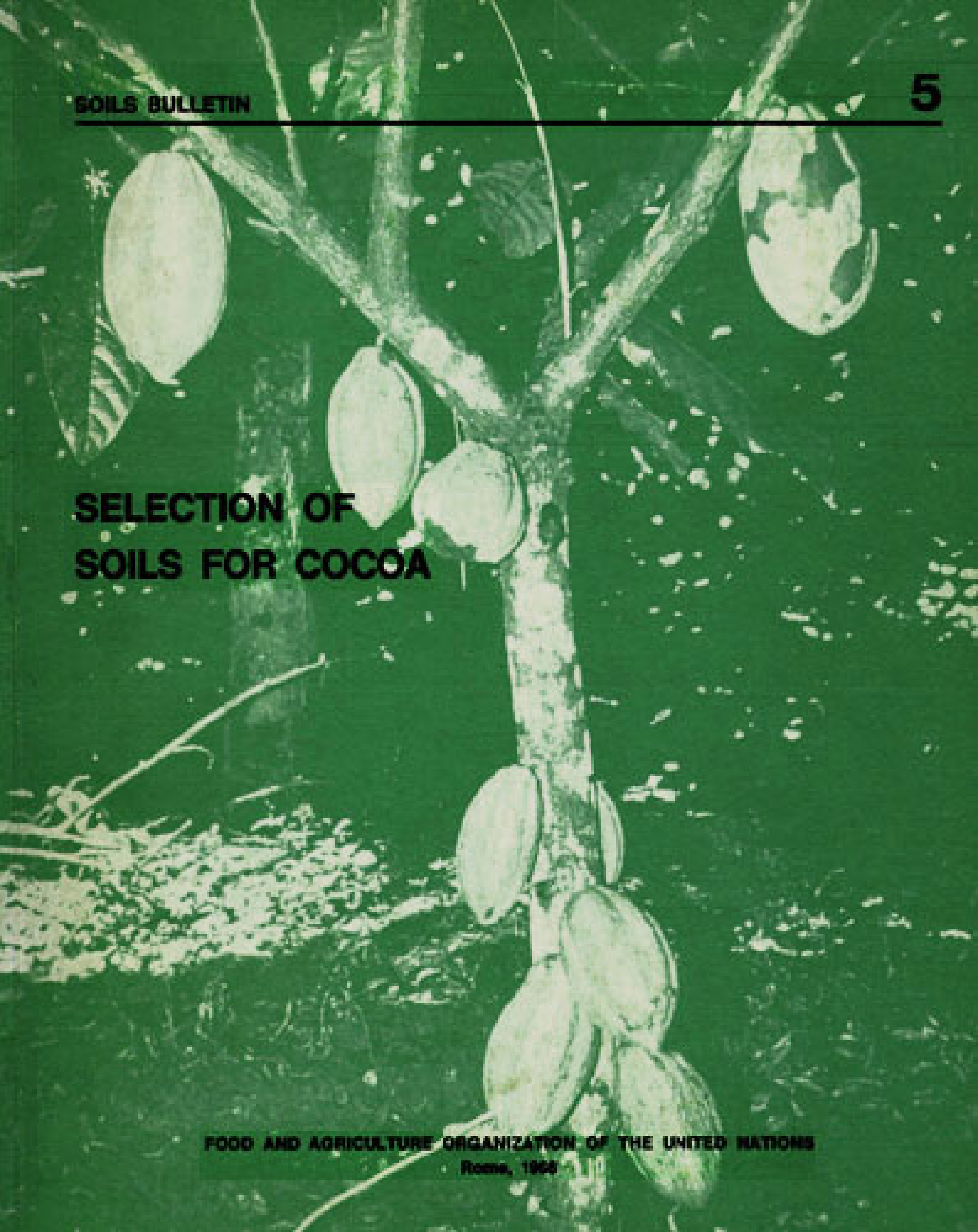


SOILS BULLETIN **5**

SELECTION OF SOILS FOR COCOA

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 1966

CONTENTS

Page

INTRODUCTION 1

ACKNOWLEDGEMENTS 2

CHAPTER ONE: CLIMATIC CONSIDERATIONS 5

Climatic Requirements: 5

    Air Temperatures 5
    Rainfall 6
    Other Climatic Factors 7
    Effects of Shade on Climate 7

Soil Forming Processes in Potential Cocoa-Growing Areas: 8

    The Influence of High Temperature and Intense Rainfall 8
    Biological Influences 8
    The Influence of Parent Material and of the Age of the Soil 9

CHAPTER TWO: ROOT PENETRATION AND ROOTING VOLUME 13

The Root System of Cocoa 13

Factors Within the Soil which Impede Root Penetration: 14

    Drainage and Aeration 14
    Texture and Structure 16
    Content of Large Particles 18

Summary of Required Soil Characteristics 19

CONTENTS (Cont'd.)

Page

CHAPTER THREE: MOISTURE AND AIR REQUIREMENTS 20

Biological Evidence of the Moisture Requirements of Cocoa 20

Factors Within the Soil which Affect Moisture Retention, Drainage and Aeration: 21

General Considerations 21

Soil Texture and Structure 22

Soil Colour 23

Factors External to the Soil which Affect Drainage and Aeration 24

Soil Moisture Requirements under Different Climatic Conditions 25

CHAPTER FOUR: NUTRIENT REQUIREMENTS 28

The Evaluation of Laboratory Data: 28

Sampling Problems 29

Nutrient Exchange Characteristics 30

(a) Base Exchange Capacity 30
(b) Organic Matter Content 32
(c) Percentage Base Saturation 33
(d) pH 33

Carbon/Nitrogen Ratios 36

The Level of Individual Nutrients 37

Selected Analysis Data from Different Parts of the World 39

Assessing Nutrient Status in the Field: 42

Physical Characteristics of the Soil 43

(a) Texture 43
(b) Colour 43
(c) Consistence and Structure 44

CONTENTS (Cont'd.)

Page

(d) Content of Large Particles 44
(e) The Nature and the Degree of Weathering of the Parent Material 46

The Agricultural History of the Site 47

CHAPTER FIVE: QUALITY CLASSIFICATION OF POTENTIAL COCOA SOILS 50

The Choice of Quality Classes 50

Criteria for Distinguishing Soil Quality Classes: 52

Nutrient Status 52

Soil Depth and Rooting Volume 53

Drainage - Moisture Supply and Aeration 54

Individual Physical Characteristics of the Soil 54

(a) Texture 54
(b) Soil Colour 55
(c) Soil Consistence and Structure 56
(d) Other Physical Characteristics 56

Assessing the Validity of a Soil Quality Classification: 56

Cocoa Yield Maps 57

Distribution of Surviving Cocoa 59

CHAPTER SIX: SURVEY METHODS 64

The Scale of Mapping 64

Field Methods 66

BIBLIOGRAPHY 69

APPENDIX: Further Explanation of Chemical Criteria Determined by Soil Analysis 74

INTRODUCTION

At a time when many of the leading cocoa producing countries are concerned about the price which they receive for their product and are considering ways and means of diversifying their agricultural economies, the need for a publication on the selection of soils for cocoa may be questioned. Yet, it is in a competitive market that high production efficiency is most essential and a vital factor in efficient cocoa production is the choice of soil on which the crop is grown. By careful selection of soils, equal and perhaps greater yields of cocoa can be obtained on a countrywide basis from a greatly reduced area of land. Areas at present occupied by unthrifty cocoa can then be released for the production of other cash crops, to which the soils may be better suited, or to produce the food requirements of increasing populations.

In many cocoa-producing countries a large proportion of the present crop is harvested from trees which are already past their prime and the need for large areas of new plantings is foreseen if the present level of production is to be maintained. In choosing sites for these new plantings maximum use should be made of experience on the soil requirements of cocoa which has accumulated in different parts of the world.

In one sense, the publication is premature, for many gaps remain to be filled in our knowledge of the soil requirements of cocoa and, as yet, few of the desired soil characteristics can be defined in exact terms. The relative importance of individual soil characteristics differs in different environments, however, and only rarely is the expression of a single characteristic so extreme that it alone dictates the suitability of a soil. More important, at this stage of knowledge, is a general understanding of the interrelationships of different soil characteristics and of their mutual influence on the healthy growth of cocoa. For this reason, and because it is hoped that the publication will be of value to readers who are not soil specialists, considerable space has been devoted to discussion of the basic principles which underlie these relationships.

The influence of individual soil characteristics on the suitability of a soil for cocoa are so closely inter-related that it is difficult to avoid some degree of repetition in discussing different aspects of the subject. An attempt has been made to minimize this repetition by summarizing the conclusions of earlier chapters within Chapter Five, where they are discussed in relation to the recognition of soil quality classes.

Insofar as it has been possible to suggest specific criteria as minimal soil requirements for cocoa planting, rather high standards have been deliberately chosen. The reason for this is clear for mere survival of the trees is not sufficient. In the future, the economic use of land for cocoa production will demand the use of modern management practices and these are only profitable if the soils on which the trees are planted are capable of supporting high yielding cocoa for many years, with or without the aid of fertilizers.

ACKNOWLEDGEMENTS

In preparing this monograph, the author received very valuable assistance from a large number of people who, in correspondence or in personal interview, provided advice, scientific data and reprints of scientific papers which would otherwise have been difficult to obtain. In particular, he wishes to thank the following contributors:-

P. de T. ALVIM, Director, Centro de Pesquisas do Cacau, Itabuna, Brazil.

B.O.E. AMON, Chief Agricultural Research Officer, Ministry of Agriculture and Natural Resources, Western Region, Nigeria.

F.W. AMSON, Soil Scientist, Agricultural Experiment Station, Paramaribo, Surinam.

J.L.W. BAXTER, General Manager, Bomeo Abaca Ltd., Sabah.

J. BENNEMA, formerly Soils Expert, FAO Mission, Brazil.

H. BRAMMER, Soils Expert, FAO Mission, East Pakistan.

J.B. CARSON, Estates Department, Messrs. Harrisons & Crosfield Ltd. Indonesia.

J.K. COULTER, Principal Scientific Officer, Rothamsted Experimental Station, Harpenden, England; formerly Head of Soil Survey and Research Section, University of the West Indies, Trinidad.

W.R. CROGGAN, Malayan Cocoa Ltd., Malaysia.

R.G. DONALD, formerly Senior Entomologist, Cocoa Research Institute of Ghana, Ghana.

H. EVANS, Director, Bookers Sugar Estates Ltd., British Guiana.

F.F. FOSTER, Department of Agriculture, Sarawak.

J.D. GILLESPIE, Research Officer, Tiger Estate, Borneo Abaca Ltd. Sabah.

D.E. GOLLIFER, Agricultural Officer (cocoa development), British Soloman Islands.

H. GREENE, Late Advisor in Tropical Soils, Rothamsted Experimental Station, Harpenden, England.

F. HARDY, Consultant to the Inter-American Institute of Agricultural Sciences, Turrialba, Costa Rica; formerly Professor of Soils, Imperial College of Tropical Agriculture, Trinidad.

G. HAVORD, Director, Inter-American Institute of Agricultural Sciences, Turrialba, Costa Rica.

S. HUNTER, Ag. Manager, Fiji Development Co., Ltd., Fiji.

V. IGNATIEFF, Deputy Director, Land and Water Development Division, FAO.

G.V. JACKS, Director, The Commonwealth Bureau of Soils, Rothamsted Experimental Station, Harpenden, England.

G.A. JONES, Cocoa superintendant, Bookers Sugar Estates Ltd., British Guiana.

R.H. KENTEN, Deputy Director, Cocoa Research Institute of Nigeria, Ibadan, Nigeria.

G. LEMS, Agriculturist, Agricultural Experiment Station, Paramaribo, Surinam.

J.F. LONGWORTH, Cocoa Research Institute of Nigeria, Ibadan, Nigeria.

G. K. MALIPHANT, Head, Citrus Research, University of the West Indies, Trinidad.

J.W. McPAUL, Agricultural Chemist, Department of Agriculture, Fiji.

A.R. McWALTER, Assistant Director (Research), Department of Agriculture, Malaysia.

W.F. MEREDITH, Director of Agriculture, Western Samoa.

R.F. MONTGOMERY, University of Newcastle, England; formerly Principal Research Officer (Soils), Ministry of Agriculture and Natural Resources, Western Region, Nigeria.

C.A. PANABOKKE, Head of Land-Use Division, Department of Agriculture, Ceylon.

T.R. PATON, Soils Division, C.S.I.R.O., Brisbane, Australia.

E. QUARTEY PAPAFIO, Agricultural Officer (Tropical Crops), Plant Production and Protection Division, FAO.

B.S. RAMDAS, Under Secretary, Indian Council of Agricultural Research, New Delhi, India.

C.A. ROWLES, Professor of Soils, University of British Columbia, Canada; formerly Soils Expert, FAO Mission, Venezuela.

J. SORIA, Head of Cocoa Research, Inter American Institute of Agricultural Sciences, Turrialba, Costa Rica.

C.S. SIMMONS, Soils Expert, FAO Mission, Honduras.

S. SIVARAJASINGHAM, Soils Expert, FAO Mission, Sierra Leone.

J. STARK, Soils Specialist, Regional Research Centre, University of the West Indies, Trinidad.

I.T. TWYFORD, Officer-in-Charge, Windward Islands Banana Research Schemes, St. Lucia, West Indies.

D. H. URQUHART, formerly of Messrs Cadbury Brothers Ltd., Bournville, England.

H. VINE, Lecturer in Soils, University of Leicester, England; formerly Lecturer in soils in the University of Ibadan, Nigeria and of the West Indies, Trinidad.

M. WESSEL, Cocoa Research Institute of Nigeria, Ibadan, Nigeria

G.A.R. WOOD, Messrs. Cadbury Brothers Ltd., Bournville, England.

A.C.S. WRIGHT, formerly Soils Expert, FAO Mission, Chile and Western Samoa.

CHAPTER ONE

CLIMATIC CONSIDERATIONS

Research aimed at discovering the environmental conditions most favourable to cocoa has made it increasingly clear that conclusions on the soil and nutrient requirements of the tree cannot be drawn without reference to the climatic conditions under which the tree is to grow. Generalizations on the climatic requirements of the tree without reference to soil conditions are apt to be equally misleading (Havord, 1958). Climate, itself, represents a complex inter-relationship between the major factors of temperature, rainfall (quantity and distribution), humidity, cloud cover and windspeed. Nevertheless, some limits, defined largely by temperatures, can be placed on the climatic requirements of cocoa, within which the relative success of cocoa farming will depend on the methods and plant material employed and on the nature of the soil. Climatic conditions exert a large influence on the processes of soil formation and so, by placing limits on the climatic range, a certain degree of limitation is also placed on the range of soils which can be considered for cocoa. Thus, to provide a setting for subsequent discussion, a brief resumé of the climatic requirements of cocoa is necessary, although different aspects of this subject have been considered in detail in various publications.

CLIMATIC REQUIREMENTS

Air Temperatures

Air temperatures are known to influence various physiological processes of cocoa and world cocoa distribution is largely dictated by the narrow range of temperature conditions under which the plant thrives. Hardy (1960) has discussed research on the temperature relations of cocoa carried out in Costa Rica, Trinidad, Ghana and Brazil and concludes that the optimum average temperatures throughout the year should be around 25.5°C (78°F) with a daily range of 9°C (16°F). Daily temperature fluctuations of this order appear to be necessary to initiate bud-bursting, but bud-bursting and leaf-flushing may be excessive if the daily range greatly exceeds 9°C, particularly if maximum temperatures rise much above 28°C (83°F). Low temperatures adversely affect the tree and, on the basis of Erneholm's studies in South America (1948), Hardy suggests that 15°C (60°F) should be regarded as the lowest mean daily minimum temperature acceptable for cocoa, with an absolute minimum of 10°C (50°F). At temperatures below 25.5°C flower formation appears to be inhibited and trunk growth appreciably reduced.

From these, and other considerations, Hardy (1960) concludes that the limits of the temperature range favourable for cocoa may be set at 15°C (60°F) as the monthly mean minimum and 30°C (86°F) as the monthly mean maximum. Ideally seasonal temperature variations should be small and the diurnal temperature range almost constant throughout the year. Such temperature conditions are found in low-lying areas at, or near, the equator. North and south of the equator diurnal temperature ranges increase and conditions become progressively less suitable for cocoa. In fact, although the limits of cocoa cultivation extend to almost 20°N (in Mexico) and to almost 30°S (in Brazil), the bulk of the world's crop is harvested within 10° of the equator, mostly at elevations below 1,000 ft. (Urquhart 1955). In latitudes greater than 15°N or S, temperature relations are likely to be marginal for cocoa and may even constitute a factor limiting production (Hardy 1960).

Rainfall

Whilst the majority of cocoa-growing areas enjoy 1,500-2,500 mm. (60"-100") of rainfall per annum cocoa is, in fact, grown under a much wider range of rainfall conditions. With the aid of irrigation, satisfactory crops are obtained on the sandy desert coast of Peru where rainfall is less than 100 mm. (4") a year (Alvim, 1959). Even without irrigation, cocoa is grown quite extensively in parts of Nigeria and Ecuador where annual rainfall is less than 1,250 mm. (50") and four months of the year are almost dry. On the other hand some cocoa is grown in New Guinea under rainfall approaching 5,000 mm. (200") per annum. Nevertheless, few cultivated plants are as sensitive as cocoa to water shortage or excess in the soil and successful cultivation under the extremes of rainfall quoted demands careful water management or, at least, very careful selection of soils.

The relationship between soil moisture conditions and rainfall involves not only the nature of the soils but also other environmental factors, particularly temperature. The relationship is so complex that generalizations on the rainfall in any period is less than the water loss caused by evapotranspiration. According to Hardy (1960), measurements made in several cocoa-growing countries indicate this loss to be of the order of 100-125mm. (4-5") a month, implying that a minimum monthly rainfall of the same order is required to avoid depletion of soil moisture during dry months. Pronounced dry seasons, in which losses by evapotranspiration exceed rainfall for several successive months, profoundly affect the flowering and fruiting behaviour of cocoa and there can be no doubt that excessively prolonged dry spells could be fatal to cocoa in the absence of irrigation. There appears to be no evidence to support the theory that a resting period from growth, induced by dry conditions, is beneficial to cocoa (Urquhart, 1955). On the contrary, rainfall evenly distributed throughout the year appears desirable.

The difficulties inherent in attempting to extrapolate apparent climatic requirements from one territory to another, in which environmental conditions may be subtly different, can be illustrated by a comparison of rainfall conditions in the neighbouring West African countries of Ghana and Nigeria. Thus, whilst Adams and McKelvie (1955) noted that very little cocoa was grown in those areas of Ghana in which rainfall during the period November to March was less than 10" (250 mm.), in the greater part of the important cocoa-growing areas of Western Nigeria rainfall during this same period rarely exceeds 7" (180 mm.) (Smyth and Montgomery, 1962). Yet yields from Amelonado and Amazon cocoas, produced by comparable farming methods in Ghana and Nigeria, do not differ very greatly.

In some areas the size, as well as the distribution, of cocoa harvest is regulated by rainfall more than by any other ecological factor. Alvim (1959) quotes a number of authorities from different parts of the world who have noted a close relationship between harvest distribution and the distribution of rainfall 5-7 months previously. This, Alvim points out, indicates the predominant direct effect of moisture availability on flower and fruit formation. In Bahia, Brazil, where temperature cycles appear to exert a greater influence than rainfall distribution on crop rhythm, the same author reports a strong positive correlation between rainfall and yield about two years later. This he explains as an indirect effect effect of rainfall on yield caused primarily by the influence of water supply on vegetative growth and bud wood formation. On the other hand, negative correlation between yield and rainfall 2-3 months before harvest has been recorded in West Africa, probably because of increased incidence of fungal pod diseases under wetter conditions. These relationships require consideration in the interpretation of experimental work on cocoa and, for field trials on mature trees, make it desireable to calibrate yields in relation to rainfall on the trial site preferably for at least two years before treatments are applied.

The selection of soils for cocoa planting under different rainfall regimes is discussed in some detail later.

Other Climatic Factors

Atmospheric humidity and windspeed are both factors controlling the rate of evapotranspiration and their combined influence can be of considerable significance in areas where soil moisture tends to be deficient. In some parts of West Africa, for example, increasing frequence and intensity of the hot dry "harmattan" winds, sweeping south from the desert areas in the early part of the year, are major factors limiting the spread of cocoa farming northwards.

Relative humidity is usually very high in cocoa-growing areas and this has frequently been stated as a requirement for successful growth. However, as Alvim (1959) points out, there is no experimental evidence that lower humidity *per se* would be harmful to cocoa and he himself was unable to detect signs of water stress in cocoa when midday relative humidity decreased to about 40-50%, provided soil moisture was adequate. Nevertheless, high humidity and continuous cloud cover may serve to ameliorate the adverse effect of long periods of very low rainfall and this may explain the rather surprising success of cocoa farming in parts of Nigeria and Ecuador where, as mentioned earlier, the volume and distribution of rainfall is far from optimum. Where soil moisture is adequate, very high humidity can be considered undesirable since it undoubtedly favours the development of various diseases of cocoa.

Cocoa is exceptionally susceptible to mechanical damage by wind. The surface concentration of its root system offers weak anchorage in the face of very strong winds and even light winds of less than 16 miles per hour can cause appreciable damage to young leaf flushes, which, unlike those of many other trees, reach their maximum size before hardening (Venning, 1958).

Effects of Shade on Climate

The majority of the world's cocoa is grown under some form of shade which inevitably modifies climatic conditions in the immediate vicinity of the cocoa tree. Since direct insolation and air movements are reduced, the chief effect of shade trees is to reduce the daily temperature range of the air surrounding the cocoa by lowering maximum temperatures and raising minimum temperatures (Hardy 1960). An experiment in Trinidad showed that, during the dry season, the mean diurnal range in a well-shaded plot was 13.9°F compared with 20.4°F in a poorly-shaded plot (McDonald, 1932). In a shade experiment in Ghana a 2-3°F temperature difference was noted in the canopies of shaded and unshaded cocoa (Hurd and Cunningham, 1961) and Hardy (1960) estimates that, in general, shade trees reduce the maximum air temperature range by about 2.6°C (4.7°F). Reduced temperatures under shade increase the relative humidity within the cocoa canopy and, since the vapour pressure within the leaf is reduced in relation to that of the atmosphere, water loss through transpiration is reduced (Alvim 1959). As much as 20% of the rainfall is intercepted by the leaves of the shade trees and evaporates before reaching the soil but this is of no significance unless soil moisture is already depleted, since in evaporating it absorbs a part of the energy that would otherwise be dissipated by transpiration and surface evaporation so that the total water loss at the site of evapotranspiration remains essentially the same (Hardy, 1960).

SOIL FORMING PROCESSES IN POTENTIAL COCOA-GROWING AREAS

To provide a background for subsequent discussion it is worth considering in broad terms the significance of the climatic limitations of cocoa described in the previous section in relation to the soil forming processes which are likely to be active, and thus the range of soil characteristics one can expect to encounter, in areas climatically suitable for cocoa. For this purpose we will neglect the possibility of irrigation and consider only those processes which are active in the soil under the conditions of high temperature and moderately high annual rainfall, variable in distribution, which prevail in the humid equatorial regions.

The Influence of High Temperature and Intense Rainfall

In these regions soils remain moist throughout most, if not all, of the year and with soil temperatures at levels even higher than those of the atmosphere, chemical processes within the soil proceed continuously at a high rate. Thus weathering of rocks and of parent material is rapid, tending to produce deep soils, and the breakdown of rock minerals and clay mineral formation proceeds further than is the case under temperate conditions. Appreciable, sometimes dominant, quantities of the free sesquioxides of iron and aluminium are released, and under conditions of good drainage, the silicate clay minerals formed are predominantly of the 1: 1 lattice, Kaolinitic, type. Such a clay complex has a low capability for moisture absorption and for storing and exchanging nutrient cations. Absorbing little moisture, the clay complex expands little on wetting and contracts little when dried so that structural units within the soil are rarely strongly developed. However, the sesquioxides present assist in 'cementing' the ultimate particles of the soil into fine, very stable, aggregates (Bates, 1960) and preserve an open microstructure to great depths in the soil profile. Typically, therefore, soils of the humid equatorial regions, although almost structureless in the mass, are friable in consistence and are filled with minute inter-connecting pore spaces, which permit free air and water movement.

Intense tropical rainfall, rapid release of soluble compounds by weathering, the low retention properties of the clay complex, and the freely draining nature of the soils, combine to produce conditions favouring the rapid loss of nutrient elements by leaching. Such losses tend to increase progressively as total annual rainfall increases and in some areas may deplete the soil to an extent that makes cocoa farming an unattractive proposition from the economic, if not the technical, point of view.

Biological Influences

The influence of vegetation on soil formation is particularly vigorous in humid equatorial regions. Under warm, moist conditions plant growth is very rapid and root systems proliferate to considerable depths in the porous soils. Actively growing vegetation reduces nutrient losses due to leaching by transpiring moisture to the atmosphere, thus reducing percolation, and by absorbing anions, especially nitrate, from the soil solution (cations are also absorbed, of course, but in a fertile soil these would merely be replaced in the soil solution by further cations from the exchange complex) (Nye and Greenland, 1960). The nutrients taken up by the vegetation, some from the depths of the soil, are eventually returned to the surface soil in fallen leaves and dead plant material. In this way, under mature tropical forest, the nutrients are maintained in a nearly closed cycle from which few nutrients are lost in the drainage (Nye and Greenland, 1960). Furthermore, the process leads to a very marked concentration of nutrient elements, especially those in forms readily available to the plant, in the top few centimetres of the soil. Clearing, or drastic thinning, of the natural vegetation in order to plant cocoa or other crops, breaks this nutrient cycle and, at least until a new canopy is restored, nutrients are lost by leaching and the soil is exposed to torrential rain which breaks down surface soil structure and may cause erosion.

Climatic conditions also influence microbiological processes in the soil. The high soil temperatures prevailing in the tropics favour the development of soil bacteria in relation to soil funghi and, since bacteria work much faster than funghi in the breakdown and mineralization of organic matter and store much less of the transformed material in their own bodies, a predominance of bacteria leads to rapid and complete destruction of organic matter (Mohr and van Baren, 1954). The process is accelerated by the relative rapidity of straight chemical reactions under high temperatures. Mohr and van Baren (1954) estimate that the rate of decomposition of humus, assumed to be due largely to bacterial activity, will exceed the rate of accumulation of humus when temperatures rise above 25°C (77°F). Hardy (1960) quotes this estimate in connection with the climatic requirements of cocoa and stresses the need for adequate shade precautions when air temperatures rise much above this figure, in order to lower soil temperatures and conserve organic matter.

Warm, moist conditions also favour the multiplication of some larger soil fauna, such as earthworms, termites and ants. These creatures play an important role in the tropics in the breakdown of organic matter and, in some areas, exert a strong influence on the morphology of the upper soil horizons (Nye, 1955). Their activities are also responsible, in part, for the rapid changes in surface texture which are characteristic of many areas of tropical soil.

The Influence of Parent Material and of the Age of the Soil

To provide an understanding of the broad range of soils which occur in potential cocoa growing areas, further factors of major importance in the development of soil characteristics need to be mentioned, although neither is directly related to climate. The first is the nature of the parent material from which the soil is formed; the second is the age of the soil. These two factors are to some extent inter-related.

The parent material of a soil is itself derived from one or more parent rocks, which may be directly beneath or, if the parent material has been transported, may originally have been some distance from the present site of the soil. In either case, the parent material and thus the soil, derives many of its characteristics from the parent rock, or rocks, from which it forms. In this connection the structure and grain size of the rock influence the ease with which it weathers and may be reflected in the coarseness of the texture of the soil to which it gives rise; the mineral assemblage of the parent rock also influences ease of weathering and largely determines the proportional distribution of nutrient elements and the nature of the mineral weathering products found in the Soil. Almost all geological suites are represented within a belt lying 20° on either side of the equator but a broad pattern can be detected and some generalizations made on the significance of this pattern in relation to soil formation.

The continental masses within the equatorial belt are largely developed on stable geological shields composed mainly of acid igneous and metamorphic rocks of great age. These areas have been subjected to little geological movement in recent eras and usually present a mature topography with gentle slopes at the present day. Although the rocks of these stable shields are predominantly acid in mineralogical composition, minor areas occur of more basic rock, containing a lower proportion of silica and a much higher proportion of ferromagnesian minerals. The latter areas are more important than their limited geographical distribution might suggest, since the more basic rocks generally give rise to soils of higher agricultural potential, often well suited to cocoa.

Within the continental masses quite extensive areas of the basement shield are covered by alluvial, colluvial and sedimentary deposits. These areas are mainly to be found in the great river basins and in relatively narrow strips of land following the present coast line. Although small in relation to the continents as a whole, the areas occupied by these deposits are commonly those climatically best suited for cocoa and thus are of importance in this study.

The western side of continental South America, comprising the mountain range and footslopes of the Andes, is exceptional in that its structural geology is unstable and its topography relatively immature. In this respect it has much in common with Malaysia and the major islands of Indonesia and of the Far East. In these areas soils are derived from a wide variety of igneous, sedimentary and, especially in parts of Indonesia, volcanic rocks. On the steep slopes associated with the immature topography young soils can be expected, but it must be borne in mind that processes of soil formation proceed very rapidly in those areas which have very high rainfall.

In Central America and some of the equatorial islands, extensive areas of soil are formed directly or indirectly from volcanic rocks and ash deposits. Other equatorial islands are composed largely of limestone.

The nature of the soils developed on these rocks in any given area depends upon the prevailing rate of different soil forming processes and upon the length of time during which the soil parent material has been exposed to these processes. Since temperatures are uniformly high in the tropics, the rate of soil development in turn depends largely on the amount of rainfall. Once the parent material has weathered sufficiently deeply to support a tree crop, the further action of soil forming processes tends to reduce the agricultural quality of the soil for continued weathering releases soluble nutrients, which are either lost in the drainage waters or transferred to the natural vegetation and thence, in part, to the surface soil. In either case, nutrient reserves in the main body of the soil are depleted. Prolonged weathering may improve the physical characteristics of the soil, particularly in regard to structure, but this seldom outweighs the disadvantage of the loss in nutrient status.

Considerations such as these have led Hardy (1958) to list the young soils derived either from fresh volcanic materials or from alluvium containing unweathered minerals as the most suitable soils for cocoa.

The stage of profile development reached is of particular significance in relation to the agricultural quality of soils in areas overlying ancient geological shields. The fact that not all the soils in these areas are of very great age reflects past climatic changes, with dry periods in which little soil formation occurred and very wet periods in which dramatic erosion removed much of the soil material that had formed. In some areas, for example parts of Western Nigeria and of the Ivory Coast, extensive development of cuirasse ironstone in the past may have effectively reduced rock weathering. Rock weathering has proceeded after the cuirasse has decomposed or been eroded away but the soils retain many youthful characteristics (Aubert, 1963; Smyth and Montgomery 1962). These influences are undoubtedly partially responsible for the apparent differences in maturity which are observed in tropical soils, not all of which can be simply related to present-day climatic zonation or geology. At the same time, present knowledge is insufficient to state with certainty that the profile characteristics displayed by different tropical soils derived from similar parent materials represent separate stages in a continuous process of soil formation. Subtle differences in environmental conditions, particularly in rainfall distribution, may result in diverging lines of soil formation tending towards differing end products.

Important differences can be recognized in tropical soils derived from similar parent materials which can be loosely related, bearing in mind the qualifications given in the previous paragraph, to differences in the degree of maturity of the soils. Thus in 'younger' soils, usually those under only moderate rainfall and especially where a dry season is pronounced, not all the silicate clay minerals are of the Kaolinitic type and there may be appreciable quantities of weatherable minerals remaining almost unchanged in the profile. The profiles are relatively shallow and may show quite well-developed soil structure. In addition, there may be evidence of clay movement within the profile in the form of zones of clay accumulation or as 'clay films' on the faces of the structural units. Although base exchange capacity is usually only moderate to low, the exchange complex, may, in some instances, be highly saturated. Where other environmental conditions are satisfactory such soils are likely to be suitable for cocoa, provided they are not too sandy or too shallow.

In areas of higher, more continuous rainfall, or where tropical soil forming processes have been active on the parent material over a longer period, or where the parent material is impoverished from the outset in weatherable minerals (as is commonly the case over sedimentary formations, particularly sandstones), the soil characteristics described as typical of the humid tropics at the beginning of this section are more clearly developed. Profiles are deep, almost structureless and show little differentiation into separate horizons. They lack weatherable minerals and their clay fractions are composed almost entirely of Kaolinitic silicate clays and free sesquioxides. Both base exchange and base saturation are low and such available nutrients as are present are largely concentrated in the top few centimetres of soil. Physically such soils may be ideal for tree crops but their nutrient status may be too low to be acceptable for cocoa.

In some areas, notably in parts of the Congo (Sys, 1959) and of Brazil (Bennema, 1963), processes of tropical weathering are so far advanced that silicate clay minerals are almost totally absent from the soils, which are composed, therefore, almost entirely of oxides of iron and aluminium. Such soils are unsuitable for cocoa, for not only is their nutrient status very low but the technical problems involved in improving this status by the use of fertilizers are very great. Unfortunately, it is sometimes difficult to distinguish such soils from less 'mature' profiles of much greater potentiality by physical examination alone and their true nature may be revealed only by chemical or mineralogical analysis.

Within and between areas of older soils, developed on plateaux and in basins, soils of much higher nutrient status may be found developed in relatively young colluvial material on and at the foot of steep slopes. Such soils are frequently very suitable for cocoa.

Reference has already been made to the suitability of soils derived from young volcanic materials. Such materials are predominantly basic in mineral assemblage and are usually rich in the nutrient elements required for plant growth. Volcanic glass, present in large quantities in ash deposits, weathers readily to amorphous allophane with exceptionally high base exchange properties. Thus the nutrient status of soils derived from volcanic ash is usually high (although, in some cases, the availability of phosphorus may be low). Again a general trend in changing soil characteristics may be noted in relation to the degree of 'maturity' of these soils, due either to the age of the parent material or to the effects of increased temperature and rainfall (sometimes related, in turn, to decreased altitude) on the rate of soil forming processes. They range from very young soils in which, as yet, soil formation has had little effect on the unconsolidated ash; through soils containing high proportions of allophane and usually or organic matter; to older soils, similar in their morphology to those described previously as typical of the tropics but commonly of rather higher nutrient status (Dudal and Soepraptohardjo 1960). As a generalization it may be said that all but the extreme members of this range of soils are well suited to cocoa.

Soils derived from calcareous rocks are usually rather shallow and clayey in texture since an exceptionally high proportion of such parent material is lost in solution. Characteristically, the upper portion of the profile in such soils is black to dark reddish brown in colour and strongly structured for, under the conditions of poor drainage which usually prevail, the clay fraction is commonly rich in expanding-lattice clay minerals (beidellite, montmorillonite). Such soils will support excellent cocoa provided their humic topsoil is thick (over 20 cms.) and neutral to acid in reaction (Hardy, 1960); provided drainage conditions are not too adverse; and provided the soils are not so shallow that a high proportion of the roots penetrates into the highly alkaline subsoil.

Lastly, but by no means least, there are the soils derived from alluvium. Where moisture conditions are satisfactory and the alluvium includes a proportion of unweathered minerals, or is replenished periodically with fresh mineral and organic materials from flood water, these soils will also support excellent cocoa (Hardy, 1960). However, it must be remembered that unlike the alluvium of temperate areas, which is very largely composed of rock debris physically shattered during glacial periods, most of the alluvia of the large tropical basins are composed of preweathered material very poorly provided with nutrient elements (Edelman and van der Voorde, 1963). Thus, contrary to widely-held belief, many tropical alluvial soils have low nutrient status and, for this reason alone, may be ill suited to cocoa.

CHAPTER TWO

ROOT PENETRATION AND ROOTING VOLUME

In the selection of soils for cocoa special attention must be paid to factors within the soil which are likely to limit root penetration, for the root system of cocoa appears to be more sensitive to such obstructions and less vigorous in overcoming them than is the case with many tree crops. Hardy, in particular, has stressed the importance of "root room" and of "physiological depth", which he defines as the thickness of the layer of soil that is adequately aerated and structurally suitable for the unrestricted growth of roots, in relation to the soil requirements of cocoa (Hardy, 1958, 1960; McCreary et al, 1943).

"Root room" is important since the ability of a soil to supply moisture and other nutrients depends not only on the quantity of these nutrients available in a unit volume of the soil but also upon the total volume of soil which the plant roots can exploit. Failure to develop an adequate root system and thus to exploit such nutrient reserves as may be present in the soil is probably a major cause of cocoa failure under adverse soil conditions. "Physiological depth", is particularly important in the case of cocoa since other considerations, such as the need to establish a closed canopy as quickly as possible, limit the planting distance between trees and thus, to some extent the horizontal dimensions of the rooting volume.

THE ROOT SYSTEM OF COCOA

Various authorities have described the root systems of cocoa growing in different parts of the world. Their descriptions differ only in detail.

Mature cocoa growing on deep well-drained soils possesses a bulky tap root which usually penetrates to a depth of about 1.0 to 1.5 metres (4 to 5 ft.), although Charter (1948) pointed out that thin terminal roots may penetrate much deeper and, in some soils, may reach depths of up to 3 metres (9-10 ft.). In soils lacking any physical obstructions to downward growth the tap root is commonly straight and undivided (Figure 1b) but in passing through gravel-concretion layers it may split into one or more main divisions and follow a tortuous path (Hardy, 1960, Charter, 1948) (Figure 1a). The tap root terminates in a number of fine rootlets but these carry few, if any root hairs and the role of the tap root is a subject of mild controversy between authors. Some assert that its function is largely confined to anchoring the tree (van Himme, 1959), others assert that it is equally important in nutrition (Aubert and Moulinier). There is no doubt, however, that cocoa is mainly a lateral feeder.

There is a definite collar where the tap root meets the trunk and most of the lateral roots arise just below this collar (Hardy, 1960). Out of about 12 lateral roots developed by the young tree, 8-10 progressively assume greater importance, the most vigorous being those closest to the collar. In a large number of root systems examined by van Himme (van Himme, 1959), 56% of the principal laterals arose from the top 10 cms. of the tap root; 26% from the next 10 cms; 14% between 20 and 30 cms; and only 4% were more than 30 cms. below the collar. The lateral roots show marked chemi-tropism and almost all arising from the top 30 cms. of the tap root grow rapidly upwards and ramify in the top few centimetres of the soil. The few remaining grow downwards towards the parent rock or water table (Hardy, 1960; Charter, 1948).

The principal lateral roots are thin and sinuous, frequently changing direction at acute angles to avoid obstacles. They give off many side branches, divide repeatedly, and at their extremities develop long tufts of fibrous rootlets and root hairs (Hardy, 1960; van Himme, 1959). These rootlets, which are concentrated in the organic litter and frequently are exposed at the surface, are dark brown in colour and fairly hard, in marked contrast to the white and tender rootlets of coffee (van Himme, 1959).

The pronounced superficial character of the lateral feeding roots and rootlets of cocoa is clearly of great importance in assessing the suitability of soils for this crop. It should be noted, however, that in some young, very fertile soils, in which the surface concentration of nutrients is not marked, the vertical distribution of lateral roots about the tap root may be more symmetrical (Hardy, 1944). Wright (pers. comm.) reports this to be the case in certain calcareous soils of British Honduras and basaltic soils of Western Samoa.

van Himme (1959) has described the development of roots in seedling cocoa. The rootlet that will become the tap root grows rapidly but remains thin. It grows 6-7 cms. in the first two weeks and then more slowly, attaining a length of about 30 cms. after 4½ months. Principal lateral roots appear about two weeks after germination and attain a length of 8-9 cms. after 4½ months. van Himme draws the conclusion that potting baskets for cocoa seedlings should be, at least, 25 cms. long and 12 cms. in diameter. In fan cuttings, roots are adventitious and a secondary tap root usually develops from a bud on the main stem (McKelvie, 1962). van Himme, however, asserts that such tap roots are similar in all respects to those produced by seedlings.

In old cocoa, 30-40 years or more in age, the trunk and root system commonly become senile and decay, to be replaced by chupons which develop their own tap root and lateral root system in a way similar to the parent tree (Figure 1d). Replacement of the parent tree in this manner occurs earlier where soil conditions are unfavourable than it does where soils are well suited to cocoa (Charter 1948).

The root system of cocoa shows some ability to adapt itself to adverse soil conditions as described in the following section.

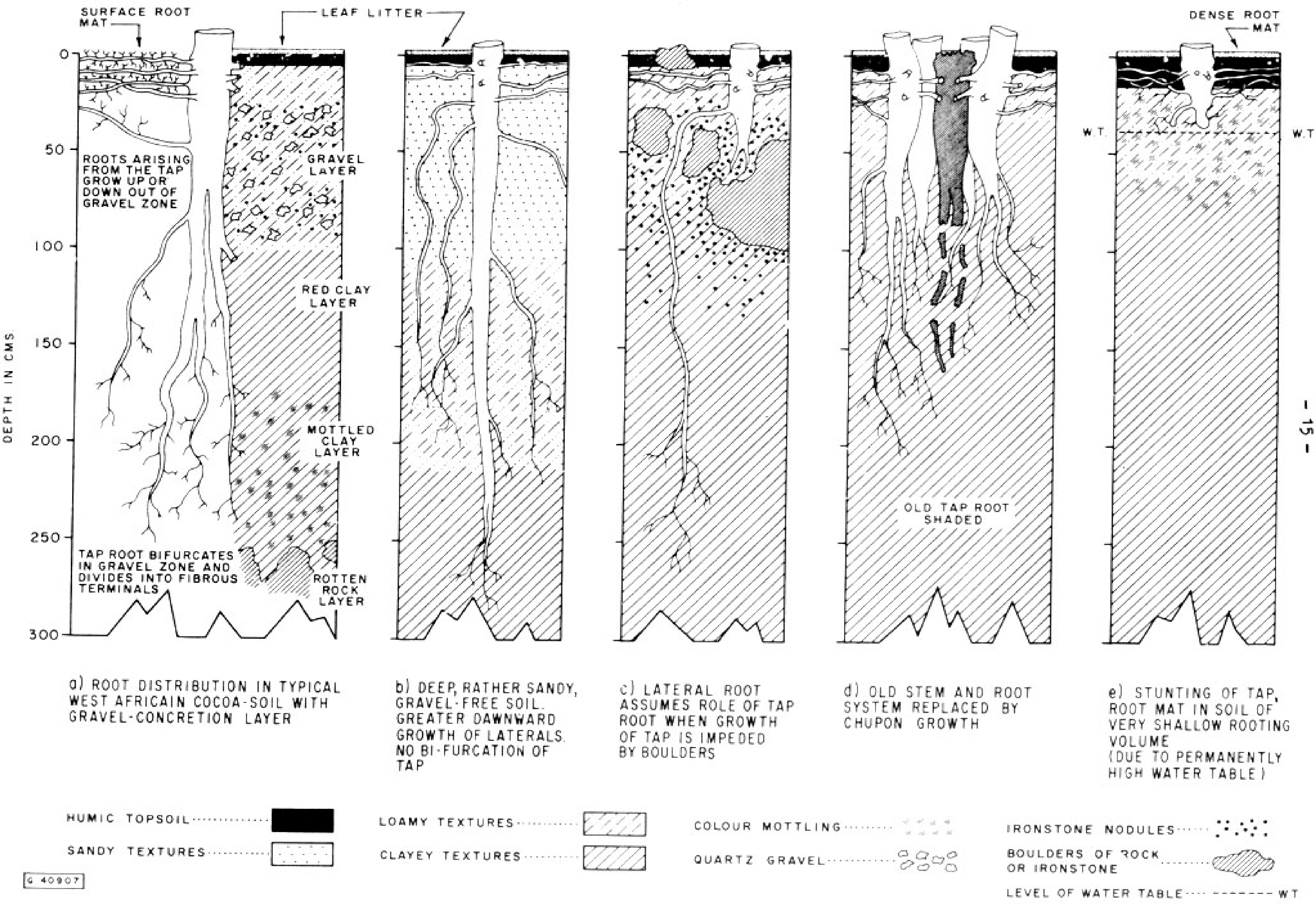
FACTORS WITHIN THE SOIL WHICH IMPEDE ROOT PENETRATION

The most obvious examples of inadequate rooting volume occur in soils which are shallow over a continuous rock surface, or an indurated layer, and yet it is surprising how frequently attempts are made to establish cocoa and other tree crops in such soils. Less obvious factors that may impede downward root growth include anaerobic conditions due to poor drainage; adverse textural or structural conditions; and excessive quantities of large particles, including rock fragments, quartz and ironstone gravels. These factors are discussed individually in the following paragraphs.

Drainage and Aeration

Frequent renewal of soil oxygen, required for root respiration, and the removal of carbondioxide and other gaseous products of this respiration, are essential for the active growth of cocoa roots. This exchange of gasses is largely effected by simple gaseous diffusion between the soil pores and the atmosphere and

Figure I - SOME FORMS OF COCOA ROOT DISTRIBUTION (Based Largely on Charter - 1948)



a) ROOT DISTRIBUTION IN TYPICAL WEST AFRICAIN COCOA-SOIL WITH GRAVEL-CONCRETION LAYER

b) DEEP, RATHER SANDY, GRAVEL-FREE SOIL. GREATER DAWNWARD GROWTH OF LATERALS. NO BI-FURCATION OF TAP

c) LATERAL ROOT ASSUMES ROLE OF TAP ROOT WHEN GROWTH OF TAP IS IMPEDED BY BOULDERS

d) OLD STEM AND ROOT SYSTEM REPLACED BY CHUPON GROWTH

e) STUNTING OF TAP, ROOT MAT IN SOIL OF VERY SHALLOW ROOTING VOLUME (DUE TO PERMANENTLY HIGH WATER TABLE) may cease (or be greatly reduced), if the pores are even partially filled with water. Thus, in a poorly drained soil downward growth of the roots will halt at levels in which anaerobic conditions prevail continuously. Evans (pers. comm.) cites an extreme example of such conditions in riverain alluvial soils with a high watertable in British Guiana, where all but the surface roots of plantation cocoa end in knobs a few inches from the surface and the trees need to be propped artificially to prevent them falling over!(see Figure 1e and Figure 2) Evans states that abnormal root development of this kind is not uncommon on the heavy clay soils of north eastern Trinidad and probably elsewhere in the world where a moderately deep humic layer overlies stiff poorly-aerated clay. In these circumstances, cocoa develops an especially dense mat of fibrous rootlets in the surface horizons (McCreary et al, 1943; Charter 1948) and fairly satisfactory growth and yield may be obtained. Nevertheless, cocoa growing under such conditions is extremely sensitive to relatively minor changes in the moisture regime of the soil and, if the watertable falls, the very shallow root system is left high and dry and the tree dies rapidly from drought (Alvim, 1959, Smyth and Montgomery, 1962; Charter, 1948).

The roots of cocoa appear to be tolerant to short periods of inundation so that root growth is not seriously impeded by a fluctuating water table providing the inherent drainage of the soil is good and good aeration is rapidly restored at depth once the water level falls. On heavy clay soils, subjected to periodic flooding, the tap root may penetrate deeply during dry periods but is often thin and has many branches following the cracks which open in the soil (McCreary et al, 1943). Conversely, on deep sandy soils, which dry out rapidly to depth, a number of the lateral roots grow vertically downwards towards remaining sources of moisture (Charter, 1948).

Texture and Structure

Soil texture is a measure of the relative abundance of particles of sand, silt and clay sizes in a given mass of soil, such as a single soil horizon. The textural characteristics of a soil depend not only on the particle size distribution in any one horizon but also on the vertical arrangement of horizons of differing texture.

In fact, the distinction between sand and clay particles does not rest only on size, for some forms of clay mineral have the ability to absorb water within their crystal structure and thus of expanding very considerably when moistened. The much larger sand grains and silt particles do not possess this property.

In sandy soils, large voids very rarely form, since individual sand grains are unaffected by moisture and lackthe cohesion required to stabilize tunnels and fissures made by animals and plant activity. Thus, ease of root penetration in a sandy soil depends very largely on the size of the pore spaces between the sand grains through which the root tip must be insinuated as the root advances. To some extent, the growing root may be able to push grains to one side, but this will not be easy in a normally compacted sandy soil and the roots of cocoa have been shown to be exceptionally sensitive to physical obstructions (van Himme, 1959). Hardy (1960) points out that even the smallest root tips have finite dimensions of the order of 0.1mm. diameter. Pore spaces of similar diameter would, in theory, exist between close packed uniform spheres 0.33 mm. in diameter which correspond in size to grains of medium sand (in the U.S.D.A. system of particle size classification). Larger pore spaces, adequate to receive the larger root tips would be common only in even coarser textured sand. Thus Hardy blames failure experienced with fine textured propagating media to poor root penetration as well as to poor drainage. He advocates very coarse

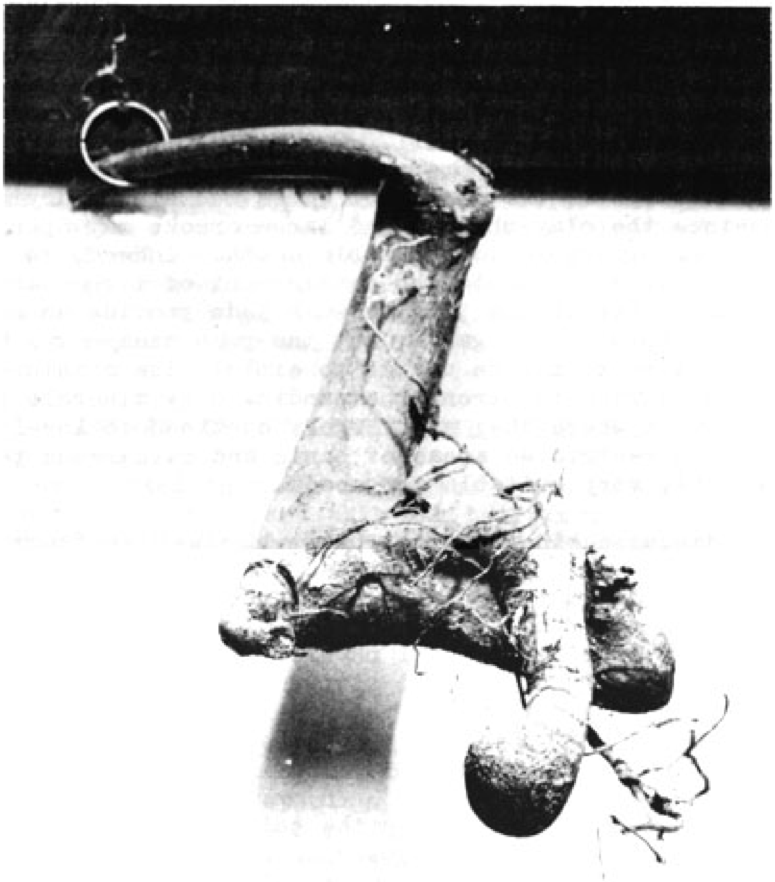


FIGURE 2:- Stunting of the roots of cocoa grown in British Guiana in soils having a permanently very high water table. (Photo by courtesy of Dr. H. Evans).

sand or fine gravel, "whose particle size is about the same as a small rice grain" (Hardy, 1960), as the best sandy medium for use in rooting bins for cocoa cuttings. Structureless, fine sandy soils, which commonly occur on river levées, should be avoided for the field planting of cocoa partly for the same reasons.

In a clayey textured soil, ease of root penetration depends, in part, on the nature of the minerals which make up the clay fraction. If clay minerals having strong properties of expansion on moistening form a significant proportion of the clay fraction then ease of root penetration is likely to change considerably with changes in the moisture status of the soil. On wetting, swelling of individual clay particles tends to close the larger pore spaces to exclude air and to create a dense anerobic medium unfavourable to the growth of cocoa roots. On drying, more favourable conditions develop since the clay shrinks and large cracks may open permitting the penetration of roots and oxygen to considerable depth. Indeed, seasonal swelling and contraction in a clay soil may lead to the development of large structural units, or 'peds', within the soil. The spaces between such peds provide an easy path for the growth of roots and the movement of gases, but the peds themselves may become very hard on drying and plant roots may be unable to exploit the moisture which they retain. In fact, soils so rich in strongly expanding clay minerals are comparatively inextensive in the tropics where they are largely confined to low-lying flat areas, to valley bottoms and to restricted areas of basic and calcareous parent materials. They are not, in general, very suitable for cocoa.

Furtunately, as discussed in the first Chapter, the clay fraction of most soils in the humid tropics is composed of Kaolinitic clays and of iron and aluminium oxides. Such clay expands little when moistened and large structural peds are only weakly developed. Nevertheless, the finer particles tend to form stable aggregates of about coarse sand size and thus provide an ideal physical medium for the development of the cocoa root system. This finely aggregated structure is easy to recognize in the field since, whether moist or dry, handfulls of soil are friable, crumbling in the hands under only slight pressure, and the porosity of the soil between the aggregates is clearly visible.

Rapid changes of texture with depth in the soil can have a profound effect on ease of root penetration. Usually the proportion of clay in the soil increases with depth and, occasionally, soils may be encountered in which there is a clay 'pan' close to the surface. If the 'pan' is compact and poorly structured it may form a physical barrier to root penetration. Attempts to dig in such a soil will usually reveal the presence of the pan immediately, especially under dry conditions, and its effect on root growth can best be judged by studying the pattern of root development of existing vegetation.

More rarely and usually only in soils formed in alluvial or volcanic deposits, coarse sandy and gravelly horizons may be found below layers of finer texture, yet fairly close to the surface. Such horizons may also impede downward root growth since they are liable to remain dry even when the layers of soil above them are almost saturated.

Content of Large Particles

There is no doubt that excessive quantities of stones and gravel in the soil profile impede root penetration and cause bifurcation and poor development of individual cocoa roots, especially the tap root (Charter, 1948; Aubert and Moulinier, 1954). In some instances, when the downward growth of the tap root is prevented by large boulders, lumps of ironstone or by dense masses of concretions or gravel, one or more of the lateral roots may succeed in avoiding these obstacles and, taking over the role of the tap root, will grow downwards, sometimes reaching depths of over seven feet (2.1 metres) (Charter, 1948).

Good cocoa is to be found, notably in West Africa, growing on soils which contain substantial quantities of quartz and ironstone gravel below depths of 25-30cms. from the surface (Smyth and Montgomery, 1962). The problem is to decide what quantity of gravel should be regarded as excessive and this can be expected to vary from place to place, particularly in relation to the texture and consistence of the fine earth and to the size and shape of the gravel. It seems certain that any appreciable quantity of gravel in the top 25-30 cms. of the soil, where the bulk of the feeding roots of cocoa are normally developed, is undesirable. At greater depths quite large quantities of small stones and gravel are acceptable but should the quantity exceed about 40% of the total volume of any one horizon, the danger of severely impeded root penetration must be recognized. Once again a study of the root pattern of existing vegetation can provide a rough guide to the extent to which root penetration is impeded by gravel in a particular soil.

SUMMARY OF REQUIRED SOIL CHARACTERISTICS

Hardy (1958) has stated that for cocoa the depth of root-penetrable soil should be at least five feet (150 cms.) and this may be regarded as a useful general rule. However, deeper soils are desirable where average annual rainfall is low, especially if the soils tend to be rather sandy or nutritionally impoverished (Charter, 1948). Conversely, where all other aspects are particularly favourable, soils little more than a metre deep may be acceptable.

In many areas, soils derived from young colluvium may be best suited to cocoa. Such soils often include unweathered boulders and their effective depth may vary widely over a limited area. This necessitates checking the depth of soil at every planting hole and adjusting the position of holes to effect the best compromise between soil depth and desirable spacing. Auger borings provide the only practical approach to such checking but care must be taken not to be misled when penetration of the auger is prevented by relatively small stones.

CHAPTER THREE

MOISTURE AND AIR REQUIREMENTS

Few tree crops are more susceptible than cocoa to shortages of soil moisture. Poor soil aeration, usually caused by excess of soil moisture, can be almost equally detrimental to the health of cocoa. Therefore, in the selection of soils for cocoa very careful consideration has to be given to those physical characteristics of the soil which determine its ability to retain moisture. This is especially true in potential cocoa growing areas where there is a wide variation in the amount of rainfall received at different times of the year.

BIOLOGICAL EVIDENCE OF THE MOISTURE REQUIREMENTS OF COCOA

Alvim (1959) has discussed in some detail the available knowledge on the responses of cocoa to water shortage and, in a series of experiments, has shown that cocoa is less tolerant to drought than most tree crops. In an experiment which compared the wilting characteristics of detached leaves, he showed that the first signs of tissue death occurred when cocoa leaves lost about 17% of their original water content, whereas this figure was 22% in the case of coffee leaves subjected to the same treatment. When cocoa leaves lost 25% of their original water content, 50% of the leaf area was killed, whereas a 57% water deficit was required to kill an equal proportion of the coffee leaf area. Yet coffee itself is a plant with little tolerance to drought.

In other experiments, Alvim studied the opening and closing of leaf stomata and showed that those of cocoa were extremely sensitive to water deficiency. A loss of only 4.5% of the original water content of the cocoa leaf is apparently sufficient to induce complete stomatal closure and when a leaf with wide open stomata is plucked from the tree stomatal closure occurs within 5 or 6 minutes. By way of comparison Alvim (loc. cit.) states that in the case of rubber and mango stomata close 10 to 15 minutes after leaves are removed from the plant and that in most plants, including coffee, citrus and bananas, the process takes at least 20-30 minutes. In pot experiments on 6-month-old cocoa seedlings, stomatal opening started decreasing when soil moisture was reduced to about 60% of the available range between field capacity and permanent wilting point. Closure was complete when soil moisture approached the permanent wilting point.

Stomatal closure drastically reduces carbon dioxide absorption and also transpiration by the plant and thus the results just described go far to explain the results of Lamée's experiments (Lamée, 1955) on the effects of water deficiency on the photosynthetic, transpiration and growth rates of cocoa. These showed that the photosynthesis of seedlings was reduced from 90% to 30% of the maximum rate when soil moisture was reduced from two-thirds to one-third of the available range; that transpiration was reduced to about 20% of the maximum value when soil moisture reached one-third of the available range; and that growth diminished progressively when soil moisture dropped below about two-thirds of the available range. At or near the wilting point, growth and photosynthesis virtually ceased and transpiration was reduced to about 10% of the maximum value.

A particularly interesting feature of all these results, of special importance in considering irrigation practice for cocoa, is that they show that cocoa begins to suffer moisture stress when soil moisture is reduced below about two-thirds of the available range between field capacity and the permanent wilting point. In other words quite a slight reduction in soil moisture status may be deleterious to cocoa and growth will be severely impeded well before the permanent wilting point is reached.

FACTORS WITHIN THE SOIL WHICH AFFECT MOISTURE RETENTION, DRAINAGE AND AERATION

General Considerations

Under forest, or a well-developed cocoa canopy, the surface soil usually has an open structure readily permitting the penetration of any rainfall which reaches it and, under these conditions, loss of moisture through surface run-off can be regarded as negligible (Hardy, 1960). After a heavy rain shower almost all the interconnecting pores in the upper horizons of the soil may be filled with water and the soil air displaced. However, assuming the lower soil horizons are not saturated and free escape of water to depth is possible (i.e. the soil has 'good drainage'), the water held in the larger pore spaces of the upper horizons rapidly drains away under the influence of gravity and is replaced by soil air. Moisture then remains only in the smaller interstices, especially in the minutely porous colloidal material comprised of clay and humus, where capillary and other attractive forces are sufficient to resist the pull of gravity. After two or three days, if no further rain falls, downward movement of moisture under gravity becomes negligible in most soils and a soil in this condition is said to be at its 'field capacity'.

The suction which roots must exert to remove moisture from a completely saturated soil is virtually zero. Once the larger pore spaces are emptied, however, a suction force must be applied to remove moisture from the smaller interstices and the required force increases very greatly as the soil dries out progressively. In most soils a suction equivalent to one atmosphere is required to remove moisture when the soil is at 'field capacity'. As the required suction increases so it becomes increasingly difficult for the plant to obtain the moisture it requires until a point is reached when the plant can no longer obtain sufficient moisture even to maintain turgor in its soft aerial parts. The moisture status of the soil is then said to have reached 'wilting point'.

The importance of these considerations lies in their indication that not all of the moisture held in the soil is equally available to cocoa or to any other plant. The available range of water holding capacity is commonly taken to be the range of moisture content between 'field capacity' and the 'wilting point'. This is not strictly correct since a plant can readily obtain moisture from the larger pore spaces in a partially saturated soil, provided at least 10% of these spaces offer free air movement to permit healthy root growth (Hardy, 1960). Furthermore, the evidence given in the early part of this Chapter shows that the growth processes of cocoa are severely affected by moisture shortage long before the wilting point is reached.

Properties of moisture retention within the soil constitute only one of several factors which decide the drainage qualities of a soil. Other factors, external to the soil, are discussed later in this Chapter. Since air and water occupy the soil pores in reciprocal amounts, the most important direct effect of poor soil drainage is in relation to root aeration. By filling the larger soil pores, excess water excludes air and drastically reduces gaseous exchange between the soil and the atmosphere. This leads to a shortage of oxygen and to an accumulation of carbondioxide in the soil both of which inhibit root respiration and prevent the roots from developing the energy which they require to absorb moisture and nutrients. An example may be quoted from the Cauca Valley in Colombia, where cocoa growing on poorly-drained soils showed stomatal closure in the midday hours, indicative of great reduction in the rate of life processes, although more than adequate moisture was present in the soils. Alvim (1959) describes this cocoa as suffering from "physiological drought" induced by poor soil aeration.

Experiments on soil aeration under cocoa conducted by Vine and others (1942,1943) in Trinidad suggest that anaerobic conditions, unfavourable to the growth of cocoa, prevail in the soil when the volume of free air space falls below 12% of the total soil volume. In the soils studied in these experiments, marked differences in the quantity and composition of soil air during wet and dry seasons were noted, as is to be expected. Under dry soil conditions the soil air in all the soils examined contained adequate oxygen (taken to be 10% or more) to meet the needs of actively growing cocoa roots to depths of at least four feet. Under wet soil conditions, even the sandy soils examined often contained considerably less than 12% free air space in their top 12 inches and in most of the soils there appeared to be inadequate oxygen for root growth at depths below 18 inches. Toxic levels of carbon dioxide accumulation (taken to be 6% or over) were noted in the top four inches of some soils under wet conditions and exceptionally high levels of carbondioxide (in excess of 10%) were recorded within 12 inches of the surface. Hardy (Vine et al, Part III 1943) discussing these investigations, pointed out that in an average Trinidad cocoa soil, toxic concentrations of carbondioxide could be expected at and below depths of 75 cms. (2½ feet) under normal Trinidad moisture conditions (i.e. about three quarters of saturation).

In Trinidad, and indeed most other areas, the main growing and fruiting period of cocoa coincides with the wet season when conditions of soil aeration are least satisfactory. Thus it was concluded from the experiments in Trinidad that fluctuations in oxygen supply during the period of most active growth must greatly affect the performance of the tree and that high cocoa production can only be expected on freely-drained and exceptionally well-ventilated soils. These conclusions are no doubt valid in other cocoa-growing areas although average conditions of soil drainage and aeration are more favourable in many areas than they are in Trinidad.

Soil Texture and Structure

The importance of soil texture and structure was discussed in the previous Chapter in relation to root penetration. The differing physical properties of particles of sand and clay sizes are no less important in relation to moisture retention and drainage within the soil. Moisture is retained most strongly in the smallest pore spaces in the soil so that the drainage qualities of a soil are closely related to the proportion of large and small sized pores which it contains. In turn, the size of pores is related to the effective average particle size in the soil which depends not only on the proportion of sand, silt and clay sized particles (i.e: - on the texture of the soil as determined by laboratory mechanical analysis) but also on the degree to which the finer particles are aggregated together to form larger fairly stable particles (i.e: - on the structure and micro-structure of the soil).

Coarse sandy soils have a very low capacity for moisture retention since only a very small proportion of their pore space is of capillary size and moisture is retained only as a thin film on the particles themselves and as small wedges between the particles. The moisture content of a sandy soil at field capacity may be less than 15% by weight and only one or two percent of this moisture will be available to plants. In consequence, however, sandy soils have excellent properties of drainage and aeration.

A clayey soil usually contains a far greater volume of pore space per unit volume of soil than does a sandy soil. There is also much greater variation in the size of the individual pores in the clay soil and greater variation in the proportion of pore space available when the soil is wet or dry. On wetting, very large amounts of water can be absorbed on and between the surfaces of the minute clay particles and absorbed, to a greater or lesser extent depending on the nature of the clay minerals, within the clay particles themselves. At field capacity a clay soil may contain 50-60% by weight of water. As discussed in the previous Chapter, swelling and contraction of the clay may lead to the formation of large structural units in the soil between which both roots and air can freely penetrate. But relatively large quantities of water retained within the structural units may remain unavailable to plants. Indeed, quite a large proportion of all the moisture held in the minute spaces between and within the clay particles is retained by forces greater than can be exerted by a plant and appreciable amounts of water (30 to 40% by weight) may be held in a clay soil at its wilting point.

Better suited to cocoa than either clays or sands are the soils which are composed of mixtures of sand, silt and clay-sized particles. In the tropics, as discussed in previous Chapters, the finer particles in such soils are very often aggregated to form larger particles of about coarse sand size. The soils thus possess the desirable characteristics of free drainage and good aeration associated with coarse sandy soils, whilst retaining the properties of large moisture capacity and high moisture retention associated with their content of very small particles. In the uppermost horizons of the soil the aggregates are often larger and are mainly cemented by organic compounds derived from the breakdown of organic matter and secreted by the microfauna. Such aggregates are relatively unstable. When moist they break down readily under the impact of intense tropical rainfall so that aeration of the surface horizons may be impaired. The need to protect the surface structure from such bombardment provides an additional reason for maintaining a closed canopy over the cocoa farm. In the lower horizons of the soil the aggregates are cemented by other compounds, such as hydrated iron oxides, and are usually very stable, remaining unaffected by repeated seasonal wetting and drying of the soil. Free air and water movement and easy root penetration is usually possible, therefore, at considerable depths in mature tropical soils in upper slope sites. Their total pore space volume may exceed 60% and at field capacity they may hold 50% by weight of water.

Soil Colour

The colour of a soil does not affect its drainage and aeration but it does reflect these conditions and is, therefore, a characteristic requiring study in the selection of soils for cocoa. Differences in soil colour are, in part, due to differences in the degree of hydration and oxidation of iron compounds. The least hydrated, most highly oxidized, iron compounds are reddest in colour and soils that have a bright red matrix colour have excellent aeration and are rarely, if ever, saturated with water. Orange-brown, brown and yellow colours arise through hydration of the iron compounds and reflect slightly inferior aeration and longer periods of high moisture status in the soils.

Under anaerobic conditions, due to flooding, reduction of the iron compounds takes place to produce dull grey, blue and even green colours in the soil. Alternating aerobic and anaerobic conditions, which occur under the influence of a fluctuating watertable or periodic surface flooding, produce a mottled colour pattern in the soil with bright 'rusty-orange' patches of reoxidized material and dull coloured patches in which the iron remains in a reduced state. In clayey soils, especially those with rather poor structure, the presence of this type of colour mottling provides an accurate indication of the maximum rise of the water table within the soil. In coarser textured soils, however, the lack of such mottling is no guarantee that the watertable does not approach the surface at some time of the year, since, in soils with good aeration, reoxidation may be sufficiently rapid to mask the effects of temporary anaerobic conditions in the upper parts of the soil.

In many tropical soils, brightly mottled clays, in shades of red, brown, yellow and white, are found at depth. Although this mottled colouration may reflect poor drainage conditions in the past, the bright colours are indicative of present aerobic conditions and this type of mottling should not be confused with the mottling of presently poorly-drained soils described above.

FACTORS EXTERNAL TO THE SOIL WHICH AFFECT DRAINAGE AND AERATION

Factors external to the soil, notably the intensity and distribution of rainfall and the topographical position of the site, are especially significant in relation to soil drainage conditions in the tropics for, as described previously, the physical properties of tropical soils commonly favour free air and water movement. In freely-draining soils the downward movement of water is restricted only if the lower soil horizons are already saturated. This is most likely to occur in low topographical sites where the groundwater table may approach, or even rise above, the surface of the soil. Perched watertables over impervious layers are comparatively rare.

In tropical areas with a pronounced dry season the level of the groundwater table may fluctuate widely, often through several metres. These fluctuations are usually most marked in valley bottom sites high above the base level of major rivers. In valleys of this kind a temporary stream may flow for a few weeks at the end of the wet season but saturated or flooded conditions in the soil are likely to be only of brief duration and the water table may sink several metres below the surface during the dry season, even in the lowest sites. The success of cocoa planted near the bottom of such valleys depends very largely upon the extent to which the trees can succeed in developing a root system capable of maintaining an adequate moisture supply during the dry months.

Cocoa tolerates short periods of complete flooding but, if the watertable remains close to the surface for a large part of the year, anaerobic conditions in the soil will prevent the formation of deep roots and, unless the properties of moisture retention of the upper soil horizons are very favourable, cocoa planted under such conditions is likely to suffer and perhaps die from drought soon after the watertable falls away. An example may be quoted from Bahia, Brazil, where many cocoa trees died from water shortage during the severe dry summer of 1951-52 and where it was noted that the trees most frequently affected where those in lowlying sites, having shallow root systems due to wet season waterlogging (Alvim, 1959).

Fluctuations in the level of the watertable are usually less rapid and less pronounced in sites close to major rivers which flow all the year round. Here it may be possible to select areas for cocoa with a fair degree of certainty that the root systems are unlikely to be left high and dry. Even in these circumstances, however, a continuously high watertable must be regarded as far from ideal for cocoa since the trees, forced to rely upon a dense surface root mat, will be extremely susceptible to unexpected droughts encountered in exceptional years.

SOIL MOISTURE REQUIREMENTS UNDER DIFFERENT CLIMATIC CONDITIONS

From the preceding discussions it will be apparent that the selection of soils for cocoa involves a delicate compromise between two partially opposed requirements, that of good moisture retention on the one hand and that of good drainage and aeration on the other. A soil which combines these requirements, by virtue of its content of well-aggregated fine particles, can be regarded as ideal for cocoa under any climatic condition in which the crop will grow. However, the extent to which soil physical characteristics can be allowed to depart from this ideal or, in other words, the range of soil physical characteristics which can be regarded as acceptable for cocoa varies from area to area in accordance with differences in climate and, in particular, with differences in the volume and distribution of rainfall.

In areas where rainfall is very heavy throughout the year, as in parts of New Guinea and the Cameroons, adequate root aeration is a primary consideration and exceptionally well-ventilated soils on gently-sloping sites high above the reach of groundwater are most suitable for cocoa. Under these conditions clayey textures are acceptable only when good aeration is preserved by stable aggregation of the finer particles and the clay minerals have low properties of expansion. Course sandy soils have physical properties appropriate to such areas but under continuous rainfall their nutrient status is likely to be so low, and further nutrient losses due to leaching so heavy, that their use for cocoa may prove impractical. Nevertheless, in areas where there is little or no risk of drought, and where the use of fertilizers is economically possible, sandy soils may be accepted as marginal for cocoa, especially when they are well supplied with organic matter. Organic matter is especially important in the soils of high rainfall areas. In soils of sandy texture it serves as a storehouse for moisture and plant nutrients and, in finer textured soils, it serves to improve topsoil structure and thus aeration. In an experiment conducted on heavy clay soils in Surinam, for example, organic matter content was the soil factor most closely correlated with pod production over a five year period on young clonal cocoa (see Figure 3). The higher yields on soils with higher organic matter content were ascribed, in this case, to improved topsoil structure and better air/moisture relationships (Amson and Lems, 1963).

Where rainfall is moderate to low and especially where a dry season is fairly pronounced, as in most of West Africa, problems of moisture supply are more severe than those of aeration and sandy soils with excessively free drainage are to be avoided. In Western Nigeria, for example, where rainfall distribution is far from optimum, it was concluded that a minimum of 25% clay plus silt was required in the fine earth fractions of soil horizons between depths of 10 and 20 inches (25-50 cms.) to support healthy cocoa (Smyth and Montgomery, 1962). The best soils for cocoa under Western Nigerian conditions appeared to be those with 35 to 55% clay plus silt (the silt content being low) in all horizons.

Where rainfall conditions are marginal special attention should be paid to topographical position in the selection of planting sites for cocoa. So long as rainfall is adequate, well-drained upper slope sites are to be preferred since in these sites root penetration is less likely to be impeded by a seasonally high water table and the environmental conditions in general, and lower humidity in particular, are less favourable to the spread of insect and fungal pathogens. However, where total precipitation is low or the dry season too prolonged for healthy growth, as is the case near the forest-savanna boundary throughout most of West Africa, cocoa must either be. irrigated or planted in valley bottom sites where trees can draw benefit from the proximity of seasonal streams and groundwater (Aubert and Moulinier, 1954). Under such conditions, soils having a high content of clay in their upper horizons and a correspondingly high capacity for moisture retention are essential for non-irrigated cocoa.

The choice of site is especially difficult in areas having a climate that combines very heavy wet season rainfall with a severe and prolonged dry season, as in the Eastern Provinces of Sierra Leone. Here the benefit of dry-season groundwater in

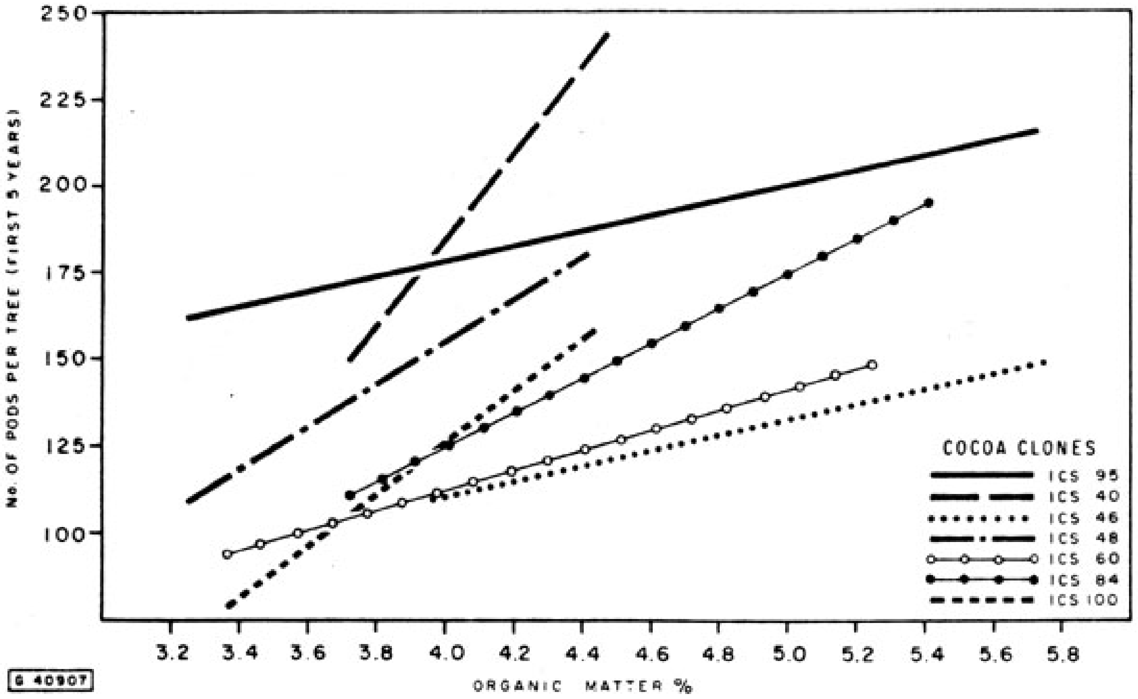


FIGURE 3:- Graph showing the relationships between organic matter content and pod yield in a clonal cocoa experiment on soils of poor drainage in Surinam (from Amson and Lems, 1963).

lower slope sites may be essential to healthy growth of cocoa but the soils chosen must be well-drained to minimize the effects of poor aeration during the periods of heavy rainfall. Permeable soils in which rapid and deep root growth is possible, occupying terrace sites immediately above areas of prolonged flooding, are best suited to cocoa in these circumstances.

The range of acceptable textures is widest in areas where rainfall is adequate, but not excessive, throughout the year. Under such conditions, texture is of relatively minor importance in the selection of soils for cocoa since only the extremes of texture, the pure sands and the strongly cracking clays, need to judged as physically unsuitable. As climatic conditions depart from this ideal so the range of acceptable textures narrows, although optimum textural conditions remain very similar throughout the possible climatic range. Thus, in a dry or strongly seasonal climate, a fairly heavy clay may be acceptable but not a loamy sand* or coarse sandy loam, whilst in very wet climates the reverse is likely to be the case. In both climates, however, an intermediate texture such as sandy clay, clay loam or fine sandy clay loam can be expected to prove the most suitable for cocoa. Where the acceptable textural range is narrow and changes in soil texture occur frequently within limited distances, which is the case in many parts of West Africa, it is particularly difficult to find contiguous areas of suitable soil for the establishment of large cocoa plantations.

Where textural changes occur within the soil profile, the influence of the various horizons on the suitability of the soil for cocoa under given climatic conditions will depend not only on their textural dissimilarity, but also on their thickness. As Aubert and Moulinier (1954) noted in the Ivory Coast, for example, a fairly sandy topsoil may serve to offset the disadvantages of a rather too clayey subsoil. This is especially true in regions of high rainfall where the accumulation of cocoa feeding roots close to the surface would otherwise be rendered inactive by conditions of poor aeration. On the other hand, deep sandy textured surface horizons effectively constitute a sandy soil and, in drier areas in particular, it is important that horizons with a reasonable capacity for moisture retention be found close to the surface. These considerations raise the question of the depth at which soil textures should be determined in assessing the relative suitability of soils for cocoa. This question is discussed in some detail in Chapter Five.

---

* Textural names refer to the U.S.D.A. textural classification (U.S.D.A., 1951)

The marked changes in chemical character which occur at different levels below the surface in most soils complicate the problem of interpreting analytical data in relation to the needs of a deep rooted crop such as cocoa. It is very difficult, if not impossible, to arrive at an integrated assessment of the contributions which these differing layers will make towards the overall ability of the soil to supply plant nutrients. The problem may be less severe in the case of cocoa than with many other tree crops, for as described in earlier Chapters, a large proportion of the feeding roots of cocoa are to be found in the surface soil layers where, in most areas potentially suited to cocoa, there is a marked concentration of plant nutrients. These considerations indicate that analysis data from the top 10 to 15 centimetres (4-6 ins.) of potential cocoa soils are likely to be especially informative.

Nevertheless, in selecting soils for cocoa we should not ignore the chemical properties of deeper soil horizons. In the first place, the enriched layers may be very thin and may differ very greatly in nutrient status from the soil immediately below; points which are illustrated by the data given in Tables 2, 4, 6 and 7. Secondly, the high levels of fertility found in surface horizons largely reflect the contribution of organic matter, both as a source and as a means of retaining nutrient elements; a contribution which may diminish significantly within the desired life of a cocoa plantation. Lastly, the chemical characteristics of mineral component of the soil, which are more permanent in nature and which are most clearly reflected in the analysis data of sub-surface horizons, may have an important positive or negative influence on the suitability of a soil for cocoa.

In young soils formed from nutrient-rich parent materials, the nutrient contribution of fairly deep horizons can be expected to be substantial and to become increasingly important in relation to that of the surface horizons as the cocoa grows older. Brammer (1959) reports that the best cocoa crops obtained in the Forest Ochrosol Zone of Ghana are to be found on relatively immature soils over biotite or hornblende schists and granites, where roots can reach the zone of rock-weathering within about 5-10 feet of the surface; "good yields are maintained up to about forty years on such soils" whereas on other soils in the same zone "yields decline greatly in most cases after about twenty to thirty years from planting". On the other hand, excessively alkaline or acidic horizons within a metre, or so, of the surface, may inhibit downward root growth and have other adverse effects on the nutrition of the tree. Some account can be taken of these factors in making broad assessments of the suitability of a soil for cocoa but the problems of interpretation which they invoke severely limit the possibilities of drawing subtle distinctions on the basis of laboratory data.

Nutrient Exchange Characteristics

The laboratory data which are most informative in drawing broad conclusions on the relative suitability of soils for cocoa are those which relate to the ability of the soil to store and release nutrient elements, namely "base (or cation) exchange capacity" and "organic matter content", and those which indicate the extent to which this storage capacity is filled with nutrients, namely 'percentage base saturation' and 'pH'.

(a) Base exchange capacity

(a brief explanation of 'base exchange capacity' is included in the Appendix).

The higher the base exchange capacity of a soil, the more likely is it that the soil in its natural state will be able to supply the nitrient requirements of a plant in balanced amounts. Furthermore, additional nutrients, in the form of fertilizers,

TABLE 2:- The Average Nutrient Content of the Surface Layers of some Soil Associations in Western Ashanti, Ghana (selected from Radwanski (1957))

Soil Association	General Suitability of Association for Cocoa *	Approx. Depth	% Organic Matter	pH	% Free $CaCO_3$	Cation Exch. Capacity me./100grms. Soil	Exchangeable Cations me./100 grms. soil		
							Ca	Mg	K
Kese	Very good	0-3"	10.10	7.31	0.221	47.32	40.41	8.02	0.71
		3-8"	3.03	6.65	0.123	29.74	21.37	5.32	0.32
Adujansu	Good	0-3"	6.82	6.42	0.061	22.54	15.62	4.35	0.53
		3-8"	1.74	5.91	nil	9.22	3.82	1.03	0.20
Fwidiam	Good	0-3"	6.65	7.07	0.095	21.04	17.24	3.46	0.57
		3-8"	1.29	6.03	0.029	9.60	6.86	1.10	0.19
Kumasi	Good	0-3"	8.24	7.00	0.073	20.50	16.77	2.81	0.72
		3-8"	2.40	6.80	0.012	8.39	4.70	1.27	0.27
Akumadan (forest phase)	Poor	0-3"	4.30	6.61	0.062	16.50	12.40	2.30	0.35
		3-8"	1.72	6.28	0.001	6.70	4.60	0.96	0.14
Atukrom	Poor	0-3"	5.04	5.65	nil	18.73	9.20	3.30	0.35
		3-8"	2.27	5.52	nil	13.34	4.93	2.50	0.21
Pepri	Poor	0-3"	4.00	6.42	0.030	13.64	10.14	1.80	0.65
		3-8"	1.01	6.30	0.006	4.63	2.63	0.60	0.25
Achinasi	Very poor	0-3"	3.90	5.12	nil	12.30	5.11	1.22	0.33
		3-8"	1.60	4.85	nil	7.22	1.45	0.28	0.15

* Estimates of the general suitability of the various associations for cocoa are based on comments given in the text of Radwanski's paper (Radwanski 1957).

In the West Indies, chlorosis of cocoa leaves (loss of green colouration) due to iron deficiency has been noted on moderately alkaline soils which include free calcium carbonate in the surface horizons (Havord, 1954).

Similarly, Cunningham (1964) related symptoms of iron, manganese and zinc deficiency in some Ghanaian cocoa to moderately alkaline soil conditions (pH 7.9). In pot experiments, Cunningham (loc. cit) was able to show that incidence of abnormal leaves due to micronutrient deficiency was greatly reduced, and those due to zinc deficiency completely eliminated, when the pH of the potting mixture was lowered from 8.0 to 7.2 by the addition of sulphur. Induced deficiencies of micronutrients are doubtless one reason why cocoa growth is found to be less satisfactory on soils of pH higher than 7.5.

In very acid soils, on the other hand, the high availability of iron and possibly of manganese, zinc and copper, could have toxic effects on the growth of cocoa. Jones (personal communications) reports that cocoa growing on 'acid pegasse' soils, of pH about 4.0, in British Guiana was reasonably healthy in sites where the concentration of 'water-soluble' iron in the soil was below 50 ppm, but was stunted and produced unhealthy looking, yellowish coloured leaves on soils having 250-300 ppm 'water-soluble' iron. The leaf symptoms were similar to those associated with nitrogen deficiency but the trees did not respond to applications of nitrogen.

Hardy (1960) has suggested that cocoa, like coffee and tea, is more tolerant to acid soil conditions than are many other tropical crops but the desirability of avoiding soils of pH below 6 is supported by data from Ghana given in Table 3. In presenting this data in its original form, Charter (1955) emphasized that the sample sites were scattered throughout the forest region of Ghana and that they could be considered to have been selected at random as far as land-use was concerned. He considered it reasonable to assume, moreover, that peasant farmers had attempted cocoa planting on most of the sites sampled, so that the distribution recorded provides an indication of the relative survival of cocoa on soils of differing surface soil pH. In the form in which this data is now presented it will be noted that the distribution of cocoa shows a bias in favour of survival on soils of pH higher than 6.0 and against survival on soils of lower pH. Although a high rate of survival is recorded on sites of pH 'more than 7.4' it is unlikely that values very much higher than 7.4 were recorded in the forest belt of Ghana.

The pH values which have been quoted refer to pH determinations made on a 1:1 mixture of soil and water. pH can also be determined on a mixture of soil and a Normal solution of potassium chloride. In almost all soils the latter method yields appreciably lower values for pH. One exception to this rule, however, concerns highly weathered tropical soils developed on basic rocks which have unique exchange properties in their subsoil horizons and which yield higher pH values with potassium chloride than with water. Although the physical characteristics of these soils may appear almost ideal for cocoa, their subsoil horizons contain little or no exchangeable bases and, nutritionally, they are totally unsuited to cocoa. Soils which are very deep, very friable, neither sticky, nor plastic in consistence despite a clayey texture and are dark red to dark reddish brown in colour can be suspected to possess these undesirable exchange properties.

TABLE 3:- Distribution of Cocoa in Ghana in Relation to Surface Soil pH
(Recalculated from data given by Charter (1955))

pH Range of Surface Soil	less than 4.0	4.0- 4.4	4.5 4.9	5.0 5.4	5.5 5.9	6.0 6.4	6.5 6.9	7.0- 7.4	more than 7.4	TOTAL
Total soils examined a) No. of soils in each pH range	12	88	223	495	417	424	271	209	60	2199
b) % of total soils in each pH range	0.5	4.0	10.1	22.5	18.9	19.2	12.3	9.5	2.7	100%
Sites supporting cocoa c) No. of cocoa sites in each pH range	0	0	13	55	84	129	95	91	31	498
d) % of total cocoa sites in each pH range	0	0	2.5	11.0	16.8	25.9	19.0	18.2	6.2	100%
Distribution Ratio:- $\frac{(d)}{(b)}$	0	0	0.25	0.48	0.89	1.35	1.54	1.92	2.30	

NOTES: (a) In the above table pH data determined colourimetrically and electrometrically, quoted separately by Charter, have been combined.

(b) The 'distribution ratio' is merely a device for relating the proportion of a particular crop found on a particular soil to the availability of that soil in the area. If there was no relationship between cocoa distribution and soil pH in Ghana the 'ratio' for each pH range should be close to 1.0. Values rising above 1.0 indicate preferential survival of cocoa on soils having the pH range in question. Values below 1.0 indicate reduced survival. (see Chapter Five).

Carbon/Nitrogen Ratios (a brief explanation of the significance of these ratios is included in the Appendix).

Hardy (1958, 1959, 1960) has laid particular stress on the value of the carbon/nitrogen ratio as a means of distinguishing good from bad soils for cocoa and has suggested a value of 9.0 as the lowest acceptable C/N ratio ("limit of adequacy") in the top 0-6" (0-15 cms.) of soils being considered for the crop. He argues that in soils in which organic matter is not constantly replenished and in which, as a result, C/N ratios fall below 10, "the store of nutrient bases and of phosphorus rapidly diminishes, though the soil may still be capable of supplying nitrogen" (Hardy, 1958). Havord (1959) considers that low carbon/nitrogen ratios in Trinidad, which Hardy had shown were correlated with low yields of cocoa, can be attributed on the island to 'degradation' of topsoil following long term substitution of the original forest cover by cocoa sometimes preceded by arable crops. The carbon/nitrogen ratio, together with determination of organic matter content, appears to provide a satisfactory measure of the present suitability of these particular soils for cocoa. This may be especially true of some Trinidadian soils, and possibly of soils from other areas which Hardy considers, in which the soil horizons below the layer of organic matter accumulation are poorly suited to cocoa. That Hardy himself was thinking on these lines is illustrated by the possible explanations for low carbon/nitrogen ratios which he offered, namely; accumulation of nitrogen by leguminous shade trees commonly planted between cocoa in the West Indies; decreases in leaf litter under cocoa in comparison with that under natural forest; and, erosion of the topsoil which might occur under poorly shaded cocoa or cocoa planted on steep slopes (Hardy, 1959).

From Hárdy's evidence it is very probable that soils with a C/N ratio below 9.0 in the surface horizon should be regarded as unsuitable for cocoa, but this statement requires qualification in two ways. Firstly, the depth of the 'surface horizon' sampled for this purpose should not be chosen arbitarily, but should be adjusted to coincide with the thickness of the layer of organic matter accumulation in the soil, established by field observation. In many tropical soils this layer is appreciably thinner than the 15 cms. (6 inches) commonly used for surface soil analysis. Inclusion of material from lower horizons provides a lower average value for C/N ratio and so gives a misleading indication of the state of decomposition of the greater part of the organic matter in the soil. Secondly, the statement will not be true of soils in which the subsoil horizons are exceptionally fertile by nature of their mineral assemblage and in which fertility is not primarily dependent, therefore, upon their organic matter content or its nature. The need for these qualifications is well illustrated by analytical data for soil on São Tome, given in Table 6 on which Lains E Silva (1958) reports that cocoa production is 'high'. It will be noted that values for base exchange and base saturation suggest that the deeper horizons of this soil are exceptionally fertile and that although a very low value is quoted for the C/N ratio (8.5) this refers to a surface sample 20 cms. thick and may not reflect, in fact, the condition of the bulk of the organic matter in the soil.

In most potential cocoa growing areas carbon/nitrogen ratios lower than 10 will rarely be found in the surface horizons of soils recently cleared from well developed natural vegetation. On the other hand, undesirably high values for this ratio (greater than about 14) may occur. These high values are suggestive of a shortage of nitrogen and, in some cases, of an undesirably slow rate of release of nutrient elements from the soil organic matter. In areas of very high rainfall, high C/N ratios are found in very acid soils, whilst in areas of rather low rainfall, high C/N ratios are found in soils under grassy vegetation (Nye and Greenland, 1960). In both cases, criteria other than that of the C/N ratios are likely to eliminate the soils from consideration for cocoa planting.

The value of carbon/nitrogen ratios in the selection of soils for cocoa lies, therefore, in the indication they provide of situations where surface soil fertility has been lost as the result of past agricultural practice, or erosion. If the majority of the soils under consideration are under natural forest, C/N ratios will provide very little indication of their relative merit.

The Level of Individual Nutrients

With present knowledge, laboratory determinations of the level of individual nutrients are of very limited value in the selection of soils for cocoa. In attempting to interpret such data it is essential to bear in mind the major difficulties which stand in the way of devising analytical techniques that will provide a reliable measure of the nutrient levels required to support a healthy crop.

The problems involved can be summarized under three headings:-

(a) The problem of determining what proportion of the total quantity of each nutrient element present in the soil is, in fact, available to cocoa;

(b) The problem of assessing the influence, if any, of other nutrients in the soil on the uptake of a particular nutrient;

(c) Problems related to the time and place of sampling for analysis.

In discussing pH, it was mentioned that nutrients are present in the soil in a variety of forms. This is illustrated in the case of soil phosphorus by data obtained by Bates and Baker (1960) for a soil in Western Nigeria and given in Table 4. This soil, although sampled under forest, belongs to a soil series widely used in Western Nigeria for cocoa. It is fairly obvious that not all nutrient forms will be equally available to plants and experience has shown that analysis data on the total amounts of individual nutrients present in a soil provide little guidance to the performance of crops.

TABLE 4:- Phosphorus in the fine earth fraction (less than 2mm.) and in ironstone concretions at different depths in a Western Nigerian soil (selected from Bates J.A.R. and Baker T.C.N. (1960).

	Worm Casts	0-2"	2-7"	7-12"	12-20"	20-30"	40-50"	60-73"
Total P in fine earth (p.p.m.)	603	553	210	283	275	230	252	260
Organic P in fine earth (p.p.m.)	450	405	95	70	45	42	50	103
Total P in concretions (p.p.m.)		718	715	665	563	570	510	358
'Available P' - Truog (p.p.m.)	32	29	1.5	1.7	1.2	1.2		

Determination of the proportion of the total quantity of a given nutrient which is available to plants in a particular soil is hampered by our present lack of knowledge of the exact method, or methods by which plants themselves obtain nutrients from the soil. Chemical reagents can be selected which also extract only a proportion of a given nutrient in a soil sample and the laboratory analysis of such extracts may yeild data which can be correlated with actual crop performance in field or greenhouse trials. In many areas, satisfactory correlation has been achieved in this way between analytical data and the performance of specific crops on specific suites of soil. Elsewhere, however, notably in the humid tropics where cocoa is grown, very little success has attended attempts to obtain such correlations, even when the test crop was a short-term arable variety. It can be presumed that this lack of correlation reflects differences in soil chemistry to which the analytical methods are insensitive but which affect nutrient uptake by the plant.

Thus, the significance of small differences in the level of individual nutrients, as determined by soil analysis, can only be interpreted with confidence within limited areas in which a relationship between the analysis values and crop performance has been established and calibrated experimentally. In the case of cocoa, practical problems of field experimentation make the establishment of such relationships extremely difficult.

Strictly speaking the required level for each nutrient cannot be established without reference to the level of other nutrients in the soil for, in some cases at least, uptake of a particular nutrient apparently present in sufficient quantity may be suppressed by the presence of excessive, or inadequate quantities of one or more other nutrients. The major plant nutrients, nitrogen, phosphorus and potassium, appear to be absorbed independently of one another (Sutcliffe, 1964) but excessive quantities of potassium, for example, are known to suppress root absorbtion of magnesium, manganese, zinc and other nutrients. Sickle-shaped cocoa leaves, symptomatic of zinc deficiency, have been noted in Ghana on trees growing close to heaps of rotting pod husks, which possibly serve as a source of excessive quantities of potassium (Chatt, 1953). Charter has suggested that some other instances of zinc shortage in cocoa trees in Ghana may be due to deficiency of magnesium in the soils, rather than to excess of potassium or to deficiency of zinc itself (Charter, 1955).

The problem of determining the required nutrient balance is very complex, for the ratios between laboratory determined levels of nutrients which could be regarded as acceptable for cocoa very probably differ in different environments and for different soils. Imbalanced amounts of minor nutrients, essential to plant growth although only in very small quantities, are unlikely to be detected by, or even considered in, normal analysis procedures. Yet the presence of deficient, or toxic, quantities of these minor nutrients could make nonsense of the most carefully considered analysis interpretation.

The requirements of a perennial crop such as cocoa for individual nutrients doubtless changes at different stages of growth and even at different seasons of the year. This raises a problem in determining what these requirements are, for an ideal soil would be capable of meeting the largest requirement of any particular nutrient at all stages of growth. More serious is the problem of determining the possible contributions of different layers of the soil towards meeting these requirements. This problem of interpretation has been referred to earlier, but is especially difficult in relation to the supply of individual nutrients. The marked differences between the level of 'available' phosphorus close to the surface and that at depth has been seen in Table 4. Comparable differences in the levels of other nutrients can be seen in Tables 6 and 7.

In view of these difficulties, it is not surprising that very few attempts have been made to establish standards for the level of individual soil nutrients required for cocoa. Hardy, however, on the basis of his very extensive experience of 'cocoa-soils', especially in the West Indies and in Latin America, has suggested standards for 'exchangeable' calcium, magnesium and potassium (i.e: exchangeable cations held in the exchange complex of the soil) and for 'available' phosphorus (i.e: that proportion of the soil phosphorus extracted by 'Truog's reagent'). These standards, which refer to values determined for the top 0-6 inch (0-15 cms.) layer of soil having loamy texture are shown in Table 5.

TABLE 5:- Provisional standards suggested by F. Hardy for assessing nutrient levels in cocoa soils.

(Top 6 inch layer)

Category of Soil	'Available' Phosphorus (Truog) p.p.m.	'Exchangeable' Bases me/100 grams of fine earth		
		Calcium	Magnesium	Potassium
High nutrient status1/	120	24.0	6.0	0.55
Medium nutrient status	60	12.0	3.0	0.35
Low nutrient status	20	4.0	1.0	0.20
'Limits of adequacy'2/	40	8.0	2.0	0.24

1/quoted by Hardy (1960) 2/Hardy (1958)

These standards provide a useful general guide to the level of soil nutrients desirable for cocoa, although failure to meet these limits does not, in itself, provide sound grounds for eliminating a particular soil from consideration for cocoa planting. Many of the better cocoa soils of West Africa, for example, fail to meet Hardy's "limits of adequacy" for 'available' phosphorus (see Tables 1, 4 and 6). Admittedly, responses to phosphatic fertilizers suggest that the phosphate status of some of these soils is indeed lower than desirable for cocoa.

With regard to the balance between individual nutrients Hardy (1958) has tentatively suggested that the ratio between values for exchangeable calcium and exchangeable magnesium (Ca/Mg) in the top 6" (15 cms.) of the soil should not be more than 4.0 and that between calcium plus magnesium in relation to potassium ((Ca+Mg)/K) should not be less than 25. Both Charter (1955) and Homès (1953, 1957) have stressed the undesirability of excessive amounts of potassium in relation to magnesium in soils being considered for cocoa. It is very doubtful, however, whether present knowledge justifies quotation of any numerical values for the desirable ratios between individual nutrients in relation to the soil requirements of cocoa.

Selected Analysis Data from Different Parts of the World

In preceeding sections emphasis has been placed on the difficulties attending the interpretation of individual aspects of laboratory data in relation to the requirements of cocoa. More informative is an overall comparison of such data with data obtained from soils known to support cocoa successfully. For this reason a section of laboratory data relating to soils used for cocoa in different parts of the world is given in Tables 6 and 7.

With one exception the soils for which data is quoted can be regarded as being suitable for cocoa and, in general, they meet the requirements for individual criteria suggested in previous sections. The exception is the soil of "Jerangau Series" from Malaya (Table 7). Although the physical properties of this soil appear to be almost ideal for cocoa (Panton, 1958) it will be noted that its chemical properties fail to

TABLE 4.- Selected analytical data for soils used for cocoa-growing in West Africa

Country	Soil Series	Depth of Sample (inches)	Carbon %	Total Nitrogen %	C/N Ratio	pH	B.E.C. me/100g. soil	% Base Saturation	Exchangeable Bases me / 100 grams fine earth							'Available' P ppm	Total P ppm	% Clay (in fine earth) < .002mm.
														Ratios				
									Ca	Mg	Mn	Na	K	Ca/Mg	Ca+Mg/K			
Ghana (source:- H.Brammer, 1959)	Wacri (developed on hornblende-biotite granodiorite)	0-1.5"	5.68	0.50	11.4	7.5	45.0		34.12	7.42	1.15	0.75	0.52	4.60	79.9		550	
		1.5-8"	0.84	0.10	8.6	7.1	10.3		5.99	1.25	0.15	0.18	0.12	4.79	60.3		341	10.8
		8-14"	0.20	0.03	7.1	6.5	5.8		1.89	0.64	0.10	0.13	0.10	2.55	25.3		274	7.1
		14-20"	0.21	0.06	3.4	6.3	5.1		2.55	1.07	0.13	0.18	0.15	2.76	26.8		318	17.3
		39-55"	0.29	0.06	5.0	5.6	19.5		5.12	5.57	0.08	0.22	0.11	0.92	96.5		257	43.3
	Kumasi (developed on biotite granite)	0-4"	3.86	0.25	11.7	7.5	23.5		14.58	4.00	0.23	0.48	1.35	3.65	13.7		333	20.6
		4-9"	0.71	0.07	5.7	7.1	6.8		2.94	0.80	0.07	0.20	0.24	3.68	15.6		128	13.2
		9-18	0.34	0.04	5.2	5.5	6.7		1.52	1.02	0.06	0.14	0.07	1.49	36.3		126	36.4
		18-32"	0.27	0.04	6.6	5.7	6.5		1.26	0.86	0.04	0.16	0.04	1.47	53.0		126	41.3
		55-94"	0.17	0.02	7.4	5.6	7.0		0.48	0.41	0.02	0.24	0.02	1.17	44.5		133	40.2
Nigeria (Western Region) (source:- Smyth and Montgomery, 1962)	Egbeda (developed on fine-grained biotite gneiss)	0-3"	3.35	0.27	12.5	7.3		80.2	12.90	5.40	0.17		2.17	2.34	8.6	28.4		11.6
		3-7"	1.02	0.10	10.2	7.1		84.6	4.75	1.63	0.09		0.51	2.91	12.5	1.9		14.6
		7-11"	0.49	0.05	9.8	7.2		73.0	2.88	0.75	0.09		0.51	3.84	7.1	0.9		16.0
		11-18"	0.41	0.04	9.8	7.1		75.5	2.50	1.05	0.06		0.84	2.38	4.2	1.7		33.6
		18-28"	0.41	0.04	9.8	6.9		75.0	2.87	1.47	0.06		0.61	1.95	7.0	2.2		43.8
		44-60"	0.19	0.03	7.5	6.4		71.1	3.63	1.31	0.05		0.26	2.77	19.0	2.3		31.6
	Iwo (developed on coarse granitic gneiss)	0-2"	2.32	0.14	16.2	7.6		57.6	10.90	3.00	0.09		0.64	3.63	21.7	42		6.0
		2-6"	0.92	0.08	11.8	6.1		72.0	5.20	2.30	0.06		0.35	2.26	21.4	10.5		8.0
		6-9"	0.64	0.06	10.2	6.3		76.4	5.60	1.30	0.07		0.22	4.31	31.4	7.6		11.6
		13-18"	0.48	0.05	8.9	6.4		77.1	7.40	1.70	0.02		0.35	4.4	26.0	5.0		34.6
		18-34"	0.47	0.06	7.7	6.6		75.2	8.00	2.70	0.02		0.45	2.96	23.8	4.7		43.2
		45-62"	0.25	0.04	6.4	6.7		74.9	6.60	3.20	0.05		0.45	2.06	21.8	4.5		33.6
Nigeria (Eastern Region) (source:- K.Wessel, 1965)	(derived from basaltic rocks)	0-6"	2.50	0.27	9.3		14.2	75	7.50	1.80		0.48	0.89	4.17	10.4	5.4		42.0
		6-12"	1.30	0.14	9.3		13.4	78	6.40	2.80		0.48	0.77	2.29	11.9	2.4		52.0
		12-24"	0.70	0.06	11.7		8.7	77	5.60	0.50		0.37	0.26	11.20	23.5	1.6		54.0
		24-36"					8.6	77	5.50	0.50		0.42	0.18	11.00	33.3	3.0		55.0
		36-48"					8.0	66	6.60	0.70		0.42	0.30	9.43	24.3	2.8		55.0
Ivory Coast (source:- B.Faignien 1963)	(derived from amphibolite)	0-4"	2.63	0.36	7.37	7.7			33.0	6.38		0.11	0.68	5.17	57.9			24.7
		12-16"				7.3			15.9	6.64		0.13	0.06	2.39	375.7			30.2
		24-36"				7.6			16.5	21.18		0.36	0.04	0.78	542.0			
Ivory Coast (source:- Leneuf and Riou, 1963)	(derived from amphibolite schist)	0-8"	2.54	0.77	?	7.1			15.50	5.52		0.11	0.70	2.81	30.6		551	34.0
		8-12"	0.72	0.10	7.5	5.5			6.36	1.68		0.11	0.12	3.78	67.0		489	42.2
		35"				5.8			3.80	2.80		0.12	0.06	1.36	110.0			55.5
		78"				5.6			1.00	2.24		0.13	0.03	0.45	108.0			49.5
Ivory Coast (source:- G.Verliere 1965)	(derived from granitic rocks)	0-8"	15.4	1.60	5.6	6.9			8.28	1.66			0.09	4.99	110.3		530	33.3
		20"							2.90	2.21			0.05	1.31	102.2		360	36.2
		39"							0.66	0.72			0.06	0.91	23.0		740	27.1
West Cameroon (source: Hawkins and Brunt, 1964)	(derived from volcanic ash)	0-6"	2.52	0.32	9.0	6.3			16.8	3.24	0.0		0.43	5.15	46.6		330	37.3
		6-14"	0.89	0.11	7.8	6.2											327	39.4
		14-42"	0.50	0.07	6.7	5.6											358	48.6
São Tome (source:- H.Laine E.Silva, 1958)	(probably derived from basalt)	0-8"	1.65	0.20	8.3	5.8	24.6	65.0										41.0
		8-36"				5.4	24.3	66.8										71.0
		36-60"				5.5	18.0	76.7										66.0

TABLE 7:- Selected analytical data for soils used for cocoa-growing in the West Indies and in the Far East

Country	Soil Series (or location)	Depth of Sample (inches)	Carbon %	Total Nitrogen %	C/N Ratio	pH	B.E.C. me/100 grms.soil	% Base Saturation	Exchangeable Bases me / 100 grams fine earth							'Available' P ppm
														Ratios		
									Ca	Mg	Mn	Na	K	$\frac{Ca}{Mg}$	$\frac{Ca+Mg}{K}$	
WEST INDIES Trinidad (source:- G.K.Maliphant pers. commun.)	River Estate Sandy Loam, (derived from alluvium). Data is averaged from 32 or 40 samples at each depth	0-3"	1.72	0.19	9.1	6.0	11.49	100	9.71	2.07		0.22	0.14	4.65	84.1	18.8
		3-6"	1.21	0.15	8.0	5.7	10.17	90	7.56	1.84		0.20	0.11	4.11	85.5	11.5
		6-12"	0.99	0.13	7.7	5.5	9.58	77	5.97	1.55		0.16	0.10	3.75	75.6	8.5
		12-18"	0.69	0.09	7.3	5.5	7.60	72	4.33	1.35		0.18	0.10	3.21	56.8	5.9
Grenada (source:- I.T.Twyford pers. commun.)	Hope Estate	0-6"	2.40	0.17	14.1	6.5	39.5	59	28.0	12.1		0.68	0.80	2.31	50.1	128
	Grand Bacelet	0-6"	3.70	0.32	11.2	6.4	28.2	75	15.9	7.3		0.46	0.48	2.18	48.3	9
	Mount Horne	0-6"	2.30	0.23	9.9	6.2	44.9	81	17.9	20.6		0.68	0.32	0.87	120.3	13
	Mirabeau Ag. Station	0-6"	2.80	0.29	9.7	5.6	24.5	49	8.1	4.9		0.46	0.28	1.65	46.4	7
	Birmington Estate	0-6"	2.60	0.27	9.6	4.9	14.3	40	3.0	2.0		0.26	0.30	1.50	16.7	7
Malaya (source:- W.P.Panton 1958)	Jerangau (developed on granodiorite or hornblende granite). Data from two profiles.	0-1"	1.63	0.18	9.1	4.1										2
		1-4"	0.90	0.12	7.5	4.2										2
		4-10"	0.75	0.12	6.3	4.7										1
		21-39"	0.30	0.09	3.3	5.4										1
		49-61"	0.02	0.05	0.4	5.1										
		0-1"				4.4	13.9	9.5	0.30	0.51		0.24	0.28	0.59	2.9	
		1-3"				4.5	11.7	8.1	0.20	0.29		0.23	0.23	0.65	2.1	
		5-12"				4.8	5.75	7.2	0.15	0.22		0.14	0.20	0.68	1.9	
		25-36"				4.9	8.60	6.6	0.15	0.18		0.21	0.20	0.83	1.7	
		44-59"				4.9	8.40	8.8	0.16	0.21		0.19	0.18	0.76	2.1	
Sabah (source:- J.D.Gillespie pers. commun.)	Jarangan (developed on basalt)	0-4"	5.80	0.46	12.6	7.32			27.61	2.11			.40	13.09	74.3	17
		4-15"	5.75	0.45	12.8	7.36			20.52	2.30			.43	9.10	54.0	17
		15-72"	1-20	0.16	7.5	6.40			11.28	0.78			.08	14.46	150.8	1
Western Samoa (source:- A.C.S.Wright 1963)	A'ana bouldery clay. (Derived from basalt)	0-5"	5.1	1.02	5.0	6.6	47.9	100	36.8	10.2		0.20	0.70	3.6	67.1	20
		5-15"	2.9	0.32	9.0	6.4	18.0	53	6.8	3.0		0.10	0.10	2.27	98.0	80
	Saunga clay (derived from basalt)	0-6"	4.0	0.37	11.0	5.1	24.6	39	5.1	4.8		0.20	0.30	1.06	33.0	20
		6-12"	0.6	0.08	8.0	5.1	13.2		1.3	2.6		0.20	0.06	0.50	65.0	10

reach the standards suggested in previous sections in almost every respect. It is of interest, therefore, that cocoa grown on this soil and on other soils with similar properties in Malaya suffers so severely from a disease, or disorder, known as 'die-back' that, as Haddon wrote in 1961, "cocoa is not recommended as a crop to farmers anywhere in Malaya". Despite considerable research, no pathogen responsible for 'die-back' in Malaya has been identified and it seems probable that nutritional deficiency, or imbalance, is an important contributory factor, if not the sole cause, of the disorder.

The data from Grenada (Table 7) are included since they are of particular interest, although they relate only to surface samples. The site sampled at Mount Horne is representative of soils which have proved extremely fertile in cocoa trials and, with the addition of potash, have given yields equivalent to 7,000-8,000lbs of dry cocoa per acre per annum. The site at Hope Estate suffers from a fairly severe dry season but supports excellent cocoa when the soils are irrigated. In contrast, good yields are obtained at Mirabeau Agricultural Station and at Brimington Estate only when fertilizers are applied (a 12:8:24 Mixture) although the physical properties of the soils and the climatic conditions at these sites are very favourable (I.T.Twyford, personal communication).

A few examples could be quoted of soils, notably in the Congo, which have supported cocoa successfully but which appear from their analysis data to be of very low nutrient status. Their data is similar in fact to that quoted for Jeranagau series in Malaya. The Malayan experience, however, illustrates difficulties which may be encountered when such soils are selected for cocoa planting and emphasizes that it may not be easy to overcome these difficulties by application of fertilizers or by other management practices.

ASSESSING NUTRIENT STATUS IN THE FIELD

Under this heading we can consider inferences which may be drawn, not only from a field study of the soils themselves but also from knowledge of their recent agricultural history. Such inferences are qualitative in nature and will only provide valid comparisons between soils occupying an essentially uniform environment.

If the soils under consideration occupy an area which includes no major variation in present climate, natural vegetation, topography or soil parent material, observations made in the field can be used with some confidence to predict probable variation of the nutrient status of the soils. If cocoa is already growing in such an area, the relative success of the crop on different soils provides standards of comparison and permits qualitative assessment of the probable nutritional suitability of the soils without resort to laboratory analysis. These assessments are especially valuable for they represent the integrated affect of many different aspects of the chemical character of the soils which would be extremely difficult to evaluate separately.

Circumstances permitting this approach are not as rare as might be expected. In both Ghana and Nigeria, for example, soils occupying very extensive areas have been classified in relation to their suitability for cocoa almost entirely on the basis of their physical characteristics (Crosbie, 1957; Smyth and Montgomery 1962). Such classifications do not, in fact, ignore probable differences in nutrient status, for these are likely to be related to the physical criteria selected to differentiate the soils. In Western Nigeria, it was possible to show that, in appropriate circumstances, soil quality classification based on morphological characteristics of the soils provide a reliable guide to sites on which cocoa will grow successfully (Smyth and Montgomery 1962).

Physical Characteristics of the Soil

Of the soil characteristics which can be studied in the field, texture is the most informative in relation to probable nutrient status, but additional clues are provided by soil colour; consistence and structure; the content of large particles; and by studies on the nature and degree of weathering of the parent material. Conclusions on nutrient status must be based on a summation of these factors and their reliability will depend to a large extent on the experience of the observer and his familiarity with the soils of the area examined. Field observation is inevitably subjective and if conclusions are to be drawn from data obtained by different members of a team, it is most important that all members of the team are carefully trained to use a standard system in observing and recording data.

(a) Texture

Within a limited area differences in texture provide a valuable, if rough, guide to probable differences in soil nutrient status. The higher the clay content of a soil the higher is its nutrient status likely to be. A number of factors contribute to this relationship. In the first place, the parent materials and conditions of weathering which yield soils of clayey rather than sandy textures are usually those which provide and serve to retain nutrient elements in greatest quantity. Secondly, the good properties of moisture retention associated with a high clay content ensures that nutrient loss through downward leaching is at a minimum in clayey textured soils. Thirdly, cation exchange phenomena on the relatively enormous surface area of the clay particles themselves, make an important contribution to the capacity of a soil to retain and exchange nutrient elements.

Lastly, but of particular importance in the soils of most cocoa-growing areas, is the relationship between clay content and organic matter content. In sandy soils, organic matter accumulation under natural vegetation tends to be slower than is the case in clayey soils, largely because the growth of vegetation is likely to be less vigorous. Furthermore, for reasons which are only partly understood, organic matter decomposes more rapidly in coarse than in fine textured soils, especially when land is cleared for cultivation (FAO, 1962). In general, therefore, within areas in which environmental factors are more or less uniform, soils distinguished because of their higher clay content will also be the soils of higher organic matter content. This relationship has an important bearing on soil nutrient status, since organic matter provides not only a rich source of nutrients, but also a very active colloidal exchange complex in which relatively large amounts of nutrients and moisture can be held.

Since soil organic matter content is so important in relation to plant nutrition it may be questioned why the level of organic matter should not be determined by direct field observation. Reference has already been made, however, to the need for laboratory analysis to obtain a reliable measure of organic matter content in tropical soils. Furthermore, in establishing broad groupings of soils in relation to their suitability for cocoa, differences in organic matter content are likely to be localized following local differences in agricultural history and rarely provide a satisfactory criterion for differentiating soil mapping units. Textural differences are likely to be much more useful for this purpose. The relationship noted between texture and organic matter content serves to increase the significance of broad groupings on the basis of texture, in relation to the requirements of cocoa.

(b) Colour

Soil colour provides a crude, but useful, guide to probable soil nutrient status. Soils with strongly developed colour, especially those which are dark red, dark brown or dark reddish brown, usually have higher nutrient status than pale coloured soils. The reason for this is twofold. Firstly, in many areas, differences in soil colour reflect differences in the nature of the parent rocks from which the soils have developed and the soils of reddest, or dark chocolate brown, colour are usually those derived from the most nutrient rich rocks (rocks containing a high proportion of ferro-magnesian minerals). Secondly, soil colour may reflect the degree of leaching to which the soil has been exposed. Very pale coloured soils are likely to have lost a large proportion, not only of the compounds which are responsible for colour, but also of the nutrient elements required by plants.

It must be emphasized, however, that judgment of nutrient status on the basis of colour can be very misleading. Some rocks which are poor in nutrient elements but rich in iron, such as ferruginous sandstones, can give rise to bright red soils of low nutrient status. Other red soils of the tropics, which are in a very advanced stage of weathering, consist predominantly of oxides of iron and aluminium and have very low nutrient status. Thus, additional evidence on nutrient status, derived either from laboratory data or by observation of existing cocoa in surrounding areas, is needed to support inferences based on soil colour.

(c) Consistence and structure

A study of the consistence and structure of clayey textured soils provides a broad indication of the probable nature of the clay minerals which they contain. Since, as explained previously, different clay minerals differ in their ability to retain and exchange nutrient elements this indication is of value in comparing the probable nutrient status of different soils. Standard terms for the identification and description of soil consistence and structure are to be found in the Soil Survey Manual of the U.S. Department of Agriculture (1951) but it must be admitted that considerable experience is needed to interpret these characteristics reliably.

Soils which are rich in non-expanding clay minerals having low base exchange capacity, are usually not more than slightly sticky and slightly plastic in consistence when moist and show little, if any, development of macro structure. Stickiness and plasticity of the moist soil increases in soils which have a progressively larger proportion of expanding lattice clay, of relatively high base exchange capacity, in their clay fraction. The tendency for soils to crack and to form well developed structural peds also increases with an increasing content of expanding clays. Thus, very broadly speaking, the more sticky and the more plastic is the clay, and the more strongly developed is the structure, the greater is the base exchange capacity of the mineral fraction of a soil likely to be. This does not imply, however, that the soil is necessarily more suitable for cocoa, for as discussed in the previous Chapter, high proportions of expanding clay minerals are usually associated with undesirable physical soil characteristics which are more likely to prove limiting to cocoa than are nutritional shortcomings of the soil. High exchange capacity in the mineral fraction of a soil is only desirable, therefore, insofar as it is compatible with acceptable physical properties.

(d) Content of large particles

Large inert particles, such as quartz gravel or ironstone concretions, reduce the nutritional capacity of a soil mainly because their surface area is very much smaller per unit volume than that of the fine earth which would otherwise fill the space which they occupy. Thus, other factors being equal, soils containing appreciable quantities of gravel and stones will be nutritionally inferior to gravel-free soils, even when the quantity of gravel is insufficient to have any marked effect on root penetration. Account is rarely taken of the soil volume occupied by large particles in considering laboratory data but Brammer (1962) provides calculated values for the quantity of nutrients in the top three feet of some Ghanaian soils in which allowance is made for differences in the volume of fine earth in different horizons. Such data for two soil profiles in the cocoa-growing area of Ghana, both of them classified as "Forest Ochrosols", is given in Table 8. The marked difference in the calculated total

TABLE 8:- Calculated values for major nutrients in lbs per acre in horizons to a depth of three feet in profiles of two soil series from the cocoa growing area of Ghana (selected from Brammer (1962))

Kumasi Series						Bekwai Series					
Horizon Depth (inches)	% fine earth (less than 2mm)	Exchangeable bases (lbs nutrient per acre)				Horizon Depth (inches)	% fine earth (less than 2mm)	Exchangeable bases (lbs nutrient per acre)			
		Ca	Mg	Mn	K			Ca	Mg	Mn	K
1. 0-4"	97.4	3032	505	66	548	0-2"	100.0	2534	510	53	62
2. 4-9"	86.8	910	150	30	145	2-11"	93.9	982	100	41	117
3. 9-18"	81.2	792	306	43	71	11-21"	41.6	149	54	8	40
4. 18-32"	93.4	1175	486	51	73	21-33"	31.4	124	39	7	37
5. (32-36")	(92.8)	233	109	14	10	(33-36")	(78.7)	54	34	7	9
Total for 3 feet		6142	1556	204	847	Total for 3 feet		3843	737	116	265

Notes:- The calculation is based on laboratory data for exchangeable bases and for the % of oven-dry fine earth (less than 2mm diameter), using assumed values for dry soil density (1.2 in the surface horizon and 1.6 in the horizon below).

quantities of nutrients in these two soils is not assigned entirely to differences in their content of stones and gravel, but the effect of this factor is apparent when the values in each horizon are compared in relation to the given percentage of fine earth. It will be seen that the subsoil layers of the gravelly Bekwai series contain only one-third as much 'fine earth' as comparable horizons in the Kumasi profile. Since these figures are calculated they do not prove anything but they serve to illustrate the possible magnitude of the effect.

(e) The nature and the degree of weathering of the parent material

Fragments of weathering parent material at depths within the reach of cocoa roots provide a source of additional plant nutrients which may be gradually released to replace those taken up by plants or lost in the drainage waters. The rate of such release depends on the size and nature of the fragments, the processes active in the soil and upon climatic factors, so that it is almost impossible to tell from field investigations whether or not this additional source of nutrients is likely to have a significant direct influence on plant growth. Nevertheless, the presence of such fragments is an indication that weathering processes in the soil are unlikely to have reached a stage at which the soil is severely depleted of plant nutrients. The presence of weathering rock or rock minerals, either in deep layers potentially within reach of cocoa roots or as fragments in the upper part of the soil, should be regarded as a desirable factor in comparing the probable nutritional status of different soils in the field.

Knowledge of the nature of the parent rock from which a soil is derived is a very valuable clue in assessing the probable nutrient status of the soil. In some cases the nature of the rock can, with experience, be inferred from the morphology of the soil. In others, sufficiently fresh samples of rock for identification occur as fragments in the soil, although care must be taken to ensure that odd rock fragments are not of extraneous origin. Surface rock out-crops in upper slope sites may also be misleading, since they commonly consist of rocks more resistant to weathering than those which have given rise to surrounding soils. Outcrops in stream beds provide a more reliable guide to the local geology. In many potential cocoa-growing areas geological surveys have been carried out and the resulting maps can be useful, especially in selecting areas in which detailed investigations are most likely to disclose soils suitable for cocoa.

Providing weathering processes are not too far advanced, soils derived from basic volcanic ash or basaltic lavas are likely to be of exceptionally high nutrient status. Amongst igneous and metamorphosed igneous rocks, those which are most basic in mineral composition are also most likely to give rise to soils of high nutrient status. Thus nutritionally, soils derived from amphibolites and from hornblende gneisses or schists are likely to be superior to those derived from biotite-rich gneisses which, in turn, are usually superior to those derived from acid rocks, such as granites and granitic gneisses, in which the predominant rock minerals are quartz, felspar and white micas. In the case of sedimentary deposits, (including metamorphosed sediments), coarse grained rocks, such as sandstones, usually give rise to soils poor in nutrients; somewhat higher nutrient status may be found in soils derived from finer grained mudstones, clays and shales, but only calcareous rocks and recent alluvia are likely to give rise to soils of high nutrient status.

In the absence of adequate laboratory data, soils known to be formed from very acid crystalline rocks or sandstones should not be recommended for cocoa, even if their physical characteristics appear to be suitable.

The Agricultural History of the Site

There is little doubt that cocoa is most likely to succeed on land that, up to the time of planting, has been under a stand of well developed forest. In 1953, Charter stated "it is well known in the Gold Coast* that, using traditional methods, it is difficult or impossible to establish cocoa economically on land that has previously been exploited". Using modern methods of establishment and plantation management we need no longer take so drastic a view, but many have suffered disappointment in attempting to establish cocoa on old cocoa land or land used previously for other crops. In general, growth is poor on such land in comparison with that obtained on 'virgin' soils (Adams and McKelvie, 1955). It would be a mistake to suppose that the poor growth invariably stems from reduced fertility of the soil as the result of previous cropping. Other factors play an important part, not least of which is the increased competition with weeds, especially those of light-loving species likely to flourish under the conditions which prevail following cultivation or the clearing of old cocoa plantations (Charter, 1955). Indeed, effective weed control and rapid re-establishment of shade (artificial, temporary or permanent) seem to be essential factors in the successful establishment of cocoa on such land.

Nevertheless, some reduction in soil fertility following cropping is to be expected and, if past management practices have been poor, the loss in fertility may be serious. Apart from the mineral nutrients carried away in the crop, the annual return of vegetative matter to soils under cocoa, or most other crops, is much less than that received by soils under forest. Moreover, increased exposure of the topsoil under conditions of cultivation leads to more rapid breakdown of organic matter and a possible loss of nutrients released too rapidly to be exploited by the crop. Under poor management, a significant proportion of the richest surface soil layer may be lost completely by erosion.

In Table 9 (A, B and C) comparative analytical data is given for the surface horizons of soils under various types of vegetation in three cocoa-growing areas. In each case the values for organic matter content are lower in soils that have been exploited than in those under forest. In the Nigerian data, pH values and information on the exchange complex indicate that the level of soil fertility under cocoa is appreciably less than that under forest and diminishes progressively with increased spacing between the cocoa trees. This is to be expected since under the wider spacings the soil can be assumed to suffer more exposure and to receive lower quantities of leaf fall per unit area. The Nigerian data is especially significant since the soils in the closely adjacent sites sampled by Kowal (1959) were morphologically almost indistinguishable and were presumably equally fertile before part of the forest was cleared for cocoa planting.

Interpretation of the data from Ghana is less straight forward for, although fertility is clearly lower in the soils under arable crops and under thicket or forb fallow, than under forest, those under cocoa are apparently the most fertile. The data is derived from quite a large number of samples, however, and although all the soils are classified within one Great Soil Group considerable variation in their fertility could be expected even under uniform vegetation. Since early cocoa plantings in Ghana were made on a trial and error basis, survival of cocoa is most likely on the soils of above average fertility, whilst other soils may have been left under forest because much longer experience with other crops had shown them to be infertile. That the average inherent fertility of the sites sampled under cocoa is in fact higher than that of the sites under forest is suggested by a comparison of data for organic matter content and for base exchange capacity.

---

* Now Ghana.

TABLE 9: Comparison of analytical data in surface samples of soils under different vegetation in three cocoa-growing areas.

A. Ghana: Data for 9 inch surface samples of 'Ochrosols' (Selected from Charter, 1955)

Kind of Vegetation	No. of Samples	Organic Matter %	C/N ratio	pH	Base Exchange Capacity me/100gms.	Exchangeable Cations me/100gms. of soil		
						Ca	Mg	K
Forest	23	3.59	9.74	6.27	14.01	9.45	2.40	0.36
Cocoa	53	3.22	10.07	6.73	14.38	10.52	2.21	0.41
Thicket	14	2.56	9.61	6.37	10.14	7.08	1.45	0.30
Forb Regrowth	21	2.78	9.47	6.63	11.15	8.73	1.72	0.34
Farmland	16	2.37	10.63	6.25	10.53	6.58	1.73	0.39

Notes: Forest - Includes recent secondary forest as well as primary forest.
Thicket - Woody shrubs 20-30 ft. high representing natural fallow a few years old.
Forb Regrowth - Succulent plants and grasses representing the first one or two years of fallow.
Farmland - Land actually under subsistence arable cropping.

B. Nigeria: Data for 4 inch surface samples of a single soil series under different spacings of cocoa and under forest in adjacent plots (after Kowal, 1959)

Spacing of cocoa	Depth	pH	Carbon %	Nitrogen %	C/N	Base Exch. Capacity me/100gms.	Total Exch. Bases me/100gms.	Base Satn. %
5' x 5'	0-4"	6.45	2.11	0.222	9.6	7.7	6.6	86
7½x7½'	0-4"	6.20	2.06	0.196	10.5	7.3	5.7	78
15' x15'	0-4"	6.00	2.05	0.188	10.9	6.8	4.7	69
Forest	0-4"	6.40	2.83	0.270	10.5	11.4	10.3	90

C. Trinidad: Data for soils of similar morphology under forest and under 20 year old neglected cocoa (selected from Hardy, 1933)

Vegetation	Depth of sample	Silt clay (less than .02 mm.)	pH	O.M. %	Total N%	C/N ratio	'available' nutrients(p.p.m)	
							P_2O_5	K_2O
Forest	surface crumb	78	5.0	20.9	0.83	14.4	62	329
	0-6"	74	5.0	4.0	0.24	9.1	14	96
Cocoa	surface crumb	70	4.7	11.7	0.56	12.1	28	230
	0-6"	77	4.6	2.9	0.20	6.8	15	124

Note: Values for 0-6" horizons represent weighted averages of data for four horizons quoted by Hardy.

In presenting the data from Ghana, Charter (1955) pointed out that whilst the level of exchangeable magnesium fell appreciably in exploited soils, that of exchangeable potassium remained much the same. It will be noted that in the data from Trinidad the level of 'available' potassium in the 0-6 inch samples is slightly higher under cocoa than under forest, whilst the pH data suggests that the levels of exchangeable calcium and magnesium are probably lower. Charter (loc. cit.) has emphasized the importance of magnesium in relation to the nutrition of cocoa and suggests that imbalance between magnesium and potassium may be an important factor in relation to the poor growth of cocoa on previously exploited soils.

Careful consideration should be given, therefore, to past agricultural history in assessing the relative suitability of possible sites for cocoa planting. Special attention should be paid to the conditions of the surface horizons, for soils that have suffered erosion are unlikely to prove suitable for cocoa. Whilst forest vegetation is desirable, a well developed stand of forest is not, in itself, a guarantee that the soils are suitable for cocoa. Indeed, in areas which are already extensively exploited, sites under old forest should be viewed with suspicion - they may have been deliberately avoided by the local farmer, or deliberately left under extended fallow, because the soils had been found to be of below average fertility.

The most difficult problem is that of assessing the suitability of old cocoa land. Here other factors, such as the experience of the farmer with the crop and his desire to replace trees that have died, or have been cut out following disease, may influence the decision to replant. It should be emphasized, however, that more expensive methods of establishment and management will be required on such land and that even these may not achieve success equal to that obtained with less effort on long fallowed soils. Unfortunately, the sites on which cocoa replanting is most likely to be considered tend to be those on which it is least advisable, the cocoa being old and neglected and the soil badly exposed through extensive gaps in the canopy. Sites on which young cocoa has been cut out for phyto-sanitary reasons should prove satisfactory for replanting but the soils should be examined, nevertheless, to ensure that they are the most suitable available for the purpose.

CHAPTER FIVE

QUALITY CLASSIFICATION OF POTENTIAL COCOA SOILS

The identification of suitable sites for cocoa planting can be done on an 'ad hoc' basis, each site being considered on its individual merits. A far more satisfactory approach, however, is to study the problem within the framework of an overall soil and land-use survey covering the whole area in which planting may be considered. Such a survey not only provides a basis for deciding the merits of individual sites but permits their comparison with those of other sites and ensures that the areas chosen for planting are the most suitable available.

When cocoa is likely to be an important crop in a soil survey area it is desirable to establish a soil quality classification specifically related to the soil requirements of this crop and to produce separate maps showing the distribution of the different soil quality classes which have been recognized. This is primarily a problem of soil survey interpretation but at a very early stage in the survey, when the criteria which are to be used to distinguish the individual soil mapping units are being defined, careful consideration must be given to those soil characteristics which are especially important in relation to the requirements of cocoa. If this is not done, the units mapped may include soils of differing potential for cocoa which it will be impossible to separate at the interpretation stage of the survey. This point requires emphasis, for some of the factors of importance to cocoa, notably differences in texture, are not always easy to relate to topographical features which, because they are easily recognized in the field, tend to play an important part in defining boundaries between different soil mapping units. Boundaries which can only be recognized by intensive soil sampling add greatly to the time and effort required for a soil survey but are often essential to distinguish soils of varying suitability for cocoa.

THE CHOICE OF QUALITY CLASSES

Discretion is required in the choice of the number and nature of the soil quality classes which are to be recognized in a particular survey. There is a temptation to multiply the number of classes in order to provide more detailed information and to make allowance for subtle distinctions in suitability between rather similar soils, or between the same soils in different situations. Large numbers of quality classes are only justified insofar as:-

(a) they can be mapped individually and their mapped location subsequently recognized on the ground;

(b) the criteria on which they are defined are of a reasonably permanent nature;

(c) their significance can be exactly defined;

(d) they do not so complicate the interpretation as to frighten away would-be users of the information.

The value of a particular soil quality class, or sub-class, is greatly reduced if its distribution can not be shown on a map, or, if shown, its position cannot be accurately located in relation to permanent features on the ground. For practical purposes, one good map is worth several volumes of printed words. However, there are some factors affecting cocoa cultivation, such as variations in the steepness of slopes, which the farmer will need to examine personally when planning his planting programmes. The importance of these factors may have to be pointed out to him but, once on the site, he is unlikely to refer to the map for guidance in matters which he can see more accurately with his own eyes. Little advantage is gained, therefore, in complicating the soil quality map with such information.

No map is of very much use if the boundaries it shows cannot be located with reasonable accuracy on the ground. The standard of accuracy required, however, increases in proportion to the amount of interpretative detail shown. Therefore, the amount and accuracy of topographical detail on available base maps may limit the minimum area of a single unit which is worth showing and, thus, the number of quality classes which are worthy of recognition.

Consideration of the permanence of the criteria used to define the separate quality classes raises a difficult issue. Differences in suitability which by their nature can be regarded as temporary, such as those relating to differences in present vegetation, should be disregarded in defining quality classes. These, again, are best considered by the planter at individual sites. On the other hand, there is the possibility that the deliberate introduction of improved farming practices will change the suitability of soils suffering from limitations such as low nutrient status or poor drainage at the time of the survey. It is important to recognize the possibility of such improvements. At the time of the survey, however, it is often very difficult to estimate all the technical, economic and social factors which dictate the degree of improvement which is likely to be achieved. This being so, it is best to class the soils according to their suitability at the time of the survey and to indicate separately, possibly by means of subclasses, soils which suffer from specific limitations which may be amenable to improvement.

The significance of each quality class needs to be clearly defined. For convenience it is desirable to provide simple names such as 'Fairly Good', or 'Poor', for each class but the meaning of such names is subjective and, to avoid misunderstanding, the classes should be further defined not only in the survey report, but also on the soil quality map. Unfortunately, the least ambiguous definitions, those based on comparative estimates of expected yield, or on the economics of cocoa production on the soils of each quality class, can rarely be used; for these parameters are too unstable. The introduction of higher yielding varieties, the use of fertilizers and of other improved practices may drastically change the magnitude and possibly the pattern of the yield potential and fluctuations in the economics of production are almost impossible to predict.

Bearing in mind the advantages of simplicity, it is suggested that four main quality classes, defined as follows, would meet the needs of most surveys:-

Class I Good soils - Soils which have very few, if any, characteristics likely to limit the growth and yield of cocoa. Recommended for planting in preference to all other soils.

Class II Fairly good soils- Soils which, although not as suitable as the soils of Class I, suffer from no serious limitations. Recommended for planting in areas where no Class I soils are available.

Class III Poor soils - Soils having one or more undesirable characteristic likely to restrict, if not prevent, the growth of cocoa. Not recommended for planting in their present state.

Class IV Unsuitable Soils - Soils suffering from severe limitations likely to prevent the satisfactory growth of cocoa. Unsuitable for planting.

The most important division is that between Classes I and II on the one hand and Classes III and IV on the other - between the soils that are recommended for planting and those which are not. Recognition of Class I soils provides an opportunity of distinguishing exceptionally suitable soils deserving of priority in planting. Likewise, Class IV serves to distinguish exceptionally poor soils on which planting should not be attempted, even when these soils occur as small patches within areas of suitable soil selection for a cocoa plantation. In similar circumstances it might be convenient to plant up soils of Class III on which complete failure of cocoa is not anticipated.

Soils suffering from a variety of limitations may be included in Class III and, in many areas, it will be desirable to recognize subdivisions of this Class to distinguish soils which could be expected to respond to different aspects of improved management. The most appropriate subdivisions will vary from area to area but the following are quoted as possible examples:-

Subclass III(n)	Poor soils in which the only major limitation is low nutrient status. Likely to prove satisfactory for cocoa if the right fertilizers are applied.
Subclass III(d)	Poor soils in which the major limitation is poor drainage. Likely to prove suitable for cocoa if artificially drained.
Subclass III(p)	Poor soils suffering from various limitations and offering little prospect of improvement by management.

It may be desirable to recognize subclasses suffering from more than one curable limitation but, if the subclasses are not to be misleading, consideration should be given to the practical possibilitiesof effecting improvement. Soils in which conditions of texture, structure or topographical position would make effective artificial drainage almost impossible to achieve, for example, should be included in subclass III(p) rather than in III(d) of the classification proposed above. In very detailed surveys a much wider variety of limitations, and combinations of limitations can be recognized and related to the management practices required. Havord, in "A detailed soil and land capability survey of a cocoa area in Trinidad" provides details of such a classification.

CRITERIA FOR DISTINGUISHING SOIL QUALITY CLASSES

The quality classification which has just been proposed provides a basis for summarizing the conclusions reached in previous Chapters and for showing how these conclusions may be applied in practice in the selection of soils for cocoa. Each of the criteria discussed previously will now be considered, therefore, in relation to the proposed soil quality classes. It must be emphasized, however, that quality classification of a particular soil depends on a summation of all these criteria considered jointly in relation to local environmental conditions.

Nutrient Status

Assessment of nutrient status, based on laboratory data, serves primarily to distinguish poor soils of Class III from the fairly good and good soils of Class I and II. Summarising the conclusions reached in the previous Chapter, laboratory data for Class I and II soils should show:-

(a) base exchange capacity in the surface horizon not appreciably less than 12 me./100 grams of fine earth and in subsoil horizons not less that 5 me./100 grams;

(b) average organic matter content in the top 0 - 15 cms. (0-6") of the profile not less than 3.0% (1.75% organic carbon);

(c) base saturation in subsurface horizons not appreciably less than 35% (unless base exchange capacity is exceptionally high);

(d) pH in the range 6.0 to 7.5 in the surface horizons and no excessively acid (pH below 4.0) or alkaline (pH above 8.0) horizons within one metre of the surface;

(e) levels of individual exchangeable bases in top 0 - 15 cms. (0-6")

Calcium	not	lower	than	8.0 me./100	grams	fine earth
Magnesium	"	"	"	2.0 me./100	"	" "
Potassium	"	"	"	0.24me./100	"	" "

Failure to meet these limits does not imply that cocoa will not grow on the soils in question but does imply that nutritional conditions are not optimum and that the soils should be considered as 'poor' or 'unsuitable'.

Laboratory data for Class I soils can be expected to be more favourable than those of Class II soils but normally these classes will be distinguished on the basis of other criteria. Similarly, classification as 'unsuitable' will rarely be based on laboratory data alone. In most cases, soils of extremely low nutrient status also suffer from undesirable physical or environmental characteristics, notably very sandy textures. Exceptions to this rule undoubtedly exist, including soils with positive charge exchange characteristics (pH in potassium chloride solution higher than that in water) and other strongly acid and alkaline soils. Present knowledge is inadequate, however, to even suggest limiting values for individual analytical criteria which could serve in all circumstances to distinguish soils as totally unsuitable for cocoa as opposed to soils which, although poor, offer possibilities of improvement through management.

Soil Depth - Rooting Volume

Exceedingly shallow soils are perhaps the most obvious candidates for Class IV in the soil quality classification but effective rooting depth is a factor which requires consideration at all levels in the classification. The probable influence of soil depth cannot be estimated without reference to other factors which affect the quality of the soil. It was suggested in Chapter Two, that soils little more than a metre deep may be acceptable for cocoa if all other characteristics of the soil are particularly favourable. This is a conservative estimate and cocoa is grown successfully in different parts of the world on even shallower soils.

Only in exceptional cases, however, should soils with less than 150 cms. of earth readily penetrated by roots be classified as 'good' (Class I). Failure to meet this requirement may justify downgrading otherwise good soils into Class II. In areas where shortage of moisture is a factor limiting growth in some seasons of the year, or where the sub-soils are of rather low nutrient status, adequate rooting volume is essential and soils less than 150 cms. deep will normally be regarded as 'poor' (Class III). In these circumstances, soils less than a metre deep should be considered unsuitable. From these remarks it will be clear that no simple numerical values can be quoted for the minimum depth of soil appropriate to each quality class under all condtions.

Drainage - Moisture Supply and Aeration

As discussed in Chapter Three, the drainage qualities of a soil and its related properties of moisture retention and aeration, have to be considered in relation to prevailing climatic conditions, bearing in mind that factors external to the soil itself, notably topographical position, influence these qualities. The combination of adequate moisture retention, good drainage and good aeration found only in strongly aggregated soils containing moderately high amounts of non-expanding clay minerals from the surface downwards, provides the ideal physical medium for cocoa in all situations. Soils with characteristics departing appreciably from this ideal should not be classified in Class I. The interpretation of departures from this ideal differs, however, in different situations. Some soils with sandy textures in the top 40 to 50 cms. of the profile, for example, may have good properties of moisture retention only in the surface horizon, due to organic matter, and in the deep subsoil. Such soils may be satisfactory for cocoa and be classified as 'fairly good' (Class II) in areas where rainfall is moderately heavy and uniformly distributed. The same soils would be classed as 'poor' (Class III), or even 'unsuitable' (Class IV) in areas of marginal rainfall conditions. On the other hand, in areas of high rainfall, properties of aeration are of critical importance and soils with poor drainage, which may even be desirable under dry conditions, would not be acceptable for cocoa planting.

Individual Physical Characteristics of the Soil

(a) Texture:-

The importance of texture in relation to root penetration, drainage qualities and nutritional characteristics has been stressed in previous Chapters. High clay content is desirable in that it implies good properties of retention of both nutrients and moisture and suggests that nutrient status is probably high; but is undesirable insofar as it adversely affects aeration and root penetration. These partially opposed requirements need to be considered simultaneously in assessing textural characteristics. Intermediate textures, ranging from sandy clay loam to sandy clay (U.S.D.A. 1951) are optimum for cocoa in most circumstances. Even in areas of high rainfall, soils of loamy textures are preferable to those of sandy texture in which nutrient status would be suspect. In dry areas, good moisture retention is essential and soils with clayey textures close to the surface are desirable, providing root penetration is not seriously impeded.

In considering the suitability of individual sites on an 'ad hoc' basis the whole profile of each soil may be studied and allowance made for variations in texture which may be noted at different depths. It is more difficult, however, to make allowance for textural changes with depth in any broad system of classification of soils intended for interpretation in relation to the requirements of cocoa. Since a large proportion of the feeding roots of cocoa are to be found in the top 20 cms. of the soil, textural differences in the uppermost soil horizon are of special significance. In most potential cocoa-growing areas, however, textures in the top 15 - 20 cms. of the soil often vary so rapidly as to be almost valueless as criteria for mapping soils, even within the area of a small farm. Textures below a depth of about 60 cms. on the other hand, are commonly so uniform over wide areas that they are equally useless as a basis for soil classification and mapping. Thus, in many areas, it is convenient to base broad textural distinctions between different groups of soil on differences of texture determined at an intermediate depth, say, between 20 and 50cms. Differences in texture between these depths undoubtedly influence conditions in the surface horizons and thus have a strong influence on the suitability of a soil for cocoa. Where practical, further sub-units of soils may be recognized, on the basis of textural differences above or below this 'control section' at intermediate depth.

The soil classification developed for the cocoa growing area of Western Nigeria includes textural distinctions similar to those just described. In the areas surveyed rainfall is marginal and the dry season quite severe so that properties of moisture retention related to texture are of special importance in selecting soils for cocoa. Soils with sandy textures (not finer than loamy sand or sand) at depths between 10 and 20 inches (25 to 50 cms.) were classed as 'poor' (Class III) and as 'unsuitable' if sandy textures continued in horizons below 20 inches. The 'fairly good' soils (Class II) had textures of sandy loam or finer in the 'control section' and were usually more clayey at depth. Texture was also an important consideration for distinguishing 'fairly good' from 'good' soils (Class I) in which the whole profile, including horizons between 10 and 20 inches, had textures of sandy clay loam or sandy clay (Smyth and Montgomery, 1962). Surveyors in Western Nigeria were able to show a close relationship between both the distribution and quality of surviving cocoa, planted without professional advice, and the distribution of soils of different quality classes recognized largely on the basis of the textural differences described (see Table 11). These criteria will only be appropriate in areas having soil and environmental conditions similar to those in Western Nigeria but they serve to illustrate the assessment of texture in relation to soil quality classification. In areas of moderately heavy and well distributed rainfall less weight should be given to textural considerations in assessing soil quality for cocoa.

(b) Soil Colour:-

Marked differences in colour should be regarded as an important criterion in distinguishing soils at the level of classification required to separate soils of differing potential for cocoa. In the first place soil colour is a valuable guide in judging the drainage characteristics of a soil, as discussed in Chapter Three. Secondly, in the absence of exhaustive laboratory data, soil colour provides a crude measure of comparative nutrient status and so is useful in the classification of soils into groups within which nutrient status is likely to be similar.

Quality classification on the basis of drainage has already been discussed. Judgement of quality in relation to nutrient status on the basis of colour can only be tentative and requires the support of observations on the success of existing cocoa on the soils in question or of laboratory data. Nevertheless, 'good soils' (Class I) will usually show strongly developed red or dark brown colours although, over calcareous rocks or recent alluvia, they may be dark brownish grey or even black. In the absence of other evidence, it is prudent to classify pale red, pale yellowish red and yellowish brown soils with otherwise good characteristics as only 'fairly good' (Class II). Similarly, pale yellowish brown and pale yellow soils should provisionally be classified as 'poor' (Class III). Very pale colours are usually associated with very sandy textures and such soils are usually unsuitable for cocoa (Class IV).

(c) Soil Consistence and Structure:-

Marked differences of consistence and structure may also be important criteria in distinguishing soils which are satisfactory for cocoa (Classes I and II) from those which are not (Classes III and IV). In some tropical areas, however, no great difference is observed in the expression of these characteristics in the more extensive soils.

In considering consistence and structure special attention should be paid to their influence on drainage characteristics and on root penetration. Good structure is especially important in areas of high rainfall to ensure adequate aeration. In dry areas, structure and consistence at depth requires careful study to ensure that the roots of cocoa will be able to reach deep seated moisture during dry periods.

(d) Other Physical Characteristics:-

The content of quartz stones and gravel, of ironstone concretions and of weathering rock and minerals, provide examples of other criteria which have to be considered in assessing the quality of a soil for cocoa. Depending on their quality and their nature, the presence of such particles may reduce the value of an otherwise suitable soil from 'good' to 'fairly good' or even to 'poor'. A soil consisting predominantly of large inert particles is, of course, 'unsuitable'. A moderate content of weathering rock or rock minerals, at depths potentially within the reach of cocoa roots is a favourable factor but would rarely justify placing a soil in a higher quality classification than that suggested by considerations of texture, colour, consistence and structure.

ASSESSING THE VALIDITY OF A SOIL QUALITY CLASSIFICATION

At some stage in a soil survey, preferably as early as possible, it is clearly desirable to check the validity of the soil quality classification which is being established and at the same time obtain information which may permit refinements to be made in the choice of criteria for this classification. Yet very little reference is to be found in soil survey literature on suitable methods for carrying out such checks, or on results that have been obtained.

In areas where cocoa has never been grown before little can be done until the results of trial plantings are available. In the early years, such plantings will provide little information on the relative ability of different soils to support sustained high yields over long periods, which is the ultimate test of soil quality for cocoa. One cannot wait thirty years, however, to discover whether or not the soil quality ratings are reasonably reliable and preliminary indications must be based on the vigour of the trees at an early age. Establishment problems may prove to be related to undesirable soil characteristics which were previously unsuspected and nutritional deficiency symptoms are often most clearly revealed on young plants. Experiments in Trinidad (Jones and Maliphant, 1958; Maliphant, 1959) have shown that a close correlation exists between girth measurements of cocoa trees three and a half years old and their subsequent yield when six, seven or eight years old. Similar results have been obtained in other parts of the world. Needless to say, girth increments, and indeed the whole early vigour of the cocoa tree, depend on many factors other than the suitability of the soil. Comparisons averaged from a large number of observations made on environmentally similar sites will be necessary before any subtle conclusions can be drawn on the relative suitability of the soils. The point to be emphasized is that work on assessing the quality of the soils should not cease upon completion of the first draft of a quality map based on theoretical principles.

In areas where cocoa is already a firmly established crop wider opportunities for checking the validity of a soil quality classification exist. The obvious approach, that of making observations and of checking yields on each of the soil types, is not always practical, however, and it is very difficult to avoid subjective errors if more than one observer is engaged in such work. Two other methods which have been used successfully in the field will be described, although each is applicable only in specific circumstances.

Cocoa Yield Maps

Burridge and Cunningham (1960) have described a successful exercise in mapping the yield of cocoa within a single large cocoa farm in Ghana and in relating this to differences in soil. The method can only be used conveniently where comparatively large areas are planted with reasonably uniformly spaced cocoa and yield data can be obtained for individual trees over at least a two year period. The cocoa itself must be of uniform age and variety and subject to uniform management practices. These conditions severely limit the practical application of the method but it is useful, nevertheless, for investigating the influence of individual soil characteristcs.

The investigation in Ghana was carried out as follows:-

(a) The site was divided into small square plots, each including 25 trees,* and the total yield of every four adjacent plots was marked on a plan of the site at their common corner. Thus, in Figure 4a, the total yield of plots a, b, e and f is marked on the Plan at A and that of plots e, f, i and j is marked on the plan at D.

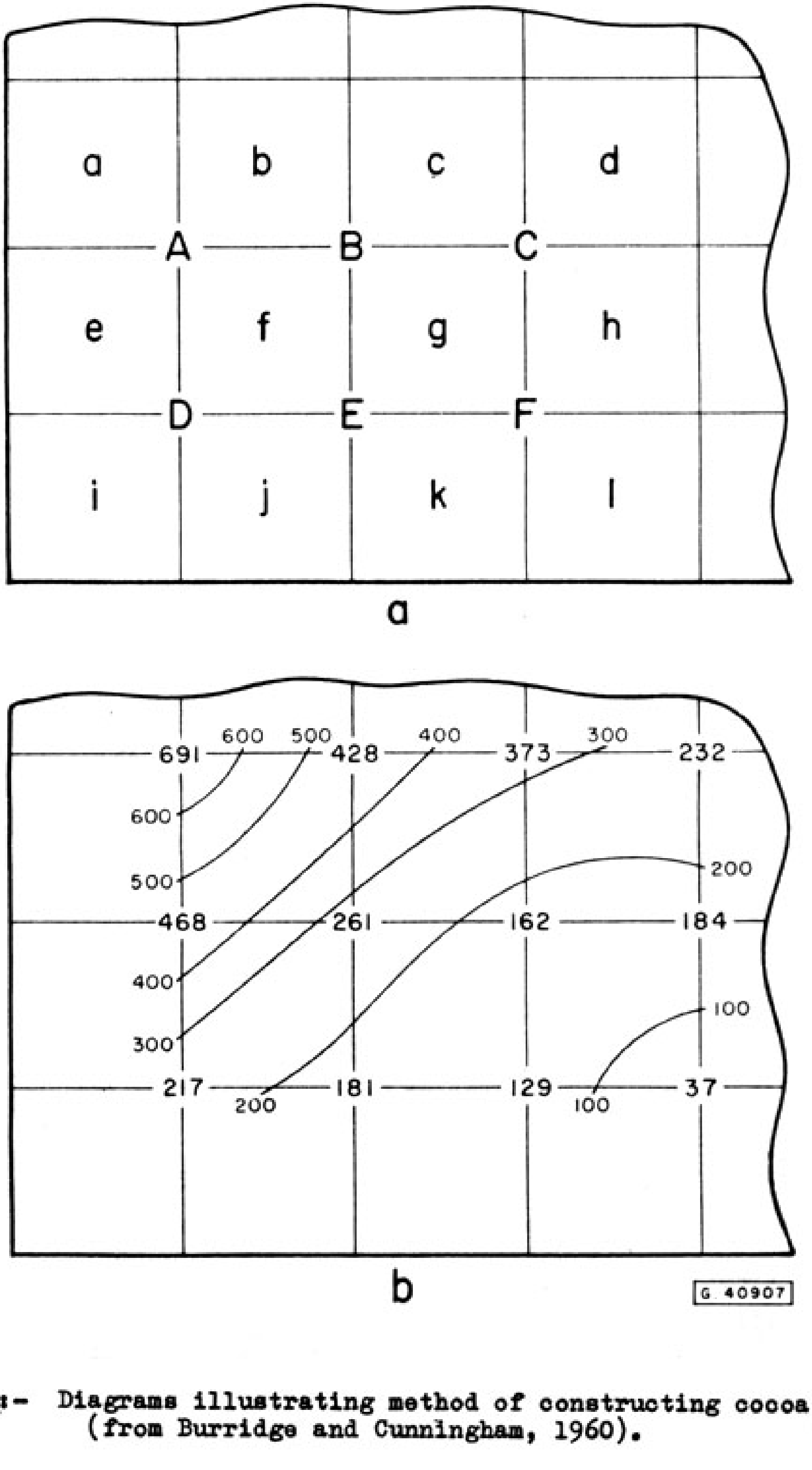
(b) Convenient yield values can then be scaled between the common corners, A, B, C etc. and connected by lines of equal yield - yield contours. This is illustrated, using hypothetical values, in Figure 4b. In this way a yield contour map of the site similar to that shown in Figure 5 can be constructed.

(c) The exercise should be repeated using data for yield from at least one more consecutive year and the yield contour maps thus obtained may be compared to indicate areas of consistently high or low yield. Alternatively, the data at each reference point may be averaged to provide a contour map of average yield. The more years of data, the more significant the map.

(d) Finally the yield contour maps may be compared with detailed soil maps; or the soils at sites showing especially high or low yields may be investigated and compared individually. Analytical data obtained for soils from sites having consistently high, medium and low yields in the Ghana investigation are shown in Table 1 (Chapter Four).

---

* Under the conditions of the Ghana experiment the yield patterns obtained using smaller plots with less than 25 trees were too complex, those from 100 tree plots were oversimplified.



FIGURES 4a and b:- Diagrams illustrating method of constructing cocoa yield maps (from Burridge and Cunningham, 1960).

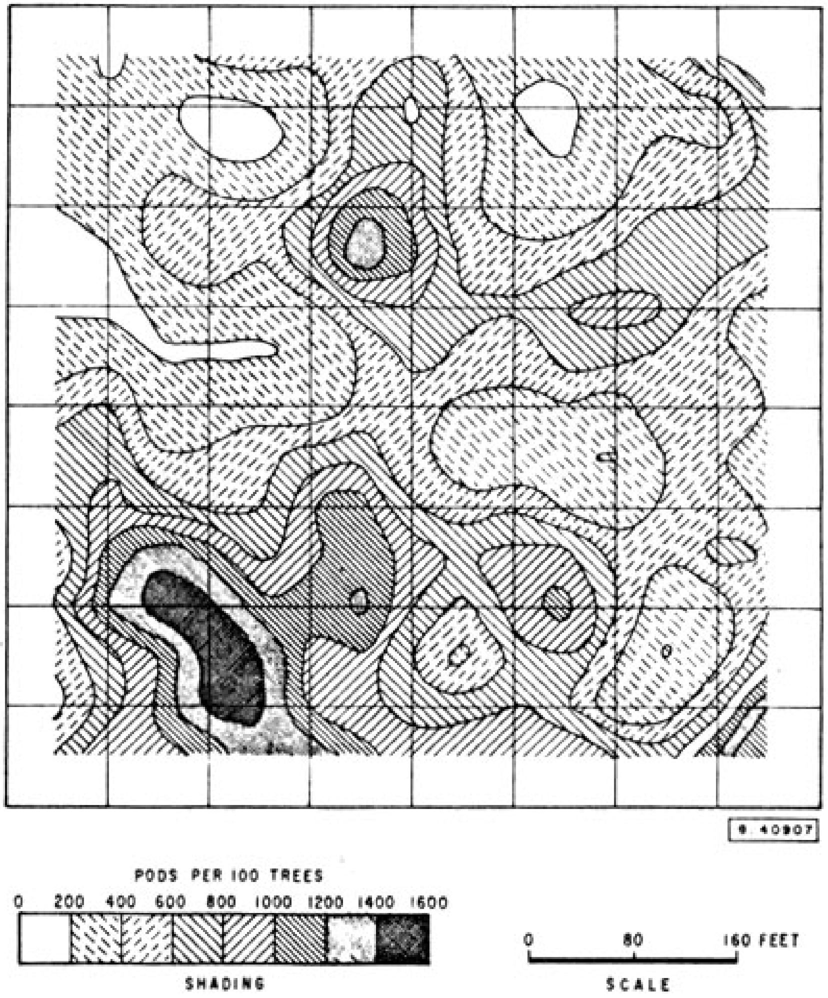


FIGURE 5:- A cocoa yield map prepared by the method described in the text (from Burridge and Cunningham 1960).

Distribution of Surviving Cocoa

In several of the main cocoa growing areas of the world, notably in West Africa and the West Indies, cocoa has been planted extensively by peasant farmers without professional advice on both suitable and unsuitable soils. The present distribution of surviving cocoa in these areas thus provides a fairly reliable measure of the relative suitability of the different soils. Increased bias for the cocoa to be found on the most suitable soils arises partly through the greater length of useful life of cocoa planted on such soils and partly through deliberate selection of these soils wherever possible by farmers who have learnt by trial and error. Study of the present distribution of such cocoa is perhaps the only way the scientist can benefit from this accumulated experience, for it can rarely be communicated more directly.

Simple comparisons of the acreage of cocoa planted on different soils usually fails to give a reliable indication of their relative suitability because there may be great variation in the quality of the cocoa recorded and great differences in the total areas occupied by the different soils. Thus, in an extreme case, an ideal soil may be entirely devoted to high quality cocoa but the total acreage under cocoa on this soil may be small, simply because there is very little of this soil in the area. In comparing the distribution of cocoa in relation to soil type, it is necessary, therefore, to make allowance for the availability of each type of soil. A very simple method of making these allowances has been demonstrated in relation to the distribution of cocoa in Western Nigeria (Smyth and Montgomery, 1962).

The method can be applied to any form of vegetation but in the case of cocoa consists simply of dividing the percentage of the total acreage of cocoa found to be growing on a particular soil type by the percentage of the total area which is occupied by that soil type. The resulting ratio was referred to in Western Nigeria as the "distribution ratio":

$$\text{Distribution ratio for cocoa} = \frac{\text{Percentage of total area of cocoa found on a single soil type}}{\text{Percentage of total area occupied by that soil type}}$$

If the distribution of cocoa were to be entirely unrelated to the distribution of the soils and a sufficiently large area is considered, it can be assumed that the percentage distribution of cocoa on each soil type would be essentially the same as the percentage of each soil type in the area. In these circumstances, the distribution ratio would be very close to 1. Values for the distribution ratio higher than 1 indicate that cocoa shows preferential survival, or planting, on the soils in question, whilst values lower than 1 indicate a bias against survival or planting. When distribution ratios have been calculated for all soil types the relative bias for or against survival will usually be clearly apparent. Environmental conditions, especially with regard to climate, must be essentially similar throughout the area analyzed and the larger the area considered the more reliable are the conclusions likely to be.

One advantage of this simple method is that it can be applied to any convenient grouping of the soils. Thus distribution ratios can be calculated in relation to the distribution of cocoa on soils belonging to individual soil series (or other mapping units), or on groups of soil units considered to belong to a single Class in the soil quality classification, or on soils grouped in relation to their expression of a single soil characteristic. Once the soils of an area have been mapped in distinct units having clearly defined characteristics, the units can be grouped in any convenient way for the purpose of calculating distribution ratios.

A further advantage of the method is that it can be applied equally well to situations in which detailed maps of the soil units and of the overall vegetation are available, or to situations in which information on the distribution of vegetation in relation to soils is only available on a spot sample basis. In the first case, mapped information on the distribution of cocoa is superimposed on the soil map, or the soil quality map, and the percentage distribution on each soil type is then calculated directly on an area basis.* In the second case, each spot sample is taken to be representative of a specific fraction of the total area depending on the density of sampling and a numerical count of each variety of sample (i.e.:- each type of soil under each type of vegetation) is then converted into percentages for calculation of the ratio. The density of spot sampling must be sufficient to ensure that a truly representative picture of the area as a whole is obtained. A method of carrying out the required calculations simply and accurately has been described in detail by Smyth and Montgomery (1962).

---

* The simplest method of carrying out this task is to cut up the map into small pieces representing each of the soil types, with or without cocoa, and determining the total weight of each group of pieces. The weights determined are proportional to the area in each case, if variation in the weight of the mapping paper per unit area is neglected.

TABLE 10: Percentage distribution of different kinds of vegetation on each of four quality classes of soil in the main cocoa-growing area of Western Nigeria. The data refers to an area covering over 9,500 sq. miles (Smyth and Montgomery, 1962).

VEGETATION	SOIL QUALITY				ALL SOILS
	good	f.good	poor	v.poor	
Cocoa	25.0%	36.7%	25.5%	12.8%	100%
Bush Regrowth and Cultivation	15.3%	28.4%	30.8%	25.5%	100%
Thicket (& Grassland)	12.4%	26.6%	34.0%	27.0%	100%
Forest	9.6%	24.7%	35.1%	30.6%	100%
All Vegetation	14.4%	28.1%	32.2%	25.3%	100%

TABLE 11: The same data shown in TABLE 10 (with additional data relating to different qualities of cocoa) recalculated in the form of "distribution ratios" for each type of vegetation (see text).

VEGETATION	SOIL QUALITY			
	good	f.good	poor	v.poor
Good cocoa	2.04	1.29	0.73	0.43
Medium cocoa	1.58	1.36	0.83	0.49
Poor cocoa	1.46	1.28	0.85	0.61
All Cocoa	1.74	1.31	0.79	0.51
Bush Regrowth & Cultivation	1.06	1.01	0.96	1.01
Thicket (& Grassland)	0.86	0.95	1.06	1.07
Forest	0.67	0.88	1.09	1.21

TABLE 12: Distribution of surviving cocoa and kola planted by peasant farmers within an area of detailed soil survey in Western Nigeria (Smyth and Montgomery 1962)

VEGETATION	FACTOR	KINDS OF SOIL (see table below)				ALL SOILS
		G and FG	P	VP	W	
Cocoa	Area(acres)	193	68	108	78	447 acres
	% distribution	43.28%	12.2%	24.1%	17.5%	100%
	Distribution Ratio	1.64	0.77	0.60	1.29	
Kola	Area(acres)	130	40	87	26	283 acres
	% distribution	45.9%	14.2%	30.7%	9.2%	100%
	Distribution Ratio	1.74	0.72	0.77	0.66	
All Vegetation	Area(acres)	995	742	1,511	526	3,774 acres
	% distribution	26.4%	19.7%	40.0%	13.9%	100%

Note on kinds of soil:-

G and FG :-	Fairly clayey deep soils considered suitable for cocoa.
P :-	Rather sandy soils considered poor for cocoa.
VP :-	Very sandy soils and shallow soils over ironpan, considered very poor for cocoa.
W :-	Soils with water table seasonally within 48" of surface.

As stated, distribution ratios can be calculated for any class of vegetation. Indeed, a single type of vegetation can be divided into quality subclasses on the basis of its visual appearance or on the basis of yield and the distribution ratio for each subclass calculated separately. Theoretically it would be possible to calculate the distribution ratio on the basis of the percentage of the total yield, rather than of the total area, on each soil type. This would provide much more valuable comparative data but, in practice, it is rarely possible to obtain the required yield information.

Tables 10 and 11 show results obtained by the application of the method to spot sample data obtained during a reconnaissance soil survey of the main cocoa-growing area of Western Nigeria covering over 9,500 sq. miles. Table 10 shows the data expressed as simple percentages of each vegetation type on each of four quality classes of soil. The percentage distribution of "all vegetation" in this table reveals the relative availability of the soils of each soil quality class. In Table 11 the same data, augmented by additional data on different quality classes of cocoa, is presented in the form of 'distribution ratios' for each type of vegetation in relation to the soil quality classes. The bias for cocoa to be found on the better quality soils is clearly apparent in this data. The fact that this bias is more pronounced in relation to the better qualities of cocoa is especially interesting, for in this assessment cocoa quality is based entirely on the visual appearance of the trees which in the area in question is strongly influenced by different levels of insect and virus attack. Also of interest is the fact that distribution ratios for Bush Regrowth (young fallow land) and Cultivation (arable farmland) are very close to 1 for each soil quality class, indicating that the factors which dictate the distribution of arable farming are unrelated to those which are chosen to decide the soil quality classes. Very probably, choice of soil is not a decisive factor in the distribution of arable farmland in this area, in marked contrast to the distribution of cocoa. The reversed pattern of distribution ratios for Thicket and for Forest vegetation, both representing stages in long term natural fallow, largely reflect the reduced availability of the better quality soils as the result of their preferential use for tree crops.

Table 12 provides an example of distribution ratios calculated directly from area measurements made on a detailed map which combined information on the distribution of different soils and that of both cocoa and kola. In this case a different grouping of the soils has been used and the distribution ratios serve to demonstrate that, whereas cocoa shows preferential distribution on the soils of moderately high water table,* this is not the case with the other tree crop, kola.

Table 3 (Chapter Four) shows how the distribution ratio can be applied to soils grouped on the basis of a single characteristic, in this case soil pH.

---

* The area surveyed has a marked dry season.

CHAPTER SIX

SURVEY METHODS

Surveys which have, as their primary objective the location of soils suitable for cocoa do not differ in basic principle from other kinds of soil survey. It would be a mistake, in fact, to carry out a survey with the sole intention of identifying soils suitable for cocoa, or for any other severely restricted purpose. A large part of the cost of a soil survey is often incurred in assembling and locating the soil survey parties and their equipment in the area of the survey. Once these expenses have been met, therefore, it is essential to obtain as much information as possible so that the resulting soil maps can later be interpreted in a variety of ways and are adequate to meet all foreseable needs. The greatest care must be taken in selecting criteria to distinguish the individual soil units and all characteristics of these units must be closely investigated and clearly described. If this is not done, future planning demands may necessitate a complete resurvey of the area.

A summary of soil survey methods would be out of place in this publication and this Chapter is included merely to highlight certain practical problems which are likely to arise in surveys of potential cocoa-growing areas. These problems are connected with the detailed nature of the survey required to locate suitable planting sites and with the environmental conditions which normally prevail in areas suited to cocoa.

The Scale of Mapping

The sensitivity of cocoa to quite subtle differences in the physical characteristics of soils has been stressed in previous Chapters. In a general purpose soil survey it is unlikely that all these differences would be recognized in the soil classification, much less mapped individually, yet this is necessary if a survey is to demarcate exactly those areas which are most suitable for cocoa. Havord (1955;1957) in particular, has stressed the need for surveys of a very detailed nature for the selection of planting sites for cocoa. This need is especially pronounced in districts where the soil pattern is very complex, due to hilly topography or complex geology, or both of these factors. Such conditions are commonly encountered in areas suited to cocoa.

Havord himself (1961) has demonstrated the advantages of a survey carried out at a very large scale, working on field sheets at a scale of 1:2,400 with subsequent publication at a reduced scale of 1:5,000. In Nigeria it was found to be necessary to examine between 50 and 100 profiles per square mile and to publish maps at a scale of approximately 1:8,000 in order to indicate the distribution of individual soil series distinguished with special regard to the requirements of cocoa. Even at this level of detail it was not possible to map variations of series based mainly on differences of colour and texture which, although minor, were thought to have significance in relation to performance of cocoa, (Smyth and Montgomery, 1962).

Surveys of very large areas at scales less than 1:10,000 are both time consuming and expensive and, in the first instance, such surveys are usually restricted to areas of special interest. Indeed, as a general rule, it is not advisable to embark upon very detailed surveys until a general picture of soil distribution in the area has been obtained from surveys at smaller scales. Unless such information is available, much time can be wasted during detailed investigations in attempting to distinguish criteria which will provide a practical basis for soil mapping. Minor variations in soil character of extremely localized occurrence tend to obscure the more significant differences which would provide suitable criteria for mapping - one cannot "see the wood for the trees". Failure to carry out a preliminary reconnaissance survey has other more serious disadvantages. It is often difficult, for example, to correlate the soil classifications erected in separate detailed surveys so that unrelated classifications tend to proliferate in areas where no broad reconnaissance has been carried out. Furthermore, in the absence of reconnaissance data, it is impossible to say whether the pattern of the soils examined in detail is representative of surrounding soils, or whether or not it is likely that more suitable soils are to be found beyond the boundaries of the detailed survey.

In almost all cases, therefore, it is desirable to carry out a rapid reconnaissance survey of the area under study before commencing on detailed surveys. It may not be necessary for the reconnaissance survey to cover an entire region. Preliminary investigations, existing maps of soils, geology or vegetation, and local knowledge may indicate that some large areas offer little promise of immediate development, and these may be temporarily neglected.

The reconnaissance survey should be carried out as rapidly as possible making maximum use of air photo interpretation and of traverses along roads and other easy routes of access. The studies should, however, be sufficiently detailed to obtain a representative picture of the major kinds of soil available, their proportional distribution and their relationship with vegetation, topography and other environmental factors. The reconnaissance survey should give rise to soil maps at a scale of 1:100,000, or possibly 1:250,000, together with an informative supporting text so as to ensure that the data obtained will be available to other workers in the future. The mapping units used in this survey will doubtless refer to complexes of soil, associations of soil series or of Great Soil Groups, but the more extensive soils included within these units should be identified and described individually to provide the required framework for more detailed classification. Some fairly detailed studies will almost certainly have to be carried out in support of the reconnaissance survey to obtain information on individual kinds of soil and of the broad topographical and geographical relationships between these soils. Very often, government owned farms or other areas of special interest, provide suitable sites for such studies and the detailed maps prepared are then of immediate practical value.

Once reconnaissance information is available areas can be selected within which detailed surveys are likely to prove of most value. Deserving of high priority are surveys for the selection of planting sites for improved cocoa varieties destined to provide future planting material and of sites for field experiments on cocoa. The selection of sites for experimental work provides an excellent example of the value of a preliminary reconnaissance survey for, if the experiments are to yield results having wide application, the soils on which they are conducted must be representative of a large proportion of the soils in surrounding areas on which cocoa is likely to be grown. The best soils available, although clearly desirable for especially valuable planting material, may not be the most representative and so may not be particularly suitable for experimental work. In the absence of preliminary reconnaissance data, neither the best nor the most representative soils of an area can be identified until the entire area has been surveyed in detail. Such a delay is rarely acceptable.

The ultimate aim should be to obtain complete coverage by soil surveys at a level of detail sufficient to indicate suitable planting sites exactly. In most areas surveys at a scale of 1:10,000 or even larger, will be required for this purpose. It is very doubtful if the expense of such a comprehensive survey could be justified solely on the grounds of selecting soils for commercial cocoa plantings but, as basic documents for the overall planning of land-use and soil management, the maps produced would be invaluable.

Until detailed survey data is available selection of sites for commercial cocoa planting must be done on an 'ad hoc' basis. This is not difficult if the identity and characteristics of the more extensive soils of the area have been recognized and related to a soil quality classification during a reconnaissance survey supported by some detailed mapping. In most cases, factors other than soil, notably ownership, limit the number of possible sites which can be considered for individual commercial plantations and each can be studied in considerable detail. Where demands for advice on planting sites are very frequent and the plots concerned are small, which is likely to be the case in a peasant farming economy, it may be impossible for a soil scientist to visit all possible sites. In this case, the soil scientist can usually obtain assistance from junior extension workers or from staff trained specifically for the purpose. Depending on the level of education and intelligence of the staff concerned, they can be trained, either to pronounce on the suitability of the soils themselves, or to complete a simple questionnaire on environmental conditions and to collect representative soil samples from each site on which the soil scientist may pass judgment at his base office.

Field Methods

In potential cocoa-growing areas the climax of natural vegetation is usually fairly dense rainforest; topography is rarely flat; local farmers usually practice 'bush-fallow' or 'shifting cultivation' methods rather than more stable systems of agriculture; road networks are often inadequate and basic documentation, such as geological and even topographical maps, is sometimes lacking. These factors combine to create exceptionally difficult conditions for soil survey. In particular, they limit the use which can be made of air photo interpretation and create severe difficulties of access and of accurate mapping.

In recent years air photo interpretation has earned an increasingly important place amongst soil survey methods. Under favourable circumstances use of photo interpretation can reduce the time spent on a reconnaissance survey by 70% to 80% of that necessary for a conventional ground survey, without loss of accuracy. This time saving is achieved mainly by reducing the amount of field work necessary to establish the boundaries between soil units. The characteristics of the units themselves can only be determined by examination on the ground and it is essential that the sites examined for this purpose are located fairly exactly on the photographs. This may be difficult to achieve in areas of high forest vegetation, especially if the pattern of land-use is continually changing as peasant farmers shift the sites of their arable cultivation. The pattern of such cultivation is often confusing in itself, for it is rarely closely related to the pattern of the soils, and patches of forest of uneven height can mask minor changes in topography which may be significant in relation to soil distribution.

Despite these difficulties, air photo interpretation can be of great value in reconnaissance surveys of areas suited to cocoa. Under a stereoscope the photographs draw attention to areas of differing topography in which different soils may be anticipated. Preliminary mapping units, based on position in relation to slopes of differing shape, can be recognized and these may later be related to differences in the soils by ground investigation. The drainage pattern of the area can usually be mapped in great detail, which is often difficult to do at ground level. In the absence of more reliable geological information, changes in topography and the general arrangement of hills, escarpments and streams detected on the photographs provide clues to the pattern of the underlying rocks. Finally, sites which appear to be representative of individual topographical units, and presumably, therefore, of individual groups of soils, can be selected for close investigation on the ground. With the aid of photographs the sites chosen for ground investigation can be those which are most easy of access. This last consideration alone can save weeks of arduous field work.

The more detailed the survey the greater the amount of actual field work required whether or not air photo interpretation is employed. In addition, in detailed surveys the location of sample points and boundaries between soil units requires to be much more accurate. Thus, in detailed surveys of most cocoa-growing areas, the assistance provided by air photo interpretation is very greatly reduced and one is forced to rely almost entirely on ground survey methods.

In areas of rainforest vegetation, and perhaps of hilly topography, problems of access and of mapping the position of sample holes and soil boundaries can be very severe. Visibility within the forest is often only a few metres in each direction and it is often impossible to obtain a broad view of the district as a whole, much less locate oneself in relation to natural landmarks. A certain amount of sampling can be done on roadsides or from footpaths but these are normally routed through the least steep sections of the topography and so provide an unrepresentative sample of the area as a whole. Furthermore, the time required to survey the tortuous routes followed by most footpaths outweighs the advantage of easy access which they offer.

The alternative is to cut traverses on compass bearings. A parallel grid of such traverses, not only provides easy access to the area but enables sample points, spaced at equal intervals on each traverse, to be located accurately on base maps with a minimum of difficulty. Havord (1961) was unable in Trinidad to cut straight compass traverses because of the large amount of cocoa in the area which he surveyed. This was not the experience in Western Nigeria, where traverses were aligned using three ranging poles and marked by inserting pegs, cut from thicket vegetation at intervals of only 66 feet (1 Gunter chain - approximately 20 metres). There it was found that the amount of damage caused by well-trained traverse cutters when traversing cocoa or even closely planted arable crops was acceptable, even to the farmer! Where unavoidable, a rectangular deviation was made in the traverse, to avoid houses, rock hills, impassable swamps, etc., but the traverse was returned to its original course as soon as the obstruction was passed, (Smyth and Montgomery, 1962).

The spacing between traverses and the spacing between sample holes on the traverse is adjusted in accordance with the density of sampling required. In reconnaissance surveys, the number of traverses required depends very much on the adequacy of the road network and on the amount of supporting information available from geological maps or air photographs. Where much is already known, only an occasional traverse is likely to be necessary. The best direction and starting point for individual traverses of this kind can be decided by inspecting air photographs to ensure that each traverse will cross a representative cross section of the topography.

In detailed surveys a complete grid of traverses is usually necessary. Unless the traverses are closely spaced, a considerable amount of additional checking between traverses will be required to establish the exact position of soil boundaries. Such work is likely to prove more arduous, equally time consuming and less reliable in its results than additional traverse cutting. As a general guide, a spacing of, at most, 200 metres (or yards) between traverses and a similar spacing of sample holes along traverses, will be required for surveys intended to locate suitable planting sites for cocoa exactly.

Surveys using a complete grid of traverses are slow and, therefore, expensive. However, they offer several important advantages over less systematic methods. Providing the sampling density is adequate and the area sufficiently large, the data obtained from sample points on traverses can be used to estimate the proportion of different kinds of soil, different kinds of vegetation and the relationship between kinds of soils and vegetation in the area surveyed, even if the units considered are too complex to map individually. If the starting points and bearings of the traverses are accurately recorded they provide a simple means of relocating areas of good soil after the survey has been completed. In areas of dense vegetation it is often worth while to keep some traverses underbrushed and open for this purpose until access roads have been constructed and planting is actually underway.

Most important, however, is the opportunity which traverse surveys offer for the employment of semi-skilled assistants. Experience in West Africa has shown that junior survey staff of very low academic attainment can be trained to do much of the field work of such surveys, separate teams being instructed to carry out the cutting of the traverses, the sampling of the soils, and the simple description of vegetation. Professional soil scientists are not relieved from all field work, of course, but, having established a general understanding of the field relationships of the different soils, the time they spend in the field can be occupied more profitably in the study of areas which present special problems. Each of the junior teams can be trained to prepare simple records of their work and these, together with samples representing the several horizons of complete soil profiles, can be brought into a base office for study by the soil scientist. In this way, the soil scientist can carry out the routine examination and classification of samples from a far larger number of sample holes than he could possibly visit personally in a given time period.

In West Africa the problems of classifying and correlating soil profiles was found to be greatly facilitated when samples from individual soil horizons, brought from the field in canvas bags, were laid out in vertical sequence in the hollow of a piece of bamboo, split lengthwise. Each length of bamboo thus contained samples representing a single soil profile which, with care, could be preserved for considerable periods and carried about for comparison and correlation with other 'profiles'. Profiles classified within a single unit can be grouped side by side, thus drawing immediate attention to the range in characteristics that has been permitted within the unit and to profiles which have been erroneously classified. Since bamboo is usually available and is inexpensive, this tequnique may prove useful in other cocoa-growing areas. Other tequniques appropriate to traverse surveys using large numbers of semi-skilled staff have been described in some detail by Smyth and Montgomery,(1962).

BIBLIOGRAPHY

Adams, S.N. Agriculture and land-use in Ghana. Chapter 18F, Soils
1962 and manuring of cocoa. Oxford University Press, Ed. by
J. Brian Wills.

Adams, S.N. & McKelvie, A.D. Environmental requirements of cocoa
1955 in the Gold Coast. Cocoa, Chocolate and Confectionery
Alliance, Proc. of the Cocoa Conf. London 1955

Alvim, P. de T. Water requirements of cocoa. First FAO technical
1959 cocoa meeting, Accra, Ghana (unpublished document).

Amson, F.W. & Lems, G. De invloed van de bodem op de kolfproduktie
1963 in een cacaoklonen experiment [The influence of the soils on
pod production in a clonal cocoa experiment]. Mededeling
No. 33: Landbouwproefstation: Surinam.

Aubert, G. Soil with ferruginous or ferallitic crusts of tropical
1963 regions. Soil Science: Vol. 95: No. 4.

Aubert, G. & Moulinier, H. Observation sur quelques caractères des
1954 sols de cacoỳeres en Côte d'Ivoire. L'Agronomie Tropicale,
Vol. IX: No. 4.

Bates, J.A.R. Studies on a Nigerian forest soil, Part 1. The
1960 distribution of organic matter in the profile and in
various soil fractions. Journal of Soil Science: Vol. 11:
No. 2.

Bates, J.A.R. & Baker, T.C.N. Studies on a Nigerian forest soil,
1960 Part II. Distribution of phosphorus in the profile and in
various soil fractions. Journal of Soil Science: Vol. 11:
No. 2.

Bennema, J. The red and yellow soils of the tropical and subtropical
1963 uplands. Soil Science: Vol. 95: No. 4.

Brammer, H. Soils: In Wills ed. Agriculture and land-use in Ghana.
1962 Oxford University Press, London.

Burridge, J.C. & Cunningham, R.K. Cocoa yield maps and soil fertility
1960 in Ghana. Empire Journal of Experimental Agriculture. Vol.28:
No. 112.

Charter, C.F. Cocoa soils: good and bad. Mimeographed circular issued
1948 by West African Cocoa Research Institute, Tafo, Ghana.

Charter, C.F. The need for manuring cocoa in the Gold Coast
1953 in order to maintain and augment the level of production.
Cocoa, Chocolate and Confectionery Alliance. Proceedings
of the Cocoa Conf. London 1953: Appendix III.

Charter, C.F. The nutrient status of Gold Coast soils: with special
1955 reference to the manuring of cocoa. Cocoa, Chocolate and
Confectionery Alliance. Proceedings of the Cocoa Conf.
London 1955.

Chatt E.M. Cocoa. Interscience Publishers Inc. New York and
1953 London.

Coleman N.T. & Mehlich A. The chemistry of soil pH. Soil. The 1957
1957 Yearbook of Agriculture. United States Dept. of Agriculture.

Crosbie A.J. The suitability of forest soils in Ghana for cocoa
1957 production. Proceedings of the Cocoa Conf. London

Cunningham, R.K. Micro-nutrient deficiency in cacao in Ghana.
1964 Empire Journal of Exper. Agric: Vol 32: No. 125.

Dudal, R & Soepraptohardjo, M. Some considerations on the genetic
1960 relationship between latosols and andosols in Java
(Indonesia). Proc. of the 7th International Congress
of Soil Science. USA: Vol IV.

Edelman, C.H. & van der Voorde, P.J.K. Important characteristics of
1963 alluvial soils in the tropics. Soil Science Vol.95: No. 4.

Erneholm, I. Cacao production of South America, historical
1948 development and present geographical distribution.
Gothenburg, Sweden.

Food and Agriculture Organization of the United
1962 Nations. Dynamics of tropical soils in relation to their
fallowing techniques. FAO Publication.

Haddon, A.V. Variety trials of seedling cacao in Malaya.
1961 Malayan Agricultural Journal. Vol. 43: No.3.

Hardy, F. Some soil relations of the root system of cacao;
1944 further results of investigations in Trinidad. Tropical
Agriculture (Trinidad), 21.

Hardy, F. The deterioration of cacao soils in Trinidad. Report
1953 on Cacao Research, 1945-51: 1. C.T.A. Trinidad.

Hardy, F. Cacao soils. Proc. of the Soil and Crop Science Soc.
1958 of Florida. Vol. 18.

Hardy, F. Carbon: nitrogen relationships of cocoa soils. "Turrialba",
1959 Journal of the Inter-American Institute of Agricultural Sciences,
Vol. 9: No. 1. (in Spanish).

Hardy, F. Cacao Manual. Inter-American Institute of Agricultural
1960 Sciences, Turrialba, Costa Rica.

Havord, G. Lime induced chlorosis of cocoa seedlings. Report on
1954 Cocoa Research 1954. I.C.T.A. Trinidad.

Havord, G. Soil Conditions for cocoa and their amendment for
1955 maximum yield. Cocoa, Chocolate and Confectionery Alliance.
Proceedings of the Cocoa Conf. London 1955.

Havord, G. Detailed soil and land capability surveys for cocoa.
1957 Cocoa, Chocolate and Confectionery Alliance. Proceedings
of the Cocoa Conf. London 1957.

Havord, G. The nutrition and shade requirements of cocoa. First FAO
1959 technical cocoa meeting, Accra, Ghana. (Unpublished document).

Havord, G. A detailed soil and land capability survey of a cocoa
1961 area in Trinidad. Soil and Land-Use Surveys No. 13. University
College of the West Indies.

Homès, M.V. L'alimentation minérale du cacaoyer. Série scientifique
1953 No. 58. INEAC.

Homès, M.V. L'alimentation minérale et la fumure du cacaoyer. Cocoa,
1957 Chocolate and Confectionery Alliance. Proceedings of the Cocoa
Conf. London 1957.

Hurd, R.G. & Cunningham, R.K. A cocoa shade and Manurial experiment
1961 at W.A.C.R.I., Ghana, Part III, Physiological Results. Journal
of Horticultural Sciences: Vol 36: No. 2.

Jacob A. & von Uexküll H. Fertilizer use: nutrition and manuring of
1958 tropical crops. Verlagsgesellschaft für Ackerbau mbH. Hanover.

Jones, T.A. & Maliphant G.K. Yield variations in tree crop experiments
1958 with specific reference to cocoa. Nature: Vol. 182: pp. 1613-1614.

Kaden, O.F. Untersuchungsergebnisse über nicht parasita Kakaokrankheiten
1933 auf San Thomé und Principe Tropenpflanzer, Berlin.

Kowal, J.M.L. The effects of spacing on cacao in Nigeria. Part II,
1959 Empire Journal of Experimental Agriculture: Vol.27: No. 106.

Lains, E. Silva, H. Caracterizacao de algumas das principais unidades
1958 pedologicas do Esboco da Carta dos Solos de São Tome e Principe.
Proceedings 7th Interamerican Cocoa Conf. Colombia.

Lamée, G. Influence de l'alimentation en eau et de l'ombrage dur
1955 l'economie hydrique et la photosynthese du cacoyer. Agronomia
Tropicale, 10.

Leneuf, N. & Riou G. Sols rouges et sols jaunes de Cote d'Ivoire.
1963 Sols Africains Vol. VIII: No. 3.

Maignien, R. Les sols bruns entrophes tropicaux. Sols Africins
1963 Vol. VIII: No. 3.

Maliphant, G.K. The cocoa tree size-yield correlation. Report on
1959 Cacao Research 1957-58, ICTA. Trinidad.

McCreary, C.W.R. et al. The root system of cocoa; results of some
1943 preliminary experiments in Trinidad. Tropical Agriculture
(Trinidad) 20.

McDonald, T.A. An environmental study of the cocoa tree. Imperial
1932 College of Tropical Agriculture, Trinidad, Annual Report on
Cocoa Research for 1931.

McKelvie, A.D. Agriculture and land-use in Ghana: Chapter 18b - Physiology
1962 of cocoa. Oxford University Press. Ed. by J. Brian Wills.

Mohr, E.C.J. & van Baren, F.A. Tropical soils. Interscience Publishers
1954 London

Nye, P.H. Some soil-forming processes in the humid tropics: Part IX:
1955 The action of the soil fauna. Journal of Soil Science: Vol.6:
No. 1.

Nye, P.H. & Greenland, D.J. The soil under shifting cultivation.
1960 Technical communication No. 51. Commonwealth Bureau of Soils.
England.

Panton, W.P. Reconnaissance soil survey of Tengganu. Bulletin No. 105,
1958 Ministry of Agriculture, Federation of Malaya.

Radwansky, S.A. Cocoa soils of Western Ashanti, Ghana. Cocoa, Chocolate
1957 and Confectionery Alliance. Proceedings of the Cocoa Conf.
London, 1957.

Smyth, A.J. & Montgomery, R.F. The soils and land-use of Central Western
Nigeria. The Government Printer, Ibadan, Western Nigeria.

Sutcliffe, J.F. The absorbtion of inorganic nutrients by plants.
1964 Proceedings of The Fertilizer Soc. London, November 1964.

Sys, C. La classification des sols au Congo Belge. Proceedings of
1959 the 3rd Interafrican Soils Conference, Dalaba, Guinea: Vol.I.

Urquhart, D.H. Cocoa. Longmans Green, London.
1955

U.S.D.A. Soil survey manual. US Dept. of Agriculture Handbook
1951 No. 18. USDA Washington.

van Beers, W.F.J. Notes on the growing conditions for cocoa in
1950 Indonesia. Contributions of the Central Agric. Res.
Station, Bogor, Indonesia: No. 101.

van Himme, M. Etude du systeme radiculaire du cacoyer. First FAO
1959 technical cocoa meeting, Accra, Ghana (unpublished document).

Venning, F.D. Mechanical damage to cacao trees caused by winds of
1958 low velocity. 7th Interamerican Cacao Conf. Palmira, Colombia.

Verliére, G. Un essai d'engrais sur cacaoyers en Cote d'Ivoire -
1965 I.Amelioration des rendements par la fumure minerale et
rentabilite. International Conf. on Cocoa Research,
Abidjan, Ivory Coast 1965.

Vine, H., Thomson, H.A. & Hardy, F. Studies on aeration of cacao.
1942, 1943 Soils in Trinidad, Pts. I to IV. Tropical Agriculture,
Trinidad, Vol. XIX: Nos. 9, 11: Vol.XX: Nos. 1,3.

Wessel, M. The cocoa-growing area of Ikom in Eastern Nigeria.
1965 Cocoa Research Institute of Nigeria (unpublished document).

APPENDIX

Further Explanation of Chemical Criteria Determined by Soil Annalysis

a) Base exchange capacity

The surfaces of most tiny mineral and organic particles (colloids) in a soil carry negative electric charges. These attract the positively charged particles (cations) of nutrient base which are created by the dissociation of the base and acid radicles of a nutrient salt when it dissolves in the soil water. The attracted cations sit on, or near, the surface of the colloid particles, but the bond between them is not very strong and exchange takes place between cations on the colloids and similar, or different, cations in the soil solution. An equilibrium is established between the cations in solution and those held on colloid surfaces. In a given soil, the cations of a number of different nutrient bases may be serving to balance the charge on the colloid surfaces and the proportion of each is related to the concentration of each cation in the soil solution. When plants withdraw nutrient cations from the soil solution, these are replaced by 'exchangeable cations' from the colloid surfaces, so long as they are available, and the system remains in equilibrium. This ability of the colloidal particles of a soil to 'hold' cations provides a 'storehouse', therefore, from which nutrients can be released to meet the requirements of plants and 'within' which nutrients are preserved from loss by downward leaching in the drainage waters or by chemical 'fixation' in forms unavailable to the plant.

Base exchange capacity (B.E.C.), alternatively referred to as cation exchange capacity (C.E.C.), is a measure of the quantity of cations which are required to balance the negative charges in a unit volume of soil under a given set of conditions. The magnitude of this quantity depends on the amount and nature of colloidal material present in the soil and on the degree of acidity of the soil at the time the measurement is made. Base exchange capacity is usually expressed in terms of the milliequivalents of cations which are required to neutralize 100 grams of soil (m.e./100 grams soil) at pH7. In interpreting laboratory data on base exchange capacity it is most important to know the pH at which this value has been measured since, under more alkaline conditions than pH7, much higher values for base exchange capacity will be recorded. For example, the high values of B.E.C. recorded for soils in Ghana in Table 6 (Chapter Four) were measured at pH 8.2.

The average base exchange capacity of soil organic matter, measured at pH 7, is near to 200 milliequivalents per 100 grams. That of clay minerals is much lower and varies widely, depending on their crystal structure. Montmorillonitic clay minerals, of expanding lattice structure, carry permanent negative charges equivalent to a base exchange capacity of 80 to 120 milliequivalents per 100 grams of clay. Non-expanding clay minerals of kaolinitic type, which predominate in well drained soils of most potential cocoa-growing areas, carry permanent charges equivalent to only 1 to 8 milliequivalents per 100 grams of clay (Coleman & Mehlich, 1957). In surface soil horizons the magnitude of base exchange capacity is closely related to the proportion of organic matter present but, in deeper horizons, where the content of organic matter is usually very low, values for base exchange capacity largely reflect the nature and amount of clay minerals in the soil.

b) Percentage base saturation

Percentage base saturation is a measure of the proportion of the total base exchange capacity of a soil sample that is balanced by basic cations such as calcium, magnesium, sodium and potassium. In a base saturated soil nearly all the negative charges of the exchange complex are balanced by these cations, whereas in a base unsaturated soil the most abundant exchangeable cations are those of hydrogen and aluminium.

Percentage base saturation read in conjunction with base exchange capacity provides a measure of the total quantity of nutrient cations which are held in the exchange complex of the soil and which are potentially available, therefore, to the plant. If the soil is freshly cleared from forest, or some other natural fallow, it can be assumed with some confidence that the balance of individual nutrients contributing to saturation approximates that required by cocoa, or most other plants, at least in the upper horizons of the soil. This may not be true, of course, in soils in which high levels of base saturation are the result of additions of artificial fertilizer, possibly in unbalanced and injudicious amounts.

Low percentages of base saturation are an indication that the soil has suffered prolonged weathering, severe leaching, intensive cultivation or combinations of these factors and thus is poorly provided with nutrient bases. Furthermore, in unsaturated soils the quantity of aluminium ions in equilibrium between the exchange complex and the soil solution can reach levels which are toxic to many plants and possibly to cocoa.

c) pH

pH is a measure of the acidity or alkalinity of any chemical system, including that of a soil. pH is, in fact, the logarithm of the reciprocal of the concentration of hydrogen ions in such a system:-

$$\text{pH} = \log \frac{1}{(\text{concentration of hydrogen ions})}$$

As the concentration of hydrogen ions increases, that is to say, as a system becomes more acid, so the pH value is reduced. A neutral system has pH 7. pH values below 7 indicate that the system is acid. pH values above 7 indicate an alkaline system.

In soils which are acid to neutral in reaction, including the majority of soils in potential cocoa growing areas, soil pH is closely related to the percentage base saturation of the base exchange complex. The lower the percentage saturation, the larger is the proportion of the negative charge of the exchange complex which is balanced by exchangeable hydrogen ions and the more acid is the soil. Reversing this argument, low soil pH values are an indication, therefore, of low concentrations of nutrient bases in the exchange complex of the soil. In strongly alkaline soils, having high pH values, a large proportion of the exchange capacity is occupied by sodium ions. Quite apart from their nutritional shortcomings, the physical characteristics, and especially the structure, of soils rich in sodium are usually unsuitable for cocoa.

In the first section of this Appendix reference was made to the fact that the magnitude of base exchange capacity itself, is dependant, in part, upon pH. This is especially true of that part of the exchange capacity provided by organic matter, which is almost entirely dependant upon pH. Thus the exchange capacity of an acid soil is less than that of a neutral soil containing the same percentage of organic matter and having the same mineral assemblage.

In addition to the nutrient bases held in the exchange complex, nutrient elements are present in the soil in a variety of other forms, not all of which are equally available to plants. The degree to which some of these nutrient forms are available depends, in part, on the acidity or alkalinity of the soil and their availability changes with change in soil pH. The availability of soil phosphorus, in particular, is closely related to pH. Soil phosphorus is most readily available in neutral soils (pH 6.5 to 7.5) and its availability is reduced if pH rises or falls beyond these values. Reduced availability of phosphorus is especially marked as pH falls below 6.5 and, in very acid soils, very little phosphorus is likely to be available to plants. Nitrogen, potassium, sulphur, calcium and magnesium, also show reduced availability as soil acidity increases.

Some other nutrients, notably iron, zinc and manganese, which are required for healthy plant growth although only in small amounts, decrease in availability as pH rises into the alkaline range (above about pH 6.5).

As an indicator of the nutritional suitability of soils for cocoa pH possesses the outstanding advantage that it can be determined conveniently and with acceptable accuracy in the field, preferably using a portable electric pH meter.

d) Carbon/Nitrogen ratios

Undecomposed organic matter contains, on average, about fifty times as much carbon as nitrogen, thus it has a carbon/nitrogen ratio of about 50. During the process of decomposition, much of the carbon is released to the atmosphere as carbon dioxide so that, with increasing decomposition, the carbon/nitrogen ratio of the soil organic matter decreases. The rate of decomposition depends on many factors, but an equilibrium is eventually established when the rate of decomposition is balanced by the supply of fresh organic matter and the ratio between carbon and nitrogen in the surface soil horizons then becomes fairly stable. Thus the ratio between total carbon and total nitrogen in the horizons rich in organic matter provides a crude measure of the state of decomposition of that organic matter - crude, because, in different soils, we are uncertain how much of the total carbon and total nitrogen determined in the laboratory is directly derived from the decomposing organic matter.