microbial activity* in soils. In Chapter XXIII we have already discussed the most important functions of microbes as well as their requirements. Favourable living conditions depend, directly or indirectly, mainly on a sufficient humus supply in the soil.

In spite of all the literature on humus this remains one of the most complicated subjects in connexion with soil fertility, and one on which authorities hold divergent views. However, that a sufficient humus supply is of great practical importance in the soil is certain. Whether this importance is considerably less in the case of crop production under semi-arid conditions, as some maintain, the future will tell.

GREEN MANURING IN SOUTH AFRICA

At the beginning of the chapter we said that one of the chief aims of green manuring is to supplement the humus supply in the soil and maintain it at a satisfactory level if possible. Very little research has, as yet, been done in this connexion in South Africa. The publications on this question show that green manuring every third or fourth year in rotation with maize in no way checks the rapid depletion of humus under dry-land conditions in the summer-rainfall area (Pretoria). Maize yields did increase slightly subsequent to green manuring, but evidently this increase did not even pay for the expense of green manuring. In any case, the leguminous green-manure crop (cowpeas) could have been utilized much better as animal food. Therefore we must conclude that in spite of the desirability of supplementing the humus content, green manuring is not profitable under dry-land conditions. At other places in the summer-rainfall region similar conclusions have been arrived at, although on less evidence.

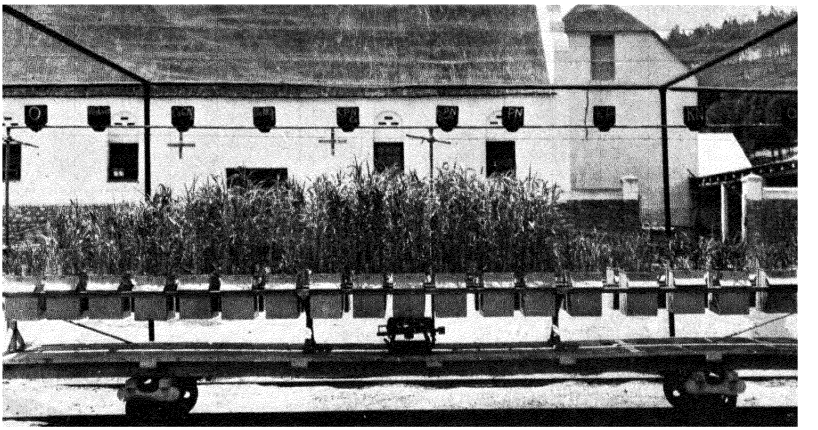
Even in the winter-rainfall region, where the wheat crop may show an increase in yield of 25–50 per cent. subsequent to successful green manuring, it has been shown that the practice is too risky, that it does not fit in the present system, and that, therefore, it is not to be recommended. In this region experiments proved definitely that the application of organic matter to fallowed land is very necessary and that it is responsible for definite increases in yield. However, organic matter should be applied as

follows: (*a*) more half-rotted strawy kraal manure be produced and ploughed under at fallowing (braaking) time, (*b*) all the remaining chaff and straw on grain-producing farms should be ploughed under at fallowing time, and (*c*) a crop-rotation system should be followed in which the lands are used as lucerne leys for three to four years and then sown to grain again for the same number of years. Even Rhodes grass will produce good grazing (and hay) in many parts of the south-western districts.

In the summer-rainfall region also, good crop-rotation systems should be followed. Maize, wheat, and potatoes can be alternated with grass (teff and Rhodes grass) or leguminous crops that can be grazed or can be turned into hay or silage. From the humus point of view it will be better still to 'rest' the lands for three to four years as pastures. In other words, the rotation system under dry-land farming conditions should aim at conserving the humus content. In addition, more animals should be kept and more manure should be made in order to supplement the humus content.

It seems as if green manuring, in the strict sense, is only practicable in the case of orchards and vineyards (and Turkish tobacco) in the winter-rainfall belt and in (citrus) orchards in the summer-rainfall area. It is notably in providing cover crops that this system is so effective, as already outlined. This aspect will receive more attention in Chapter XXXIV. Because irrigated soils are cultivated very intensively and because their structure is apt to be impaired on account of irrigation and intensive cultivation, green manuring is absolutely essential to irrigated soils. Therefore, the rotation system in these cases should provide for periodic green manuring unless large amounts of animal manure can be applied to the soil.

In some form or other, green manuring dates back to very early times, but it only came into use in the northern European countries during the second half of the last century. In South Africa green manuring was probably first practised in orchards in the Western Cape Province at the beginning of this century. Agricultural authorities tried to introduce the practice also in connexion with field crops, but it proved too risky and, in general, not sufficiently economical to be recommended.



a Trolley with pots and scale the black plates The fertilizer applied to four pots can be seen on Experimental Farm, Stellenbosch

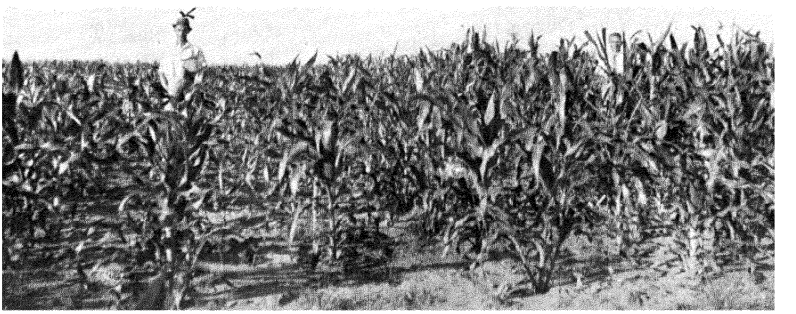


Photo A. A. Ferreira

b On left the maize received no superphosphate whereas on right 200 lb superphosphate were applied per morgen Hoopstad district, O.F.S.

Photo Dr H H Dodds

a. Sugar-cane, variety N Co 318, 18 months old plant cane, at the Sugar Experimental Station, Mount Edgecombe

Photo Dr H H Dodds

b Sugar-cane, variety Co 301 growing on Powerscourt Estate, Umbumbulu, Natal On left no phosphate, on right 1,200 lb per morgen of superphosphate applied at time of planting

CHAPTER XXX

MANURIAL REQUIREMENT OF SOILS

THE LAW OF THE MINIMUM

ON several occasions we have used the expression 'limiting factor' in connexion with plant growth without giving a clear explanation of it. In the first part of this book we discussed the essential requirements of plants. This included the different plant nutrients, and the fact that every plant nutrient has its own specific function in connexion with plant growth was stressed. From this one may logically conclude that if there is a total absence of any one essential plant nutrient in the soil, plant growth will not be possible even though all the other plant food ingredients be available in sufficient quantities. In agriculture, soils in which some plant nutrient or other is totally absent hardly ever occur, although soils often occur in which the available supply of a nutrient is too small for satisfactory crop yields. In such cases we say that there is a deficiency in this plant nutrient. The deficiency in the particular plant nutrient would 'limit' the growth and hence, also, the yield of the crop, and thus we speak of limiting plant nutrients or, more generally, of limiting growth factors in this connexion.

A hundred years ago Justus von Liebig had already realized that there is some relation between the amount of available plant food on the one hand and crop yields on the other. This relation is expressed in the Law of the Minimum, which he formulated more or less as follows: crop yields are determined by that nutrient which is relatively in the minimum. Subsequently it was found that not only the plant nutrients, but all growth factors such as moisture supply, aeration, light, heat, &c., may act as limiting factors.

Up to the beginning of the present century research workers thought that yields were in direct proportion to the limiting growth factor; or, to express it differently, that yields increased proportionately as the limiting factor becomes more favourable until, of course, another growth factor manifests itself as the limiting factor. Assume that a soil is rich in all the plant nutrients except nitrogen, and that the other growth factors such as water, heat, &c., also are favourable. If an application of 50 lb. of sulphate of ammonia per morgen raises the yield by one bag of wheat above the yield from the same unfertilized soil, we would expect every further 50 lb. increase in the sulphate of ammonia dressing to bring about a corresponding increase in yield of one bag of wheat per morgen. This would proceed until another growth factor, e.g. water, becomes insufficient for a larger yield, and the increase in yield as a result of nitrogen applications would cease *suddenly* even if more nitrogen is applied (see Fig. 19 A). The other growth factor now will limit production and an increase in yield will only be possible if this factor again is rendered more favourable. Thus we get

the popular representation of the Law of the Minimum in the form of a wooden vessel of which all the side staves are of different lengths. Obviously, the amount of water which the vessel can hold will be limited by the shortest stave. Similarly it may be represented as a chain which is only as strong as its weakest link.

As a result of accurate research it is to-day generally realized that the relation between growth factors on one hand and crop yields on the other is very

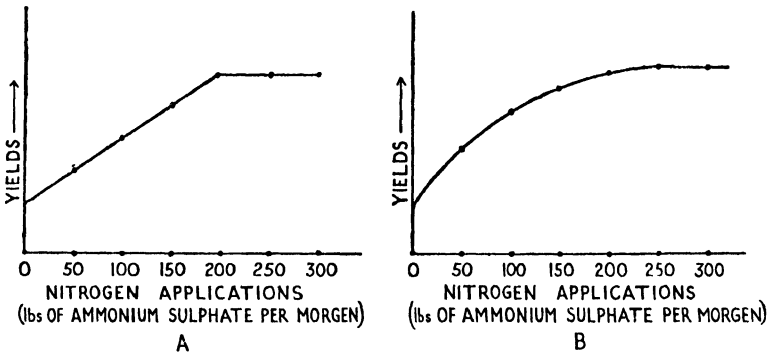


FIG. 19. Graphic representation of the Law of the Minimum.

complicated, and it is not yet possible to express this relation mathematically. In any case, there is no direct proportion between fertilizer applications and plant yields as scientists once believed. If all the growth factors except one were kept constant and this one were applied in increasing amounts (in the case of fertilizers), the corresponding plant yields would form a curve if reproduced by way of a graph. Fig. 19 B gives us an example of such a curve where ammonium sulphate is applied in increasing amounts of 50 lb. per morgen. By the path of the curve we see clearly that the rate of increase, for a corresponding increase in fertilizer application, becomes less until it stops completely. It has even been shown that a further increase in the nitrogen applications may actually be responsible for a decrease in yield. This relation applies more or less to all growth factors.

Apart from the fact that increase in yield is not directly proportional to increase in fertilizer applications, recent research has revealed the important fact that in a given case all growth factors that are not very favourable will have a limiting effect on plant growth and not only the factor that is in the minimum. For example, let us assume that we have a piece of land that is very deficient in nitrogen, fairly deficient in phosphate, and only slightly deficient in potash. According to the old interpretation of the Law of the Minimum, an application of a phosphatic fertilizer will have no effect on plant growth because the soil is most deficient in nitrogen. According to the new interpretation there will be a considerable increase in yield on an application of phosphate and even a potash application may be responsible for a small increase in yield. However, there is also such a

thing as a balance or harmony between the different nutrients, and therefore the highest increase in yield will only be obtained by improving *all* the factors that seriously limit plant growth.

This theoretical knowledge is of the utmost importance to practical agriculture. The agriculturalist should pay all his attention to improving these limiting factors, especially those which can be rendered more favourable with the least extra expense. Thus, he should see to it that the soil is tilled efficiently, that the water relationships in the soil are as favourable as possible, e.g. eradicating all weed growth, and, in connexion with the 'chemical' factors of soil fertility, that especially those plant nutrients in which the soil is very deficient are supplemented by way of fertilizing.

DETERMINING THE MANURIAL REQUIREMENT OF SOILS

Of the many methods to-day that may be used in order to determine the manurial requirement of soils, the following two are the most important. The first method is to analyse the soil chemically with different solvents. The most important methods of chemical analysis and their drawbacks were discussed in Chapter XX.

The second method is to determine the qualitative and quantitative plant nutrient requirements by way of fertilizer experiments. This can either be done in pots or on the land under natural conditions.

POT EXPERIMENTS

From the outset it should be remembered that any results obtained with pot experiments are not directly applicable in the field. Pot experiments are carried out under artificial conditions. The fertilizers are well mixed with the soil, the soil depth and hence the root space is limited, the production of carbon dioxide by root respiration is very intensive per unit of soil volume, the water-supply may be maintained at a constant and favourable level, and weeds can be removed as soon as they appear. These and other factors are, therefore, under control, which is never the case to the same extent on the land. Consequently pot experiments are less liable to failure than field experiments but, on the other hand, they have not the same practical value as field experiments.

Nevertheless, pot experiments are a valuable aid in examining soil fertility problems and other questions in connexion with plant growth. The effects of different fertilizers and plant food substances on plant growth can be determined exactly; the relative manurial value of fertilizers containing one and the same nutrient can be determined on different soil types; the water requirements of crops under prevailing climatic conditions can be studied; in short, the fundamental principles of plant nutrition can be demonstrated and scientifically investigated. Here we will only explain how pot experiments may be used as an educational aid in demonstrating the effects of a deficiency of plant nutrients or of any particular nutrient on plant growth. For research work much greater precautions must be observed.

At schools, half or three-quarter paraffin-tins (2–3 gallon capacity), medium-sized earthenware or tin flower-pots, or even wooden boxes may be used. For scientific experiments enamelled iron pots, round or square, are often used. Attention should be paid to the drainage, and hence the aeration, in the pots. For this purpose it is essential that the bottom of the pot should have one or more holes and that a layer of small stones or coarse gravel be put into the pot before it is filled with soil.

Two soil types may be used for the experiment, a poor sandy soil and a fertile garden soil. At least two or three pots should receive the same treatment (Duplicates, Triplicates):

Series	I. No fertilizer	(O)
,,	II. Potash and Phosphate	(KP)
,,	III. Potash and Nitrogen	(KN)
,,	IV. Phosphate and Nitrogen . . .	(PN)
,,	V. Potash, Phosphate, and Nitrogen . .	(KPN)

If the soil we are using is acid we may have another series:

Series VI. Potash, Phosphate, Nitrogen, and Lime . (KPNCa)

Note. K (Kali, Arabic) stands for potash, P (Phosphorus) stands for phosphate, N (Nitrogen) stands for nitrogen, and Ca (Calcium) stands for lime.

For these experiments we must use fertilizers which contain only one of the major plant nutrients. As potassic fertilizer we may use muriate of potash, as phosphatic fertilizer, superphosphate, and as nitrogenous fertilizer, ammonium sulphate. Lime may be applied in the form of agricultural lime (carbonate of lime).

The experiment aims merely at indicating the plant nutrients in which the soil is deficient and does not attempt to determine the optimum quantities in which the deficient elements should be applied. Therefore, the amounts that are applied to the pots are not of great importance provided the dose is not so high that it harms the plants. For approximately 20 lb. (air-dry) soil the following quantities will be safe: 1 gm. of muriate of potash, 2 gm. of ammonium sulphate, 3 gm. of superphosphate, and 10 gm. of agricultural lime. The muriate of potash and ammonium sulphate may be weighed off in larger quantities and dissolved in water in two lots so that, say, one test-tube of the solution (or 50 c.cm.) contains the required amount of fertilizer. The solutions are added to the soil concerned and the soil is then mixed thoroughly.

The fertilizers should be mixed accurately with the soil and no errors should slip in. The best procedure is to take a small enamel bath, weigh the required amount of soil into it from the well-mixed heap, and add the fertilizers, either dry or dissolved, after which everything is mixed thoroughly. The soil should be slightly moist but neither completely dry nor very wet. The soil is then put into the pot and firmed down slightly. After all the pots receiving the same treatment have been filled the bath is 'washed' with some untreated soil and the person who has mixed the soil washes his hands and dries them.

After the pots have all been filled and numbered they are watered with a watering-can with a fine rose until the soil is moist throughout its depth. After a week the seed is sown. The day before sowing the soil may again be moistened slightly. Small furrows or holes are made in the soil and the seed is sown fairly thickly. For example, about 30–40 oat seeds may be sown in a paraffin-tin; 7–14 days after the seedlings have come up they are thinned out to about 20–25 per tin. Oats, rye, millet, teff, mustard, and many different flowers grow well in pots. Naturally, in selecting plants the season should be taken into consideration.

The pots must be so situated that they all receive the same amount of light. They stand outside so that they also get rain. This does not matter in the case of such qualitative experiments, because if too much plant food leaches from the pots a top dressing of these nutrients can be given. Water is applied according to the needs of the plants and every time they are watered it should be done thoroughly. It is, in any case, advisable to give a top dressing of 2 gm. of nitrate of soda (in solution) per pot, after the plants have been growing for about a month, in those pots to which nitrogen has been applied.

The effects of each of the treatments on plant growth may be determined by comparing the plant growth in the pots that were fertilized completely with the stand in those pots that did not receive the nutrient concerned. Thus, the effect of nitrogen may be determined by comparing the stands in the KPN and KP pots. As an exercise to the pupils the ripe, air-dry seed from all the pots may be weighed and the difference in yield and the average yield determined.

CHAPTER XXXI

FIELD EXPERIMENTS

FERTILIZER experiments on the land, with the specific crop, are still the most reliable way of determining the manurial requirement of a particular soil type. Unfortunately the method also has its drawbacks. It entails considerable expense and expert direction. The results are available only after a growing season so that it is only then that the farmer can make use of the information thus obtained. Furthermore, different consecutive seasons may differ widely from one another so that actually only the average result of prolonged experiments covering several seasons can be used as a reliable criterion. This is especially the case when testing out the nitrogen requirement of soils. Wind, drought, hail, frost, insect pests, fungus diseases, or other factors may be the cause of failures of the experimental plots, and hence we must always reckon with a certain percentage of 'casualties', especially when conducting so-called co-operative fertilizer experiments on farms. A chemical analysis can be carried out quickly and of course at any time of the year. Thus, chemical analysis would be of great value to farmers if the results were as reliable as those of accurately conducted field experiments.

Soil variation is another obstacle with which the experimenter has to contend. When a piece of land which appears to be uniform is divided into plots and these plots are all fertilized similarly, different plots may produce widely different yields. This is why it is absolutely essential to replicate plots receiving the same treatment several times and to distribute them preferably at random over the experimental field. The average yield on all such plots is then calculated with its so-called probable error.

Fertilizer experiments on lands, in orchards and gardens, may be divided into two kinds. The first kind may be called *demonstration or qualitative experiments*. They are conducted (*a*) in order to illustrate and explain to farmers and pupils the known manurial requirement of a particular soil type or the deficiency symptoms of the major plant foods, and (*b*) to determine the qualitative manurial requirements of soils of unknown fertility. The term 'qualitative' indicates that we are demonstrating or investigating which plant food ingredient or ingredients are lacking, and not the most profitable rate of application of a possibly deficient plant food. Small differences in yield are not taken into consideration in this case. Consequently it is not necessary with this type of experiment to replicate each treatment beyond, say, three times. This simplifies the experiment. Progressive farmers, extension officers of the Department of Agriculture, and teachers of agriculture in high schools will confine themselves mainly to this type of experiment. Usually the results of such experiments will also give an indication of the probable quantities in which the fertilizers concerned should be applied to the soil.

The second kind of fertilizer experiment should be conducted on strictly scientific lines so that even small differences in yield may be accurately determined. They are called scientific or *quantitative fertilizer experiments*. Such experiments are essential when we have to determine the most profitable rate of application of a deficient plant food, the availability and relative manurial value of different fertilizers carrying the same major plant food (e.g. phosphatic fertilizers), the effect of humus in the form of farm manure, green manure, or straw on the productivity of the soil, &c. Such quantitative experiments differ in two ways especially from qualitative experiments: the different treatments should, in the case of quantitative experiments, be replicated at least four to six times and the plots should be randomized so that statistical methods may be employed in working out the results; secondly, an experiment on a certain soil should, if possible, be continued for several years so that the seasonal influences and residual effect of fertilizers may be determined. Only persons with adequate training can carry out such experiments, which are therefore expensive. Consequently only well-equipped agricultural institutions and financially strong agricultural companies can conduct such experiments.

We wish to confine ourselves to discussing briefly how a demonstration experiment is conducted. First of all a suitable piece of ground should be chosen. It should be as level as possible and its texture and depth should be as uniform as possible. It is advisable to select the piece of ground the year before when it has a crop growing on it which has received the same treatment throughout. The natural vegetation may also be a useful guide. It will then be possible, especially during the first half of the growing period, to determine whether there are any visual irregularities in the field. The piece of land should be away from headlands, roads, houses, trees, and furrows because near such places the yields are apt to vary and to divert from the normal.

The most important question to be answered by demonstration experiments is: Which of the major plant nutrients are deficient in the soil or, in other words, what is the qualitative manurial requirement of the soil? As in the case of pot experiments the following fertilizer plan (A) should give us a clear answer:

Treatment	I. No fertilizer	(O)
,,	II. Potash and Phosphate . . .	(KP)
,,	III. Potash and Nitrogen . . .	(KN)
,,	IV. Phosphate and Nitrogen . . .	(PN)
,,	V. Potash, Phosphate, and Nitrogen .	(KPN)

Here also, if the soil is acid, a sixth treatment may be added consisting of a complete fertilizer together with lime or, otherwise, one-half of each plot may be limed. On acid soils it is always advisable to use basic fertilizers, especially when the lime requirement is not being tested out at the same time.

Because South African soils are usually very deficient in phosphate, moderately deficient in nitrogen (in the case of soils that have been under

cultivation for a long time), and because the potash deficiency is usually very doubtful, the following simplified plan (B) is also very suitable:

Treatment	I. No fertilizer	(O)
,,	II. Phosphate	(P)
,,	III. Phosphate and Nitrogen . . .	(PN)
,,	IV. Potash, Phosphate, and Nitrogen .	(KPN)

If the yield of treatment III is significantly lower than that of treatment IV there is a shortage of potash. If the yield of treatment II is significantly lower than that of treatment III there is a lack of nitrogen, and treatment II will practically always give a greatly increased yield over treatment I, indicating a great deficiency in phosphate.

If the soil is markedly deficient in, say, both phosphate and nitrogen then the B plan is not as reliable as the A plan, because in the case of treatment II, where only phosphate is given, there may only be a small increase in yield over treatment I because the nitrogen would also limit the yield to a large extent. Consequently treatment III will give a much higher increase in yield than treatment II, and we may draw the erroneous conclusion that the soil has a greater deficiency of nitrogen than of phosphate. This conclusion is wrong because the increase in yield in the case of treatment III may be due largely to the fact that the phosphate responded much better because the other deficient nutrient, nitrogen, was also supplied. Unfortunately this uncertainty in connexion with the *quantitative* deficiency is not quite excluded in the A plan either. For example, if the soil has a marked deficiency of all three of the major plant nutrients, we will find that the sum of the increases in yield of treatments II, III, and IV above the yield of treatment I is smaller than the increase in yield of treatment V over treatment I. The reason for this is that on the completely fertilized plot every separate nutrient has a greater effect on plant growth than on the plots in which there is a deficiency, in other words, the 'harmonious' balance of the plant nutrients allows the plants growing on the completely fertilized plots to grow incomparably better.

Formulae have been proposed according to which the yields obtained according to the A plan may be used in calculating the quantitative fertilizer requirements. However, they are not quite reliable and it is best to apply one's common sense when interpreting the results, bearing in mind what we have said before. The main object in connexion with demonstration experiments is to determine a marked deficiency in one or other plant nutrient and not the extent of that deficiency.

The size, form, and arrangement of the plots depend on circumstances. About one-hundredth of a morgen, i.e. 100 square yards, is a suitable size for most crops. The bigger the individual plant the bigger should be the plots in order that a sufficient number of plants may be harvested so that the individual variations may be eliminated. In the case of fruit-trees on standardized stocks the plots may also be quite small, but fertilizer experiments in orchards are rather complicated and we do not wish to discuss them here.

The form of the plot may either be oblong or square. For demonstration plots the oblong ones are preferable (e.g. 5×20 yards) because differences in the stand between adjoining plots are more clearly discernible. Also, in the case of oblong plots the chances are that irregularities in the soil will be more evenly spread over the plots. This is of special importance where relatively few replications of every treatment are made. Another result of this limited replication is that there is no sense in randomizing the plots and hence they are repeated in a systematic way.

One of the following arrangements of plots may be adopted, depending on the size and suitability of the piece of land at one's disposal (it is assumed that the A fertilizer plan has been selected and that every treatment is replicated three times; see following page).

In the A arrangement there is an unfertilized or check plot between every two fertilized plots. The object of the check plot is to determine the uniformity of the experimental field. The yields obtained on the check plots also give an indication of what the yields on the other plots might have been had they been unfertilized. If such hypothetical yields are calculated the increases in yield as a result of fertilizing may be estimated more accurately (see later). The closer the check plots are to one another, the more reliable are the results of the experiment, but the larger must be the experimental field. In the B arrangement there are three fertilized plots between every two check plots. If need be, four fertilized plots may be placed between every two check plots, but such an arrangement can be applied only on a piece of land that is very uniform. The main thing is that there should be a check plot at the beginning and at the end of every experimental series. On account of its slightly more square form, the A 2 arrangement is preferable to the A 1 and B schemes unless the land has a slope. In such a case the experimental field should lie along the slope.

If the soil is so poor that only a very small yield will be obtained without any fertilizer, it is better to use a fertilized plot as a check plot to test out the uniformity of the soil. In South Africa a medium phosphate dressing may be given in such cases.

For demonstration purposes it is best to peg off the experimental field on land that has been freshly ploughed. Dead or open furrows should run across the plot and not lengthwise. At the one end of the field a firm wooden or iron peg should be driven into the ground. From here a rectangle should be measured off, the rest of the field measured off accurately, and the other corner pegs driven in. As in the case of establishing an orchard, the borders of the different plots are marked off by small shallow furrows, or all the pegs are driven in on the corners of the plots and every plot marked off with suitable rope or wire. The fertilizer should have been weighed off accurately and mixed beforehand and placed in small, clean bags. The bags are placed at the sides of the plots to which the fertilizer is to be applied, everything is checked once again on the plan, and then the fertilizer is distributed. It is always advisable to mix the fertilizer with slightly moist soil in a basin before distributing it. If there is any wind,

A1

I
II
III
I
IV
V
I
II
III
I
IV
V
I
II
III
I
IV
V
I

B

I
II
III
IV
I
V
II
III
I
IV
V
II
I
III
IV
V
I

A2

I	II	III	I	IV	V	I	II	III	I
I	IV	V	I	II	III	I	IV	V	I

FIG. 20. Plot arrangements according to which fertilizer experiments may be carried out.

however slight, this is absolutely essential. The fertilizer should be distributed with one's hand close to the ground to prevent blowing and distribution should be as even as possible.

After the fertilizer has been broadcast the pegs in between the corner pegs, if there are any, can be pulled out and the plots lengthwise harrowed

thoroughly. In the case of winter cereals the seed is then sown with a seed drill running across the plots, or the seed is broadcast by hand and harrowed in along with the fertilizer. In the case of maize, potatoes, &c., the rows should always run lengthwise over the plots. The seeds or tubers should be as pure and healthy as possible and should have a high germinating power.

As far as the choice of fertilizers and the quantities per morgen are concerned, the following recommendations may act as a guide: 100 lb. sulphate of ammonia, 400 lb. superphosphate, and 25–50 lb. muriate of potash or sulphate of potash. These quantities are meant for winter cereals and for maize. For potatoes, mangels, and sugar-beet the quantities may be three times as high. In general we may use slightly higher dressings than would be customary for the area and the crop concerned because our aim is not to determine economical amounts. On comparatively acid soils, basic slag or basic superphosphate is used instead of superphosphate. Sometimes it is advisable to give a portion of the nitrogen as top dressing, and then some nitrate fertilizer such as nitrate of soda, or even sulphate of ammonia, may be applied. Naturally in an experiment where the aim is to determine whether one or more of the major plant nutrients is deficient, one may only use straight or single fertilizers. Consequently, bird guano, farm manure, bone-meal, &c., are unsuitable for this purpose. All plots which are to receive a certain plant nutrient should receive it in the same fertilizer.

After the experiment has been laid out, the pegs between the corner pegs are driven in again so that the borders of the different plots will be apparent when observations are afterwards made. The same crop should be planted round the experimental field, and if observation paths are made along the borders of the plots they should be removed at least 3 feet from the border. It is important that notes should be made in connexion with any differences in the germination of the seed on differently treated plots, in connexion with the climatic conditions during the growing period of the crop, and in connexion with all visual differences in growth (stand) and ripening of the crop.

Great care should be taken in harvesting. Because the plants on and along the borders of the plots did not receive in full the intended fertilization, they are not included when harvesting. In the case of winter cereals, ropes are drawn a foot from the borders of the plots and 2-foot-wide paths are cut along the lengths of the plots. This is done only shortly before harvesting. With plants that are growing in rows, such as maize, potatoes, &c., one row along each long border is reaped separately and not added to the yield. Thus, the plots that are harvested are smaller than the fertilized plots and when calculating morgen yields the smaller area should naturally be taken into consideration.

The threshing of winter cereals is one great difficulty in connexion with fertilizer experiments because usually a small experimental threshing-machine is not available. Sometimes it is possible to cut off the ears and bag them after the air-dry sheaves have been weighed and then the ears

can be sent to an Agricultural Experiment Station, to be threshed and weighed. In any case, the sheaves should be left on the land or in a barn for a few weeks to become air-dry and then they should be weighed on a spring-balance hanging from three poles, set up in tripod form, so that the yield of every plot may be determined. In the case of potatoes and root crops the soil should be washed from the tubers and roots and the crop should only be weighed after drying. The crop should always be harvested and weighed as accurately as possible, and one should never be satisfied with a mere visual estimate of the yield on the land.

A final word about the elimination of soil heterogeneity with the aid of the yields from the check plots. Let us assume that we followed the A 1 arrangement of plots, that we grew potatoes, and that the following potato yields were obtained per plot on the first seven plots. The elaboration of the results is illustrated in the following table:

TABLE 24

No. of plot	1	2	3	4	5	6	7
Fertilization	Nil	KP	KN	Nil	PN	KPN	Nil
	lb.	lb.	lb.	lb.	lb.	lb.	lb.
Actual yield per plot	24	70	60	33	85	100	45
Probable yield per plot (unfertilized)	(24)	27	30	(33)	37	41	(45)
Probable increase in yield through fertilization	..	43	30	..	48	59	..

Using the yields of the check plots as a measure, we assume that the soil gradually improves in the direction of 1 to 7 and that the increases in yield as a result of fertilizing are probably lower than can be deduced from the preceding unfertilized plots. The probable yield of the plots in between the unfertilized plots, had they not been fertilized, are obtained by first dividing the difference in yield between two consecutive check plots by the number of plots in between, plus one; this figure is added to or subtracted from the yield of the preceding check plot, depending on whether the soil improves or deteriorates. This method of calculating the probable yields is called interpolation and the table illustrates it better than a long explanation would.

After the corrections for soil heterogeneity have been made, the average yields or, rather, increases in yield are calculated and any deficiency in one or more of the major plant nutrients is deduced, as we have already explained in connexion with the pot experiments. Because demonstration experiments are not carried out very scientifically, no attention should be paid to small differences in yield.

Fertilizers cost money and if a fertilizer gives only a small increase in yield that is sufficient justification for us not to recommend it. In any case, the experimenter should always use his common sense and all the

circumstances should be taken into consideration when he makes recommendations on the strength of fertilizer experiments.

Experiments with different varieties of the same crop differ from fertilizer experiments in that small but reliable differences in yield are of great economic importance. When working out the results of the yields of different varieties, it is essential to establish mathematically the significance or reliability of the differences in yields between the different varieties.

CHAPTER XXXII

THE MANURING OF SPECIFIC CROPS

INTRODUCTION

IN this and the following chapters we wish to stress the main points which should be borne in mind when manuring the most important types of agricultural crops. All crops use the same plant nutrients, but the quantitative proportions in which they are utilized and in which they should be applied, as also the ability of the crop to utilize the reserve food, differ widely. In this connexion we often differentiate between the nutritive requirement of the crop and the manurial requirement of the soil. By the latter we mean the general level of fertility in the soil in respect of the major plant nutrients; whether it has a high, medium, or low phosphate, potash, lime, and nitrogen (and humus) content. The more intensive the system of cropping is, the higher should be the level at which fertility is maintained, even if fertilizing brings no immediate profitable increase in yields, because under an intensive system of crop production the total cost of production per morgen is high and consequently it is a good policy to maintain as favourable a level of fertility as possible. Thus high yields of good quality will be possible if climatic conditions, &c., permit. Fruit and wine production, the growing of vegetables and tobacco, sugar-cane culture, and irrigation settlements are examples of intensive branches of agriculture.

As a rule winter cereals and maize are produced extensively. Usually the growing of winter cereals or maize constitutes the main activity on the farm and practically no other crops are grown in rotation. Agronomists call this a system of monoculture, and in the case of annual crops, such as the cereals mentioned above, such a system is very detrimental to soil productivity. The humus content sinks rapidly and attains a low, more or less stable level, but, coupled with the resulting poor soil structure, such a soil is very vulnerable towards erosion by wind and water.

With regard to manuring, such purely 'grain soils' need not be as rich in potash as soils that are under a system of crop rotation that includes, e.g., the 'potash devouring' root crops. However, in South Africa there exists the peculiar state of affairs that, when producing any crop, the manurial requirement of the soil needs first consideration because our soils are so poor in phosphate. Consequently, phosphate is almost always the main plant-food ingredient of any fertilizer mixture, even though the crop in question is not supposed to make any special demand on the phosphate supply.

Naturally, the recommendations which we are making should be regarded merely as a general guide because the question of specific manuring depends on many varying factors, the most important of which are the varying soil types and the amount and distribution of the annual rainfall.

MANURING OF WINTER CEREALS

Winter cereals are grown chiefly in the winter-rainfall area of the Cape Province. Other important areas are the Eastern Free State and Northern Transvaal (Lydenburg). The outstanding feature of the grain lands of the South-western Cape Province which have been under cultivation for a long time is their low humus and phosphate content. Even virgin soil is always poor in phosphate. Physically, the soils are usually of a gravelly loam type. Usually 20–50 per cent. of the total weight of the soil is gravel or pebbles. On account of their low humus content the older soils have a very poor structure and readily become compact after rains, forming a hard soil crust. Near the coast and at the foot of mountains sandy soils are encountered. Winter cereals are grown almost exclusively (monoculture) and the following system of cropping is mainly followed: wheat—fallow—wheat (or oats)—fallow. Rye is grown especially in the 'Sandveld' area of Clanwilliam, Piquetberg, and Malmesbury, and barley mainly in Robertson and Swellendam.

Wheat and barley prefer fairly heavy loams and make big demands on soil fertility. Also, the soils should not be markedly acid; a pH above 6·0 is desirable. Oats and rye will still give good yields on sandy soil types and they are tolerant of soil acidity.

If readily available fertilizers are used the following quantities of plant nutrients may be applied per morgen in the case of wheat (and barley) in the South-western Cape Province: 20 lb. nitrogen, 70–100 lb. phosphoric oxide, and 0–30 lb. potash. In the form of fertilizers this would mean: 100 lb. sulphate of ammonia, 400–600 lb. superphosphate, and 0–50 lb. muriate of potash. The heavy application of superphosphate (or any other available phosphatic fertilizer) is only given on virgin soil during the first few years. Subsequently, the normal application of 400 lb. per morgen is given. As far as the nitrogen is concerned, nothing is applied on land that has been newly broken up, but farmers should try to maintain the humus content of the soil as much as possible by at least ploughing in the chaff and straw. On older soils that are poor in humus, e.g. in the Malmesbury–Koeberg area, it is advisable to give a top dressing of 100 lb. sulphate of ammonia or nitrate of soda per morgen, during July–August, in wet winters. Potash applications are only recommended where wheat is grown on sandy soils. Farm manure is essential for such soils, and if it is applied an extra application of potash is not necessary.

The grain farmers of the Western Cape Province usually have a certain amount of kraal manure and Government guano at their disposal. The kraal manure is usually applied in autumn on the fallow lands at a rate of about 8 tons (6 wagon loads) per morgen. It has already been explained (p. 224) that it is more advantageous if semi-rotted, straw-containing manure is ploughed in towards the end of winter. Soil to which kraal manure has been applied should receive an additional 200 lb. superphosphate or basic superphosphate at sowing time, otherwise the wheat does not seed satisfactorily. Experiments have proved that if the kraal manure

is applied only at sowing time, an additional application of 100 lb. of sulphate of ammonia per morgen gives good results because the manure contains too little available nitrogen.

The following mixtures may be made up with Government guano:

1. *Without potash*: 4 bags (800 lb.) Government guano and 6 bags (1,200 lb.) superphosphate. At sowing time 500 lb. of this mixture are applied per morgen, i.e. 5 bags to every bag of wheat sown.
2. *With potash*: 4 bags Government guano, 6 bags superphosphate, and ¾ bag (150 lb.) muriate of potash.

If the farmer has too little Government guano for all his lands, sulphate of ammonia may be used to provide a portion of the nitrogen requirement. Several mixtures are possible, depending on the amount of Government guano at the farmer's disposal. The following two mixtures are suitable (without addition of extra potash):

(*a*) 1 bag sulphate of ammonia, 2 bags Government guano, and 7 bags superphosphate.

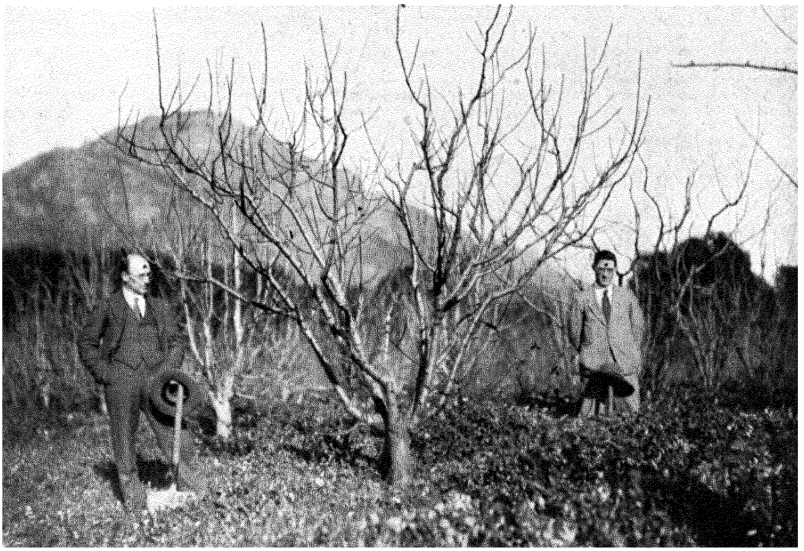
(*b*) 1 bag sulphate of ammonia, 1 bag Government guano, and 6 bags superphosphate.

Each of these mixtures is applied at a rate of 500 lb. per morgen. On sandy soils the (*a*) mixture is preferable to the (*b*) mixture. If any of the above mixtures is applied through a fertilizer drill it is necessary that the Government guano should first be sifted through a quarter-inch sieve.

In districts where there is no farm manure all the chaff and straw should be braaked into lands which are to be sown the following year. An application of 100 lb. ammonium sulphate per morgen on the straw before it was ploughed in proved unprofitable, but the same application at sowing time proved advantageous. Naturally, the ordinary phosphate dressing should also be given at sowing time.

These fertilizer recommendations for wheat are meant specially for the South-western Cape Province. In the other wheat-producing areas of the Union a phosphate application of about 400 lb. superphosphate or basic superphosphate per morgen should be given. The nitrogen requirement will depend on the length of time that the soil has already been under cultivation and whether it is possible to follow a rotation system that includes a legume. The manuring of oats (and rye) depends on the manner in which they are grown. If the oats is grown on wheat-stubble land, less phosphate but more nitrogen is required than for wheat; 250–300 lb. of Government guano per morgen will be practically all that is necessary. If one has not sufficient Government guano, 400 lb. of the following mixture may be applied per morgen: 1 bag Government guano, 1 bag of sulphate of ammonia, and 2 bags superphosphate. On sandy soils 100 lb. of muriate of potash should be added to this mixture. Where oats is sown on braaked (fallow) lands this mixture will also be suitable but the dressing should be 300 lb. instead of 400 lb. per morgen.

As far as the winter-rainfall area of the Cape is concerned, experiments proved beyond doubt that in the larger section of the grain area dry-land



a Orchard fertilizer experiment, showing the poor growth of the cover crop (*goudblom*) on the left plot, which has received no nitrogen for twelve years On the right side the cover crop grows luxuriantly Experimental Farm, Stellenbosch

Photo S A Potash Co Ltd

b Gradual dying back of apple branches on account of potash deficiency in the soil (right), the tree on left has received heavy potash applications for three years Krakeel, Langkloof, C P.

lucerne can be grown successfully, and to-day this is the policy that is advocated. All the grain land should in rotation be laid down to lucerne for about four years followed by approximately four wheat (or oat) crops. This system has many advantages from the point of view of soil fertility and also of checking soil erosion on sloping ground. Furthermore, the humus and nitrogen content may be maintained at a higher level, the structure of the soil is improved, and the increased acreage of good pasture enables the farmer to keep more livestock. This again means a larger production of manure with the result that a larger acreage of the land under annual crops can receive farm manure. This, together with the fact that the lucerne enriches the soil in nitrogen, will mean that less nitrogen will have to be applied by way of fertilizer.

MANURING OF MAIZE

As far as the maize-producing area (over 3,000,000 morgen) is concerned, maize is by far our most important field crop in South Africa. Being a summer crop it is grown almost exclusively in the summer-rainfall area. Where it is grown under irrigation outside this area, mainly for silage, it should be fertilized like wheat. If sufficient irrigation water is available it pays very well to grow such maize after green manuring with peas, &c.

The actual maize areas in South Africa have, of course, various soil types, but in general they still have a relatively favourable humus and nitrogen content, and phosphatic fertilizers are the most important, and usually the only, fertilizers that are applied. Where the rainfall is very erratic and fairly low, e.g. in the Western Transvaal and the Western Free State, approximately 150–300 lb. of superphosphate per morgen is the only profitable fertilization. In the remaining maize areas where the rainfall is usually higher, 400 lb. of superphosphate per morgen is usually the dressing that is recommended.

Experiments proved beyond doubt that in these warm ferruginous soils of the summer-rainfall area, water-soluble phosphate is so soon fixed and rendered insoluble that superphosphate has hardly any residual effect in the second year after application. Therefore, the same amount of superphosphate must be given year after year. Some research workers are therefore of the opinion that in the long run it would pay better to use a mixture (in equal quantities) of superphosphate and rock phosphate at a rate of 400 lb. per morgen—provided the ton price of high-grade superphosphate is approximately the same as that of high-grade rock phosphate. Although the rock phosphate only becomes available gradually it remains available for years, and because rock phosphate is added annually its cumulative effect becomes progressively more prominent. After six to eight dressings of the above mixture it may, therefore, be possible to omit the superphosphate altogether and an annual dressing of 200 lb. of rock phosphate will be sufficient to replace annual consumption.

As a rule a potassic fertilizer is unnecessary for maize, and if farm manure is applied at intervals the potash supply in the soil will remain fairly high.

In connexion with nitrogenous fertilizers for maize we have already mentioned that the practice is to apply phosphatic fertilizers only. At Potchefstroom and Pretoria it was found that in experiments where maize had been grown continuously for at least ten years, a nitrogenous dressing was still unnecessary. Nitrogenous fertilizers have no effect, and where farm manure is applied or where the soil is green manured with cowpeas, &c., an increased maize yield is attributed to the increased availability of the phosphate or to other favourable growth conditions—the result of organic matter—and not to an increase in the available nitrogen.

Research by Dr. J. J. Theron on the red, sandy loam of the University Farm, Pretoria, clarified this matter considerably. His analyses show that during ten years (1930–40) the original nitrogen content (and carbon content) of the upper 9 inches of soil decreased by 25–30 per cent., viz. from 0·08 to about 0·06 per cent. This decrease took place on the following plots:

(*a*) Plots on which maize was grown every year and fertilized either with fertilizers only, including 400 lb. of superphosphate per morgen, or with the mentioned fertilizers plus 20 tons of farm manure every third year.

(*b*) On plots where cowpeas were grown every year, fertilized with the fertilizers mentioned under (*a*) and harvested when ripe.

(*c*) Where the soil was ploughed every year and left fallow.

A simple calculation will prove that if the fertilizer nitrogen and that nitrogen which the cowpeas may have fixed from the atmosphere are not considered, nitrification of 2–3 per cent. of the nitrogen reserve in the topsoil would supply about 120–140 lb. of nitrate nitrogen per morgen per year. This is sufficient for twenty-five bags of maize plus the aerial portions of the crop. The subsoil (9–18 inches) supplied much less nitrogen, but for the sake of simplicity we may assume that nitrogen to be sufficient to meet the demands of the root system. Over a period of ten years Dr. Theron's lysimeter experiments showed that the amount of nitrate nitrogen leached from similar uncropped soils corresponded to the above estimate of nitrate production. One would expect that the intensity of nitrification would decrease as the humus and nitrogen content of the soil decreases, and experiments elsewhere indicate that this is the case.

The above findings explain why maize lands in the summer-rainfall area, depending on their original nitrogen content, do not require nitrogen fertilizers for a considerable period. However, they also show how rapidly the decomposition or nitrification of the nitrogen reserve in the soil takes place and thus, sooner or later, there will arise a nitrogen deficiency. The Kroonstad experiments (D. J. van der Berg) seem to indicate that on that deep sandy soil, with 0·05 per cent. nitrogen, maize began to respond to nitrogen treatment after about seven crops, averaging annually about twenty-one bags per morgen. The results of a fertilizer experiment extending over several years at Tweespruit, O.F.S.,[1] are clearer. In this case the topsoil also contains about 0·05 per cent. nitrogen, but the subsoil is less

[1] J. J. Eksteen, *Farming in South Africa*, June 1945.

suitable to crops than that of Kroonstad, and after three years plots which received 100 lb. of sulphate of ammonia per morgen showed a significant increase in yield over those that received only superphosphate. In the same experiment, maize following in a rotation on peanuts which had been harvested for hay showed an even greater increase over the maize that received only superphosphate. Periodic determinations of the nitrate content proved that it was the higher nitrate content of the 'peanut' soil that was responsible for the increased yield. It is interesting, in passing, to observe that teff as a hay crop has the opposite effect and depressed the subsequent maize yield considerably.

In order to maintain the level of fertility of soils in the maize belt sufficiently high and to combat soil erosion effectively, on all sloping land, it is necessary that maize should not only be grown on the contour, but that the rotation system should also include a protein—rich fodder crop. Furthermore, the rapid decrease in the humus content (carbon and nitrogen) should definitely be halted. Evidently there is only one effective way by which this can be done and that is, in the higher rainfall regions at any rate, to rotate the maize with *perennial pasture grasses* or *dry-land lucerne*. If the grass ley is fertilized intensively with nitrogen the humus content of the soil will probably increase to such an extent in, say, four years' time that the soil will, *inter alia*, maintain a good crumb structure, when it is thereafter sown to maize for a similar period of years. Such a system of crop rotation will not only mean a much higher feed production for South Africa's most important agricultural industry, viz. animal husbandry, but it should also ensure a higher and more stable maize production, even though the actual maize acreage will be reduced.

MANURING OF LEGUMINOUS CROPS

Lucerne is our most important legume, and it is widely grown under irrigation on alluvial soils which are fairly deep and fertile. As a rule these soils are not fertilized at all. Once again, phosphate is the nutrient which is relatively deficient even in most alluvial soils, and it will pay very well to apply 600–1,000 lb. of superphosphate per morgen just before planting and again every third or fourth year thereafter.

Where lucerne is grown outside the arid region it is absolutely essential to give regular applications of phosphatic fertilizer. On acid soils basic slag or basic superphosphate should be applied instead of ordinary superphosphate or the soil should be limed periodically, because lucerne requires a sweet soil and removes tremendous quantities of lime (calcium) from the soil. For animal nutrition it is essential that the lucerne should contain the normal high calcium content. On sandy soils about 100 lb. of muriate of potash should also be applied annually per morgen because lucerne is rich in potash. Under certain conditions fertilizing with a nitrogenous fertilizer such as nitrate of soda or sulphate of ammonia in spring and in early autumn may be profitable, especially when the price of nitrogenous fertilizers is relatively low. If lucerne is grown on non-irrigated land in a

rotation system such as that suggested for winter cereals or maize, at least 600 lb. of superphosphate per morgen is ploughed deeply into the soil before the lucerne is sown. If the pH of the soil is lower than approximately 6·0 it will pay to apply at least one ton of agricultural lime per morgen beforehand and, in any case, basic superphosphate or basic slag should be used instead of superphosphate.

For the other leguminous crops such as ordinary beans, peas, peanuts, cowpeas, soya-beans, &c., a phosphatic fertilizer is used at the rate of 400–600 lb. per morgen. Here, also, an application of a potassic fertilizer is often essential on sandy soils and a light nitrogen application of 100–200 lb. of nitrate of soda per morgen, at the beginning of the growing season, is conducive to good development of the crop. Theoretically, legumes require no nitrogenous fertilizer provided the nodule-forming bacteria are present in the roots, but in practice it has been found that legumes do respond in the young stage to a light dressing of a nitrogenous fertilizer.

MANURING OF POTATOES AND ROOT CROPS

Potatoes and root crops such as mangels, sugar-beet, and sweet potatoes react very well to an application of farm manure or green manure and, especially on soils that have a low humus content, farm manure or green manure should always form the basal manuring for these crops. Manure containing a considerable amount of bedding may be applied at the rate of 20 tons and more per morgen. In the summer-rainfall area, kraal manure may be applied at a rate of 6–8 tons per morgen. Karoo manure should be avoided when growing potatoes because it promotes potato scab. However, for root crops it may safely be used at a rate of 5–10 tons per morgen.

In addition to farm manure, 600–1,000 lb. of phosphatic fertilizer should be applied per morgen. Where potatoes are grown on a large scale, only farm manure and superphosphate are applied, although one should always experiment to see whether a top dressing of 200–400 lb. of sulphate of ammonia per morgen does not give a profitable increase in yield. If no kraal manure is available, only a potato fertilizer at the rate of 800–2,000 lb. per morgen is applied in the summer-rainfall area. In the Western Province potatoes are treated more as a vegetable crop and are more heavily manured. The stable manure which is used is sometimes of an inferior quality and, therefore, supplementing with phosphate, nitrogen, and sometimes potash also, is necessary. About 20 tons of stable manure and 600–800 lb. of superphosphate are applied per morgen before or at planting. About a week after the potatoes are up they receive a side dressing of 200 lb. ammonium sulphate or 400 lb. Government guano or 600 lb. potato fertilizer per morgen. The soil is then cultivated whereby the potatoes are ridged at the same time. If sufficient farm manure is not available it is necessary that the top dressing should contain all three of the major plant nutrients, or at least nitrogen and potash. A potato fertilizer may be used or a mixture consisting of 200 lb. sulphate of ammonia, 300 lb. superphosphate, and 100 lb. sulphate of potash per morgen.

Sweet potatoes may be fertilized on the same lines as potatoes with the important difference that only half the amount of nitrogen is used, lest the sweet potatoes produce excessive vegetative growth. Potatoes as well as sweet potatoes grow well on moderately acid soils.

Mangels, swedes, and sugar-beet are very heavy feeders and they should be fertilized at least as heavily as potatoes. They differ from potatoes and sweet potatoes in that they grow best on 'sweet' soils. For this reason basic slag or basic superphosphate is used instead of ordinary superphosphate and nitrate of soda instead of ammonium sulphate (as side dressing). Furthermore, one can use muriate of potash with them instead of sulphate of potash. The quantities of these fertilizers which should be applied per morgen, together with the farm manure or green manure, are more or less the same as mentioned for potatoes. It is well known that mangels grow very well on saline (brak) soils.

When no farm manure is available and green manuring is not possible, or when the soil is rich in humus, fertilizers only as previously mentioned may be applied to the above crops: 1,200–1,500 lb. of a phosphatic fertilizer, 400–500 lb. sulphate of ammonia and/or nitrate of soda, and 200–300 lb. muriate of potash per morgen.

Although they are not 'root crops' the manuring of the brassicas (cabbage, cauliflower, kale, &c.) may be mentioned under this heading. Their manuring corresponds closely to that of mangels. They prefer a sweet soil, respond well to applications of farm manure, and use large quantities of nitrogen and potash (and calcium). Because they have such a long growing period they respond very well to a side dressing of nitrogen.

CHAPTER XXXIII

THE MANURING OF SPECIFIC CROPS (*cont.*)

THE MANURING OF NATURAL AND ESTABLISHED PASTURES

By THOS. D. HALL, B.A., M.SC.AGR., D.SC. (HON.)[1]

The Basic Problem and Background

APPROXIMATELY 15 per cent. of South Africa's land can be cultivated, the rest is pasture, good, bad, and indifferent. The pastoral area thus comprises the greater part of our country and has been in the past century not only sadly neglected but recklessly, almost criminally, exploited. To-day we are paying for this harvest of greed at compound interest in trying to cure our erosion troubles.

Since about 1930 we have learnt much about our natural veld, particularly the grass and bush veld, and we have come to realize that our veld is not only one of our greatest assets when properly managed, but that well-managed veld is one of the easiest and cheapest ways not only of preventing erosion but of curing it. There is to-day much less talk of introducing new grasses and ploughing up the natural veld than heretofore, and a better appreciation of the fact that Mother Nature in her wisdom has selected the species best adapted to a particular climatic area. There has also been a better appreciation of the value of veld-grass hay, and to-day hundreds of farmers are getting the bulk of their hay from veld instead of burning it, as once was the case. Dr. H. H. Bennett, America's great soil conservationist who came here at our Government's request in 1944 to suggest remedial measures, said that as far as grasses were concerned we were well blessed and that some of our common veld grasses were being used to heal soil-erosion wounds in the U.S.A. He said further that he could tell us little about their management, but that if farmers followed the basic principles established by our pasture research stations, he was convinced we should make rapid progress in stemming erosion and increasing pastoral production.

One of the ways by which our veld is being impoverished is the custom of picking up cattle dung and making it into cakes for fuel, thus preventing any return of the organic matter and minerals to the soil. The planting of trees for fuel and the use of our cheap coal would do much to prevent this.

Fertilizers and Veld

If a general rule is required it is, that the higher the rainfall, the poorer the veld, and the greater the likelihood of benefit from fertilizers. It seldom pays to fertilize veld which gets less than 20 inches of rainfall, and generally better results will be obtained on that getting 25 inches upwards.

[1] Agricultural Adviser, African Explosives and Chemical Industries, Ltd., Johannesburg.

As regards soils, sandy soils under a low rainfall will respond far better to fertilizers than a clay loam in the same area. At one time the writer had over 600 morgen under veld fertilizer experiments, scattered all over South Africa from the Cape to the Zambesi. We learnt a lot from these, and chiefly that nitrogen always gave a good response, but that to get the best results from nitrogenous fertilizers you must use phosphatic ones as well. Superphosphate or a mixture of super and rock alone, however, gave very little indication of improvement as far as the eye could see, but such veld was generally better grazed and cattle put on more weight. From our results we could see little benefit from potash or lime. In general we also reached the conclusion that the nitrogenous fertilizer could be increased and the phosphatic one decreased—e.g. instead of applying 200 lb. sulphate of ammonia and 400 lb. superphosphate per morgen, mix together 300 lb. of each of these and apply 400–600 lb. of the mixture per morgen.

'How do you apply fertilizers to veld?' is a question frequently asked. Wait until there have been good soaking rains, with the prospect of more, and apply the fertilizer just on the surface without any cultivation. Do not fertilize veld if you cannot control the grazing, or the added palatability of the fertilized area will cause it to be overgrazed and most likely damaged. Every farmer needs hay, and well-fertilized veld will give him earlier hay and a more certain crop than sown hay on cultivated lands. Start your fertilizing then on a hay area, and you will get not only much more hay, but hay of a higher protein and phosphoric oxide and lime content, and of much greater nutritional value for milk or meat production. It will also give you a better chance to observe the benefits of fertilizing.

'What kind of veld shall I fertilize?' is frequently asked. Once the writer should have replied, 'Fertilize only good veld', but since then we have had a lot of experience. On a piece of sour veld just off the Pretoria Road, at Frankenwald, reckoned among the worst veld in the Transvaal, we grew all kinds of indigenous and exotic grasses as we were confident they would outyield the poor veld. During the last few years we have learnt, however, that this poor veld, if given the same fertilizer as the specially selected species got, grew more steadily, especially in the drier periods, grew for a longer period, and gave a better and more regular liveweight increase on the different lots of beef cattle we tested over a period of years. As a result of this work, our respect for the natural veld and its potentialities has grown greatly. Our work also showed that increased dressings of nitrogenous fertilizer paid in that not only did the animals put on more weight, but the veld carried more animals per morgen.

There is so little natural grazing of any value left in the Western Province winter-rainfall area, that we have said little about it. Such vleis and areas as are available could be fertilized as already detailed just after the first winter rains, when the soil is wet enough for the fertilizer to dissolve and not blow away. Cultivation in the vleis with a heavy harrow will probably be of greater benefit than on the Highveld.

Established Pastures

1. *The summer-rainfall area*

The area under established pastures is difficult to calculate, but it was estimated as only 40,000 morgen about 1939. With the difficulty in obtaining fertilizers for grass during the war years, this acreage has probably diminished rather than increased. From experience gained all over the world in the last decade, however, it would seem that the soundest practice will be to make the established pasture part of the crop rotation, and put it down as a ley for two to four years, not only as a source of hay and grazing, but as a soil improver. There has been much evidence accumulating of late, to the effect that the fibrous and multitudinous roots of the grass crop are the best means of restoring soil structure and fertility. Russian and other work has also shown that fertilized grass has a much more prolific root system, and this adds more organic matter to the soil. The weight of roots in the soil is proportional to the weight cut above it.

We have many fine grasses in South Africa and many which, when hand planted, give excellent results both for hay and grazing. So far, however, the seed production side has not been developed, and as hand planting large areas is too expensive, farmers sow the seed of such grasses as is obtainable. In the summer-rainfall area these are Rhodes grass (*Chloris gayana*) and *Paspalum dilatatum*. Rhodes is suitable for drier sites than Paspalum, but often the two are sown together—6–8 lb. Rhodes, 20–24 lb. Paspalum per morgen with 6–8 lb. lucerne seed mixed with them. When sown alone 10–12 lb. Rhodes grass is used and 24–28 lb. Paspalum, the amount of lucerne remaining the same. Both Rhodes and lucerne are, however, sensitive to acid soils, and if a soil test shows a lime requirement that soil must be limed if success is expected. It is also a good plan to apply compost or kraal manure before seeding the grass crop rather than later, together with 400 lb. per morgen of a phosphatic fertilizer. The next year 200–400 lb. per morgen of a nitrogenous fertilizer like nitro-chalk, nitrate of soda, ammonium nitrate, or sulphate of ammonia is all that will be required.

Farmers are very interested in frost-resistant grasses, and although there are a number of these most promising, the area where they can be grown is very limited. They like 30–40 inches of rain well distributed, including some in the winter, and a fair amount of mist and cool weather. New Zealand Tall Fescue (*Festuca arundinacea*), Cocksfoot (*Dactylis glomerata*), Rye grasses (*Lolium* spp.), *Agrostis tenuis* and *A. vulgaris*, Kentucky blue grass (*Poa pratensis*), *Phalaris tuberosa*, and wild white clover (*Trifolium repens*) fall into this category and are sown either as a mixture or as pure species with clover. There is usually little trouble in growing them where rainfall can be augmented with irrigation. They do best along the eastern foothills of the Drakensberg.

2. *The winter-rainfall area*

There are a few odd spots in the winter-rainfall area, east of Sir Lowry's Pass, which get some summer rain as well as winter, where the frost-resistant grasses make fine pastures. For the greater part, however, they are of little use excepting *Phalaris tuberosa*—often called the queen of winter grasses—which is a real winter-rainfall area grass. It grows during the cool rainy months, seeds by October, and becomes dormant during the hot dry weather. It is certainly a grass that should be given a greater chance in the winter-rainfall area. As little as 8 lb. of good seed per morgen in rows 2–3 feet apart is sufficient as the stools grow large; it is as well to add some lucerne too.

So far the outstanding success of all fodder and soil-building crops for the Western Province has been lucerne. The Langgewens Experiment Station proved that it could be grown on well-prepared soil in July. Elsenburg, Jongensklip, and Langgewens stations all proved that when lucerne had been down three to four years it greatly improved the subsequent wheat crops, and in some cases two or three good crops could be grown in succession after lucerne had been ploughed down. Its good service did not stop there, however, as there was always some lucerne growing in the wheat, which made the stubble lands of greater grazing value. Lucerne is rejuvenating the wheat lands of the Western Province and restoring their fertility, and doing good work as far east as Riversdale. There are, of course, many volunteer grasses and legumes on old grain lands, and in fertilized lucerne they increase and make a good mixed pasture. Such useful 'weeds' are: wild oats (*Avena* spp.), canary grass (*Phalaris canariensis*), Quaking grass (*Briza* spp.), *Bromus* species, 'Gousblom' (*Cryptostemma* spp.), Crane's Bill (*Erodium moschatum*), Burr clover (*Medicago hispida*), &c.

3. *Winter- and summer-rainfall areas*

From Swellendam eastwards to Riversdale and beyond, Rhodes grass has been most promising and is very popular with farmers. Near Riversdale, Rhodes grass in summer and subterranean clover in winter give an all-the-year-round pasture—a wonderful achievement, and one which may revolutionize farming and bring in more animal husbandry. In winter there is a thick stand of clover with hardly any sign of Rhodes grass, and during the summer the reverse is the case and the Rhodes grass flourishes. The clover again germinates and starts growth with the first autumn rains.

Subterranean clover is a true winter-rainfall area crop, but even the hardiest strain, Extra Early Dwalganup, will not grow in less than 15–20 inches of rainfall distributed over four to five months. The 'Mount Barber' is a later maturing strain which is more suited to the higher rainfall areas near the mountains. Subterranean clover has the advantage of being tolerant of acid soils. The soil should receive about 600 lb. of basic superphosphate per morgen and the clover seed should be sown in autumn. It is a great soil builder and more will undoubtedly be heard of it in future.

THE MANURING OF SUGAR-CANE

By H. H. DODDS, M.SC., D.SC., F.R.I.C.[1]

General Introduction

Sugar-cane is a perennial giant grass, probably of tropical origin, that can be economically cultivated in tropical and sub-tropical regions of a mean annual temperature not less than 68° F. and free from severe frosts; it requires reasonably fertile soil and a moderate to generous supply of water. The average annual rainfall should not be much less than about 40 inches per annum unless the crop be irrigated.

Within recent years a great change has taken place in the varieties of sugar-cane grown in South Africa. Up to the year 1935 the South African sugar crop was produced almost entirely from the Uba variety, which was introduced into the country from India in 1883 by the late Daniel De Pass. This variety soon established its superiority in Natal over all other varieties, but about the year 1923 it was found to be infected with a virus disease to which the name of streak disease was given.

Many other varieties from different parts of the world were introduced and tested, with the ultimate result that the Uba variety has now been almost entirely replaced by the varieties Co. 281, Co. 301, and P.O.J. 2725, each of which is very highly resistant to streak disease. It was found that these varieties were also superior to Uba in yield of sugar per acre to an unexpected degree, with the result that mainly from this cause, but also partly from the more rational use of fertilizers for sugar-cane, and higher manufacturing efficiency in the sugar factories, the average yield of sugar per morgen in South Africa has increased by more than 50 per cent., that is, from 4 tons to well over 6 tons of sugar per morgen per crop over the past decade.

Climatic and Soil Requirements of Sugar-cane

The mean annual rainfall (42 in.) and temperature (69° F.) on the Natal coast are near the lower limits of the ranges required for the successful production of sugar-cane, and the available soil is by no means always of the best; but results of recent seasons show that the yield of sugar per morgen in Natal now compares very favourably with that from all other sugar-growing countries, with the exception of Hawaii and pre-war Java, which were outstanding in production per unit area.

Sugar-cane will grow successfully in a wide range of soils, and it is difficult to say that any one soil type is particularly suitable, since much more depends on the depth and fertility and moisture supply and drainage than on the soil texture or origin. The recent alluvial soils of the Natal river flats are the most productive, mainly because of their high water table; but these soils are very limited in area, except for the fairly extensive

[1] Director, Experiment Station of the South African Sugar Association, Mount Edgecombe, Natal, South Africa.

Umfolozi and Umhlatuzi river flats in Zululand. Another highly productive soil of very limited area, about 7,500 morgen in all, is the upland basaltic formation north of Empangeni in the Zululand section of Natal.

Other typical and more extensive soils which have been brought into sugar cultivation on the Natal coast are: (1) the granitic soils located mainly to the south between Umzinto and the Umzimkulu river; (2) Table Mountain sandstone soils, forming the hinterland of almost the whole of the Natal coast; (3) soils overlying Dwyka conglomerate, occurring mainly in the central portion of the coast between Durban and the Tugela river; (4) soils derived from the Ecca Shales, which also occupy large portions of the central area; (5) doleritic soils, distributed widely and resulting from the weathering of doleritic intrusions; and (6) perhaps the most extensive of all, the recent sands nearest to the coast and parallel with it as a relatively narrow belt on the south coast and gradually widening up the north coast.

All of these soils vary greatly in fertility and depth, but each is capable, under favourable circumstances and good cultivation, of producing a good sugar-cane crop. They also vary in extent, but all occupy much greater areas than the two first mentioned.

Sugar-cane cultivation along the coastal area of Natal extends from Port Shepstone in the south to Hluhluwe in the north, about 220 miles, mainly within 7 or 8 miles of the coast but occasionally spreading 20 miles or more inland. The topography consists mainly of gently rolling hills and river valleys. The total area occupied by all sugar plantations in South Africa is about 380,000 morgen, of which approximately one-half is under cane and about 90,000 morgen harvested each year. The average annual crop yield over the seven-year period 1937–44 is 4,900,000 tons of cane or 550,000 tons of sugar.

Maintenance of Soil Fertility in the Sugar Plantation

A good average sugar-cane crop of 80 tons per morgen removes from the soil the following quantities of the principal fertilizer elements: nitrogen 224 lb.; phosphorus as P_2O_5, 127 lb.; potassium as K_2O, 300 lb.; and calcium as CaO, 142 lb. Only one-half to one-third or even less of these quantities is actually removed with the cane from the field, the remainder being left on the ground in the form of tops and leaves.

It is unfortunately a common labour-saving device to burn off the leaves of the cane before harvesting, which of course results in a considerable loss of nitrogen and organic matter.

The ultimate main product of the sugar-cane plantation is of course pure sugar, which is a carbohydrate, so that none of the fertilizer elements is lost in this way, but they are recoverable in the by-products. The only by-product of much economic value as a manure, however, is the so-called filter cake, the solid material filtered out from the juice expressed from the cane after heating and treatment with sulphurous and phosphoric or carbonic acids, and lime, to precipitate various salts and organic non-sugars in solution or suspension in the original juice.

Most of the phosphorus and a considerable proportion of the nitrogen originally in the cane is contained in the filter cake, amounting over the whole of the South African crop to an annual equivalent of 17,000 tons of superphosphate and 4,000 tons of ammonium sulphate. It contains also lime to the equivalent of 25,000 tons of calcium carbonate, and potassium to the equivalent of 300 tons of potassium chloride.

This 250,000 tons of otherwise waste product, containing 100,000 tons of dry matter, is thus a very valuable manure, notwithstanding its bulky, moist, and often malodorous nature. It also contains a large and very valuable proportion of organic matter, and since this consists very largely of fine particles of cellulosic fibre, the cake may have an unfavourable carbon–nitrogen ratio, making it necessary to weather it for several months before use; this has the advantage also of drying out some of the excessive moisture.

Soils for sugar-cane, like almost all other crops, need to be at least moderately well supplied with organic matter for the usual reasons, that is to say, to maintain the moisture-retaining capacity of the soil, to retard erosion by wind or water, to maintain porosity and good structure, and to help to make fertilizer elements more available to the plant. However, sugar-cane soils, though they may become seriously deficient in organic matter through neglect to maintain it, are not liable to become so acutely deficient in organic matter as overgrazed and neglected pasture lands, or soils under various small crops. The reason for this is that a big crop like sugar-cane, which is usually 8–12 feet high at time of harvesting, leaves a large residue of root material in the soil, which may amount to many tons of organic matter per acre. For this reason it is said in Hawaii, and has been amply demonstrated there over many years, that the best way to conserve organic matter in sugar-cane fields is to make them grow big crops. This may be sufficient under Hawaiian conditions of an originally highly fertile soil, and ample supply of moisture from rain supplemented when necessary by irrigation, and liberal applications of fertilizer. But in South Africa circumstances are generally by no means so favourable so that it is very advisable to restore organic matter directly by return of crop residues such as leaves and tops, organic waste products such as filter cake, and by having a fallow year between crop cycles when a green-manure crop or a succession of such crops should be cultivated and ploughed into the soil. The crops found by experience to be the best for this purpose are the legumes sunn hemp (*Crotolaria juncea*), velvet beans (*Mucuna* spp.), and the non-legume buckwheat (*Fagopyrum esculentus*).

The legumes are best sown after the last cane crop has been ploughed out, preferably from September to December, according to the rainfall, and may be sown as late as February or March, but will in that case give a poor crop should there be an early cessation of the summer rains. These leguminous green-manure crops not only enrich the soil with organic matter and give a beneficial change of crop to the soil, but contribute variable but very considerable quantities of nitrogen gained from the atmosphere by nitrogen-fixing bacteria in their root nodules. Thus, it is

found that the first following cane crop at least will be amply supplied with nitrogen in this way, so that it will not be necessary to apply any expensive nitrogenous fertilizer.

After the end of the summer no suitable leguminous crop for green manuring has yet been found, so that buckwheat is frequently used with good effect. Buckwheat needs a moderate amount of moisture to ensure its germination and early growth but will thereafter give a good crop even with very little rainfall, if the weather is not too warm or the soil too poor. It contributes organic matter liberally to the soil, thoroughly cleans the field by overcoming weeds, and has the property of utilizing potassium and phosphorus in relatively less available soil forms and leaving them appreciably more available after having been ploughed in. Incidentally buckwheat is an excellent bee plant, yielding an abundance of honey of high quality.

Rock phosphate or a mixture of rock phosphate and superphosphate may be applied with advantage to the green-manure plant up to 600 lb. per morgen, thus lessening the phosphorus requirements of the following cane crop.

Outline of General Agricultural Practice in Sugar-cane Cultivation

The phrase 'crop cycle' was used above in reference to sugar-cane, which leads us to a consideration of agricultural practice in the sugar industry. The previous crop, whether the natural growth on a virgin or long-fallowed soil, or a previous sugar-cane crop, or a green-manure crop, is ploughed out as weather and other circumstances permit, any time from about July onwards. Sometimes if necessary the soil is ploughed again in a direction at right angles to the first ploughing; or it is harrowed after an interval of time that the agricultural experience of the planter tells him is the optimum to ensure the maximum pulverizing effect on the large clods of earth turned up by the plough. Either a drag-harrow or disk-harrow, or both, may be used. It is at this stage that soil-improving materials such as filter cake, Karoo or other kraal manure, or compost should be applied and worked uniformly into the soil.

When the time for planting cane approaches, which should be after the first good spring rains, usually from September to November, the land is furrowed into lines 4 feet 6 inches to 5 feet apart, using a ridging plough for this purpose making furrows about 8 or 9 inches in depth. The cane should be planted within a few weeks of this operation, before much renewed weed growth has taken place and before the furrows have caved in.

The cane for planting should be about a year old and of healthy and vigorous growth. It is laid in the furrow in a single continuous line and cut into short lengths of about 9 or 12 inches, each containing three or four buds. Superphosphate is usually applied at this stage, and the cane is then covered over with about an inch of soil. A recent improvement in practice is to dip the cut ends of the sett into a suitable fungicidal solution which prevents the ingress of injurious fungi; this results in a great increase in germination especially when soil conditions are unusually dry or excessively wet.

Sugar-cane is harvested in Natal usually about two years after planting during the period May to December and is cut by hand. Many attempts have been made to devise suitable mechanical harvesters, so far without success except under special local conditions. The average yield of cane in South Africa is about 60 tons per morgen, but varies considerably in different soils and districts; this is equivalent to a yield of about 7 tons of sugar per morgen. After harvesting the cane there is a covering of tops and leaves on the field, unless the cane was burned before harvesting. The usual practice is to rake this trash, as it is called, into the spaces between alternate rows. The exposed middles are then cultivated to bring the soil into a good state of tilth to absorb water with as little run-off as possible. At this stage or at similar later cultivations fertilizer is added, and if of a phosphatic nature and therefore subject to fixation, must be thoroughly worked into the soil.

The following crop, known as first ratoons, soon begins to appear and is treated as the first or plant cane crop, being cultivated as often as required to destroy weeds, and is harvested within eighteen to twenty-four months. This process is repeated several times, the average number of crops from the original planting being three to four, according to general conditions. After the second cutting the crop generally begins gradually to deteriorate, making it necessary eventually to plough out the old roots for a fresh crop cycle of green fallow followed by cane.

Fertilization and Liming of Sugar-cane

This has been referred to in previous paragraphs, and general practice may now be conveniently summarized.

The soils of the Natal coast with very few exceptions are, like the great majority of South African soils, originally very deficient in phosphorus. In many sugar-cane soils, however, this natural deficiency no longer exists since the soils have been liberally treated with phosphatic fertilizers for many years. Nevertheless, it is shown by experiment and experience that a dressing of 1,000–1,200 lb. per morgen of superphosphate needs to be applied when planting cane to get the maximum yields of cane. In some cases it is necessary to apply a lesser quantity of superphosphate, say 600 lb. per morgen, to the ratoon crops or at least to the later ones, but in other soils there is no response in the ratoon crop provided the necessary application was made to the plant cane crop.

No other phosphatic fertilizer has been found as profitable as superphosphate; thus rock phosphate and superphosphate and rock phosphate mixtures are not as beneficial as an equivalent quantity of superphosphate; the same applies to phosphates in bone form and to basic slag and the like. Similarly ammonium phosphates of various grades have been found inferior to equivalent mixtures of superphosphate and ammonium sulphate.

Nitrogen is another very important fertilizer element with sugar-cane, and it has been established that in normal times when ammonium sulphate is the cheapest form of nitrogen, an application per morgen of 800 lb. of

ammonium sulphate containing 160 lb. of nitrogen is usually the most profitable application of nitrogenous fertilizer to the plant cane or ratoon. However, as already stated, where a leguminous green-manure crop has been turned into the soil before planting cane, there is no response to nitrogenous fertilizer in the following plant cane crop. Sodium nitrate and ammonium nitrate mixed with calcium carbonate as in 'nitrochalk' are equally effective with ammonium sulphate per unit of nitrogen, but are in normal times more expensive.

Certain large sugar estates, using large numbers of oxen or mules for transport purposes, have adopted a practice of making compost on a large scale using stable manure, cane trash, and filter cake with evidently very successful results. It remains to be proved, however, whether this practice, especially on the much more numerous small estates, is more economical than the direct application of all available manures to the soil.

In many sugar-growing countries nitrogenous fertilizers must be applied to the soil with great discrimination, since there is a tendency for the ripening of the cane and consequently its sugar content to be unduly delayed. This, however, does not occur in South Africa, where the normal dry and cool winter season promotes thorough maturity of the cane. Incidentally for the same reason the sugar content of the cane in South Africa is considerably higher than in most tropical countries.

It should be noted that if inorganic nitrogenous fertilizers such as ammonium sulphate be used for the plant cane crop, it should not be applied until the cane is several inches high. The reason is that the cane plant cannot utilize it until it has developed its own root system independently of the parent sett on which it depends for nutriment until that stage; and soluble nitrogenous fertilizers applied at time of planting may therefore be leached from the soil before they can be utilized, contrary to superphosphate which soon becomes fixed in the soil near its point of application.

Little mention has yet been made of that very important fertilizer element, potassium. Fortunately most of the soils of the Natal coast are well supplied by nature with this element, though not always in a high proportion of available form, that is to say, soluble in dilute citric acid and therefore presumed to be immediately assimilable by the plant roots. Reserve supplies of potassium may be made gradually available by good cultivation, green manuring, the application of other fertilizer materials, &c., but it may be in rather exceptional cases profitable to apply soluble potassium compounds such as muriate of potash in applications of from 160 to 320 lb. per morgen, usually mixed with whatever other fertilizer is being applied.

Sugar-cane tolerates the chloride ion in the soil in moderation fairly well, so that there is no advantage in using the more expensive potassium sulphate, where the need for potassium is indicated. Although, as stated, sugar-cane takes up relatively large quantities of potassium, little of which finds its way back to the soil, there is no indication of any general shortage of reserve potassium in most Natal soils for many years to come.

Sugar-cane is tolerant of a fairly wide range of soil acidity, so that there appears to be little advantage in liming soils of a pH not lower than about 5·0. Up to the present, experiments in liming sugar-cane soils have been largely negative, but more work needs to be done on the more acid soils. Lime is used in large quantities in the clarification of sugar-cane juices in the factory, and much of this lime finds its way into the filter cake which, as stated above, contains about 25,000 tons of calcium carbonate per crop, nearly all of which is returned to the soil though not necessarily to the ones that require it most. However, with the prospective increased use of ammonium sulphate, with its acidifying effect in the soil, the matter of soil acidity may need to be more closely watched in future, and steps taken to deal with it where necessary, either by the periodical use of nitrogenous fertilizers having a basic residual effect, such as sodium nitrate, calcium cyanamide, nitrochalk, or the like, if these fertilizers come to compete economically with ammonium sulphate; or alternatively it may become necessary to apply agricultural or hydrated lime to the soil in addition to the lime already conveyed by means of the filter cake. However, that time is not yet, and indeed may never occur.

CHAPTER XXXIV

THE MANURING OF SPECIFIC CROPS (*cont.*)

MANURING OF ORCHARDS AND VINEYARDS

OUR knowledge of orchard manuring and, to a lesser extent, the manuring of vineyards is still very limited, not only in South Africa but throughout the whole world. This uncertainty in connexion with manurial requirements is due to a number of reasons, the most important of which will become clear if we summarize briefly the main differences between fruit-trees (and vines) and annual crops.

Differences between fruit-trees and field crops

1. It is much more difficult to carry out fertilizer experiments with fruit-trees than with field crops. The most important reasons for this are that a large orchard area has in the past been necessary for an experiment because trees stand far apart and individual trees differ widely in growth and yield; that a single experiment may last for years and therefore it is unlikely that any private orchard would be available for this purpose; that the harvesting of the fruit in the experiment is an intricate business because it may extend over several weeks and requires expert supervision.

2. The growth of the trees depends mainly on the physical nature of the soil, its depth, and a favourable water-supply as will be discussed under Prerequisites for a favourable response to fertilization. Moreover, the climatic factors, temperature, and humidity of the air are also of vital importance in this connexion. Naturally these soil and air conditions also play an important role in connexion with field crops, but because fruit-trees are a so-called permanent crop, i.e. a crop that occupies *the same piece of ground* for a lengthy period, these factors are of special importance in their development.

3. The bearing of trees, i.e. the fruit crop, is only partially dependent on soil fertility and is determined by the temperature and humidity of the air during certain critical periods, viz. during the winter months (deciduous fruit), at the time when fruit buds are being formed, when the trees blossom, and when the fruit sets. Provision for cross-pollination, methods of pruning, thinning of fruit, and in the case of many fruit varieties that tend to produce heavy crops in alternate years, the crop of the previous year may also affect the yield. In the case of field crops there is usually a relatively fixed ratio between vegetative growth and seed or root (tuber) yield.

4. Vines and most fruit-trees are propagated on foreign stocks. Different root stocks will behave differently in connexion with root depth, root development, ability to utilize plant food, &c., therefore individuals of one and the same fruit variety, grafted on different root stocks, may differ widely in growth and yield. In the past the choice of root stocks, especially in the case of deciduous trees, has been very haphazard. The result is that trees of one variety may exhibit wide variations in yield and growth even on a uniform orchard soil.

5. The quality of the crop, i.e. of fruit and grapes, determines to a much larger extent its market value than is the case with field crops. The quality of the fruit crop can be influenced only partially by manuring. Climatic factors, which are so important in deciding the quantity and quality of the crop, are never exactly the same in two successive years. It is, therefore, impossible to prescribe minimum margins or quantities for essential nutrients that will ensure a maximum yield of the highest quality.

6. In the case of field crops nearly all aerial portions are annually removed from the land. This permits a fairly accurate calculation of the amount of plant food which is removed from the soil by the crop. In orchards and vineyards relatively little plant food beyond that which is in the fruit crop is removed from the soil, and fruit crops may fluctuate considerably from year to year. The leaves, which contain the largest portion of the plant nutrients, are returned to the soil unless they are blown away from the orchard or vineyard. The thinner prunings also remain in the orchard and vineyard or the prunings may be used in drains or may be burnt and the ash returned to the soil. Therefore, once the orchard or vineyard soil is relatively rich in plant food the level of fertility can be maintained at relatively low cost.

PREREQUISITES FOR A FAVOURABLE RESPONSE TO FERTILIZATION

Certain requirements must be met before one can expect money, spent on fertilizers, to be a sound capital investment. These conditions under which fertilizers will have maximum effect naturally apply to all agricultural crops. But, because fruit-trees and vines, as permanent crops, differ from field crops, these conditions obtain especially for them. Much money can be wasted on fertilizers if these prerequisites are not taken into due consideration.

1. Fruit-trees and vines require soils with a favourable physical composition and of sufficient depth. There should be sufficient root space for the trees. Therefore trees should not be planted too close together and, at least, the first 4 feet of soil should not contain impervious layers such as *ouklip* (iron-stone), solid rock, or heavy potclay. If the soil below the 18-inch to 2-foot layer is very gravelly or stony it may still be suitable for trees, provided it can be irrigated, especially when the trees start bearing. If this is not done the trees will suffer from drought and die back. The same 'physiological disease' appears when the soil is shallow and contains layers that are impervious to roots and water. Money spent on fertilizers that are applied to such orchard soils is wasted. Consequently fruit growers should pay special attention to the selection of the orchard soil in order to obviate disappointments and heavy, futile expenses.

2. The water relationship in the soil should be as favourable as possible. On the one hand, one should guard against stagnant water in the root zone and, on the other hand, one should see that the trees do not suffer from excessive lack of moisture.

The roots of trees respire even when the trees are dormant and without

leaves. Thus stagnant water in the root zone during the winter months will cause the deeper roots to die off. Hence the phenomenon that fruit-trees and vines which are subject to 'wet feet' in winter are the first to suffer from drought during the summer months. A high water table is equally harmful during the growing period of trees and may cause sour sap and chlorotic and other disease symptoms. Moreover, stagnant water is at all times as effective a barrier to the downward growth of roots as a solid rock layer. Valley soils and soils containing substrata that are impermeable to water are specially subject to temporary waterlogging and in these cases effective drainage is essential.

Of much greater importance, generally speaking, is an adequate supply of soil moisture during the dry periods. These occur during the summer months in the Western Cape Province, where deciduous fruit-trees and

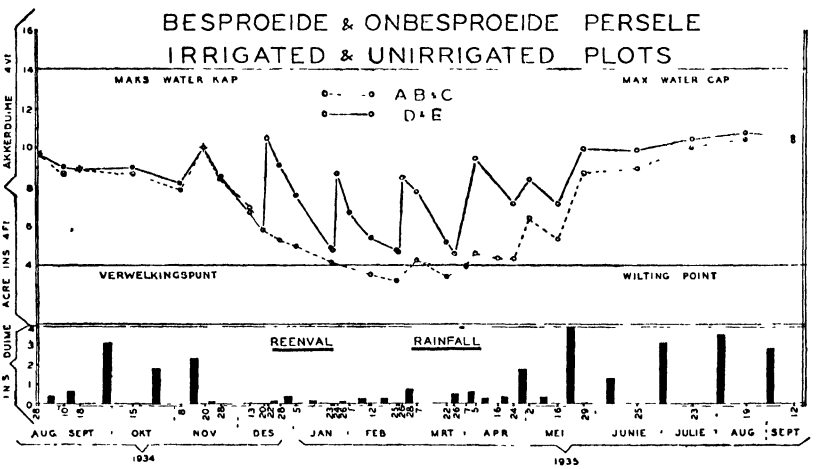


FIG. 21. Moisture curves in an orchard soil, Stellenbosch.

vines are grown, and in the winter months in the summer-rainfall area where it is citrus fruit-trees which are particularly affected. In connexion with *deciduous fruit-trees and vines* in the winter-rainfall area, the following points are of importance:

1. At the beginning of spring, orchard and vineyard soils should be saturated to their field capacity to a depth of 3–4 feet. At the most this would mean that such a soil has an available moisture supply which is equal to about 6–10 morgen inches. On sloping land especially, the measures discussed in Chapters XVI and XVII under 'Control of Soil Moisture' and 'Dry-land Farming' should be adopted as far as possible. By means of contour furrows and a cover crop, appreciable run-off of rain-water could be prevented and a thorough moistening of the subsoil during the winter months would result. During the summer months the orchards should be free from weeds and at least those soils which crack on drying out should have a soil mulch.

The first intensive study[1] of water relations in an orchard soil was conducted during 1934 and 1935 on the Welgevallen experimental farm, Stellenbosch. This study proved clearly that deciduous fruit-trees and vines, even in good, deep soils and in years with a favourable rainfall, have to endure a wilting stage. This wilting stage has a very harmful effect on the growth of the trees as well as on the development and quality of fruit (and grapes). In Fig. 21 the *average* moisture contents during the year 1934-5 are given for the three unirrigated plots A, B, and C and for the two irrigated plots D and E. The moisture contents are calculated as acre inches in 4-foot deep soil.

The maximum water capacity is 14 acre or morgen inches and was determined in the laboratory. The field capacity was actually slightly lower, about 12 morgen inches, as can be seen in the figure. The wilting-point is at approximately 4 morgen inches,[2] which means that in a 4-foot soil layer 4 morgen inches of moisture is unavailable to plants. Therefore, this sandy loam with about 16 per cent. clay cannot retain more than about 8 morgen inches of available moisture. The rainfall and its distribution are indicated at the bottom of the figure. On the plots there were 18-year-old pear- and plum-trees, planted approximately 18 feet apart.

In 1934 good rains fell towards the end of September and October and in the middle of November with the result that on 20 November the top 4-foot layer of the orchard soil was saturated almost to its field capacity. Such good rains occur in November only once every three or four years. From December till the end of April the precipitation was very low, and of no value in moistening the deeper soil layers. On the unirrigated plots the trees were in a wilted condition from the end of January to the end of April, and even in the first half of January the trees started showing signs of drought. The observation that the moisture curves are sometimes lower than the wilting-point is due to the fact that the top foot of soil becomes considerably drier than the wilting-point, and the moisture figure is the average for the entire 4-foot layer.

Soil samples were continually taken to a depth of 4 feet, with the Veihmeyer tube, and the soil moisture at the different depths determined. According to this it became clear that during the above summer months it was necessary to irrigate the soil four times (20 Dec., 24 Jan., 26 Feb., 1 April) and about 4 inches was given every time by the basin method. Each irrigation was given when the moisture content was still about 1 morgen inch above the wilting-point. The diagram shows clearly how the moisture content in the root zone drops almost to the wilting-point within a month.

The difference in the growth of new wood, between irrigated and unirrigated trees, was remarkable. While the unirrigated trees showed no

[1] P. E. le R. van Niekerk, *Moisture Studies in an Orchard, Stellenbosch.* Thesis for M.Sc. Agric. degree, Dec. 1935.

[2] According to usual determinations *by weight* the field water capacity is 16 per cent. and the wilting-point 5·3 per cent.

growth from the beginning of January onwards, the shoots of irrigated trees increased in length as well as in thickness until autumn. The premature colouring and leaf-fall of the unirrigated trees was also very noticeable, whereas the leaves of the irrigated trees only started colouring in May and shedding occurred within ten days during the beginning of June.

That water shortage is a serious problem in many orchards and vineyards of the Western Cape Province has been known for a long time, and this shortage is felt especially in the case of prune-trees. Dry tips and dying back of the leading branches are typical symptoms, and this trouble is responsible for the fact that so few prune orchards are to-day found in this area on unirrigated land. However, this study proved for the first time with actual figures, how serious this problem is.

It is easy to realize that also the fruit crop suffers if trees are subjected to water shortage. It has been found that in areas where the winters are dry it is essential that fruit-trees should be thoroughly irrigated a few weeks before they start blossoming. If irrigation is postponed till blossoming time new growth in trees is stimulated to such an extent that practically all the young fruit drops off. Again, a shortage of moisture at the time when the stones are formed affects especially the size of fruit. This often happens in the winter-rainfall area except in the case of early varieties which ripen as early as November and December. Irrigation experiments have proved that also in later developmental stages a shortage of water has a marked effect on the size of fruit. If we bear in mind that, in general, small-sized fruit are also uneconomical fruit, it is easy to realize how very important it is that fruit-trees should at all times receive sufficient moisture.

Also the eating and keeping qualities of fruit are detrimentally affected by drought. On the other hand, at the ripening stage (picking time) water should be applied judiciously because if the soil is too wet at picking time the keeping quality of the fruit is definitely impaired. It is very desirable that the moisture content of the soil should approach the wilting-point at picking time. In other words, the specific fruit variety should be irrigated two to three weeks before picking time and subsequently, if necessary, only after the crop has been removed.

Splitting of the berries of some grape varieties as a result of heavy irrigations at the wrong time seems to occur especially if the vines have previously suffered from drought, although it is also influenced by other climatic factors. The dropping of berries and drying of grapes have also been proved to be due largely to the vines having suffered from water shortage at the time the grapes were picked.

As a result of irrigation in orchards and vineyards the crop ripens approximately a week later than it does under dry-land conditions, and this is an important economic aspect. As yet no means has been discovered to eliminate this disadvantageous effect of irrigation. If the weather remains dry after the fruit crop has been harvested it is essential that irrigation should be carried on. This enables the wood to ripen normally and the

trees and vines are thus able to store a sufficient food reserve (starch and protein) in the wood. This reserve food is very important in connexion with the setting of young fruit or berries in the following spring. The opinion is often expressed in connexion with irrigation, that once an orchard or vineyard has been irrigated the tree-water relationships are upset with the result that frequent irrigation becomes essential. This is only the case if a light, i.e. a shallow, irrigation is given, the deeper soil remaining at the wilting-point. It is obvious that only the roots in the topsoil would then be stimulated to grow and consume moisture, and that after a light irrigation the trees would very soon again 'cry out' for water. Therefore, care should be taken to moisten thoroughly the complete root zone down to at least 3 feet every time the soil is irrigated.

More detailed advice on the irrigation of deciduous fruit-trees in the Western Cape Province will depend on the circumstance that water requirements vary widely according to the locality, soil type (depth and texture), size and spacing of the trees, and on the rainfall during the summer months. Probably an irrigation of 6–16 morgen inches, i.e. 2–4 irrigations of 3–4 morgen inches each, is essential in the majority of orchards and vineyards.[1] In most years the first irrigation will be required during December, depending on the rainfall during November and December. If the monthly precipitation does not exceed at least one good shower of over 1 inch, one will have to irrigate, on an average, every four weeks from December onwards. Every irrigation should be thorough so that the soil is moistened to its field capacity to a depth of approximately 3 feet. Every farmer should plan to have more irrigation water at his disposal for his orchards and vineyards than has been the case in the past.

In the case of citrus groves, trees have a considerably higher water requirement than deciduous trees, because citrus-trees are evergreen with the result, naturally, that they transpire actively throughout the year. Therefore, citrus orchards in the winter-rainfall area have to be irrigated regularly during the summer months, but because citrus-trees are chiefly grown in the summer-rainfall region we shall limit our discussion to this region.

The Division of Plant Industry, now Horticulture, has been conducting water studies in citrus orchards at Nelspruit, Eastern Transvaal, since 1933 and the first scientific data on this subject, in South Africa, were published in 1937.[2] The results of this study prove clearly that the method of irrigation with straight furrows, in this case four furrows in each row, as was applied in these two orchards, is very unsatisfactory. The soils were under constant investigation to a depth of 4 feet and it was found that 40–60 per cent. of the root zone—depending on the soil type—was not moistened at

[1] Complete data for the different localities may, to-day, be obtained from the Western Province Fruit Research Station, Stellenbosch.

[2] D. J. Esselen, 'Citrus Irrigation Practice with Special Reference to Studies of Moisture Content in Two Orchards in Eastern Transvaal', *Scientific Bulletin*, No. 159, Pretoria, 1937.

all and remained at the wilting-point during the six dry winter months. Thus it is evident that the tree cannot use all its roots to their full effect, and that the plant nutrients in the soil are utilized only partially.

As far as the water-supply itself is concerned it is true that all the aerial parts of the tree receive water (and actually also the roots in the drier soil) even if only, say, half of the root zone is moistened. However, there are sufficient data to prove that such a tree, especially during critical periods such as blossoming time and when the fruit starts ripening, does not receive sufficient moisture in this way. It has also been proved that the translocation of plant nutrients under such conditions is very unsatisfactory.

Therefore, the orchard soil should be irrigated in such a way that the complete root zone is moistened. This may be effected by a modified furrow system with zigzag lateral furrows between the trees, or by the basin method or by a combination of the two. On the other hand, over-irrigation should be strictly avoided because it causes a loss of moisture and plant nutrients. Furthermore, citrus-trees are especially sensitive to 'wet feet' and the trees suffer for a long time from the harmful effects of over-irrigation.

In regard to root distribution, it was found in the two soil types at Nelspruit, a sandy loam and a sand, that approximately 56 per cent. of the root system of 10-year-old trees is distributed throughout the 7–24-inch soil layer and the remainder in the third and fourth foot of soil. In connexion with the water requirement of citrus-trees it was found that during the six dry winter months, May to October, about 8 morgen inches of water are required for transpiration. The trees are planted on the square system 25 feet apart. This determination was made in orchards where only about 50 per cent. of the root zone was kept moist and where the trees definitely suffered from drought for a few short periods. In the case of 100 per cent. moistening of the root zone the transpiration figure will certainly be slightly higher. If we take into further consideration that only about 50–60 per cent. of the irrigation water is actually available to trees—the remainder is lost by evaporation and percolation—it means that at least about 16 morgen inches of irrigation water will be required during the winter months because the rainfall may be left out of account. Three to six irrigations, each of 5 to 3 morgen inches, should be given according to the field capacity of the particular soil.

During the six summer months, November to April, the average rainfall in the Eastern Transvaal is about 24 inches, and although transpiration requirements during these months are considerably higher than 8 inches, the rainfall is considered to be sufficient and irrigation is seldom necessary. In the Sundays River valley,[1] the rainfall is quite insufficient even in summer and it has to be supplemented with several irrigations.

[1] For detailed data see Dr. J. J. Theron, *Alkali and Irrigation Studies with Citrus Trees in the Sundays River Valley*, University of Pretoria, Publication No. 40 (Agricultural Series), 1937.

At times the rainfall in the Transvaal may be too high during the summer months, causing excessive wetness in the deeper subsoil and leaching of plant nutrients. Therefore, the growing of a green-manure crop is strongly advocated in such cases in order to maintain soil fertility, utilize the superfluous water, prevent soil erosion, and maintain the humus content of the soil. For the same reasons it is necessary, in the Western Province, to grow a cover crop in orchards during the winter months.

Finally, we must mention in connexion with the Nelspruit data that development of fruit not only stops when the moisture content in the entire root zone has reached the wilting-point, but there is also a considerable decrease in the size of the oranges when trees suffer from drought for a week or so. In such a case the leaves draw on the fruit for moisture for transpiration. This fact can be demonstrated very well by removing two equally sized branches, with half or three-quarter developed oranges on them, from a tree and removing the oranges from one branch. If the branches are left in two vases in a room it will be noticed that the leaves on the one without oranges wilt much sooner. The circumference of the oranges can also be measured before and after the leaves start wilting and it will be found that the oranges have decreased considerably in size.

3. The humus content in orchard and vineyard soils should be maintained at as high a level as possible. In a soil that is rich in humus, water relationships will be more favourable. Many of our orchard and vineyard soils are very sandy and can only retain a small portion of the winter moisture. Humus increases the water-holding capacity, thus strengthening one of the weakest links in fruit production. In the case of clayey soils addition of humus will increase their absorptive capacity for rain and irrigation water and thus the subsoil is moistened more effectively. Because humus facilitates the formation of a crumb structure in such a soil the improved aeration will enhance root respiration and microbial life. This brings us to another important function of soil humus. Humus supplies organic food for microbes and consequently the greater production of carbonic acid will release more available plant food, and the fertilizers that are applied will be rendered available more quickly in a soil that is rich in humus than in a soil that is deficient in humus.

Farm manure is relatively scarce on fruit and wine farms and therefore a green-manure crop should be grown in the orchards and vineyards during the winter months and ploughed or disked under towards the end of winter in order to maintain the humus content to a certain extent. This is possible throughout the winter-rainfall area. Where a green-manure crop of *gousblom* (Cape weed), crane's bill, or other weeds does not grow of its own accord, a legume such as peas or lupins or a non-leguminous crop such as rye may be sown during April–May. Apart from its manurial value as a green-manure crop the cover crop prevents plant nutrients, especially nitrate nitrogen, from being leached from the soil. The green-manure crop, especially if it has a tap-root system, aids in opening up the plough-sole and the more compact subsoil, improving its permeability to water because

the deeper roots die off after the crop has been ploughed under, leaving channels through which water and air can move more freely.

A very important point in connexion with the green manuring of orchards and vineyards is that the green-manure crop should be ploughed under at least four to six weeks before the trees start blossoming or the vines put forth their new growth. This allows sufficient time for the organic matter to undergo its initial quick decomposition after which nitrate nitrogen appears in the soil again. It is also necessary that the soil should receive a few good showers of rain after the plant material has been ploughed under in order that the soil may be restored to its natural structure and may have a favourable moisture content when the growing season commences.

As far as green manuring in citrus orchards is concerned, the green-manure crop is grown during the winter months in the winter-rainfall area. Undoubtedly this is the best time of the year for citrus-trees as well because during this time the trees require little nourishment as the fruit is ripening. In this area peas or lupins can be grown for green manuring if there is no *gousblom* or other weeds. However, in the summer-rainfall area water is too limited and the choice of legumes that can be grown is also very limited. That is why the green-manure crop is grown during the rainy months of summer.

Bearing in mind the nutritive requirements of citrus-trees, citrus groves should be free from weeds or any other cover crop, i.e. clean cultivated, up to about January when a green-manure crop may be grown. Indian sunn hemp is an excellent crop for this purpose because it grows quickly, yields a large amount of vegetable matter and nitrogen, and possesses no climbing propensities. It is difficult to plough under fresh sunn hemp. The best method is to put a roller over it and leave it for a few weeks, during which time it will decay somewhat. Phosphatic and potassic fertilizers, if required, are then broadcast and everything is ploughed under. This takes place during March or April. The best time for the green manuring of citrus orchards in different parts of the summer-rainfall region is a question that has still to be investigated.

4. The soil should be chemically suitable for the growing of trees. Strictly speaking, the essential plant nutrients fall under this heading but they will be discussed under manuring. We have here in mind the soil reaction and brackishness (salinity) of the soil and the presence of harmful chemical substances. A few instances have occurred in the Western Cape Province where an excessive amount of manganese compounds has harmed the growth of trees or has even rendered their growth impossible. However, in some fruit-producing areas the shortage of manganese and other trace elements is of greater importance. This has already been discussed (p. 32).

As far as the soil reaction is concerned it seems that the majority of fruit-trees and vines prefer a slightly acid reaction and we can consider a pH between 6·0 and 6·5 to be the most favourable. If the pH is lower than

4·5, fruit-trees, especially orange-trees, seem to grow very unsatisfactorily even if the soil is heavily manured. Thus it is essential, not only for the growth of trees and the quality of fruit, but also in connexion with the availability of fertilizers that are applied to soils, that soils with a pH below 6·0 should be limed periodically. Alkaline soils are not suitable for most fruit varieties and for American vine root-stocks—the trees suffer from chlorosis—but fortunately such soils occur very seldom in the real fruit-producing areas. The same holds good for brackish soils. Fig-trees (and date-palms) are amongst the few fruit-trees that will grow well on brackish soils.

THE MANURING OF ORCHARDS AND VINEYARDS

From the above discussion it will be clear why opinions vary widely about the most suitable quantities of plant nutrients that are to be applied annually to orchard and vineyard soils. The effect of manures on the growth and yield of fruit-trees cannot be observed readily within one year. The most striking effects are to be seen in the case of heavy dressings of nitrogen because this plant food affects vegetative growth in particular. But even here we may find that effects are often delayed. For example, certain plots in an orchard on the Experimental Farm, Stellenbosch, had received no nitrogen for a period of fifteen years and the difference in yield and growth between these trees and the trees which received a good application of nitrogen annually was hardly noticeable. Only the growth of *gousblom* during the winter months has in latter years been considerably weaker on the plots that received no nitrogen (see Plate IX*a*). The soil contains relatively little nitrogen (topsoil 0·075 per cent. and subsoil 0·025 per cent. in 1919) but it is a deep alluvial soil that is tilled efficiently. Irrigation experiments conducted during 1934–5 on these plots proved clearly that water shortage during the summer months was the main reason for the poor response to nitrogen.

In order to get some idea of the quantities of plant nutrients which are removed from a morgen of soil by a fruit crop, the following table may be consulted. The composition of fruit, like any other plant product, fluctuates considerably and these figures should only be looked upon as averages.

TABLE 25

Removal of Plant Nutrients by Fruit Crops

Yield per morgen	*Nitrogen*	*Phosphoric oxide*	*Potash*	*Lime*
	lb.	lb.	lb.	lb.
12 tons stone-fruit (peaches, apricots, plums)	40·0	18·0	83·0	4·5
16 tons apples and pears	31·0	10·0	44·0	4·8
10 tons grapes	30 0	10·0	55·0	5·0
20 tons oranges	73·0	21·0	85·0	39·0

If we take into consideration only the plant nutrients removed by fruit crops, it follows from the preceding table that stone-fruit, apples, and pears and grapes have approximately the same nutritive requirements and that the requirement of citrus-trees is considerably higher. Before making general recommendations it is necessary that we should outline briefly the effects of the three major plant nutrients on fruit-trees, as they are known at present.

As in the case of all other plants, *nitrogen* stimulates vegetative growth, i.e. shoot and foliage, but it is also very necessary for the formation of flower buds. It is only when there is very little phosphate and potash and an excess of available nitrogen that trees fail to bear fruit and only produce vegetative growth. Provided there is no lack of soil moisture, a good nitrogen supply will greatly enhance the size of fruit and grapes. However, to prevent fruit from ripening too late and being of inferior keeping quality, ample phosphate and potash should be applied in such cases. Some grape varieties such as Hanepoot and Rosaki show a poor fruit setting when the vines have too much available nitrogen at their disposal; in other words, they form too straggly bunches. Thus, in the case of these varieties, it is advisable to give a certain portion of the nitrogen by way of a top dressing after the berries have set. In the case of fruit-trees, especially citrus, it is maintained that a large supply of available nitrogen at blossoming time will prevent excessive dropping of young fruit.

Whereas authorities previously thought that in the case of fruit-trees that tend to bear every other year only, no nitrogen should be applied during the year in which the tree is not bearing, it is now recommended that in the year when very little fruit is borne much nitrogen should be applied in order that more 'vegetative' wood and fewer flower buds should be produced. Heavy thinning of fruit in those years in which the trees bear heavily will also encourage more regular bearing.

The fruit crop uses relatively little *phosphate*, but because our soils are so very deficient in phosphates, considerable quantities of phosphate should be applied at the outset to orchard soils. Fertilizer experiments on both orange-trees and deciduous fruit-trees including vines, proved beyond doubt that applications of phosphate greatly influenced the yield of trees and the quality of the fruit.[1] Once the soil is well supplied with phosphate, small annual applications only will be necessary because the fruit crop removes very little phosphate from the soil.

Potash is used in relatively large amounts by fruit, and therefore care should be taken that orchard and vineyard soils are always well supplied with potash. As a rule, South African soils contain a considerable amount of potash, but on sandy soils especially it is necessary to apply potash, particularly in the winter-rainfall area. In Chapter IV we saw that potash is indirectly responsible for the formation of sufficient sugars and protein

[1] Fertilizer experiments in the Transvaal showed that a high phosphorus content in the sap of oranges is responsible for a low acidity and a thin peel.

in plants, that fertilizing exclusively with potassic fertilizers increases the acidity of fruit, and that, for this reason, soils should contain sufficient phosphate. Finally, if plants have sufficient potash, transpiration is reduced somewhat and leaf-scorch is not prevalent in warm, dry weather.

Taking into consideration the foregoing data and soil conditions in South Africa, the following general manuring formula in terms of available plant nutrients for bearing, *deciduous fruit-trees and vines* can be recommended for annual application per morgen:

40–80 lb. Nitrogen = 200–400 lb. Sulphate of ammonia.
50–140 lb. Phosphoric oxide = 300–800 lb. Superphosphate or Basic slag.
100–200 lb. Potash = 200–400 lb. Sulphate of potash.

The rate of nitrogen application will depend on the size of the crop, the depth of the soil, and its water-supply. The nitrogen requirement may also be judged by the growth of the trees. A large proportion of phosphate is applied during the first three to six years of the growth of the trees, after which a smaller quantity may be given. Unless orchard and vineyard soils are limed periodically, it is essential for maintaining the residual effect of phosphatic fertilizers on acid soils that basic superphosphate or basic slag should be applied instead of ordinary superphosphate. The higher amount of potash is applied to orchards and vineyards that yield heavy crops or that yield fruit or grapes of inferior quality in spite of heavy applications of phosphate.

It is essential in the winter-rainfall area to have a green-manure crop in orchards and vineyards during the rainy months. Thus phosphatic and potassic fertilizers are applied in autumn (April) in order to ensure a better green-manure crop. When a legume is grown it is not necessary to apply extra nitrogen before the trees start blossoming. In other cases the nitrogenous fertilizer is applied when the cover crop is ploughed under. If a nitrate fertilizer is applied it is better first to plough in the cover crop and then to apply the nitrogen during the first half of September, after which the soil may be harrowed and cultivated. In the summer-rainfall area, orchard soils should be kept as free as possible from weeds during the actively growing period of the trees. A few weeks before the fruit starts ripening weeds may be allowed to grow, and this weed growth may then be ploughed in at a suitable time, late in autumn or during the winter months together with fertilizers.

Naturally, farm manure together with a phosphatic fertilizer is excellent for orchard and vineyard soils, especially where cover crops do not grow of their own accord. About 10 tons of ordinary farm manure or 4 tons of karoo manure per morgen may be applied every third year.

Citrus-trees require considerably more nitrogen than deciduous fruit-trees and in other countries enormous quantities are sometimes applied per morgen. Fertilizer experiments in South Africa also showed that nitrogen applications are very essential, but as far as the annual requirement is concerned we have not yet very reliable information. The following formula

may act as a general guide (quantities of available nutrients per morgen):

100–200 lb. Nitrogen = 500–1,000 lb. Sulphate of ammonia.[1]
50–140 lb. Phosphoric oxide = 300–800 lb. Superphosphate.
100–200 lb. Potash = 200–400 lb. Sulphate of potash.

In the winter-rainfall area, citrus orchards are manured at the same time of the year as deciduous fruit-trees and a green-manure crop is also grown in the winter months. If the growing of a green-manure crop is impossible, perhaps because the soil is shaded excessively, farm manure should be applied regularly in the winter months in order to maintain the humus content of the soil at a high level. In this case the smaller amount of the nitrogen application is given before the trees start blossoming. The humus content of the soil is of such great importance because citrus orchards have to be irrigated regularly during the dry summer months and the soil absorbs and retains water more readily if it is well supplied with humus.

In the summer-rainfall area, citrus orchards should preferably be kept free from weeds from blossoming time until about January, and then a green-manure crop should be grown.

If a good leguminous green-manure crop is ploughed under, the smaller quantity of nitrogen need only be applied and this is incorporated with the soil about fourteen days before blossoming time. As far as the rate of phosphatic and potassic fertilization is concerned, the remarks made under deciduous fruit-trees apply also in this case.

In South Africa when planting young trees and vines, it is very essential that the deeper soil in the case of holes for trees, or the bottom trenched soil in the case of vineyards, should receive an adequate application of a phosphatic fertilizer because this is the only opportunity to enrich the soil directly underneath the trees in this nutrient. Because, especially in this case, it is essential that the phosphatic fertilizer should remain available for many years, a basic phosphate such as basic slag or basic superphosphate or even rock phosphate, should always be used on acid soils. When trees are planted half a basket to a basketful of well-rotted manure can be mixed, together with the phosphate, with the deeper soil in the hole. To avoid any possible scorching this application should be given two to four weeks before the trees are to be planted.

Under 'Prerequisites for a favourable response to fertilization' we laid special stress on the water economy in orchard soils, but there is one more requirement which we have already mentioned in passing but now wish to discuss in somewhat greater detail on account of its importance. That is the *depth to which fertilizers should be worked into the soil.* It is customary to incorporate the fertilizers at a time of the year when the soil is ploughed or disked thoroughly. That means that the fertilizer is mixed with the first 6 inches or so of soil. However, tree roots occur mainly in the 7-inch

[1] Recent work by A. J. van der Merwe (Pretoria) proved conclusively that citrus trees are very adversely affected in growth and quality of fruit when the trees are compelled to absorb in preponderance ammonium nitrogen on acid soils of low nitrifying power.

to 3-foot soil layer. As far as the nitrogen is concerned, it does not matter if it is merely worked into the topsoil, provided the soil receives sufficient rain or irrigation water during the actively growing period of the trees. Nitrogenous compounds are finally converted by soil bacteria to nitrates if they are not already nitrates, and the nitrates move downwards together with the soil moisture. However, phosphate and potash compounds behave differently. They remain practically in that soil layer in which they are brought and at most they will move only a few inches downwards. Consequently the largest part of the root system does not benefit by such fertilization. The fact that phosphatic and potassic fertilizers do not move on their own in the deeper soil has been proved by numerous soil analyses abroad and in South Africa, especially in orchard and vineyard soils in the Western Province. The following data were obtained in an orange-grove at Mazoe, Southern Rhodesia.[1]

TABLE 26

Soil depth	*Available phosphoric oxide*		*Available potash*	
	Fertilized soil	*Unfertilized soil*	*Fertilized soil*	*Unfertilized soil*
	%	%	%	%
1st foot	0·0046	0 0007	0·0172	0·0071
2nd foot	0·0008	0 0004	0·0043	0·0028
3rd foot	0·0008	0 0004	0·0039	0 0012

The publication does not mention how far the fertilized soil is situated from the unfertilized and whether the soils are exactly the same in other respects. Therefore we shall not attempt to explain why the subsoil of the unfertilized plot is also considerably poorer than the subsoil of the fertilized plot. However, the fact that the first foot of soil on the fertilized ground is so much richer in available plant nutrients than the second and third foot is remarkable. The difference would have been still greater if only the first 6–8 inches instead of the first foot had been analysed. The available plant nutrient was determined in 1 per cent. citric acid extract.

The question now arises: How can these fertilizers be incorporated with the deeper soil layers in established orchards and vineyards? In vineyards it is an old custom at the beginning of winter to draw furrows of 8–10 inches in alternate rows to be treated to farm manure and phosphate and covered up. A better method which some farmers still follow is to have this material dug into the furrows with spades and forks. Formerly when labour was cheaper, the hole-method was also often used. Square holes, about 20 inches deep, were made in alternate rows between four vines and the manure was put into these holes. If kraal manure is again applied after three to four years, the deep furrows or holes were made in those rows that

[1] A. A. Morris, *Preliminary Investigations into Soil Conditions and Observations in Field Practices on Mazoe Citrus Estate*, Oxford University Press, 1933.

were previously left out. Thus it can be seen that our wine farmers have long realized that manure should be worked deeply into the soil, especially on heavy soil types.

In orchards the custom is to plough or disk manure and fertilizer in to a depth of 6–8 inches. However, in this case as well, one should attempt to work the phosphatic and potassic fertilizers deeper into the soil. In the case of deciduous fruit-trees 12-foot strips of soil in alternate rows may periodically, in winter, be ploughed to a depth of 10–12 inches, when the above fertilizers are applied. The resultant root pruning should not be too serious. In citrus orchards the question is more complicated. Furrows may be dug around the trees, fertilizer and manure put into these, and mixed with the deeper soil with forks. However, at its best this would mean a very unequal distribution of manures in the soil. Working the manure deep into the soil in most of these cases is accompanied by heavy expense. At present two other methods are being tried out abroad and in South Africa. Phosphatic and potassic fertilizers are first dissolved in water and the solution is then either pumped into the deeper soil with special pumps or it is added to the irrigation water which flows in furrows in the orchard for a considerable time. The future will tell how effective and economical these methods are.

In conclusion, we append two tables giving the amounts of plant nutrients removed by agricultural crops and the average composition of fertilizer materials respectively. As far as the removal of plant nutrients by crops is concerned, the morgen yield on which the figures are based is given in every case. Naturally, in the case of higher and lower yields, the figures will be higher and lower respectively. Furthermore, the chemical composition of plants may vary considerably according to soil fertility and general growth conditions. Therefore, even for one and the same yield the figures are not at all constant but they do give us a general indication of the plant food requirements of the different agricultural crops.

TABLE 27

Removal of Plant Food from Soils by Crops

Crop	Yield per morgen	Nitrogen (N)	Phosphoric oxide (P_2O_5)	Potash (K_2O)	Lime (CaO)
	lb.	lb.	lb.	lb.	lb.
Wheat:					
Seed	2,000	38	17	8	1
Straw	3,000	18	6	24	8
Total crop		**56**	**23**	**32**	**9**
Oats:					
Seed	2,000	30	11	10	2
Straw	3,000	24	4	45	10
Total crop		**54**	**15**	**55**	**12**
Maize:					
Seed	3,500	56	21	12	0·5
Stover	5,000	37	7	75	20
Total crop		**93**	**28**	**87**	**20·5**
Potatoes:					
Tubers	16,000	50	22	96	5
Vines	6,000	18	9	50	48
Total crop		**68**	**31**	**146**	**53**
Mangels:					
Roots	30,000	57	21	126	9
Leaves	9,000	27	7	22	14
Total crop		**84**	**28**	**148**	**23**
Virginian tobacco					
Leaves	2,000	88	10	104	100
Stems	700	24	4	34	10
Total crop		**112**	**14**	**138**	**110**
Turkish tobacco:					
Leaves	1,400	28	7	42	40
Stems	600	12	5	14	6
Total crop		**40**	**12**	**56**	**46**
Sugar-cane:					
Total crop	80 tons	**224**	**127**	**300**	**142**
Lucerne:					
Hay	12,000	**312**	**78**	**180**	**300**
Cotton:					
Fibre	1,000	3	1	5	..
Seed	2,000	63	25	22	..
Stems	4,000	102	41	71	..
Total crop		**168**	**67**	**98**	..
Beans:					
Seed	3,000	120	36	36	5
Straw and pods	3,000	45	10	60	30
Total crop		**165**	**46**	**96**	**35**

TABLE 28

Average Composition of Fertilizer Materials (Mixtures excluded)

		Phosphoric oxide (P_2O_5)			
	Nitrogen (N)	*Water-soluble*	*Citric-acid-soluble*	*Total*	*Potash* (K_2O)
	%	%	%	%	%
A. *Nitrogenous fertilizers*:					
Nitrate of soda ($NaNO_3$)	16 0	..	..	.	..
Sulphate of ammonia ($(NH_4)_2SO_4$)	20·5	..	.		
Calcium cyanamide ($CaCN_2$)	18–22	.	.		
Nitrochalk ($NH_4NO_3+CaCO_3$)	15·5	.	.		..
Ammonium nitrate (NH_4NO_3)	33·0	.	..	.	
Urea	46	..	..	..	..
Dried blood	11–12	..	..	..	.
B. *Phosphatic fertilizers*:					
Superphosphate	..	17·1–20·0	.	18–21	..
Basic superphosphate	.	.	14·5–18·0	15–19	..
Basic slag	..	..	16·1–18·0	17–19	..
Raw rock phosphate		..	..	17–36	..
C. *Potassic fertilizers*:					
Muriate of potash	..	..	..	.	60
Sulphate of potash	..	..	..	..	48
D. *Fertilizer materials with two major nutrients*:					
Nitrate of potash (Saltpetre, KNO_3)	14	..	..	..	43–45
Bone-meal (ordinary)	3–4	..	(10–20)	22–24	..
Bone-meal (degelatinized)	0·7–1	..	(24)	30	..
Whale guano	10	..	..	1–2	..
Crayfish meal	6–7	..	.	2	..
Ammophos	11	55	..	..	..
Diammophos	20·5	50	..	..	..
Karoo ash	..	..	..	2–3	8–12
Wood ash	..	..	..	2–3	6–10
E. *Fertilizer materials with three major nutrients*:					
Government guano (bird guano)	±10	±3	±9	±10	±2
Poultry manure (fairly dry)	±4·0	..	..	± 3	±1·5
Kraal manure (Western Province)	±1·0	..	..	±0·40	±1·5
Kraal manure (summer-rainfall region)	±1·0	..	..	±0·50	±2·0
Karoo manure	±1·33	..	..	±1·00	±3·5
Farm compost	±0·55	..	..	±0·25	±0·66
Municipal compost	±1·35	..	..	±1·00	±0·75

INDEX

(The numbers in italics refer to the most important data in connexion with the subject concerned.)

Absorption capacity of soils, 74.
— of cations, 80.
— of heat, 109.
Acidity of soils, 160.
Acid rocks, 45.
— -sensitive crops, 164.
— -tolerant crops, 164.
Act and regulations dealing with trade in fertilizers, 217.
Adco process of compost preparation, 230.
Aeolian soils, 59.
Aeration of soils, 74, 89, *107*, 211.
Aerobic bacteria, 174, 222.
Agate, 40
Agricultural lime, 212.
Air, composition of atmospheric, 105.
—, — of soil, 105.
—, manuring of, 14
—, nutrition of plants from, 11.
Alabaster, 43.
Albuminoids, *see* Protein
Algae in soils, 174
Alkaline brak, 167.
— reaction of soils, 161.
Alluvial soils, 58.
Aluminium hydrate, 79
— phosphate, 204, 210.
Amethyst, 40.
Ammonia, volatilization of, 177, 223.
Ammonification, 176, 223
Ammonium-containing fertilizers, 188
— chloride, 190.
— nitrate, 190.
— sulphate, 188
Ammophos, 190, 289
Anaerobic bacteria, 174, 182, 228.
Analysis, chemical, 153.
—, mechanical, 66
Anions, 79.
Apatite, *43*, 204.
Artificial farm manure, 231.
— fertilizers, 185.
Asbestos, 41, 42.
Ash constituents of plants, 6, 8, 9, 25.
— content of plants, 9, 26.
—, karoo-, wood-, stove-, 207, 289.
Atom, 4, 78, 160.
Augite, 39, *41*, 46, 54, 56.
Available plant food, 158.
Azotobacter chroococcum, 173, 183.

Bacteria, 172.
—, ammonifying, 176.
—, denitrifying, 218.
—, nitrifying, 63, *177*.
—, nitrogen-fixing, 179, 181.
Bacterium radicicola, 173, 180.
Barley, manuring of, 255.
Basalt, 44, 46.
Base exchange, *see* Cation exchange
Basic rocks, 45, 46.
— slag, 195, 201.
— superphosphate, 201.
Basin method of irrigation, 143.
Bat guano, 192.
Beans, manuring of, 260.
Bedding, *221*, 224
Biotite, 39, *41*, 45, 56.
Bird guano, 191.
Black brak (alkali), 162, *167*.
Blood meal, 193.
Blue asbestos, 41.
Bone ash, 205
— meal, 195, 204.
— — degelatinized, 205
Boron, 32, 34.
Braak (fallow) of soils, 134.
Brak, alkaline, 167.
—, black, 167.
— saline, 167.
— salts, 136, 167.
— soils, 81, 136, 167.
— water, 137, 138, 169.
—, white (white alkali), 167.

Cabbage crops, manuring of, 261.
Calcareous soils, 167, 198, 199.
Calcite, 42.
Calcium bicarbonate, 51, 163, 198.
— carbonate, 50, 55, 212.
— clay, 86, 170, 210.
— cyanamide, 191
— functions in plant growth, 30.
— hydroxide, 212
— phosphates, 195, 196, 204.
— sulphate, *see* Gypsum.
Caliche, 186
Cane, *see* Sugar-cane.
Capillarity in soils, 74.
Capillary moisture, 92.
— pores in soils, 88, 93.
Carbohydrate, 6.
Carbon assimilation, *11*, 29.
Carbonate of lime, *see* Calcium carbonate
Carbonation, 54.
Carbon dioxide in atmospheric air, 13, 105.
— — in soil air, 105.
— transformations by microbes, 175, 222.
Carbonic acid, weathering by, *54*, 107.
Cation absorption, 80.
— exchange, 81, 208.

Cellulose, 7, 62, 175, 176.
Chaff, application to soils, 256
Chalcedony, 40.
Chemical analysis of soils, 153.
— compounds, 3
— elements, 3.
— equations, 10.
— formula, 4.
— properties of soils, 153
— symbols, 3
— weathering agents, 53.
Chilean saltpetre, 85, 86, *186*
Chlorophyll, 8, *13*, 31, 173.
Chlorosis of plants, 31, 32, 275, 282
Citric acid soluble plant food, 158.
Citrus-trees, manuring of, 284
Classification of fertilizers and manures, 185, 186.
— of soils, *72*, 136.
Clay acid, 162, 210
— fraction, 66, 71, 73, 74, 78.
— origin of, 53, 54.
— soils, properties of, 74, *76*, 88, 91, 96, 111, 118, 148, 150, 211.
Cleavage of minerals, 39.
Clostridium pastorianum, 173, 181
Cohesion, 74, 76
Collar rot, 143.
Colloidal properties of soils, 77
— soil complex, 81
Colluvial soils, 57.
Colour of minerals, 39
— of soils, 109
Composition of air, 105
— of compost, 232.
— of earth's crust, 38.
— of farm manures, 226, 227, 289.
— of fertilizers, 289.
— of igneous rocks, 47.
— of plants, 7, 9, 28.
— of soils, 155.
Compost, 230.
Conglomerate, 48, 49, 267.
Conservation farming, *see* Soil conservation.
Contour furrows, 125
— ridges, 125.
Cooling of soils, 111.
Cover-crop, 179, 236, 240
Crayfish meal, 193, 289
Crop cycle, 269.
Crumb structure of soils, *85*, 211.
Crystal, definition of, 40.
Cusec, 139.

Deflocculation of soil colloids, 80, 85, 166, 167.
Delta soils, 58, 79.
Denitrification, 182, 223.
Dicalcium phosphate, 195.
Diffusion of soil gases, 107.
Dolerite, 45, *46*, 47, 56, 267.
Dolomite, 39, *42*, *50*, 56.
Drainage of soils, 146.
Drains, open, 147.
—, tile, 151.
Drought resistance of crops, 18, *132*.
Dry-land farming, 128.
Dry root-rot, 141
Dunes, 53, 59.
Dykes (and Intrusive rocks), 45

Eelworm, 181.
Electrolytes, 79.
Elements, chemical, 3.
Emulsion, emulsoid, 78.
Erosion, *see* Soil erosion
Evaluation of fertilizers, 215.
Exchange of cations in soils, *81*, 208
Excreta, composition of animal, 220
Expansion of minerals and rocks, 52
— of soils, 80.

Farm manure, 219.
— —, artificial, 231.
— —, composition of, 226, 227, 289.
— —, effect on soils, 228.
Fat content of plants, 8.
Felspar, 39, *40*, 45
Ferric and ferrous compounds, 54, 56
Fertilizer mixtures, 214
Fertilizers, classification of, 185
Field experiments, 246.
— water capacity, *95*, 144, 276.
Filter cake, 267, 271, 272.
Fixation of nitrogen, 24, *179*.
Flocculation of soil colloids, *79*, 86
Flooding method of irrigation, 142
Formations, geological, 51
Formula, chemical, 4.
Fossils, 47, 49, 51.
Fowl manure, 233.
Fractions, soil, 66.
Free water, *92*, 108, 146, 148.
Fruit-setting of grapes, 283.
Fruit-trees, manuring of, 273.
Fungi, soil, 173.
Funicular moisture, 93.
Furrow method of irrigation, 141.

Garnet, 39.
Gases, soil, 106.
Gel, condition, *79*, 80, 82.
Germination of seeds, requirements for, 11.
Glacial soils, 53.
Glucose, 7, 11.
Gneiss, 50.
Government guano, 191.
Granite, 41, *45*, 47, 267.
Grape-sugar, *see* Glucose.
Gravel content of soils, 69, 151.
Gravitational water, *see* Free water.
Green manuring, 61, 181, *235*, 280.
Ground water table, 93, 98, 129, 146.

Guano, bat, 192.
—, Government, 191.
Gully (donga) erosion, 122
Gummosis, 143.
Gypsum in superphosphate, 197.
— mineral, 39, *43*, 54, 56.
—, use in the preparation of manure, 225.
—, — on brak soils, 170.

Hardness of minerals, 39.
Hardpan, 37, 45, 55, 56
Heat, absorption of, in soils, 109.
—, conduction of, in soils, 111.
—, radiation of, from soils, 111
Hematite, 39, *42*, 54
Hippuric acid, 223
Hole method of irrigation, 142
Hornblende, 39, *41*, 56
Humic acid, 162.
Humidity of atmospheric air, 19, 103, 273.
— of soil air, 97, 106
Humus, composition of, 63.
—, content of, in soils, 64, 65, 175, 200, 235, 254, 258, 268, 280
—, decomposition of, in soils, 63, 200, 258.
—, definition of, 63
—, formation of, in soils, 62
—, importance of, 86, 228, *238*, 280
Hydrochloric acid analysis of soils, 154.
Hydrogen ion concentration, 160
Hydrolysis of silicates, 53
Hygroscopic moisture, 71, 74, *92*

Igneous rocks, 44
Indore-process of preparing compost, 231
Inoculation with nitrogen-fixing bacteria, 180
Ion, 35, 160.
Iron bicarbonate, 55.
— functions in plant growth, 31
— hydrated oxides, 31, 42, 55, 79, 99.
— phosphate, 198, 204, 210
— pyrites, 39, *42*, 56
Ironstone, 42, 45, 55, 84
— pellets, 42, 55
Irrigation of soils, 135
— water, 137

Jasper, 40

Kainite, 207.
Kaolin, 39, 41, 53.
Karoo manure, 227, 289
Kraal manure, 219
— —, composition of, 226, 289

Latent heat of vaporization, 112
Lava, 44.
Law of the Minimum, 5, *241*
Leaching of plant nutrients, 103, 141, 144, 236.
Legumes and nodule bacteria, 24, 180, 235.
—, manuring of, 259.
Leuna saltpetre, 190.
Light requirement for assimilation, 12, 184
Lignin, 7, 62, 175, 222
Lime, agricultural, 212
— dressings to soils, 213
— effects on soils, 209
— kilns, 212.
— —, quick-, lump-, 212
— requirement of soils, 210.
— —, slaked, 212
Limestone, 48, 50, 55, 212
— hardpan in soils, 37, 56.
Liming materials, 209
Limiting plant nutrients, 241
Limonite, *42*, 54, 55.
Litmus-paper, 160
Loam, 66, 72.
Loess, 59
Loss of weight on ignition of soils, 61
Lucerne, manuring of, 259.
Lustre of minerals, 39
Lysimeter, 103, 258

Magma, 44
Magnesium, functions in plant growth, 31
Magnetite, 39, 42, 46
Maize, manuring of, 257.
Manganese, essential for plant growth, 32, 281
—, harmful effects on plant growth, 281.
Manures, classification of, 185
—, composition of, 226, 227, 289.
—, definition of, 185.
Manurial requirements of soils, 153, 241, 254
Manuring of cabbage crops, 261
— of lucerne, 259.
— of maize, 257.
— of mangels, 261.
— of orchards and vineyards, 273.
— of pastures, 262.
— of potatoes, 260.
— of sugar-cane, 266
— of sweet potatoes, 261.
— of winter cereals, 255.
Marble, 4, 50.
Market value of fertilizers, 215
Marl, 212.
Materials for drains, 150.
Measurement of water, 139
Mechanical analysis of soils, 66.
— composition of soils, 66.
— sediments, 48.
Metamorphic rocks, 50.
Mica, 39, *41*, 45.

Microbes (micro-organisms) found in manure, 222.
—, soil, 37, 61, 105, *172*.
Mineral, definition of, 38.
— nutrients, 25.
— soils, 64, 91.
— theory of plant nutrition, 8, 153.
Minerals, rock-forming, 38
Minor elements, 32.
Mixing of fertilizers, 214.
Mixtures, *see* Fertilizer mixtures.
Moisture content of soils, *see* Water.
Molecule, 4, 15, 35, 78, 79, 160.
Molybdenum, 32.
Monocalcium phosphate, 195, 197, 198.
Mulch, *see* Soil mulch.
Muscovite, *41*, 45.
Mycorrhiza, 173

Natural manures, 185
Negative period in soils, 179.
Nematodes, *see* Eelworm.
Nitrate content of soils, 104, 159, 178, 236, 258
— fertilizers, 186.
— -forming bacteria, 63, *173*, 177.
Nitrate of lime, 187.
Nitrification, *177*, 223, 233.
Nitrifying bacteria, 63, *173*, 177.
Nitrochalk, 190.
Nitrogen assimilation by microbes, 24, *178*, *179*
— content of air, 24, 105.
— — of manures, 289.
— — of plants, 26.
— cycle, 182
— effects on plant growth, 23, 283.
— -fixing bacteria, 179.
— nutrition of plants, 23
Nitrolime, 191.
Nodule bacteria, 24, 25, *180*.
Norite, 45, *46*, 47, 54, 56.
Nutrition of plants from the air, 11.
Nutritive requirement of plants, 254.

Oats, manuring of, 256.
Obsidian, 44
Ochre, 42.
Olivine, 39, *42*, 46.
Opal, 40.
Open drains, 147
Organic compounds, definition of, 6.
— fertilizers, 192.
— matter in soils, 25, 36, *61*, 219, 235.
— weathering, 61.
Organogenic sediments, 45.
Orthoclase, *40*, 45, 53.
'Ouklip' (lateritic ironstone, ironstone gravel), 37, 42, 45, 55, 128, 274.
Oxidation of minerals, 56.
Oxygen content in soils, 107.
— solubility in water, 56.
—. weathering influence of, 56.

Pasture, manuring of, 262.
Peas, manuring of, 237, 260.
Peaty soil, *64*, 90, 91, 92, 208.
Pendular ('hanging') moisture, 93.
Phosmeal, 204.
Phosphate content of soils, 28, 157, 254.
Phosphatic fertilizers, 195.
Phosphoric acid, 195, 202.
— oxide content of manures, 289.
Phosphorite (phosphate rock), 48, 203.
Phosphorus, effects on plant growth, 27.
Photosynthesis, 13.
Physical properties of soils, 74, 76, 82, 211, 228, 238.
— — weathering agents, 52.
Plagioclase, *41*, 46, 54.
Plant food, available, 158.
— — removal by crops, 267, 282, *288*.
— — reserve, 154.
— nutrients, 10
Plasticity of soils, 74.
Plough-sole in soils, 236, 280.
Plutonic rocks, 44.
Pore volume, 83, *88*, 91.
Pores, *see* Soil pores
Potash content of manures, 289.
— effect on plants, 28, 283.
— -magnesia, 208.
— mica, 41.
— requirement of plants, 28.
— — of soils, 159, 209
— saltpetre, *see* Saltpetre.
Potassic fertilizers, 207
Potassium chloride, 208.
— sulphate, 208
Potatoes, manuring of, 260.
Potclay, 42, 45, 84, 147, 274.
Pot experiments, 243
Poultry manure, 233.
Primary soils (sedentary soils), 37, 57.
Profile, soil, 37, 68.
Protein, 7
— content of plants, 7, 62.
Protozoa, 174
Pumice, 44.
Pycnometer, 89.
Pyrites, 39, *42*, 56.

Quality of fruit, 27, 29, 274, 277, 283.
Quartz, 39, *40*, 45, 75.
Quartzite, 50.
Quicklime, 212.

Rainfall figures (intensity), 119.
Ratoon (sugar-cane), 270.
Reserve plant food, 154.
Respiration of microbes, 174.
— of plants, *14*, 84, 107, 146, 184.
— of soils, 108.
Rill erosion, 122.
Rock phosphate, 203.
— salt, 48, 207.
Rocks, soil-forming, 44.

Root respiration, 14.
— -rot (dry), 141.
— system of plants, 27, 75, 84, *127*, 141, 275.
Run-off (water), 116.
Rye, manuring of, 255, 256.

'Saaidam', 143.
Saline brak, 167.
Salt content of brak soils, 136, 167.
Saltpetre, 25, *187*.
Sand fraction, 70.
Sandstone, 48, *49*.
Sandy soils, properties of, 74, *76*, 83, 92.
Sardonyx, 40.
Secondary soils, 37, 57.
Sedentary soils, *see* Primary soils.
Sedimentary rocks, 47.
Seepage water, 147, 163, 168, 169, 170, 224.
Serpentine, 39, *42*.
Sewage effluent, 137.
Shale, 48, 49.
Sheet erosion, 122.
Silicate, 40, 53.
Silt content of river water, 58.
— fraction, 66, 74.
Single-grain structure, 83.
Slaked lime, 212
Soda, *see* Sodium carbonate.
Soda-lime felspars, 41.
Sodium carbonate (soda), 59, 166, 167.
— chloride, 166, 167
— clay (soil), 85, 99, *166*, 170, 187.
— nitrate, *see* Chilean saltpetre.
— sulphate, 166, 167.
Soil acidity, 81, *160*, 209.
air, 36, *105*.
analysis, chemical, 153.
—, mechanical, 66.
auger, 68.
classification, *72*, 136.
colloids, *77*, 99, 162.
conservation, 122.
crumbs (granules, aggregates), 67, 83, 84, 85.
definition of, 36.
drainage, *146*, 275.
erosion, 57, *116*.
fertility, analytical results as an indication of, 156.
fractions, 66.
gases, 106.
moisture, 92.
mulch, 103, 108, 112, 114, *128*.
origin of, 52.
pores, 83, *88*, 93, 105.
profile, 37, 68.
reaction, *161*, 175, 281.
respiration of, 108.
samples, taking of, 67.
structure, *see* Structure of soils.
survey, 136, 169.
Soil (*cont.*)
suspension, 78.
texture, *see* Texture of soils.
tillage, 118, 128.
Sol (condition), 79, 80, 85.
Specific gravity of minerals, 40.
— — of soil constituents, 89.
— heat, 111.
— surface, 77, 92.
Stable manure, 219.
Stalagmite, stalactite, 56.
Starch, 7, 8, 10, 11, 62, 175.
—, formation of, *see* Carbon assimilation.
Straw, ploughing under of, 170, 179, *256*
Strip cropping, 126.
Structure of rocks, 44, 45, 50.
— of soils, *83*, 96, 211.
Subsoil, differences from topsoil, 37, 64.
Suction pressure of roots, 15, 99
Sugar, 7.
Sugar-cane, manuring of, 266
— soils, 267
Sulphate content of soils, 31.
Sulphur requirement of plants, 31.
—, use against chlorosis, 31.
Sunn hemp, 236, 268, 281.
Superphosphate, manufacture of, 196.
—, use of, 198.
Suspension, suspensoid, 69, *78*, 80.
Symbiosis, 24, 179.

Talc, 39, *42*.
Temperature and plant growth, 12, 110.
— fluctuations in soils, 112, 129.
— of soils, 110
Tetracalcium phosphate, 195.
Texture of soils, *66*, *72*.
Tile drainage, 148.
Tillage of soils, *see* Soil tillage.
Top dressing, 187.
Trace elements, 32.
Transpiration, *17*, 23, 29, 132.
— ratio, 17
Trash, 270
Tricalcium phosphate, 195.
Turf soils, 59, 70, *81*.
Turning of kraal manure, 269.

Underdrainage, 148.
Underdrains, 150.
Unit value of fertilizers, 216.
Urea, 190, 223.
Urine, composition of, 220.

Veld burning, 121.
Vines, manuring of, 273.
Volcanic rocks, 44.
Volume weight of soils, 90.

Water, absorption of, by plants, 15.
— —, by soils, 119.

Water (*cont*)
acid, 59.
alkaline, 59.
capacity of soils, 74, *94*.
capillary, 92.
content of plants, 6.
dead, 99, 100.
evaporation of, from soils, 21, 97, 103, 108, 129
free, *92*, 108, 146, 148
from boreholes, 137, 138.
functions in plant growth, 13, *16*
funicular, 93
hard, 55, 59, 137.
hygroscopic, 92
logged soils, 54, 76, 84, 107, 141, 183, 275.
measurement of, 139.
movement in soils, 74, 96, 129.
of imbibition, 99
pendular ('hanging'), 93
requirements of plants, 16
Water (*cont.*)
run-off, 116.
seepage, 147, 163, 168, 169, 170, 224.
suitable for irrigation, 137
table in soils, 93, 98, 129, 146
units, 139.
weathering influence of, 52, 53
Weathering agents, biological, 56.
— —, chemical, 53
— —, physical, 52
— of minerals and rocks, 52.
Weight of a cubic foot of water, 91.
— of a morgen of soil, 91
Whale meat, 194.
Wheat, manuring of, 255.
White brak (alkali), 167
Wilting-point, 99, 144, 275, 276.
Windbreaks, 59
Wind erosion, 59.
Winter cereals, manuring of, 255.

Zinc, 32, 34.