FERTILIZER REQUIREMENTS OF CACAO (*THEOBROMA CACAO* L.) IN SOUTH-WESTERN NIGERIA

Proefschrift ter verkrijging van de graad van
doctor in de landbouwwetenschappen
op gezag van de rector magnificus, Mr. J. M. Polak,
hoogleraar in de rechts- en staatswetenschappen van de westerse gebieden,
te verdedigen tegen de bedenkingen
van een commissie uit de Senaat van de Landbouwhogeschool te Wageningen
op vrijdag 26 februari 1971 te 16 uur

door

M. WESSEL

KONINKLIJK INSTITUUT VOOR DE TROPEN

1971

AAN MIJN VROUW EN KINDEREN

STELLINGEN

I

De invloed van de bladouderdom op de minerale samenstelling van het blad kan in bepaalde gevallen geëlimineerd worden door de concentraties van de voedingselementen te corrigeren voor regressie op de drogestofgehalten in het blad.

Dit proefschrift

II

Voor de instandhouding van de bodemvruchtbaarheid van de cacaogronden in West-Afrika is de intensivering van de cacaoteelt een belangrijke voorwaarde.

III

De door Homès ten behoeve van de bladanalyse van cacao voorgestelde bemonsteringsprocedure beperkt de mogelijkheden om de voedingstoestand van de boom en de bodem met elkaar in verband te brengen.

HOMÈS, M. V., L'alimentation minérale du cacaoyer (*Theobroma cacao* L.). Bruxelles (1953)
Dit proefschrift

IV

Bij de herbeplanting van oude oliepalmplantages werd een hoger K-gehalte gevonden in de bladeren van de jonge palmen wanneer algehele verwijdering van de oude palmen aan de herbeplanting voorafging dan wanneer oude palmen niet of gedeeltelijk verwijderd werden. Dit verschijnsel moet niet als een lichteffekt worden opgevat.

FERWERDA, J. D., Questions relevant to replanting in oil-palm cultivation. Wageningen (1955)

V

In het licht van de resultaten van het cacao-onderzoek van de laatste twintig jaar, dient het schaduwvraagstuk in de eerste plaats als een economisch probleem te worden bezien.

VI

De uitspraak van Russell, dat het toedienen van mulch planten stimuleert tot vorming van een oppervlakkig wortelstelsel moet gepreciseerd worden.

RUSSELL, E. J., Soil conditions and plant growth. 9th Ed. Ch. XXIV, London (1961)

VII

De in 1967 geïntroduceerde nieuwe classificatie van de vertisolen betekent wel een verfijning, maar geen verbetering van het systeem.

U.S. Dept. Agric. Supplement to soil classification-system, 7th Approximation. (1967)

VIII

Een sociaal-economisch verantwoorde ontwikkeling van de boomgewassencultuur in Nigeria kan zich in de komende jaren alleen voltrekken binnen het kader van de bevolkingscultuur.

IX

De Nederlandse overheid dient in die ontwikkelingslanden, waarvan grote groepen onderdanen als gastarbeiders in Nederland werkzaam zijn, investeringen te doen die de werkgelegenheid verruimen en aanvullende scholing te verstrekken aan deze werknemers, voordat zij naar hun land terugkeren.

SAAD, M. A.: Voor thuis in Marokko. Marokkaanse werknemers in Nederland. Utrecht (1970)
COPPENS, H.: Denken en praten over de optimale internationale arbeidsverdeling. Intern. Spectator, 24, 15 (1970)

X

De plaatsing van drankautomaten met keuzeknop "chocolade" in de gebouwen van de Landbouwhogeschool voorziet in een grote behoefte van de menselijke vochthuishouding.

Proefschrift M. Wessel
Wageningen, februari 1971

VOORWOORD/PREFACE

Op één van de weinige blad: ˙˙ ˙
wetenschappelijke kritiek ni
dank betuigen aan allen, di
Landbouwhogeschool te Wag

Hooggeleerde Schuffelen, I
voorrecht beschouwd om on
zamelde gegevens in deze pul
moedigende opmerkingen zijn
van dit proefschrift. De colleges
ontvangen hebben indertijd mi
tingsvraagstukken gewekt. De l
en Mevrouw Schuffelen mochte

Zeer geachte Bolhuis, door Uw
op het West African Cocoa Reseai
aanstelling in Nigeria resulteerd
colleges en Uw vriendschap dank

Veel dank ben ik verschuldigd
heer I. Walinga die mij vertrouwd
en mij in Nigeria regelmatig van co
waarvan de juistheid van resultate

PROMOTIE IN DE AULA VAN DE LANDBOUWHOGESCHOOL
GENERAAL FOULKESWEG 1a

RECEPTIE NA AFLOOP VAN DE PROMOTIE
IN HET KLEIN-AUDITORIUM VAN HET AULAGEBOUW

I am grateful to very many pe
gratitude to Dr. L. K. Opeke, Direc
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Zeer erkentelijk ben ik voor het feit dat de Directie Internationale Technische Hulp van het Ministerie van Buitenlandse Zaken mijn werk in Nigeria als een onderdeel van de ontwikkelingssamenwerking heeft willen aanmerken. De daaruit voortvloeiende toekenning van een suppletie salaris heeft het mij mogelijk gemaakt om mijn werk in Nigeria voort te zetten.

Heel hartelijk dank ik mejuffrouw Lia Versteegen voor de accurate verzorging van het vele typewerk en de Heer B. W. Matser die een deel van de figuren tekende. Voorts dank ik Mevrouw G. Duvert voor het persklaar maken van dit manuscript.

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INTRODUCTORY REMARKS

The studies reported on were conducted in the period 1961–1970 when the author was employed by the Cocoa Research Institute of Nigeria at Ibadan, formerly a sub-station of the West African Cocoa Research Institute.

In the first three chapters information is given on the cacao industry and on the climate and soils in general and cacao soils in particular of the main cacao growing area of South-Western Nigeria. In the next chapter (4) a study on soil moisture is presented. In view of the long dry season the soil moisture relationships are the main factor determining the suitability of the soil for cacao. This chapter is followed by one on soil phosphorus which was found to be the main nutritional factor limiting yield as shown by the results of the fertilizer trials reported in chapter 6.

The results of an investigation on whether soil and leaf analysis can be used to assess the nutrient requirements of cacao are given in chapter 7. In the last chapter the results of the preceding chapters are summarized and discussed.

Analytical methods and sampling procedures are given in appendix I while some analyses of variance are given in appendix II. Most of the statistical analyses were carried out by the Statistics Department of Rothamsted Experimental Station, England.

SAMENVATTING

Het onderzoek had ten doel een verband te leggen tussen de ontwikkeling en productie van cacao en de vruchtbaarheidstoestand van de grond om zodoende te komen tot een bruikbaar bemestingsadvies voor de cacao in Nigeria.

In de hoofdstukken 1 en 2 wordt een beschrijving gegeven van de cacao cultuur, van het gebied en van de grondsoorten waar op de cacao geteeld wordt.

Het klimaat wordt gekenmerkt door een gemiddelde jaarlijkse regenval variërend van 1100 mm in het noordelijk en noordwestelijk en 1600 mm in het zuidoostelijk deel en een lange droge tijd van eind oktober tot half maart. De kaolinitische gronden hebben een lage basen-uitwisselingscapaciteit met een vrij hoge bezettingsgraad. De gronden zijn ontstaan uit zure metamorphe stollingsgesteenten, behalve in het meest zuidwestelijke deel waar ze zijn ontstaan uit sedimentaire gesteenten, voornamelijk zandsteen.

Het experimentele werk werd uitgevoerd in het Cocoa Research Institute te Ibadan waar in 1961 een begin werd gemaakt met de bestudering van de vochthuishouding in de grond en het bemestingsonderzoek.

Het doel van de vochtstudies was om in verschillende bodemtypen de hoeveelheid water te bepalen waarover de cacao in de lange droge tijd kan beschikken. Deze hoeveelheden bleken in de bovenste 150 cm van de grond te variëren tussen 125 en 165 mm, getallen die overeenkomen met volumepercentages van 8 en 11 procent, welke als zeer laag kunnen worden aangemerkt. De voornaamste factor die het beschikbaar waterbergend vermogen van de grond bepaalde was de textuur, terwijl de aanwezigheid van organische stof en grint ook van invloed was. De hoeveelheid beschikbaar water bleek met toenemende fijnheid van de grond af te nemen. Uit het feit dat kleihoudende gronden minder droogtegevoelig zijn dan de meer zandige gronden werd geconcludeerd dat de gevonden verschillen in droogtegevoeligheid berusten op verschillen in snelheid, waarmee de voorraad beschikbaar water aan de cacao ter beschikking komt. De geringe voorraad beschikbaar water in de grond brengt met zich mee dat in de drogere

streken cacao slechts onder geringe of zonder permanente schaduw kan worden geteeld. In de praktijk heeft men hier de meeste grote schaduwbomen verwijderd en het gebrek aan schaduw gecompenseerd door een nauw plantverband.

Het jaarlijkse uitdrogings- en bevochtigingspatroon van de grond laat zien dat de gronden in de droge tijd tot op grote diepte uitdrogen. De bevochtiging van het droge profiel verloopt langzaam en de veldcapaciteit van de bovenste 150 cm van de grond wordt meestal pas 2 à 3 maanden na het invallen van de regens bereikt. In de daarop volgende maanden wordt uit deze laag in het totaal ongeveer 200 mm regenwater door drainage afgevoerd. Terwijl enerzijds de totale regenval en de regenvalverdeling in grote delen van de cacaobelt marginaal zijn voor cacao, maakt de relatief geringe uitspoeling van voedingselementen het mogelijk om op de van nature tamelijk arme grond toch met succes zonder bemesting cacao te telen.

Het bemestingsonderzoek had ten doel om een voorlopig bemestingsadvies op te stellen. In het begin van de zestiger jaren werd een groot aantal proefvelden aangelegd, voornamelijk in bestaande cacaotuinen met 25–30 jaar oude, in onregelmatig plantverband staande bomen. De resultaten lieten zien dat fosfaat de voornaamste oogst beperkende voedingsfactor is, in belangrijkheid gevolgd door stikstof. Proeven met jonge cacao daarentegen toonden aan dat op pas ontgonnen bosterreinen alleen stikstof behoeft te worden gegeven maar dat daarentegen op gronden, waarop voedselgewassen of cacao hebben gestaan, zowel stikstof als fosfaat moeten worden toegediend. Op deze laatste gronden bleek de toediening van een gras mulch een gunstig effect te hebben op het verkrijgen van een uniforme aanplant en vroege vruchtdracht.

Jaarlijkse fosfaatgiften van 60 tot 90 kg P_2O_5 per ha gaven opbrengstverhogingen variërend van nihil op fosfaatrijke gronden tot ongeveer 50 procent op fosfaatarme gronden. Residuaire effecten schijnen er echter op te wijzen dat na een aantal jaren met lagere giften kan worden volstaan.

De reactie op stikstof was doorgaans het grootst op gronden met een redelijk hoge fosfaattoestand, waar jaarlijkse giften van 120 kg N per ha resulteerden in meeropbrengsten van 40–50 procent. Op gronden met een zeer lage fosfaattoestand had stikstof weinig of geen effect.

Ondanks het feit dat jaarlijks grote hoeveelheden kalium door de oogst aan de grond worden onttrokken werd buiten het gebied van de sedimentaire gronden geen kaliumgebrek gevonden.

De meststoffen hadden geen invloed op de inhoud van de kolven, wel op het aantal kolven.

Naar aanleiding van de reactie op fosfaat werd de fosfaathuishouding van de grond nader onderzocht. Met de extractie-methoden van Bray en Kurtz (nr. 1) en Olsen bleken ongeveer gelijke hoeveelheden fosfaat geextraheerd te worden. Aan de hand van de resultaten konden gronden globaal worden geclassificeerd als zeer fosfaatarm, fosfaatarm en niet fosfaatbehoeftig. De reactie op toegediend fosfaat en de resultaten van de bladanalyse bevestigden de juistheid van deze indeling. De hoeveelheid beschikbaar fosfaat (P) bedraagt in de bovengrond (0–15 cm) van bosgronden ongeveer 30 ppm. Na het aanplanten van cacao daalt het fosfaatgehalte in de loop der jaren doorgaans tot waarden beneden 10 ppm. Het totaal fosfaat varieert op gronden met een laag beschikbaar P niveau tussen 350–550 ppm. Ongeveer 40–60 procent hiervan is aanwezig als organisch fosfaat. Fractionering van het anorganische fosfaat volgens Chang en Jackson liet zien dat gemiddeld 77% bestaat uit "occluded" fosfaat, 5% uit Ca-gebonden P, 13% uit Fe-gebonden P, 4% uit Al-gebonden P en minder dan 1% uit wateroplosbaar P. De som van de "non-occluded" anorganische fracties varieerde van 25–70 ppm in de fosfaat-arme gronden en van 125–325 ppm op gronden met een voldoende tot hoge fosfaat-toestand.

Het gehalte aan totaal fosfaat is het hoogst in de bovenste 15 cm van de grond door de aanwezigheid van organisch gebonden fosfaat. Dit neemt echter snel af bij toenemende diepte. Het "non-occluded" fosfaat neemt op eenzelfde wijze af. Vooral het Al-gebonden fosfaat, welke de gemakkelijkst opneembare vorm van het onoplosbare fosfaat vertegenwoordigt, neemt zeer snel af. Dit betekent dat de cacao voor zijn fosfaatvoorziening voornamelijk op de bovengrond is aangewezen.

De fosfaatbalans van een aantal bemeste gronden liet zien dat ongeveer 20 procent van het toegevoegde oplosbaar fosfaat via de oogst aan de grond onttrokken was. Van het resterende deel kon in de bovengrond (0–15 cm) gemiddeld slechts 55 procent worden teruggevonden, hoofdzakelijk in de vorm van "non-occluded" fosfaat.

Het niet sluiten van de fosfaatbalans wijst erop, dat vrij grote hoeveelheden fosfaat uit de bovengrond uitspoelen naar diepere lagen. De oorzaak hiervan moet worden gezocht in de lage sorptiecapaciteit voor P van de veelal zandige bovengrond.

Verder werd nagegaan in hoeverre grond- en gewasanalyse gebruikt konden worden voor het vaststellen van de voedingseisen van de cacao op verschillende gronden. De reeds genoemde extractiemethoden voor beschikbaar fosfaat bleken beiden goed te voldoen.

Zoals te verwachten was leverde de bepaling van het totaal stikstofgehalte van de grond geen bruikbare resultaten op.

De gehalten aan uitwisselbaar kalium duidden op een voldoende kaliumvoorziening. De kaliumconcentraties in het blad waren echter niet met deze gehalten gecorreleerd.

Een nadere bestudering van de bladanalyse bracht aan het licht, dat het effect van verschillen in temporele leeftijd en door verschillen in lichtintensiteit veroorzaakte verschillen in physiologische leeftijd, bij jonge bladeren ten dele geëlimineerd worden door de concentraties van de voedingselementen te corrigeren voor regressie op de droge stofgehalten in het blad. Deze methode is bruikbaar voor P, K en Ca, elementen waarvan de concentraties in jonge bladeren een rechtlijnig verband vertonen met de leeftijd van het blad. Voorts bleken de concentraties van P en K binnen bepaalde leeftijdsgrenzen min of meer onafhankelijk te zijn van de leeftijd van het blad, wanneer deze berekend werden als percentages vers gewicht.

Een ander aspect van het leeftijdsprobleem is hoe bladeren van dezelfde leeftijd kunnen worden bemonsterd, aangezien de positie van de bladeren aan de takken hier geen afdoende uitsluitsel over geeft. Waarnemingen betreffende de morphologische veranderingen van de bladeren, die zich na de afharding voltrekken, lieten zien dat de aanvankelijk groene bladstelen op karakteristieke wijze verkleuren bij het ouder worden en dat aan de hand van de mate van verkleuring de absolute leeftijd van jonge bladeren en de relatieve leeftijd van oudere bladeren kan worden geschat.

Behalve de invloeden die leeftijd en lichtintensiteit (schaduw) op de samenstelling van het blad hebben, werden ook de effecten van de vorming van nieuwe bladeren, vruchtdracht, voedingsmedia en seizoenen nader besproken.

Aan de hand van de analyses van de op verschillende proefvelden verzamelde bladmonsters konden voor stikstof en fosfaat kritische waarden voor gebreksniveaux worden vastgesteld. Gezien de relatie tussen de N en P voeding was het noodzakelijk om bij kritische N waarden ook de N: P verhouding te betrekken. Voor fosfaat kon verband gelegd worden tussen kritische concentraties in het blad en in de grond en de reacties van cacao op toegediend fosfaat (tabel 35).

Bestudering van de invloed van meststoffen op de concentraties in het blad liet zien dat N en P toediening de concentraties van de corresponderende elementen in het blad verhoogde, maar dat ook wederzijdse "antagonismen" tussen elementen een rol speelden. Voor het vaststellen van kritische niveaux in de bladeren bleek april/mei de meest geschikte tijd van bemonstering te zijn. Deze periode valt ongeveer 5 tot 10 weken na de algemene "flush" in maart.

Tenslotte werd aan de hand van de resultaten van de bemestingsproeven en van de grond- en bladanalyses een voorlopig bemestingsadvies voor jonge en volwassen cacao opgesteld (tabel 39).

CONTENTS

1. THE CACAO OF SOUTH-WESTERN NIGERIA

1.1 HISTORY

The cacao industry of Nigeria has originated from imports of seeds from the island of Fernando Po during the last three decades of the nineteenth century. The seeds were brought into various parts of the southern forest belt where the establishment of trees from these seeds succeeded in some areas but failed in others. The early plantings in the Agege-Otta and the Ibadan area were very successful (WEBSTER 1964, AYORINDE 1966) and from here cacao spread over a large area which is now known as the cacao belt of South-Western Nigeria. The subsequent enormous development of the cacao industry is reflected in the production figures of table 1. Since 1960 Nigeria has been the second largest producer of cacao after Ghana with a mean annual production of about 220,000 tons of dry beans.

The success of cacao cultivation in Nigeria was in the early days almost entirely due to the initiative and enterprise of the peasant farmers. They developed their own way of planting and establishment which fitted in with the existing system of farming by means of shifting cultivation. Cacao seeds were planted in between the food crops at a variable spacing of 4 to 5 feet with 3 to 5 seeds at a stand.

As food crop cultivation was discontinued, the cacao was left to compete with the regenerating bush which itself was progressively reduced. This method produced a dense stand of cacao and thus a canopy which closed early. Cacao established in this way is more or less self thinning and results in an average mature stand of 400 to 700 trees per acre. The trees did not receive fertilizers or manure and were left to exploit the fertility accumulated in the surface layer of the soil by the tropical forest. At present however the Ministry of Agriculture encourages farmers to plant their cacao at a regular spacing under planted shade of plantains and bananas.

1.2 VARIETY

Most of the cacao is of the Amelonado variety with yellow fruits when ripe and with more or less flattened seeds with violet cotyledons. This variety is now gradually being replaced by another more vigorous Forastero variety usually referred to as "Upper-Amazon cacao" which was first introduced to West Africa in 1944.

The Amelonado trees are rather small and do not usually exceed a height of 20 ft when fully grown. The seedling plant forms a straight stem which forks at a height of about 5 ft into 3 to 5 almost horizontal branches forming the so called jorquette. The vertical growth is continued with chupons or suckers from just below the jorquette which form a new jorquette a few feet higher. *Theobroma cacao* L. is cauliflorous; this means that flowers and fruits are produced on the older leafless parts of the trunks and branches. The trees are coming into production 5 to 6 years after planting and may continue to bear fruits for 40 years or more.

The yield potential of Amelonado is high. Annual yields between 2000 and 3000 lb dry beans per acre have been obtained at experimental sites from unshaded farms receiving fertilizers, while in ordinary peasant farms yields between 500 and 1000 lb can be obtained under conditions of fair management. The yield per acre for the cacao area as a whole is much lower, of the order of 350 lb, due to old age, pest and disease incidence and planting on unsuit-

TABLE 1

Raw production of cacao in Nigeria in relation to production in Africa and world production

period	mean annual production of raw cacao, (thousands long tons)*			acreage planted in Western Nigeria ** (recorded between 1945 and 1950)
	World	Africa	Nigeria	
1900/01–1909/10	160	38	1.4	6168
1910/11–1919/20	310	130	10	70018
1920/21–1929/30	478	287	40	275873
1930/31–1939/40	665	437	85	459840
1940/41–1949/50	650	420	96	156949
1950/51–1954/55	764	485	102	
1955/56–1959/60	892	548	125	
1960/61–1964/65	1232	916	214	
1965/66–1967/68	1295	923	227	

* based on GILL and DUFFUS: *Cocoa Statistics, London (1970)*

** *Ministry of Agriculture and Natural Resources, Western Region, Nigeria, Tree crop planting projects 1963.*

(The actual acreage planted to cacao is greater than the figures indicate as unfavourable environmental conditions, pests and diseases had killed out a part of the cacao before the records were taken).

able soils (see chapter 1.5.2.) The development from flower to fruit takes about 5 months.

The main crop is produced from September to January with a production peak in November and the mid or light crop from April to July (see figure 1). Beans of the mid-crop are smaller and have a lower fat content and a higher shell percentage than those produced in the main crop (WESSEL and TOXOPEUS 1966). After harvesting, pods are carried to a central point where they are opened by hand and the beans with the adhering mucilage are removed and fermented. After fermentation and sun-drying the beans are ready for marketing.

1.3 SHADE

The shade requirement of cacao is a controversial issue. There is general agreement on the necessity of some type of overhead or lateral protection of young trees, but a wide difference of opinion whether this protection should be a permanent one or not. In Nigeria most of the cacao is grown with little or no permanent shade. This is probably so because the farmers have learnt from experience that most soils cannot store enough available water to supply both cacao and forest shade trees with adequate amounts of water to survive the long dry season (see chapter 4). There is enough evidence that well maintained unshaded cacao with a closed canopy can give high yields over a long period. But in areas where the forest environment had disap-

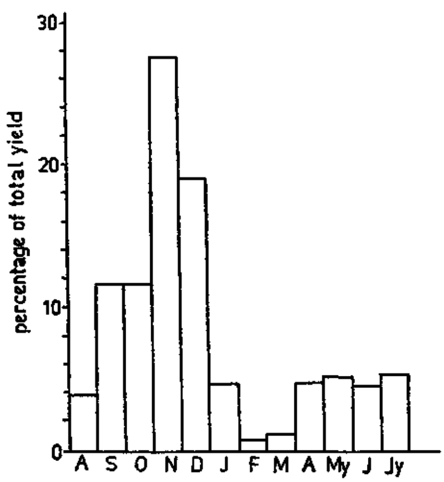


Figure 1
The monthly yield distribution of mature Amelonado cacao in Nigeria (after TOXOPEUS 1965)

peared as a result of progressive deforestation, over-exposure to sun and wind in combination with drought and pests and diseases has caused the early degeneration and devastation of large cacao areas.

1.4 Pests and diseases

The main pest of cacao in West Africa consists of mirids, in Nigeria especially those belonging to the species *Sahlbergella singularis* Hagl. (Entwistle 1964). These insects attack mainly chupons and young leaves in the canopy. Feeding punctures often become infected with a secondary fungus *Calonectria rigiduiscula* Berk. and Br. which may cause dieback of twigs and branches. Effective control by benzene hexachloride insecticides was achieved in the late nineteen fifties. This control is at least partly responsible for the dramatic increase in production from 1960 onwards (see table 1). Other serious pests damaging cacao are: thrips (*Selenothrips rubrocintus* Giard) which cause defoliation to trees of all ages, earias larvae (*Earias biplaga* Wlk.) which eat the terminal buds of young cacao, and psyllids (*Mesohomotoma tessmanni* Aulm.) which damage developing leaves mainly in the bud stage (Gerard 1964). Damage caused by nematodes has not been recorded.

Among the principal diseases of cacao should be mentioned the virus diseases in the swollen-shoot group, and the pod-rot (or black pod) disease caused by *Phytophthora palmivora*, Butl.

Swollen shoot viruses which have devastated large cacao areas in Ghana were discovered in Nigeria in 1944. The Nigerian strains are less virulent than the Ghanaian ones and mainly weaken the tree and thus predispose it for attacks by parasites which may cause the eventual death of the tree. In Nigeria the disease is mainly restricted to two areas in the western part of the cacao belt.

Phytophthora palmivora infects pods at any stage of development. The infection spreads rapidly and destroys the entire pod in a few days. Infection occurs during the rainy season under conditions of high humidity and relatively low temperature. The disease can be reasonably well controlled by fungicides but in certain very wet periods protection by fungicides may be ineffective.

1.5 The role of the Government

The Government was initially mainly concerned with improvement of the cacao quality. Improved fermentation methods were introduced and taught to the farmers while cacao fermenting associations were established at many places. In 1921 preliminary steps were taken towards a system of grading cacao for export which became effective in 1926. Later on organized marketing was introduced. The West African Cocoa Board was established in 1939, which after the second world war was replaced by the Cocoa Marketing Board. By building first the railway in 1895 and later a network of motorable roads the Government greatly reduced the costs of transporting cacao to the coast.

In the nineteen thirties the government became more and more involved in cacao cultivation itself. The discovery of swollen shoot virus and its adverse effects gave rise to the foundation of the Central Cocoa Research Institute at Tafo, Ghana. As the virus disease still increased in importance this institute became the West African Cocoa Research Institute in 1944. A sub-station was founded in Nigeria in 1953 which became an autonomous institute in 1963 under the name Cocoa Research Institute of Nigeria (C.R.I.N.).

1.5.1 *The cacao swollen-shoot survey*

In 1944 a cacao survey was started (and concluded in 1949) to assess the spread of swollen-shoot disease in Western Nigeria. In the course of this survey information on age of cacao trees, farm size and social and economical aspects of the cacao industry was collected (BALDWIN *et alii* 1955). In 1950 about 970,000 acres were found to contain cacao, 75 per cent of which was planted between 1920 and 1940 (see table 1). Planting records since 1950 are very incomplete and a figure of 1,500,000 acres for the present size of the cacao belt is only a very rough estimate. Table 2 shows that most of the cacao is grown in small holdings which are all owned by Nigerian farmers as the former colonial government was not in favour of alienation of land for plantations. Only recently some plantations have been opened but these are owned by Government-controlled development agencies.

The age structure of the existing cacao is a question of great concern. In 1968 about 50 per cent of all cacao was estimated to be older than 28 years, beyond which age a progressive decline in production usually begins. It has been calculated that between 1968 and 1980 about 700,000 acres have to be planted to cacao to rejuvenate the present cacao population and to expand the acreage to 1,800,000 acres in order to reach a target production of 360,000

TABLE 2

Distribution of cacao land between cacao farmers *

size class of holdings (acres)	percentage of farmers	percentage of acreages
– 2.49	54.9	18.9
2.50– 4.99	24.2	23.0
5.00– 7.49	10.4	17.1
7.50– 9.99	3.9	9.4
10.00–19.99	5.2	19.5
20.00–and over	1.4	12.1

* *Ministry of Agriculture and Natural Resources, Western Region, Nigeria, Tree Crop planting projecrs 1963.*

to 370,000 tons by 1979/80. (*Agricultural development in Nigeria 1965–1980*, F.A.O. 1966).

Substantial areas of land suitable to cacao are still available but social and economic factors make it necessary that large acreages under low yielding cacao are replanted. The problems of replanting have previously been discussed (WESSEL 1969d).

1.5.2 *The soil survey*

Another important survey was the soil and land use survey which covered nearly the whole cacao area underlain by metamorphic rock and was carried out between 1951 and 1960.

The purpose of this survey was to describe and classify the soils of the cacao area and to assess their agricultural potentialities especially for cacao production. The results have been published by SMYTH and MONTGOMERY (1962).

The survey data revealed that about 62 per cent of the cacao is grown on good and fairly good soils and the remaining 38 per cent on poor and very poor soils. Furthermore it was found that at least 1,000,000 acres of good quality soils under forest and thicket (excluding forest reserve areas) are still available for cacao planting.

The detailed soil maps show generally a repetitive, complex soil pattern, reflecting frequent changes of soil morphology as a result of frequent changes of parent rock and topography over short distances. This implies that good and bad cacao soils alternate over small areas and that as a result large continuous cacao plantations cannot be established in most parts of the cacao belt.

1.5.3 *Research*

Till the end of the nineteen fifties research on cacao was, for obvious reasons, mainly concentrated on pests and diseases and their control. Afterwards agronomy, plant breeding and soil fertility have been made part of the research programme. Agronomy has so far been mainly concerned with nursery techniques and establishment. The establishment of cacao has become very difficult because the adverse effects of drought are now greater than in the past when the original forest environment with its buffering effects on temperature, humidity, light and wind was still present in most parts of the cacao belt. Cacao breeding was at first apart from the early work of VOELCKER (1935) mainly concentrated on breeding of virus tolerant and resistant varieties but later on emphasis was laid on obtaining vigorous cacao with a high degree of establishment ability (TOXOPEUS 1969).

Soil studies have been concentrated on water relations of soils which are an important aspect of the establishment problem, and on the nutrient requirements of cacao. Fertilizer trials have been mainly conducted on mature cacao because after what has been said about the age structure of the existing cacao, it is clear that raising the output and prolonging the economic life of this cacao is of vital importance in maintaining and possibly increasing the present annual production. These studies are reported in this publication after introductory information on climate and soils of the main cacao growing area of South Western Nigeria has been given.

2. THE CACAO BELT OF SOUTH-WESTERN NIGERIA. CLIMATE AND SOILS

About 95 per cent of the cacao produced in Nigeria comes from a particular area called the Nigerian cacao belt which is shown in figure 2. The belt is about 200 miles long and 50 miles wide and runs in an E.N.E. direction from Lagos. It is situated on the southern slope of the watershed between the

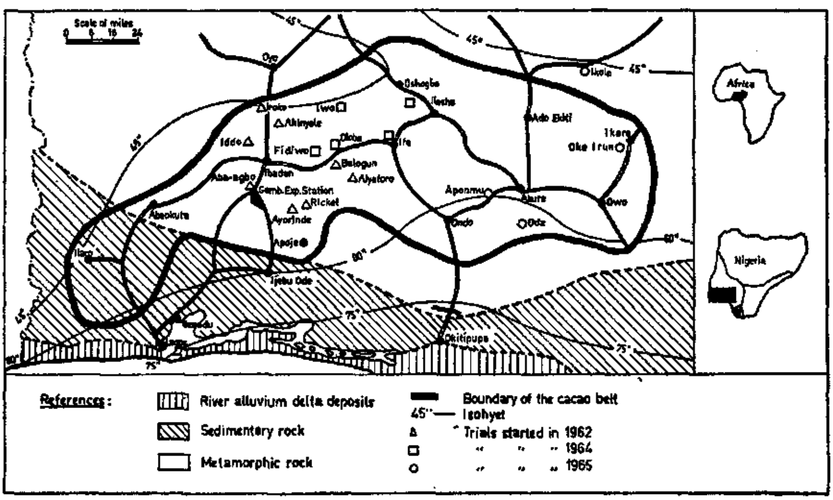


Figure 2
Map of the main cacao growing area of South Western Nigeria (modified after Galetti et alii 1956)

Niger and the Ocean. The land rises from 100 to 200 ft near Abeokuta and Ijebu-Ode to over 1600 ft in Ekiti Division in the north east of the area. The acreage of cacao inside the belt is approximately 1,500,000. In some parts less than 1 per cent of the land is under cacao but in the heart of the cacao belt (in the Ife and Ondo area) 60 per cent or more is planted to cacao (GALETTI *et alii* 1956).

The geographical position and the size of the cacao belt is determined by rainfall and the interaction between rainfall and soil. Low rainfall of 45 inches per annum limits the extension of the cacao growing area to the north and relatively high rainfall of the order of 65 inches per annum in combination with chemically poor sedimentary soils restricts cacao cultivation to the south. The northern boundary corresponds largely with the northern limit of lowland forest (KEAY 1953).

2.1 CLIMATE

The climate of S.W. Nigeria is a monsoon climate (an Am climate in Köppens classification (VAN WIJK en DE VRIES (1952)) dominated by a warm moisture laden wind from the south-west and a hot and dry one from the north-east. As a result a period of heavy seasonal rainfall occurs from June till October and a dry season from November till March. The mean dry season rainfall, from November to February inclusive is low, less than 4 inches in most parts of the cacao belt (WESSEL 1964). During the dry season a dry

TABLE 3

Mean monthly and mean annual rainfall at selected stations of the main cacao growing area in South Western Nigeria and some other cacao growing countries

Area	Station	no years recorded	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Febr.	March	year total
South-Western Nigeria*	Ilaro	6	4.06	6.54	8.79	4.19	1.13	6.40	6.85	2.03	0.49	1.28	1.50	6.44	49.70
	Ibadan	52	5.31	5.81	7.39	6.08	3.26	6.97	6.18	1.74	0.37	0.38	0.96	3.54	47.99
	Oshogho	28	4.26	5.53	5.89	4.99	3.76	7.70	7.65	1.52	0.40	0.31	1.11	3.20	46.32
	Ondo	48	6.14	6.70	8.33	9.15	5.13	9.14	7.58	2.87	0.67	0.41	1.38	4.26	61.76
Ghana**	Tafo	24	6.14	7.25	9.22	5.63	2.43	6.09	8.73	4.22	2.55	1.49	3.44	5.96	63.15
Cameroon†	Nkoemvone	5	8.90	9.58	8.44	3.02	2.00	8.10	12.36	8.91	1.48	1.18	4.42	7.97	76.36
Brazil††	Uruçuca	9	9.95	4.37	10.22	5.50	4.61	4.14	5.87	8.69	6.80	4.25	4.52	8.32	77.24
Trinidad††	St Augustine	21	1.9	5.0	8.6	8.6	9.8	7.9	6.4	7.8	6.4	2.8	1.3	1.3	67.8

* *Annual Summaries of observations 1953–57. Meteorological Services, Lagos, Nigeria*

** *W. Afr. Cocoa Res. Inst. A. Rep. 1961–62*

† BURLE (1961)

†† URQUHART (1961)

"Harmattan" wind from the Sahara may penetrate the cacao belt, lowering the humidity and thus intensifying the effect of the dry season.

The annual rainfall (table 3) is lower than in most other cacao producing countries. The dry season rainfall can be considered as being marginal for cacao. It is worthwhile mentioning that while cacao in Ghana can only be grown in areas where the rainfall from November to March inclusive, exceeds 10 inches (ADAMS and MCKELVIE 1955) all the cacao of South-Western Nigeria is grown in a zone where the rainfall during that period is less, sometimes far less than 10 inches. The fact that cacao can be successfully grown under these low rainfall conditions may be due to the prevailing high degree of cloudiness.

The annual mean maximum temperature varies between 85 and 90° F and the mean minimum temperature between 65 and 75° F. Temperatures are lowest and relative humidity highest in the rainy months. In the dry season temperatures are high during the day and relative humidities low during the afternoon. This is illustrated in table 4 which also gives figures on cloudiness and sunshine. Only 11 to 13 days have an average cloud cover of less than 1.5 eighths (8 eighths being 100 per cent cloud cover). As a result of cloudiness, periods of direct sunshine are severely restricted especially in the wet season.

The seasonal variations in temperature, wind and sunshine are reflected

TABLE 4

*Daily and monthly variation in temperature and relative humidity, cloudiness and sunshine at Ibadan and Ondo**

month	Ibadan mean screen temp .(°F)		Ibadan mean rel. humidity (%)		Ondo mean screen temp. (°F)		Ondo mean rel. humidity (%)		Ibadan over-cast** days	Ibadan fine** days	Ondo over-cast days	Ondo fine days	Ibadan mean daily hrs of sun-shine
	09 h.	15 h.	09 h.	15 h.	09 h.	15 h.	09 h.	15 h.					
Jan.	78.5	89.0	80	48	77.5	86.9	80	53	2.2	5.2	8.6	3.8	6.3
Febr.	79.0	91.3	80	45	77.9	88.9	80	52	4.0	2.8	9.4	2.6	7.0
March	79.5	89.3	82	55	79.9	85.9	83	65	7.6	0.2	17.8	0.2	6.2
April	79.8	88.2	82	61	79.5	85.5	84	68	6.8	0.0	17.2	0.0	5.8
May	79.0	85.5	84	67	78.8	83.3	84	72	8.7	0.0	18.8	0.0	6.3
June	76.7	82.4	86	73	76.6	80.3	87	78	11.8	0.0	21.0	0.0	4.9
July	74.0	79.0	89	78	74.0	77.0	89	83	23.0	0.0	28.8	0.0	3.2
Aug.	73.2	78.2	89	78	73.4	76.5	89	83	24.6	0.0	30.0	0.0	2.6
Sept.	74.8	81.2	89	74	75.1	79.1	89	80	20.6	0.0	28.2	0.0	3.1
Oct.	76.6	83.1	86	70	76.9	80.8	86	76	13.6	0.0	22.8	0.0	5.4
Nov.	78.9	86.5	84	62	79.6	85.0	84	67	5.8	0.4	11.4	0.2	7.0
Dec.	77.0	87.7	82	52	78.3	86.2	81	56	1.2	4.8	4.8	4.8	6.8

* data from *Annual Summaries of observations 1953–1957, Meteorological Services, Lagos, Nigeria.* Hours of sunshine from unpublished records 1958–1968.

** "overcast" is taken as a day when mean total cloud amount at 09 h, 15 h and 21 h is 6.5 eighths or more. "fine" is taken as a day when this amount is 1.5 eighths or less..

in the figures of mean monthly potential evapo-transpiration which have been tabulated in table 5 and will be further discussed in chapter 4.

2.2 SOILS

2.2.1 *Geology and topography*

The greater part of the cacao belt overlies metamorphic igneous rocks of Pre-Cambrian age and only a small portion of the south western part overlies sedimentary deposits of mainly Tertiary origin. In the early 20th century a thriving cacao industry had been established on these sedimentary soils north of Lagos (WEBSTER 1964) but this has rapidly declined due to combined effects of the poor chemical status of the soil and prevailing pests and diseases. Cacao cultivation in this area is at present of little economic importance and for this reason only soils overlying metamorphic rocks will be considered in this study. Information on the sedimentary soils of the cacao belt and on cacao soils of Eastern Nigeria has been given in an earlier publication (WESSEL 1969a).

The igneous metamorphic rocks belong to the Pre-Cambrian basement complex. This forms a part of the African crystalline shield which consists predominantly of folded gneisses, schists and quartzites in which have been emplaced granitic and to a lesser extent, more basic material (JONES and HOCKEY 1964). The weathered rock material from which the present soils have developed has a complicated history reflecting changes of climate resulting in cycles of erosion and periods of soil formation (DE SWARDT 1953). Due to erosion and probably also to extensive development of cuirasse ironstone in the past which reduced weathering, soils are not of such great age as the age of the parent rock suggests.

TABLE 5

Mean monthly potential evapo-transpiration (in mm) at Ibadan

	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March
measured evapo-transpiration 1957–1966*	120	115	101	98	95	98	109	117	128	132	133	137
computed potential evapo-transpiration 1957–1966*	144	140	125	115	108	115	126	130	138	134	136	155
computed potential transpiration**	177	165	135	115	100	120	145	152	165	192	207	207
mean monthly rainfall	133	145	185	152	82	174	154	44	9	9	24	89

* Summarized from *Climatic Observations at U.C.I., nr. 16, 21 and 26, Dept. of Geography of the University of Ibadan.* Evapo-transpiration is measured by means of a simple evapo-transpirometer (GARNIER 1959). Potential evapo-transpiration is computed according to THORNWAITE (1948).

** Computed by Dr. Pennman from data of the Meteorological Office London (SMYTH and MONTGOMERY 1962).

The present landscape has resulted from periodical erosion of an old peneplain of late Tertiary or early Quartenary age. The land is mainly gently to strongly undulating but there are areas of special relief especially east of Ilesha, where steep sided hills, high quartz ridges and inselbergs occur (SMYTH and MONTGOMERY 1962). The commonest type of relief and drainage consists of low hills or undulations separated by narrow streams which dry up during prolonged dry periods.

2.2.2 *The relationship between soil and topography*

The soils are closely related to both parent rock and the topography and form irregular catenary sequences from hill tops to valley bottoms. This relationship has been described by various authors (VINE, 1941; VINE *et alii* 1954; NYE 1954; SMYTH and MONTGOMERY 1962; WESSEL 1967b) and can be summarized as follows. On hill tops and upper slopes the parent material of the soil overlies solid rock. The sedentary profile is characterized by a non-gravelly top soil (0–6 inches) over a sandy- loam to sandy-clay layer (6–48 inches) usually containing both iron oxide concretions and quartz gravel which overlies sedentary mottled clay which merges into rotten rock. Textural differences between profiles are related to differences in fineness of the parent rock. Coarse grained rock gives usually rise to sandy soils with a thin mottled clay layer in the sub-soil and in these soils relatively unweathered rock is reached at depths less than ten feet. Fine-grained rock weathers in more clayey soils with thick mottled clay layers and the soil depth may well exceed 20 to 30 ft.

On the lower part of the slopes, the parent material is derived from soil material which has been carried down from the upper part of the slope. These "hill wash" soils are usually sandy and concretions and quartz gravel are absent from the top 20 inches of the soil. Textural differences are attributed partly to mechanical sorting during deposition and partly to subsequent movement of clay by leaching and accumulation (VINE *et alii* 1954). Further down the slope, where seepage products accumulate during the wet season, an inextensive zone of shallow soils over a sheet of concretionary ironstone is found.

In the bottoms of the valleys grey, sandy or clayey soils are found which are waterlogged during the rainy season and may dry out during dry periods. They are formed from either hill-wash material or local alluvium, or a mixture of both, and overlie clay with gravel and stones, merging into rotten rock.

A typical topographical sequence of the soils is illustrated in figure 3, where a cross-section of a catena over biotite gneiss is shown. The morphology of the soil profiles is illustrated in the diagrams. A detailed study of the

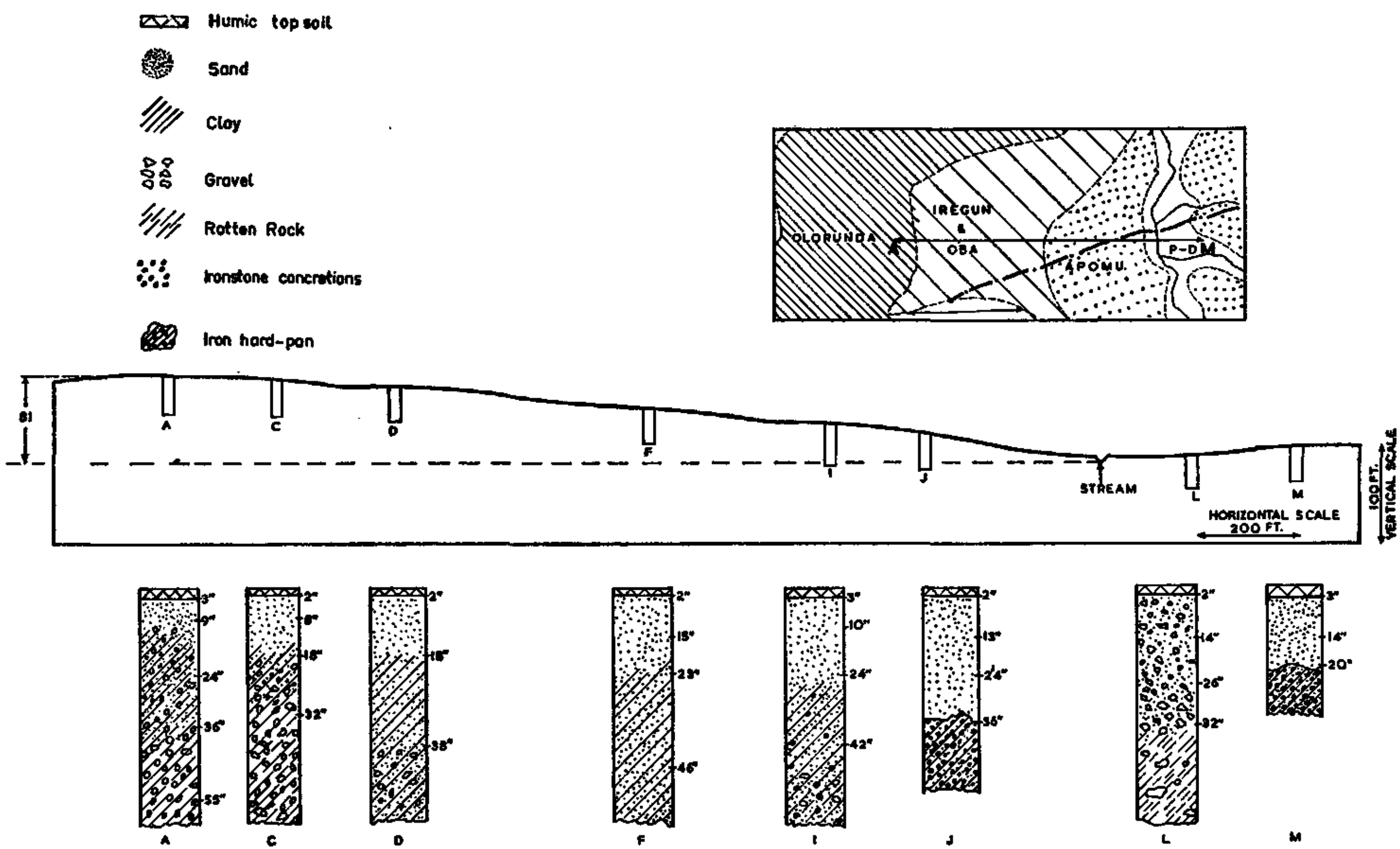


Figure 3
Cross section of a soil catena over biotite gneiss at Gambari Experimental Station

soils of this catena has been published elsewhere (WESSEL 1967b). In areas where the parent rock is very resistant to weathering, rocks and rock outcrops are usually found at the top of the hills. At the foot of these rocks weathering products accumulate and give rise to so called hill-creep soils. These usually inextensive soils thus precede the sedentary soils in the catenary sequence.

2.2.3 *The classification of soils*

The close relationship between soil morphology and parent rock is also reflected in the classification system of the soils of the cacao belt (SMYTH and MONTGOMERY 1962). In this system the well drained soils which cover most of the area, are subdivided in associations on the basis of underlying parent rock. Such an association comprises all slope members of the catena which are described as soil series on the basis of morphological differences using the clay content as a special criterion (see also chapter 4).

In the classification used for the Soil Map of Africa (D'HOORE 1960) the soils of the whole area have been described as a complex of Ferrisols and the Ferralitic soils. SMYTH (1961) however, has proposed to describe the soils as Ferruginous Tropical Soils because of their high base saturation and relatively high content of weatherable minerals, although they do not "fit" in this group in view of the predominantly kaolinitic nature of the clay fraction.

In the system of the Seventh Approximation of the United States Department of Agriculture (edited by SMITH 1960) many soils would be placed in the Great Group of Ultusalfs belonging to the Sub-order of Ustalfs in the Order of Alfisols; others in which the degree of segregation of free iron oxides is sufficient to constitute an "oxic" horizon would be placed in the Order of Oxisols and possibly in the Sub-order of Idox and the Great Group of Haplidox (SMYTH and MONTGOMERY 1962). According to the 1967 Supplement to the 7th Approximation, the Alfisols would be placed in the Great Groups of Haplustalfs and Plinthustalfs and the Oxisols in the Sub-order of Ustox and the Great Group ol Eutrustox'

3. CACAO SOILS

3.1 Soil requirements of cacao

Cacao requires a deep well drained soil with a high nutrient content, while the top soil should be rich in organic matter. Hardy (1958) states that the depth of root-penetrable soil should be at least five feet, but deeper soils are required where annual rainfall is low, especially if the soils tend to be rather sandy (Charter 1947; Aubert and Moulinier 1954). In Nigeria the cacao soils should also have a clayey texture, preferably with sandy clay loam within 4 inches of the soil surface and a sandy clay below 10 to 15 inches to ensure that the trees have an adequate moisture supply during the dry months (Smyth and Montgomery 1962). Clayey soils usually have a higher content of nutrients and organic matter than sandy soils and this is another advantage.

Well drained clayey soils are usually found on upper slopes overlying fine grained parent rock; clayey soils may also occur in the valley bottoms but they are usually not extensive and often become water-logged during the wet season. Consequently the best cacao farms always occur on the higher slopes and some cacao may grow in the valley bottoms. There is normally no cacao between these two areas but in the wetter districts of Ife-Ilesha and Ondo a little more of the sandy soils will support cacao, because of the less intense dry season (West 1945).

3.2 The physical characteristics of the soil

The general morphology of the upper-slope profile has already been described in the previous chapter while a detailed description of the horizon differentiation and formation of an upper-slope sedentary profile has been given by Nye (1954).

In table 6 data are given on the texture and chemical status of some profiles which are representative of cacao soils derived from the commonest parent rocks found in the cacao belt. A detailed description of these profiles has been given before (Wessel 1969a).

It can be seen that the clay content is low in the top soil but increases with depth. There is frequently a sudden increase in clay content at depths between 10 and 20 inches usually within the gravel accumulation horizon. The clay content of the subsoil, however, rarely exceeds 50 per cent of the fine earth. The silt content is low, usually less than 10 per cent. The clay fraction is predominantly kaolinitic with SiO_2/Al_2O_3 ratios ranging from 2.8 in the top soil to 2.1 in the sub soil (Doyne and Watson 1933; Nye 1955).

The structure of the soils is weak in the sense that the soil when dry does not break up in large structural units of a well defined shape. It is often described as structureless but this is not strictly true because the soil mass is built up of tiny particles cemented together by various agents among which "organic compounds" and "compounds of iron" are the most important ones. In the top soil organic matter is effective in aggregating smaller particles but below a depth of about 3 inches the sharp drop in organic matter is

Table 6

Selected analytical data of cacao soils derived from metamorphic rock in South-Western Nigeria

depth in inches	soil colour (moist sample)	% coarse sand	% fine sand	% silt	% clay	pH	m.e./100 g fine earth K	Ca	Mg	Cation Exchange Capacity	% C	% N
soil derived from fine-grained biotite gneiss; profile under cacao near Ife (mean annual rainfall 50″)												
0– 2	10 YR 3/4	31	47	6	16	6.5	0.20	9.8	1.9	13.3	2.45	0.21
2– 7	7.5 YR 3/4	26	44	5	25	6.1	0.18	5.0	1.0	8.6	1.12	0.10
7–19*	5 YR 4/6	25	46	5	24	6.0	0.14	3.1	1.0	5.2	0.51	0.06
19–39*	5 YR 4/8	20	47	7	26	6.1	0.15	2.7	0.9	5.0	–	–
39–53	5 YR 5/8	18	28	7	47	6.1	0.15	2.7	0.9	5.3	–	–
53–63	5 YR 5/8	28	20	6	46	6.0	0.15	2.9	0.8	5.2	–	–
soil derived from medium-grained granitic rock; profile under cacao near Owena (mean annual rainfall 57″)												
0– 3	10 YR 3/3	35	38	4	23	6.9	0.29	11.9	2.9	17.4	2.60	0.25
3– 7	10 YR 4/4	30	46	7	17	5.9	0.16	3.1	1.3	5.7	0.64	0.08
7–13	7.5 YR 4/4	11	66	3	20	5.9	0.18	2.4	0.7	4.5	0.47	0.06
13–20	5 YR 4/4	10	49	7	34	5.8	0.26	2.5	0.8	7.0	–	–
20–32*	5 YR 4/6	29	21	8	42	5.8	0.24	2.4	1.1	6.9	–	–
32–60	5 YR 4/8	21	23	8	48	5.7	0.19	2.3	1.7	6.6	–	–
soil derived from coarse-grained gneiss; profile under cacao near Oke Irun (mean annual rainfall 53″)												
0– 3	7.5 YR 3/2	44	31	8	17	6.1	0.50	5.7	1.5	10.3	1.53	0.14
3– 6	7.5 YR 3/2	44	32	7	17	6.0	0.27	3.6	1.2	7.5	1.10	0.10
6–13	5 YR 3/4	32	33	6	29	5.5	0.41	2.6	1.8	8.6	0.81	0.07
13–35*	5 YR 4/4	29	24	8	39	5.2	0.49	1.9	1.7	7.4	–	–
35–50*	5 YR 4/6	26	26	8	40	5.3	0.28	1.7	0.8	6.4	–	–
50–60	5 YR 4/6	32	26	8	34	5.1	0.22	1.8	0.9	5.1	–	–

* main horizons of gravel accumulation.

reflected in a sharp drop in degree of aggregation. A little lower down the profile aggregation increases again. BATES (1960) has shown that this increase corresponds with an increase in the percentage of free iron oxide in the profile. The role of free iron oxide in aggregation is not properly understood.

According to BATES its aggregating influence in the lower parts of the profile can most likely be ascribed to cementation due to precipitation of hydrated iron gel and its irreversible dehydration. NYE (1963) suggests, however, that the kaolinite plates are joined by iron oxide in irregular arrangement, the positive spots developed on the iron oxide being held against permanently charged negative spots of the kaolinite crystal. The decrease in pH with depth increases the number of positive spots on the iron oxide and this results in increased aggregation of soil particles.

The presence of a usually well defined horizon at a depth between 10 and 48 inches where iron stone concretions and quartz gravel have accumulated

TABLE 7

Nutrient status of soils under cacao in South-Western Nigeria (surface samples, 0–6 inches; location of sites shown in figure 2)

site	% coarse sand	% fine sand	% silt	% clay	pH	exch. bases in m.e. per 100 g fine earth			% C	% N	available P in ppm*	
						K	Ca	Mg				
Iddo	33	46	7	14	6.1	0.17	6.8	1.4	1.33	0.115	4	serie
Aba-Agbo	27	51	6	16	6.3	0.22	6.7	1.3	1.33	0.123	6	I
Ayorinde	28	45	7	20	5.8	0.24	7.6	1.8	1.60	0.148	12	trials
Ricket	42	23	7	28	5.8	0.59	7.2	1.7	1.76	0.159	5	
Iroko	43	26	9	22	6.9	0.77	17.1	3.8	2.48	0.195	40	
Akinyele	45	19	10	26	6.4	0.62	12.7	3.0	2.66	0.227	24	
Balogun	41	36	5	18	6.0	0.22	6.5	1.8	1.66	0.156	7	
Aiyetoro	35	30	10	25	6.2	0.33	12.6	2.7	2.41	0.235	8	
Iwo	31	46	5	18	5.9	0.30	7.4	2.1	1.63	0.149	8	serie
Ilesha	40	36	6	18	5.9	0.23	7.0	1.9	1.65	0.154	9	II
Fidiwo	32	40	7	21	6.3	0.31	10.7	2.0	2.20	0.193	6	trials
Oloba	46	36	5	13	6.2	0.20	5.8	1.3	1.29	0.136	4	
Ife	33	32	9	26	5.6	0.32	10.2	2.1	1.90	0.169	3	
Oke-Irun	41	29	6	24	5.4	0.48	7.8	2.2	1.84	0.161	2	serie
Ikole	50	25	7	18	6.2	0.29	12.5	1.9	2.44	0.198	23	III
Aponmu	46	29	8	17	6.7	0.26	12.2	1.7	2.02	0.189	7	trials
Oda	40	34	8	18	6.2	0.25	7.9	1.6	1.68	0.161	4	
lower limits of adequacy**					5.5	0.20	8.0	2.0	1.75	0.150	12–24†	

* determined in Bray and Kurtz nr. 1 extractant

** according to HARDY (1939, 1951, 1958), BELEY and CHEZEAU (1954), SMITH (1966)

† determined in Truog's extractant, 12 ppm lower limit for sandy soils, 24 ppm lower limit for clayey soils

is a typical feature of most cacao soils. The effect of this gravel on the growth of cacao will be discussed in relation to soil moisture in chapter 4.

3.3 The chemical status of the soil profile

The soil profiles are characterized by a low cation exchange capacity. This can be expected in soils with a predominantly kaolinitic clay fraction. However the base saturation and pH values are relatively high (see table 6). The cation exchange capacity is highest in the top soil due to the presence of organic matter. In the same horizon, bases are concentrated as a result of transfer from the lower layers, where they are absorbed by plant roots and returned to the soil surface when leaves and branches fall and decompose on the ground. The increase in acidity with depth also results from this process.

Organic carbon is concentrated in the top 2 to 3 inches of the soil and decreases sharply below this layer. The nitrogen content of the soil follows closely the pattern of organic carbon with C/N ratios of 10–14 in the top soil.

Total P is high (350–550 ppm) in the 0–6 inch soil layer due to the presence of large quantities of organic P which may represent up to 60 per cent of the total P. Below this horizon the total P content drops sharply to a level of 200–250 ppm which stays nearly constant down the profile. The amounts of available P are low in most soils and show the same trend of decrease with depth, often to trace values in horizons below 12 inches.

Detailed information on the P status of cacao soils will be given in chapter 5.

3.4 The chemical status of the surface soil

For the assessment of soil fertility the 0–6 inch layer is usually sampled. In this horizon the greater part of the nutrients are stored and in this layer a large part of the cacao roots are present. In table 7 the analyses are given of 17 sites on which the fertilizer trials are conducted which are reported in chapter 6. As these sites are fairly well distributed over the cacao belt (see figure 2) the data can be considered as representative of soils which have been under cacao for 30 years or more. In comparing the nutrient concentrations on these sites with the lower limits of adequacy at the bottom of the table, it can be seen that in most soils the minimum nutritional requirements of cacao are approximately met except for P. The available P status is low in most cacao farms. Altogether available P was determined in soils of 41 cacao farms scattered over the cacao belt. More than 75 per cent of the soils were found to contain less than 10 ppm available P and should be considered as P deficient according to the criteria given in chapter 7. This result is not surprising because in the past both in Ghana and Nigeria low figures of available P (of the order of 5–10 ppm) have nearly always been found (Nye and Bertheux 1957).

Most of the cacao has been established on soils cleared from forest. With the introduction of cacao more or less as a monoculture the existing equilibrium between soil and forest is disturbed. This results in an initially rapid decline in organic matter mainly as a result of diminished litter supply and increased mineralization in the exposed soils, which continues till the cacao trees have formed a closed canopy. A new status of approximate equilibrium is now reached which can be maintained for a long period when yields are low, provided that the canopy stays intact. Depending on shade conditions, a break-down of the canopy mostly results in the development of grass patches which extend and merge and fragment the cacao stand. Cultivation of the grass areas for other crops leads to further decline in chemical fertility. This generalized trend is illustrated in table 8 in which the nutrient status of soils under forest is compared to those under cacao of various ages and those replanted to cacao after the existing cacao trees had declined in yield due to the old age, pests and diseases (Wessel 1969d). The table shows that cacao exhausts the available P of the forest soils but not the exchangeable K. Considering that a crop of 500 lb dry beans per acre removes approximately 3 lb P (corresponding with 1.5 ppm in the 0–6 inch soil layer)

Table 8

Effect of cacao cultivation on the chemical status of the surface soil (0–6 inches)

age of cacao (years)		pH	% C	% N	exchangeable bases in m.e. per 100 g fine earth K	Ca	Mg	available* P in ppm	nr of fields	origin of samples
0 (forest)	mean	6.8	2.5	0.24	0.42	15.0	2.3	26	4	Gambari Station Experimental
	range	6.7–6.8	2.4–2.6	0.23–0.27	0.32–0.52	14.2–17.0	1.9–2.6	19–35		
3– 5	mean	6.6	2.0	0.19	0.28	13.7	1.5	35	4	
	range	6.5–6.7	1.8–2.2	0.18–0.21	0.24–0.33	13.0–14.7	1.1–2.0	20–61		
9–15	mean	6.6	1.8	0.16	0.29	12.2	2.1	14	4	
	range	6.4–6.8	1.6–2.0	0.15–0.18	0.21–0.37	11.3–13.9	1.7–2.7	6–34		
24–33	mean	6.4	1.4	0.13	0.27	8.6	1.6	12	3	
	range	6.3–6.5	1.1–1.6	0.12–0.14	0.22–0.34	8.5– 8.8	1.5–1.7	9–16		
30–40	mean	6.1	1.9	0.16	0.34	9.3	2.0	10	17	farms listed in table 7
	range	5.4–6.9	1.3–2.7	0.11–0.23	0.17–0.77	5.8–17.1	1.3–3.8	2–40		
replanted cacao farms	mean	–	1.2	–	0.28	–	–	8	17	farms within a radius of 30 miles from Ibadan
	range		0.7–1.6		0.19–0.36			2–19		

* determined in Bray and Kurtz nr 1 extractant

and 30 lb K it may be concluded that soils have only a small P reserve (see also chapter 5) but large K reserves, due to a relatively high proportion of only partly weathered mineral fragments which are often apparent in soil profiles.

A further study of the data of the soils mentioned in tables 7 and 8 revealed that total N, organic P, the cation exchange capacity and the sum of exchangeable bases (within certain pH limits) are highly significantly positively correlated with the organic matter content of the soil. This observation stresses the need for preservation of soil organic matter and indicates that for practical purposes the organic matter content together with the pH of the soil can be considered as the most important single index of soil fertility.

4. SOIL MOISTURE STUDIES

The soil moisture studies reported on were aimed at determining the available water-storage capacity of some soils and the factors on which it depends and investigating seasonal fluctuations in available water.

The data presented in table 9 have been obtained from samples from different horizons at depths between 0–60 inches in 9 profiles at Gambari Experimental Station near Ibadan. Profiles A, D, F and I are situated on the catena shown in figure 3. Profile 7 is an example of a clayey cacao soil with a low gravel content while numbers 16 and 20 are clayey soils with a high gravel content. Profiles 1 and 2 are sandy soils of the lower and upper slopes respectively which are unsuitable for cacao. In addition soil moisture observations were made on a number of sedimentary soils, to investigate whether the water regimes in these soils were different from those in soils derived from metamorphic rock.

TABLE 9 →

Results of moisture determinations in soils of nine profiles at Gambari Experimental Station

profiles	depth (inches)	bulk density		% C	% >2 mm	soil fraction <2 mm (fine earth)			
		total soil mass	fine earth			% coarse sand	% fine earth	% silt	% clay
A	0– 3	1.13		2.3	0	34	40	11	15
	3– 9	1.49	1.37	0.8	8	43	34	8	15
	9–24	1.79	1.13	0.2	37	43	28	4	25
	24–39	1.65	0.75	–	55	35	23	6	36
	39–60	1.49	0.74	–	50	28	25	10	37
D	0– 2	0.87		3.2	0	13	61	9	17
	2– 6	1.23		0.4	0	26	57	9	8
	6–18	1.38		–	0	32	49	5	14
	18–38	1.49		–	0	24	43	5	28
	38–60	1.55		–	0	23	41	6	30
F	0– 2	0.80		2.0	0	21	57	8	14
	2–13	1.31		0.3	0	19	65	8	8
	13–23	1.37		–	0	20	57	7	16
	23–46	1.47		–	0	18	52	4	26
	46–60	1.51		–	0	21	50	5	24
I	0– 3	0.84		2.4	0	20	55	9	16
	3–10	1.17		0.3	0	31	56	4	9
	10–24	1.37		–	0	35	53	4	8
	24–42	1.41		–	0	31	39	4	26
	42–60	1.60		–	0	24	49	4	23
7	0– 3	1.23		1.6	0	29	46	7	18
	3– 6	1.53	1.50	0.6	2	27	44	6	23
	6–12	1.57	1.34	0.4	15	24	48	4	24
	12–22	1.58	1.48	–	6	28	39	3	30
	22–28	1.51	1.38	–	9	23	35	4	38
	28–36	1.47	1.33	–	10	25	30	4	41
	36–48	1.52	1.42	–	7	31	22	5	42
	48–60	1.50	1.43	–	5	27	22	9	42
1	0– 2	0.98		2.7	0	21	57	12	10
	2– 6	1.22		0.8	0	43	42	5	10
	6–18	1.45		0.3	0	47	41	4	8
	18–30	1.50		–	0	46	37	3	14
	30–54	1.50		–	0	49	30	4	17
	54–60	1.64	1.00	–	39	34	35	4	27
2	0– 3	1.01		2.2	0	27	52	11	10
	3– 6	1.24		0.4	0	60	30	2	8
	6–15	1.38	1.30	0.2	5	43	50	2	5
	15–26	1.57	1.31	–	17	69	18	3	10
	26–40	1.70	1.13	–	33	59	8	2	31
	40–60	1.74	1.54	–	12	46	24	5	25
16	0– 2	1.03	0.96	2.5	7	25	51	5	19
	2– 7	1.31		0.8	0	20	53	7	20
	7–14	1.53	0.75	–	51	21	45	7	27
	14–32	1.68	0.78	–	54	17	36	7	40
	32–44	1.65	1.30	–	21	20	31	8	41
	44–60	1.46	1.40	–	4	23	23	7	47
20	0– 3	0.99		3.0	0	17	64	11	8
	3–11	1.60	1.48	0.5	9	29	52	4	15
	11–16	1.75	0.66	0.2	62	34	42	5	19
	16–28	1.68	0.87	–	48	27	36	5	32
	28–42	1.63	1.25	–	23	21	34	5	40
	42–60	1.52	1.43	–	6	19	33	7	41

moisture content % by weight					id. % cent by volume			inches of water			
F.C. total soil	F.C. fine earth	pF 2.5	pF 3.0	pF 4.2	F.C.	pF 3.0	pF 4.2	F.C.	pF 3.0	pF 4.2	F.C.– pF 4.2
19.8		20.1	16.8	9.6	22.4	19.0	10.8	0.67	0.57	0.32	0.35
15.5	16.9	16.2	12.6	7.7	23.1	17.3	10.5	1.39	1.04	0.63	0.76
10.6	16.8	16.3	13.8	9.5	19.0	15.6	10.7	2.85	2.34	1.60	1.25
11.5	25.3	24.1	21.7	16.2	19.0	16.3	12.1	2.85	2.44	1.81	1.04
14.0	28.2	25.4	22.8	18.0	20.9	16.9	13.3	4.39	3.55	2.79	1.60
24.6		19.6	17.1	10.1	21.4	14.9	8.8	0.43	0.30	0.18	0.25
14.1		11.6	8.7	4.8	17.3	10.7	5.9	0.69	0.43	0.24	0.45
14.8		11.2	8.3	5.2	20.4	11.4	7.2	2.45	1.37	0.86	1.59
17.0		18.5	15.7	11.4	25.3	23.4	17.0	5.06	4.68	3.40	1.66
18.1		19.4	15.8	11.9	28.0	24.5	18.4	6.17	5.39	4.05	2.12
27.4		15.8	12.4	6.2	21.9	9.9	4.9	0.44	0.20	0.10	0.34
13.9		9.5	6.6	3.5	18.2	8.6	4.6	2.00	0.95	0.51	1.49
14.5		12.2	9.4	6.1	19.9	12.9	8.4	1.99	1.29	0.84	1.15
16.9		18.1	13.9	10.4	24.8	20.4	15.3	5.70	4.69	3.52	2.18
16.2		16.9	12.5	9.0	24.5	18.9	13.6	3.43	2.65	1.90	1.53
26.9		18.2	16.2	7.9	22.6	13.6	6.6	0.68	0.41	0.20	0.48
12.4		7.8	6.7	3.0	14.5	7.8	3.5	1.02	0.55	0.25	0.77
9.0		6.6	5.6	2.1	12.3	7.7	2.9	1.72	1.08	0.41	1.31
16.6		17.9	14.8	10.3	23.4	20.9	14.5	4.21	3.76	2.61	1.60
14.5		16.7	13.2	9.0	23.2	20.8	13.4	4.18	3.74	2.41	1.77
23.6		16.4	14.0	8.2	29.0	17.2	10.3	0.87	0.52	0.31	0.56
19.0	19.4	15.9	14.1	9.0	29.1	21.1	13.5	0.87	0.63	0.40	0.47
15.0	17.6	15.1	13.2	9.4	23.5	17.7	12.6	1.41	1.06	0.76	0.65
18.0	19.2	17.3	16.1	11.6	28.4	23.8	17.2	2.84	2.38	1.72	1.12
18.2	19.9	21.5	19.5	15.8	27.5	26.9	21.8	1.65	1.61	1.31	0.34
20.6	22.7	23.2	22.2	17.5	30.3	29.5	23.3	2.42	2.36	1.86	0.56
22.0	23.5	26.5	24.6	18.1	33.4	34.9	25.7	4.01	4.19	3.08	0.93
24.2	25.4	27.0	25.1	20.0	36.3	35.8	28.6	4.36	4.30	3.43	0.93
22.8				5.6	22.3		5.5	0.45		0.11	0.34
13.8				3.4	16.8		4.1	0.67		0.16	0.51
10.2				2.2	14.8		3.2	1.78		0.38	1.40
11.8				4.2	17.7		6.3	2.12		0.76	1.36
12.9				6.0	19.4		9.0	4.66		2.16	2.50
9.5	15.6			10.8	15.6		9.5	0.94		0.57	0.37
22.0				8.1	22.0		8.1	0.66		0.24	0.42
12.4				3.0	15.4		3.7	0.46		0.11	0.35
10.0	10.6			2.1	13.8		2.7	1.24		0.24	1.00
8.9	10.7			4.0	14.0		5.2	1.54		0.57	0.97
10.9	16.4			11.7	18.5		13.2	2.59		1.85	0.74
11.8	13.3			10.8	20.5		16.6	4.10		3.32	0.78
25.4	27.3			11.2	26.2		10.7	0.52		0.21	0.31
20.0				9.3	26.2		12.2	1.31		0.61	0.70
8.9	18.2			11.0	13.2		8.2	0.95		0.57	0.38
12.4	26.7			16.6	20.8		12.9	3.74		2.32	1.42
17.5	22.2			17.8	28.9		23.1	3.47		2.77	0.70
23.6	24.6			20.5	34.5		28.7	5.52		4.59	0.93
23.2				8.6	23.1		8.5	0.69		0.25	0.44
16.4	17.7			6.2	26.2		9.2	2.10		0.50	1.60
9.4	25.0			8.4	16.5		5.5	0.83		0.27	0.56
12.4	23.9			14.7	20.8		12.8	2.50		1.54	0.96
17.6	23.0			18.0	28.7		22.5	4.02		3.15	0.87
21.9	23.3			20.0	33.3		28.6	5.99		5.15	0.84

4.1.2 *Relationship between soil moisture retained at field capacity and at pF 2.5*

The relation between the moisture of the soil at pF 2.5 which is often used as an approximation to field capacity (F.C.) in deeply drained soils (such as the ones under consideration) and F.C. determined by a direct field method is shown in figure 5. It can be seen that the 1/3 atm. estimations underestimate the F.C. of the sandy soils and overestimate the F.C. of the clayey soils. This is probably largely due to the fact that the pF determinations were made on disturbed samples. In soils in natural condition the amount of water at F.C. depends on the structure, the texture and the organic matter content of the soil. The effect of organic matter can here be ignored because soils with a %C > 0.5 have not been considered in calculating the regression lines, shown in figure 5. Air-drying, sieving, re-arranging and wetting of the soil will largely destroy the structure and as a result the water retention capacity of the soil sample will mainly depend on texture. In the sandy soils mainly from horizons with a low bulk density near the soil surface (see table 9) the relatively large inter-aggregate pore space will be reduced by disturbance of the soil which results in a lower water-holding capacity of the soil at pF 2.5 than at F.C. In the more compact clayey soils, changes in the existing pore space are probably less important. The discrepancies between moisture contents at F.C. and pF 2.5 are likely to arise from a less thorough wetting of the soil in the field than in the laboratory. In the field the rate of entry of water in the soil may be reduced if pores are sealed off by fine particles or iron coats while the infiltration speed in very narrow pores may be extremely slow. Differences in wetting technique may also cause discrepancies. In the field soil is wetted from the top and more air may be entrapped in the pores of the soil than in the soil samples on the membrane which are wetted from the bottom and which are only spread out in a thin layer of about 0.5–1.0 cm thickness.

From the slope of the F.C. regression line it can be seen that the amount of available water held in the range between F.C. and pF 4.2 decreases with an increase in the fraction < 20μ. The same trend can be observed in figure 6 where the moisture contents are expressed in volume percentages. The reduction in available water takes probably place in the range between F.C. and pF 3 because it was previously shown that beyond pF 3 available water increases slightly with increasing fineness of the fine earth fraction.

The F.C. and P.W.P. data of the sedimentary profiles were found to fit very well the regression lines shown in figure 6. This seems to indicate that the soils derived from metamorphic rock and the sedimentary soils do not differ much in their moisture regimes.

At the I.R.H.O.* oilpalm research station at Pobé, Dahomey, it has also been found that the amount of available water (y) decreases when the clay

* Institut de Recherche pour les Huiles et Oléagineux

content of the soil (x) increases (*Rapport Annuel I.R.H.O. 1962*). This relationship is expressed by the linear regression

$$y = -0.11x + 11.2 \; (r = -0.95)$$

which is in close agreement with the regression

$$y = -0.12x + 9.8 \; (r = -0.85)$$

which can be calculated for the soils at Gambari Experimental Station from the data in table 9.

At Pobé this decrease of available water was ascribed to the kaolinitic nature of the clay. It was thought that the F.C. of the soil depends almost entirely on the structure of the soil but that the P.W.P. is determined by the texture. The high degree of correlation between the amounts of water retained at F.C. and texture indicates, however, that in the soils studied in Nigeria structure has little effect on F.C.. The reason for this might be that the kaolinitic soils have no distinct macro-structure except in layers where organic matter is present (see chapter 3).

The point has already been stressed that the sandy soils are taken from the upper horizon and the clayey soils from layers down the profile. This applies for soils both at Gambari Experimental Station and Pobé. This may

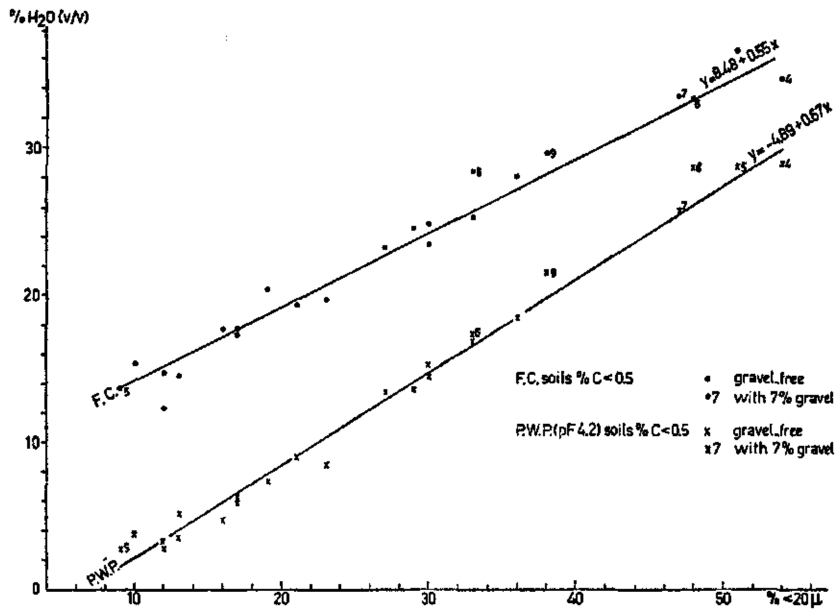


Figure 6
The relationship between the volume percentage of available water (held in the range between F.C. and P.W.P.) and texture

imply that an F.C. line with a different slope will be found when soils with different clay contents but from the same horizontal depth are studied.

4.1.3 *The effect of organic matter*

In agreement with the results of COMBEAU *et alii* the presence of organic matter in the top soil was found to raise the F.C. but to have little effect on the amount of water held at pF 4.2. This is illustrated in figure 4. Organic matter thus has a positive effect on the available water storage capacity of the soil. As appreciable quantities of organic matter are only present in the top few inches of the soil, this effect is only small when the water storage capacity of the whole profile is considered.

4.1.4 *The effect of gravel*

In table 9 it can be seen that gravelly soils (profiles A, 2, 16 and 20) have a lower F.C. and usually also a lower available water storage capacity than non gravelly soils of the same fine earth texture. This is caused by the fact that gravel and stones reduce the volume of fine earth which is the main site of water storage. Results of COILE (1953) have shown that weathered rock fragments can hold a considerable amount of water, a part of which is available to the plants. As in the profiles studied the fraction larger than 2 mm mainly consisted of unweathered angular quartz gravel, it was assumed that this fraction did not contribute to the F.C. and the available water storage capacity of the soil. When this assumption is made the F.C. of the gravel surrounding fine earth can be calculated by dividing the difference in weight of the wet field sample and oven-dry sample by the weight of the oven-dry fine earth. The figures thus obtained are presented in table 9 under the heading "bulk density of fine earth."

In soils with a low gravel content these calculated F.C.'s correspond rather well with the F.C.'s of gravel-free soils of the same texture. This is illustrated by the fact that the regression equation expressing the relationship between the volume percentage moisture at F.C. and texture for gravel-free soils hardly changes when the potential F.C.'s of the gravelly soils are included in the calculations. These regression equations are $y = 8.39 + 0.53\,x$ and $y = 8.48 + 055\,x$ respectively in which y is the volume percentage moisture at F.C. and x the fraction $< 20\mu$.

In soils with a high gravel content of the order of 50 to 60 per cent by weight, however, these calculations give F.C. values for the fine earth which sometimes considerably exceed those of comparable gravel-free or almost gravel-free soils (see figure 5).

In view of these observed differences in F.C. it was thought that the assumption that the fraction larger than 2 mm does not contain water might not be correct. To investigate this point gravel and stones from all horizons of profile A were washed free of fine earth and soaked in water for 14 days.

After removal of the adhering water the moisture contents of these particles were determined. The moisture figures found ranged from 0.5 to 1.5 per cent.

Using these figures the F.C. for the fine earth of the 29–39 and 39–60 inch soil layers of profile A were calculated. The F.C.'s of the soil including gravel and stones are in these horizons 11.5 and 14.0 per cent respectively and the calculated F.C. figures 25.3 and 28.2 per cent, when it is assumed that the gravel contains no water and 23.5 and 26.8 per cent when corrections are made for a moisture content in the gravel of 1.5 per cent. As these last two figures are still higher than those in gravel-free or almost gravel-free soils of the same texture (which are of the order of 21 and 23 per cent respectively), it seems that gravel and stones sometimes have a positive effect on the F.C. of the surrounding fine earth. This effect is likely to result from an increase in interaggregate pore space which can hold water against gravity. It is thought that in layers in which large quantities of gravel have accumulated, these particles form a skeleton with open spaces in which fine earth is present with a lower bulk density than in gravel-free horizons of the subsoil. Factors which in this situation determine the water storage capacity of the soil are not only the amounts of gravel and stones, but also the size and shape of these particles and the texture of the fine earth itself. In view of the multitude of factors involved it is clear that a positive effect of gravel on the F.C. of the surrounding earth may occur in certain soils but not in others. Routine soil moisture determinations suggested, however, that this positive effect is mainly restricted to the more clayey soils.

This positive effect is only small compared to the negative effects of gravel which are, as already mentioned in the beginning of this section, to reduce the volume of fine earth and so to lower the water storage capacity of the soil.

4.2 The amount of available water in the top 5 ft of the soil

After having discussed the relationship between available water and texture and the effect of organic matter and gravel on this relationship, the quantity of available water in the profiles from which the samples were taken will be considered.

The amounts of available moisture in each soil horizon have been calculated in table 9 while the total quantities per profile have been summarized in table 10. In these calculations it has been assumed that in the gravelly soils the fraction larger than 2 mm does not hold any water at F.C. and P.W.P. of the soil. This assumption is based on the observation that the gravel mainly consists of quartz fragments which were shown to have a very low moisture content. Table 10 shows that the quantity of available water varies for most profiles between 5 and 6.5 inches per 5 ft (60 inches) of soil, corresponding with available moisture volumes of 8 and 11 per cent.

These figures are low compared to those found in most Dutch soils, which usually range between 13.5 to 33 volume per cent (PEERLKAMP and BOEKEL 1960, HAANS 1960). Equally low figures have, however, been reported for Amazon kaolinitic latosols in Brazil (SOMBROEK 1966) and clayey kaolinitic soils at Pobé. Furthermore, it can be seen that 50 to 70 per cent of the water held at F.C. is unavailable to plants. Similar figures were found at Pobé while SOMBROEK states that in very clayey soils up to 35 volume per cent moisture is not available. In the Nigerian soils, however, this last figure did not exceed 30 per cent (see figure 6).

4.3 THE SUITABILITY OF THE SOIL FOR CACAO IN RELATION TO SOIL MOISTURE

Experience has shown that the clayey soils on the upper slopes are less drought susceptible than the sandier soils down the slope (chapter 3). To investigate the factors on which this difference in drought susceptibility depends, the moisture regimes of a typical clayey upper slope soil (profile 7) and a sandy lower slope soil (profile I) will be compared. In table 10 it can be seen that these profiles differ greatly in the amounts of water held at F.C. and P.W.P. but that they have approximately the same amount of available water. This indicates that the differences in drought susceptibility of the soil and the cacao on it, are not related to the quantities of available water but to the rates at which water is released from the soil to the trees. In the low pF range sandy soils as a rule have a higher conductivity than clayey soils but

TABLE 10

The water-storage capacity of the top 60 inches of soil at field capacity, pF 3 and pF 4.2 (soils of profiles A-20 are derived from metamorphic igneous rocks, soils at Ilaro and Ikorodu are derived from sedimentary rocks)

profile	inches of water at				inches of water held between			
	F.C.	pF 3	pF 4.2		F.C. and pF 3	pF 3 and pF 4.2		F.C. and pF 4.2
A	12.15	9.94	7.15	(58.8)*	2.21	2.79	(55.8)**	5.00
D	14.80	12.17	8.73	(59.0)	2.63	3.44	(56.7)	6.07
F	13.56	9.78	6.87	(50.7)	3.78	2.91	(43.5)	6.69
I	11.81	9.54	5.88	(49.8)	2.27	3.66	(61.7)	5.93
7	18.43	17.05	12.87	(69.8)	1.38	4.18	(75.2)	5.56
1	10.62		4.14	(39.0)				6.48
2	10.59		6.33	(59.8)				4.26
16	15.51		11.07	(71.4)				4.44
20	16.13		10.86	(67.3)				5.27
Ilaro	12.85		7.37	(57.3)				5.48
Ikorodu	17.08		11.81	(69.1)				5.27

* as % of water held at F.C.

** as % of water held between F.C. and pF 4.2

at the higher pF values the situation is the opposite. The result will be that the cacao on a sandy soil consumes in a shorter period a greater portion of the available water than on a clayey soil. The release of water to the plants is thus slower and more even in a clayey soil.

LEMÉE (1955) and ALVIM (1959) have found that when soil moisture was reduced to about 60 per cent of the available range, stomatal opening, photosynthesis and transpiration of cacao leaves started to decrease. The time at which these phenomena of water stress appear will thus occur much sooner on a sandy soil than on a clayey soil.

The water regimes of the profiles I and 7 have been summarized in the profile composition diagrams in figure 7, which show the volumetric distribution of the solid parts in relation to pore space while furthermore it has been indicated which part of the soil volume is filled with water at F.C. and P.W.P.. The pore volume in both profiles is about 40 per cent and tends

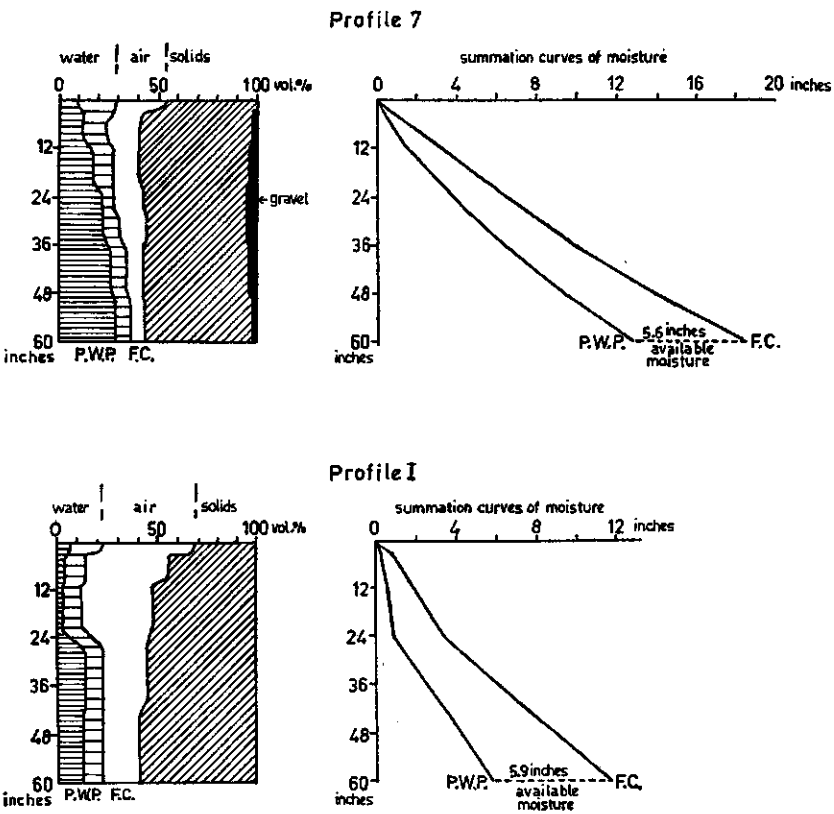


Figure 7
The solids-water-air diagram of a clayey (profile 7) and a sandy soil (profile I)

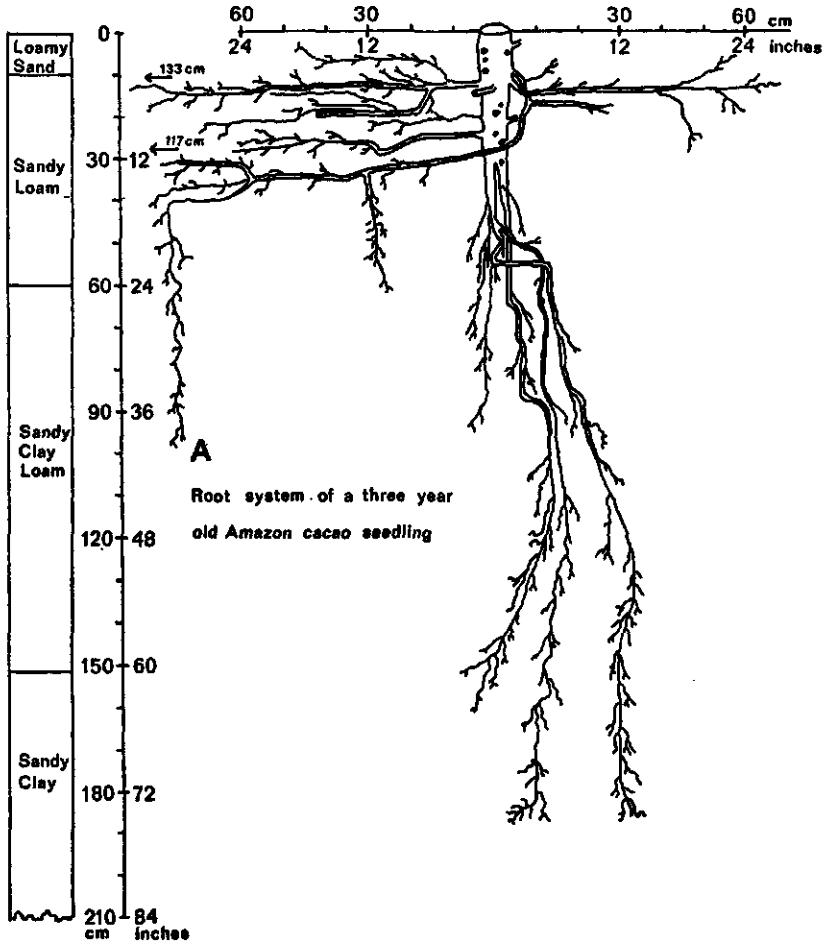
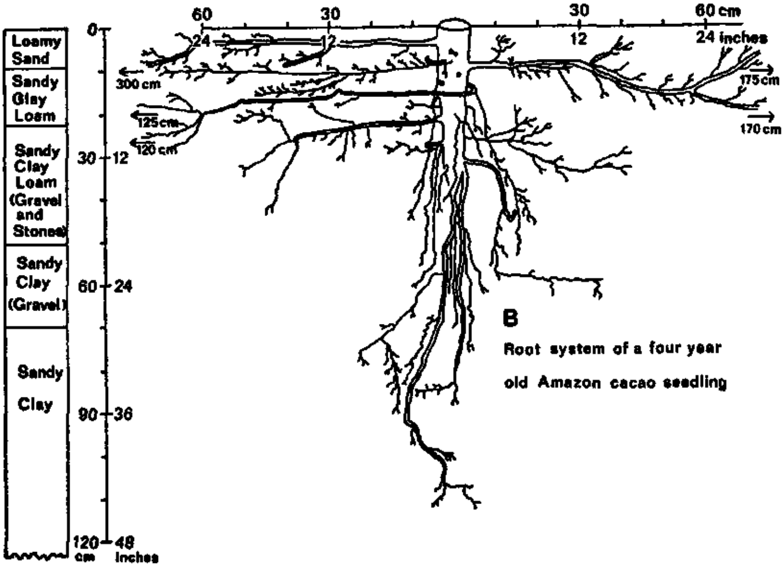


Figure 8
The rooting depth of young cacao seedling-trees in a drought susceptible soil (A) and a non drought susceptible soil (B)

out the whole profile that makes the soil drought susceptible, while in soils of the type of profile D and especially of profile F the low clay content in the top two ft of the soil is the reason that these soils are marginal for cacao.

The farmers in the drier parts of the cacao belt, having observed the high death-rate of cacao under forest shade, have removed most forest trees from their farms with the result that cacao is grown with little or no overhead shade. Lack of available water is most likely also the reason that in a number of experiments establishment of young cacao without any shade



was found to be more successful than when various types of living shade were used (BARNES 1963).

There are however also other opinions concerning the influence of shade trees on the water economy of cacao. LEMÉE (1955) maintains that shade reduces the transpiration of cacao and so protects cacao against water shortage. ALVIM (1959) also mentions a case in Costa-Rica where during a three months' dry period the water balance of cacao was favourably affected by the presence of shade trees as a result of a reduced demand for water by shaded cacao.

These conflicting opinions illustrate that the question whether shade has an adverse or a benificial effect depends on many factors such as climate, soil, planting distance and the root distribution of shade and cacao trees.

4.4 RESULTS OF MONTHLY SOIL MOISTURE DETERMINATIONS

To study the seasonal fluctuations in available water, monthly moisture determinations were made in all plots of the cacao experiment on the soil catena. Some results for a cacao plot with tree-cassava shade located on the slope just below profile D (figure 3) are given in table 11. At each sampling date a different sampling point was used and the moisture content of the soil was determined gravimetrically. The moisture content has been expressed in inches per horizon in order to make the results comparable to those given in table 9.

From table 11 it can be seen that in January 1967 (as in January 1966) the soil had dried out to the P.W.P. level of the nearby profile D. The moisture content of the top two feet of the soil increased during March but decreased again in April. Field capacity in the top 4 ft of the soil was reached by the end of June. Up till this period the actual evapo-transpiration (calculated from rainfall and changes in soil moisture) was less than the potential evapo-transpiration (given in table 5). From June 27th till July 15th the rainfall (8.2 inches) exceeded the approximate potential evapo-transpiration over this period (3 inches) by 5.2 inches and this surplus water was lost by drainage. During the subsequent almost rainless period which lasted till the end of August the actual evapo-transpiration fell again below the potential evapo-transpiration. Field capacity was reached again by the end of September and even exceeded on the day of sampling due to 2 inches of rainfall on the previous day. During October and November the actual evapo-transpiration approximately equalled the potential evapo-transpiration and fell below the potential evapo-transpiration in December. The soil did dry out again in January 1968 but stayed dry for a shorter period than in the previous year due to higher rainfall in February and April.

These observations show that a distinct annual drying-out and water recharging cycle of the soil exists. In years of normal rainfall (for the Ibadan area defined by FREEMAN 1966) the period of water deficiency starts in December and ends in May. During the following wet months rainfall is usually not so high that excessive leaching of the soil occurs. The implications of these observations for the cacao cultivation are discussed in chapter 8.

4.5 THE EFFECT OF SOIL MOISTURE ON THE ROOTING DEPTH OF YOUNG CACAO TREES

As part of the soil moisture investigations the root systems of young cacao seedlings were studied in different soils of Gambari Experimental Station. It was found that at two and three years after planting the cacao roots had reached an approximate depth of 3.5 ft and 6.5 ft respectively in soils with a sandy top soil but only about half this depth in soils with a clayey top soil. These differences in rooting depth thus confirm that the sandy soils dry out to a greater depth during the dry months than the clayey soils. These differences in root development are illustrated in figure 8.

The rooting depth of the cacao on the clayey soils corresponds with the rooting depth which VAN HIMME (1959) describes for cacao of the same age at Yangambi (Congo, Kinshasa) where the total mean annual rainfall is not much higher than in South-Western Nigeria but no severe dry season exists. This illustrates that suitable soil conditions can to a large extent compensate for lack of rainfall.

5. SOIL PHOSPHORUS STUDIES

The positive reaction of cacao to applications of P fertilizers was the reason for examining the phosphorus status of cacao soils in greater detail. The aspects studied were: the extraction of more active or available phosphate, the fractionation of total phosphate in chemical classes and the fate of soluble phosphate applied to the soil.

5.1 The extraction of available phosphate

The P figures presented in chapter 3 have been determined in the Bray and Kurtz no. 1 dilute fluoride dilute acid solution (the extraction procedure was slightly modified as described in appendix 1). This method had been chosen because it generally gives results that are highly correlated with crop responses to P fertilizers. As the P concentrations determined by this method were low in most soils, available P was also measured with the alkaline extraction method of Olsen *et alii* (Jackson 1960). The amounts of P extracted by this procedure were slightly higher but corresponded very well with the figures obtained by the Bray and Kurtz method as shown in the equation

$$\text{ppm P (Olsen)} = 2.12 + 0.95^{***} \text{ ppm P (Bray and Kurtz)}. \; (r = 0.96; n = 40)\dagger$$

The close agreement between the fractions extracted by these two procedures supports Jackson's view that both methods extract the most reactive phosphates from Al, Fe and Ca phosphates.

As furthermore good correlations were found between the P fraction extracted by either procedure and the responses of cacao to addition of P fertilizers and the P concentrations in cacao leaves (see chapter 7), it was concluded that both methods adequately measure available P in cacao soils. In further studies the Bray and Kurtz determination method was used because of its greater simplicity and rapidity.

† in equations and tables*, ** and *** indicate significance at levels $P = 0.05$, $P = 0.01$ and $P = 0.001$ respectively.

5.2 Fractionation of total phosphate

5.2.1 *Surface soils*

The distribution of the different forms of inorganic phosphorus over the soils on the fertilizer experiments has been studied using the Chang and Jackson (1957) procedure which is based on the selective solubility of various inorganic phosphates in different extractants. Total and organic phosphorus were determined on two separate samples using the perchloric acid digestion procedure and ignition method respectively (Jackson 1960). Occluded phosphates were, however, not determined but calculated as the difference between total phosphate and all fractions measured analytically. The fractions obtained were

extractable or non-occluded inorganic P	NH_4Cl – P	water-soluble or loosely bound P
	NH_4F – P	aluminium-bound P
	NaOH – P	iron-bound P
	H_2SO_4 – P	calcium-bound P

occluded inorganic P = total P – (extractable inorganic P + organic P)

organic P

The division between the inorganic fractions is, however, not clear cut. Rajendran and Sutton (1970) using ^{32}P found that the Chang and Jackson procedure under-estimates the loosely bound P fraction and over-estimates the occluded phosphate. The values for aluminium phosphates may furthermore be over-estimated by approximately 10 per cent, because of the inclusion of a portion of iron phosphates (Chang and Jackson 1957). Williams and Walker (1969) were unable to find an absolute distinction between iron- and aluminium-bound phosphate and abandoned the distinction between both fractions by terming the sum of the NH_4F – P and NaOH – P "non-occluded P" and by considering acid-extractable Ca – P separately.

The results of the P determinations are given in table 12 together with some relevant soil data and the phosphate sorbing capacity which will be discussed in section 5.3. The sites have been arranged in order of increasing amounts of available P except for Ife which position has also been based on the total amount of extractable inorganic P. The first 14 sites are low or deficient in available P. Ayorinde has a medium high and the last three sites have an adequate to high available P content.

The table shows that the total P content of the soils (except for Iddo which has a low figure and Akinyele sand Iroko which have very high figures for total P) varies between 360 and 560 ppm, of which 40 to 60 per cent is present in organic form. This fraction is highly correlated with the organic carbon content of the soil and to a lesser extent to the clay content of the soil as

TABLE 12

Distribution of phosphate in surface soils (0–6 inches) under cacao (ppm P)

site	% clay	% C	pH	P sorption capacity*	available P**	inorganic P						organic P	total P
						non-occluded or extractable					occluded		
						NH_4Cl–P	NH_4F–P	NaOH–P	H_2SO_4–P	sub-total			
Oke-Irun	24	1.84	5.4	65	2	1	2	22	6	31	223	202	456
Oda	18	1.68	6.2	57	4	0	4	22	8	34	140	201	375
Iddo	14	1.33	6.1	21	4	0	4	14	7	25	34	130	189
Oloba	13	1.29	6.2	22	4	0	6	13	10	29	139	194	362
Ricket	28	1.76	5.8	64	5	0	3	25	8	36	180	274	490
Ife	26	1.90	5.6	62	3	1	8	32	15	56	249	226	531
Aba-Agbo	16	1.33	6.3	35	6	1	9	28	9	47	193	166	406
Apoje	25	1.92	5.5	53	6	2	7	36	8	53	224	223	500
Fidiwo	21	2.20	6.3	37	6	1	8	33	17	59	183	262	504
Balogun	18	1.66	6.0	40	7	1	9	29	10	49	122	235	406
Aponmu	17	2.02	6.7	43	7	1	11	20	12	44	124	207	375
Iwo	18	1.63	5.9	37	8	1	8	29	11	49	103	196	348
Aiyetoro	25	2.41	6.2	45	8	0	9	25	17	51	221	290	562
Ilesha	18	1.65	5.9	39	9	0	9	50	13	72	203	256	531
Ayorinde	20	1.60	5.8	36	12	1	11	45	15	72	171	258	501
Ikole	18	2.44	6.2	32	23	1	22	57	40	120	86	304	510
Akinyele	26	2.66	6.4	34	24	4	23	62	56	145	185	420	750
Iroko	22	2.48	6.9	23	40	13	74	75	165	327	295	316	938

* μg P sorbed per g soil (see appendix I)
** determined in Bray and Kurtz Nr 1 extractant

shown in table 13. Since the organic carbon and clay contents are positively correlated, the relationship between organic P and carbon and clay has been expressed in a partial regression equation which is as follows:

$$\text{organic P} = -24.88 + 2.28\% \text{ clay} + 117.77^{***}\% \text{ C}$$

The multiple correlation coefficient is 0.85 and is thus only slightly higher than the single correlation coefficient between organic P and organic C. The fact that in this equation the regression coefficient for clay is not significant indicates that no direct relationship exists between organic P and clay.

The results of the fractionation of inorganic P clearly show that most of it is present in occluded form probably mainly as iron-coated Al and Fe phosphates (CHANG and JACKSON 1957) but also partly as P intimately bound with the clay lattice (KURTZ 1953). Although differences in the distribution of inorganic P exist, there seems to be a general distribution pattern which for the P deficient sites except Iddo can be described as follows: about 77 per cent of the inorganic P is present as occluded P, 5 per cent as Ca-bound, 12 per cent as Fe-bound, 4 per cent as Al-bound and less than 1 per cent as loosely bound or water soluble P. The total amounts of non occluded inorganic P range in these soils from 25–72 ppm but in the soils with an adequate to high available P content from 125–327 ppm where they constitute more than 40 per cent of the total inorganic P. In the non-occluded P fraction the proportion of calcium and iron phosphate increases and decreases respectively with increasing pH values as shown in figure 9.

Available phosphate extracted with Bray and Kurtz no. 1 solution was found to be highly correlated with total extractable inorganic phosphate ($r = 0.96$) and with each of its subfractions (all r's > 0.90). This supports the view of CHANG and JACKSON (1957) that available P determinations extract portions of all chemical forms of P having either high solubility or high specific surface.

As the amounts of P present in the available P and the Al-bound P fraction are almost the same on most sites, it seems that the Bray and Kurtz solution mainly extract Al phosphates. This is not surprising because in both determinations NH_4F is used, although in concentrations which differ by a factor of approximately 17.

TABLE 13

Correlations between some properties of the cacao soils listed in table 12

	% clay	organic P	P sorption capacity
% C	0.5729*	0.8373***	0.0245
% clay	1.0000	0.5834*	0.6423**
pH	−0.3289	0.2830	−0.6160**

Phosphate fractionations in surface soils of arable farms have been reported from Ghana by NYE and BERTHEUX (1957). Though a different fractionation procedure was followed, the analyses can be used for a broad comparison which shows that the non-occluded inorganic P content and its distribution do not differ greatly from the results in Nigeria. The amounts of organic P are much lower and do not fit the relationship between organic C and organic P previously mentioned. BURRIDGE and CUNNINGHAM (1960) found, however, organic phosphorus figures in cacao soils in Ghana which are even higher than those in Nigeria. These differences in organic phosphorus content of cacao soils and soils in arable farms might be a result of differences in mineralization of organic matter whereby more phosphate is released from the usually more exposed soils under arable crops.

5.2.2 *Soil profiles*

The distribution of phosphates over the different chemical fractions in some soil profiles is shown in table 14. The profile at Ricket was chosen because of its low and the one at Ikole because of its high extractable inorganic P content. The third profile (Ikorodu) was selected to represent the sedimentary soils of the cacao belt.

The distribution of P in the first two profiles shows an accumulation of total P in the top few inches of the soil due to the presence of large quantities of organic P. Below this level organic P drops sharply and continues to decrease with depth but more slowly than might be expected from the fall in total organic matter. The same trend is apparent for extractable or non-occluded P. In particular the Al-P fraction which is likely to be most readily available shows a sharp decrease with depth. The drop in the Fe-bound P fraction is more gradual and as a result the proportion of Fe-P increases

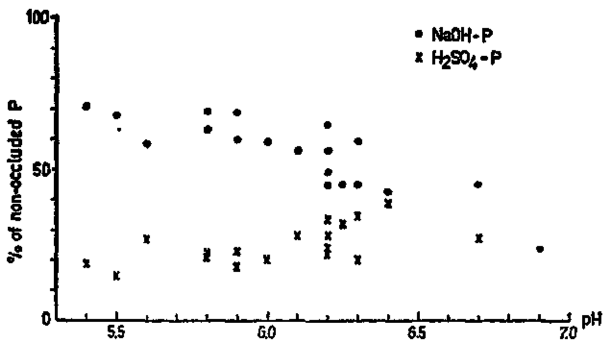


Figure 9
The effect of pH on the distribution of phosphate over the NaOH and H_2SO_4 extractable fractions

rapidly with depth. This pattern is very similar in both profiles although the quantities involved differ. It can be seen that the differences in P content between the two soils are mainly restricted to horizons above a depth of 24 inches. This seems to indicate that the differences in P status of the soil do not result from variations in the P content of the mainly granitic parent rock which can be observed in the analyses of de SWARDT (1953) and JONES and HOCKEY (1964), but from differences introduced by the habitation of certain sites.

Decrease of total and organic P with depth has also been reported by NYE and BERTHEUX and BATES and BAKER (1960). They have furthermore shown that iron concretions which occur in greatly varying quantities in most cacao soils have a high P content, between 500–700 ppm, compared with 200–300 ppm in the surrounding fine earth. This P is, however, locked up inside the concretions and is thus not available to plants.

In the sedimentary soil the distribution of P is different. Total phosphate decreases first with depth because of the drop in organic P but increases later due to considerable increase in occluded phosphate which seems to be related to an increase in the clay fraction of the soil. A similar trend can be found in two profiles of sedimentary soils described by ENWEZOR and MOORE

TABLE 14

Distribution of phosphorus in some soil profiles (all P figures in ppm)

site	depth (inches)	pH	% C	% clay	extractable or non-occluded P					oc-cluded P	org. P	total P
					NH_4Cl–P	NH_4F–P	NaOH–P	H_2SO_4–P	sub-total			
Ricket*	0– 3	6.4	1.8	29	1	8	33	12	54	247	299	600
	3–12	5.8	0.6	30	0	3	23	9	35	163	127	325
	12–32	5.7	0.2	44	0	1	16	7	24	183	93	300
	32–43	5.7	–	41	0	1	16	6	23	181	86	290
	43–54	5.6	–	42	0	2	19	6	27	173	110	310
	54–70	5.5	–	46	0	1	17	4	22	181	57	260
Ikole**	0– 4	6.3	2.8	18	1	57	73	37	168	168	377	713
	4–14	6.0	0.8	13	0	23	75	19	117	212	146	475
	14–24	5.5	0.4	40	0	9	48	12	69	240	101	410
	24–60	5.2	–	47	0	4	25	7	36	148	81	265
Ikorodu†	0– 4	5.6	1.5	11	0	15	20	10	45	15	230	290
	4– 8	5.6	0.5	9	0	7	16	8	31	20	109	160
	8–14	5.0	0.4	15	0	1	15	4	20	68	92	180
	14–26	4.5	–	40	0	1	17	6	24	271	120	415
	26–48	4.5	–	42	0	1	20	5	26	266	118	410

* parent material derived from fine-grained biotite gneiss (quarternary basement complex)
** parent material derived from coarse-grained granitic gneiss (quarternary basement complex)
† parent material derived from unconsolidated sandstone (tertiary sediments)

(1966). The non-occluded P content of the soil is low and shows in its sub-fractions the same change with depth as the two profiles in soils derived from metamorphic rock.

5.3 THE FATE OF SOLUBLE PHOSPHATE APPLIED TO THE SOIL

5.3.1 *The distribution of phosphate*

This aspect was studied in cacao plots at Iddo, Ricket and Balogun which had received triple superphosphate at a rate of 90 lb P_2O_5 per annum during 6 successive years and at Iwo where 60 lb P_2O_5 per annum had been given for 5 years (see chapter 6). Total P and non-occluded P fractions were determined in samples taken approximately 22 months‡ after the last fertilizer application and compared in table 15 with the data of soils of the same sites which had not received fertilizers. In agreement with CHANG and CHU (1961) it was found that on three sites most of the added P is present as Fe-bound P. By expressing the amounts in the various sub-fractions as a percentage of total inorganic P it can be observed that on the two moderately deficient

TABLE 15

Distribution of added phosphate in chemical fractions of the surface soil layer (0–6 inches)

		NH_4Cl–P	NH_4F–P	NaOH–P	H_2SO_4–P	total non-occluded P
Iddo	no P	0 (0)	4 (16)	14 (56)	7 (28)	25
	+ P*	2 (4)	14 (27)	23 (44)	13 (25)	52
		2	10	9	6	27
Ricket	no P	0 (0)	3 (8)	25 (70)	8 (22)	36
	+ P*	1 (1)	18 (20)	55 (60)	17 (19)	91
		1	15	30	9	55
Balogun	no P	1 (2)	9 (18)	29 (60)	10 (20)	49
	+ P*	0 (0)	16 (20)	47 (58)	18 (22)	81
		−1	7	18	8	32
Iwo	no P	1 (2)	8 (16)	29 (60)	11 (22)	49
	+ P**	1 (1)	14 (18)	49 (62)	15 (19)	79
		0	6	20	4	30

* 90 lb P_2O_5 as triple superphosphate applied during 6 successive years
** 60 lb P_2O_5 as triple superphosphate applied during 5 successive years
† figures in brackets are percentages of the total non-occluded inorganic phosphorus
‡ samples at Iwo taken 9 months after the last application

sites Balogun and Iwo the added P is distributed in proportions which already existed in the soil but that on the two sites which are very deficient in P, the very low Al-P fraction received a relatively larger share than the other fractions. The effects of applied P on yield were far greater at the last than at the first two sites which seems to support the general concept that Al-bound P is more available to the plants than the other forms of extractable inorganic P.

5.3.2 *The phosphate balance; the phosphate sorption capacity of the soil*

Using yield data, the rates of fertilizers and the soil P figures, a phosphate balance has been made for three sites which is presented in table 16. In the calculations it has been assumed that in a yield of 1000 lb dry beans 16 lb P_2O_5 are removed (see chapter 6) and that the 0–6 inch soil layer of one acre weighs 2,000,000 lb. The balance sheet shows that on the average 20 per cent of the added P can be accounted for as being removed by the harvested crop. Of the surplus about 55 per cent is recovered in the top soil mainly in non-occluded form. This means that about half of the surplus or one third of the total amount applied is leached down to deeper soil layers.* The data in the table indicate, however, that large differences exist in the P retention capacity of the soils of the various sites.

To estimate the P retention capacity of the cacao soils P sorption capacities** have been determined according to KURTZ *et alii* (1946). The results

TABLE 16

Phosphate balance sheet of three sites of the series I experiments for the period 1962–1969

site	lb P_2O_5 added*	lb P_2O_5 removed by the crop**	surplus	lb surplus recovered from the 0–6 inch layer† extractable P_2O_5	total P_2O_5
Iddo	540	110	430	124 (29)	165 (38)
Ricket	540	120	420	252 (60)	334 (80)
Balogun	540	145	395	146 (37)	187 (47)
mean	540	125	415	174 (42)	229 (55)

* six annual applications of 90 lb P_2O_5/acre
** total yield for the period 1962–69
† percentage of surplus in brackets

* The 6–12 inch layer of the P_0, P_1 and P_2 plots at Iwo was found to contain 2, 5 and 7 ppm available P respectively. This confirms that added P leaches from the surface layer.
** The general term sorption capacity has been chosen without investigating whether in addition to sorbtion precipitation also takes place. In the literature the terms fixation, retention and sorbtion capacity are often used indiscriminately.

presented in table 12 show that the P sorption capacity varies from 21 to 65 ppm P or from 96 to 298 lb P_2O_5 per acre surface soil (0–6 inches). These figures are low compared with the figures obtained by AHENKORAH (1968) in Ghana.

When the P sorption capacity figures of Iddo, Ricket, Balogun and Iwo are compared with the amounts of the added P retained in the various inorganic P fractions (table 15) a close relation is found between the sorption capacity and P retained in Fe-bound P fraction. (The sorption capacities are 21, 64, 40 and 37 ppm respectively and the corresponding amounts retained 9, 30, 18 and 20 ppm). This result suggests that a relationship exists between the sorption capacity and Fe content of the soil. A highly significant positive correlation between the P sorption capacity and the free iron oxide concentration has indeed been found in Ghana. The Fe_2O_3 concentrations in the Nigerian surface soils reported by BATES (1960) are very low and this might explain the generally low P sorption capacities.

The P sorbtion capacities were furthermore found to be positively correlated with the clay content of the soil and negatively with the pH. These relationships can be expressed in the equation:

$$\mu g\ P\ sorbed\ /g\ soil = 46.84 + 2.97^{***}\%\ clay - 10.86\ pH \quad (r = 0.74)$$

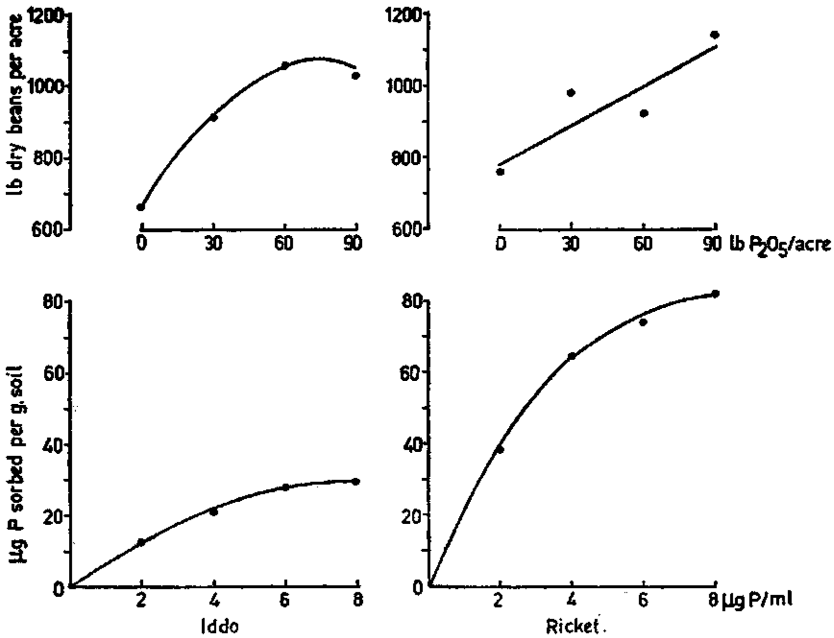


Figure 10
Yield responses to applied phosphate and the sorption of phosphate by the soil at two sites of the series I fertilizer experiments

The highly significant partial regression coefficient for clay illustrates the close relationship between the sorption capacity and the clay fraction while the regression coefficient for pH, though not significant, is sufficiently high to indicate that this relationship is pH dependent. The decrease of P sorption at higher pH values is likely to be a result of competition between phosphate and hydroxyl ions for positively charged sites at clay edges or cations (mainly Fe, Al and Ca) associated with the clay.

It is of interest to mention that while the above results and those of CHANG and CHU indicate that clay is the main site of P sorption, AHENKORAH's data suggest that not the clay but organic carbon and iron associated with it are the dominant factors in phosphate sorption.

The low P sorption capacity at Iddo throws some light on the response to phosphate at this site. While at all sites* responding to phosphate the P effect is linear, it is curvilinear at Iddo. A comparison of the P sorption curves and yield curves of Iddo and Ricket (figure 10) suggests that the cacao at Iddo does not respond to phosphate in excess of 60 lb P_2O_5 per acre because any extra phosphate cannot be retained by the soil of the main rooting zone of the cacao trees.

6. FERTILIZER TRIALS

6.1 EXPERIMENTS IN TRINIDAD AND GHANA

The fertilizer requirements of cacao were mainly studied in Trinidad and Ghana before the experimental programme in Nigeria was started.

In Trinidad a large number of field experiments was carried out between 1932 and 1939. In these trials spectacular increases in yield were sometimes obtained from phosphate and potassium fertilizers (HARDY 1937) but most experiments were greatly handicapped by the great variability of cacao and inefficient experimental designs. In this period it was found that nitrogen application had a positive effect on unshaded cacao but no effect or a negative effect on shaded cacao (HAVORD 1953). It was not until 1950 that the ap-

* except for Balogun, where both a linear and cubic P effect are significant.

parent relationship between nutrition and shade was further studied by EVANS and MURRAY (1953) and MURRAY (1954). They found in a fertilizer experiment with 5 light intensities a clear shade and fertilizer interaction as shown in figure 11. It can be seen that at low levels of nutrition shade is necessary. As the level of nutrition increases (in this experiment by addition of fertilizer) so does the light intensity requirement for maximum yield and the maximum yield itself.

Similar results were obtained in a large, 11 acre shade, spacing and fertilizer experiment in Trinidad (HAVORD *et alii* 1955, MALIPHANT 1965). In the absence of fertilizers highest yields were obtained from unshaded plots. Responses to nitrogen were (as found before) absent or negative in shaded, closely spaced plots and positive in unshaded and widely spaced shaded plots.

In Ghana as early as 1926 trials were started in which dried blood, basic slag and sulphate of potash were used, but only responses to basic slag were found (BECKET 1929). Because reduction in shade was always followed by severe insect attacks, it was not until insect control had successfully been established in 1956, that a fertilizer experiment involving removal of shade could be started at Tafo. The results of this experiment showed that the removal of shade increased the yield in the first year by approximately 90 per cent and that fertilizers raised the yield of both shaded and unshaded cacao by about 45 per cent. In the second year an interaction between shade and fertilizers started to appear which became very pronounced in the next year. The effect of shade removal is far greater with than without fertilizer application while the response to fertilizers is twice as large in the absence than in the presence of shade (SMITH 1962).

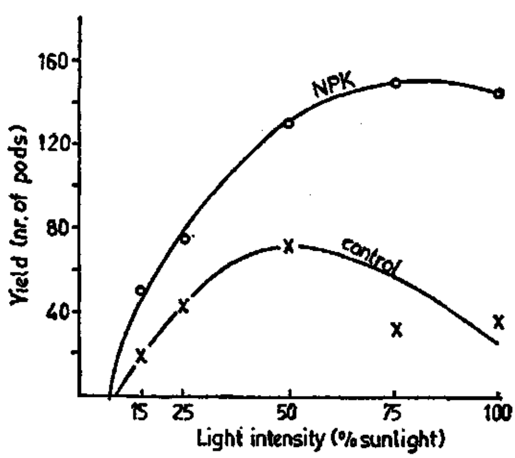


Figure 11
The relationship of yield (nr of pods for totals of 12 trees) to light intensity for control and NPK plants (after MURRAY 1954)

The cacao was planted in 1961 at a close spacing of 4 ft × 4 ft under banana shade which was removed in the third year after planting when the number of trees was also reduced by 50 per cent. Fertilizer applications were split, one half in April/May and the second half in August. The rates of application are given in table 18. A 4 inch thick grass mulch layer was applied twice a year during the first two years only. The results of some of the treatments are presented in table 19. They clearly show the beneficial effect of mulch on early growth and yields which had also been observed by LONGWORTH (1963). From the 5th year onwards the mulch effect gradually diminished and large responses to the NP treatment started to show up. There was no effect of application rates except in the second year when the dosage of NP at level 2 was too high in the absence of KMg and depressed growth and increased the death rate of plants during the dry season. When this effect was noticed, fertilizer rates were reduced in the third year.

Trials in Ghana also have shown that young cacao trees are sensitive to toxic effects of fertilizers especially N and K fertilizers. Low rates of 10g N as

TABLE 18

Annual fertilizer rates in grammes per tree as used in the fertilizer experiment on young Amazon cacao planted at Araromi in 1961 (the rates are those of level 1, the rates of level 2 are twice as high)

year of application	N (urea)	P_2O_5 (triple superphosphate)	K_2O (sulphate of potash)	MgO (sulphate of magnesium)
1961	23	18	20	7
1962	70	54	60	21
1963–66	23	23	25	9
1967–68	33	23	25	9

TABLE 19

The effect of mulch and fertilizers on growth and yield of young cacao in a replanted cacao farm at Araromi

treatments	mean stem diameter (cm) in February				yield in lb dry beans/acre				
	1962	1963	1964	1965	1963–64	1964–65	1965–66	1966–67	1967–68
control	1.41	2.91	4.87	6.51	53	236	565	901	1001
mulch	1.58	3.63	6.14	7.99	346	548	940	1260	1034
mulch + NP (1)	1.57	3.50	5.81	7.66	463	422	1013	1620	1604
mulch + KMg (1)	1.56	3.36	5.86	7.66	296	342	733	1001	1120
mulch + NPKMg (1)	1.60	3.47	6.15	8.08	464	654	1268	1626	1716
LSD (P = 0.05)	–	–	0.54	0.59	259	326	431	525	486

sulphate of ammonia and 25g as muriate of potash per tree (applied twice a year) were found to be harmful. Results of leaf analysis suggested that the adverse effect of nitrogen was tied up with a significant reduction of phosphate intake (ADAMS, 1956, 1957). Later experiments in Ghana also indicated that application of fertilizers in the planting hole depressed growth (SMITH and AKROFI 1963).

6.2.2 *Experiments on mature Amelonado cacao*

There were three groups of experiments called Series I, II and III, which will be discussed separately. For these trials sites with 25 to 35 year old cacao were selected in various parts of the cacao belt on the basis of uniformity of cacao and soil, and a farm size of 3 to 4 acres. As attempts to find suitable sites on the sedimentary soil failed, the results reported below are all obtained on soils overlying metamorphic rock.

By using these criteria for the selection of sites, it was inevitable that farms of more than average yield were chosen. The cacao was randomly planted at densities usually varying from 400 to 600 trees per acre and grown under shade of irregularly spaced forest and kola trees and oil palms (WESSEL

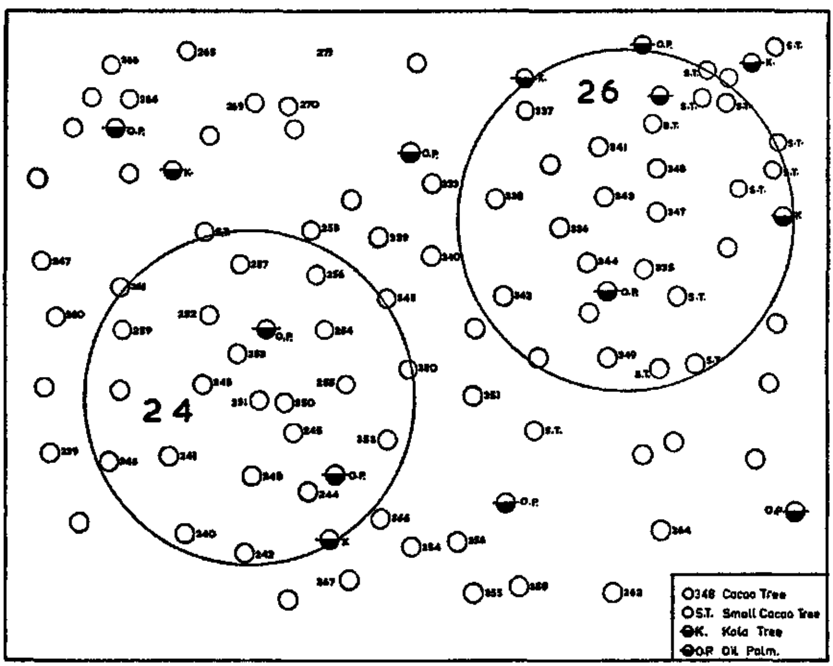


Figure 12
Part of a spot plan of the fertilizer experiment on randomly planted farmers' cacao at Ife

et alii 1967). In these cacao fields circular plots of 1/24 acre were carved out as used in Ghana and illustrated in figure 12. All trees were individually recorded for the number of harvested pods while in the Series I trials initially also wet and dry bean weights were recorded to determine the factors for converting number of pods to lb dry fermented beans. The figures* in the tables below are based on a conversion factor of 11.5 pods to one lb dry cacao, the mean of all sites for 1963–64. (*Half yearly Progress Report W.A.C.R.I., Nigeria 1964*). The yield recording started at least two years prior to the introduction of fertilizer treatments in order to have pre-treatment data for an analysis of covariance of the treatments' yields. Annual records were kept from the 1st of April till 31st of March of the following year.

The fertilizer types and their annual application rates are given in table 20. Urea was given in a split dose: 2/3 at the beginning of the major rains in April or May at the time when young fruits are setting and the remaining 1/3 in August/September, when the developing pods have their highest demands for nutrients (HUMPHRIES 1940). The other fertilizers were only given once a year in April or May. All fertilizers were broadcast by hand on the soil surface throughout the plots.

The amounts of nutrients removed in an annual crop of 1000 lb dry cacao beans per acre and its husks are approximately: 30–40 lb N, 13–16 lb P_2O_5, 70–85 lb K_2O, 12 lb CaO and 8 lb MgO (HUMPHRIES 1940, CUNNINGHAM *et alii* 1961). The quantities of nutrients supplied in the fertilizer experiments are

TABLE 20

Annual fertilizer rates in lb per acre of the series I, II and III experiments

experiment	level	N (as urea)	P_2O_5 (as triple superphosphate)	K_2O (as sulphate of potash)	CaO (as calcium sulphate)	MgO (as magnesium sulphate)
series I	0	–	–	–	–	–
	1	40	30	50	50	50
	2	80	60	–	–	–
	3	120	90	–	–	–
series II	0	–	–	–	–	–
	1	80	30	50	–	50
	2	160	60	100	–	100
series III	0	–	–	–	–	–
	1	120	30	50	–	–

* The yields are potential yields which have been obtained by converting the total number of fully grown pods, including non fermentable pods, to lb dry beans per acre. On the experimental sites the percentage of non fermentable pods did not exceed 10 per cent.

thus more than adequate, except for K, to compensate for these losses even when it is assumed that only half of the added nutrients are utilized.

The series I experiments had a $4^2 \times 2^3$ design with N and P at four levels and K, Ca and Mg at two levels.* The choice of these levels was based on the assumption that responses to N and P were more likely to occur than responses to K, Ca and Mg. The whole trial consists of 8 sites with 32 plots each. This number of plots was required to have one quarter replicate (in two blocks of 16 plots each) at each site. The first replicate consists of the farms (1) Iddo, (2) Aba-Agbo, (3) Ayorinde, (4) Ricket. The second replicate comprises the farms (5) Iroko, (6) Akinyele, (7) Balogun and (8) Aiyetoro. Pre-treatment recording was started in 1960 and fertilizer treatments began in 1962 and were discontinued in 1968 to study residual effects.

TABLE 21

Fertilizer effects in lb dry beans per acre at eight sites of the series I fertilizer trials. Mean treatment yields (1962–1968) adjusted for the pre-treatment yields, except for Iroko where adjustment increased the standard error

site	Iddo	Aba-Agbo	Ayorinde	Ricket	Iroko	Akinyele	Balogun	Aiyetoro
mean yield	914	920	1162	950	602	1053	1232	1361
N 0	881	743	964	927	495	906	1235	1351
N 1	942	848	1167	933	563	843	1251	1300
N 2	1012	961	1222	991	593	1151	1185	1380
N 3	818	1127	1296	949	757	1312	1258	1413
effect	quadr.	linear**	linear*		linear**	linear*		
P 0	659	850	1125	760	596	1004	1117	1231
P 1	911	880	1241	893	733	1066	1294	1326
P 2	1056	1000	1183	921	556	961	1175	1442
P 3	1028	950	1099	1136	552	1181	1343	1444
effect	linear*** quadr.*			linear**			linear* cubic*	linear**
S.E.	66	92	100	63	49	123	51	48
LSD P=0.05	195	272	296	186	146	364	151	141
K 0	903	932	1197	959	636	1082	1218	1329
K 1	924	908	1128	941	567	1024	1246	1392
Ca 0	880	928	1101	957	606	919	1209	1433
Ca 1	947	911	1223	943	597	1187*	1255	1288*
Mg 0	845	848	1122	974	626	1057	1229	1354
Mg 1	982*	942	1202	926	578	1049	1235	1367
S.E.	47	65	71	44	35	87	36	34
LSD P=0.05	138	192	209	131	103	257	106	100

* the design of this experiment was made by Mr. A. J. Vernon of Rothamsted Experimental Station.

The series II trials were five 3^3 NP (KMg) factorials with one replicate of 27 plots per site. Pre-treatment recording was started in 1961 and fertilizers were applied from 1964 onwards.

The third group of trials (series III) consisted of simple 2^3 NPK experiments laid down at four sites.* Three sites had 3 replicates each, and one site (Oda) only two replicates. Pre-treatment records were taken from 1961 till 1965 when the fertilizer treatments were introduced.

The mean treatment yields of the series I experiments (table 21) show positive linear N effects at four sites and mainly linear P effects on the remaining sites. The quadratic N effect at Iddo was significant in certain years. The P effect at Aba-Agbo which mainly resulted from a linear P effect on plots receiving nitrogen at level 2 and 3 is not significant due to the large standard error. The interaction between N and P was positive at Iddo and negative at Ayorinde, Balogun and Aiyetoro, the effect being significant only at the last site. Here, in the absence of P, N had a significant positive linear effect but this disappeared when P was given. Calcium increased the yield at Akinyele but decreased the yield at Aiyetoro. Magnesium increased yields at Iddo, Aba-Agbo and Ayorinde, but at the last two sites the effects were only significant during the first three years of fertilizer application. Potassium had no effect on yields throughout the experimental period.

The effects in table 21 already showed up in the analysis of the mean treat-

TABLE 22

Fertilizer effects in lb dry beans per acre at five sites of the series II fertilizer trials; mean treatment yields (1964–69) adjusted for mean pre-treatment yield (1961–64) except for Ife where adjustment increased the standard error

site	Iwo	Ilesha	Fidiwo	Oloba	Ife
mean yield	1175	1069	1191	1099	1348
N 0	1061	1001	1196	1043	1295
N 1	1241	960	1184	1171	1340
N 2	1223	1245	1193	1081	1410
effect					
P 0	1089	911	1180	900	1211
P 1	1181	1024	1245	1186	1352
P 2	1255	1270	1148	1211	1482
effect		linear*		linear**	linear**
KMg 0	1029	1045	1059	1189	1284
KMg 1	1266	1051	1200	1027	1376
KMg 2	1231	1100	1314	1081	1385
effect			linear**		
S.E.	83	99	47	59	54
LSD (P=0.05)	248	296	140	176	161

* the location of all sites is shown in figure 2.

ment yields over the first three years and they have remained more or less unchanged in subsequent years. At Ayorinde, however, where application of P has usually no effect a significant positive P effect was found during the 1966–67 cropping season when the yield was exceptionally high and exceeded 1600 lb dry beans per acre.

The analysis of the 1968–69 yields revealed very distinct residual effects of P fertilizers at all four sites where significant responses to P had been obtained before, the effects being of the same magnitude as in years of application. Large significant residual effects of N were found at Aba-Agbo and Ayorinde but not at Akinyele while the yield of Iroko could not be analysed satisfactorily due to very poor yields in certain plots. Significant positive NP interactions were found at Iddo and Aba-Agbo.

The mean five yearly treatment yields for the series II trials are given in table 22. Linear P effects were found at three sites: Ilesha, Oloba and Ife, while P also increased the yield at Iwo. The effect on this site was only significant in 1967–68 when yields exceeded 1800 lb dry beans per acre. Nitrogen had positive effects at Iwo, Ilesha and Ife, but these effects were only significant in certain years. Furthermore a significant positive NP interaction was found at Oloba indicating that N alone depressed yield and that N at level 1 increased yield when P is applied. The combined application of KMg had positive effects at Fidiwo and Iwo. At the first site the effect was linear while at the second site the mean yield of plots with KMg was significantly higher than the mean yield of plots without KMg.

The analyses of variance of the five yearly mean treatment yields over all 8 sites of the series I and all 5 sites of the series II trials are given in appendix 2. They clearly show the overall importance of the N and P effects as compared to those of the other elements. The mean yields over all sites for all

TABLE 23

Mean yields in lb dry beans/acre over a five year period for all NP combinations in the series I and II experiments

	series I experiments					series II experiments			
	P 0	P 1	P 2	P 3	means	P 0	P 1	P 2	means
N 0	832	967	911	1041	935	1076	1121	1202	1133
N 1	897	955	997	1091	985	1013	1185	1240	1146
N 2	1031	1164	985	1103	1071	1069	1319	1362	1250
N 3	909	1224	1244	1112	1122				
means	917	1075	1034	1086	1028	1053	1208	1268	1176
	S.E. 70.8 LSD (P = 0.05) 196*					S.E. 65.8 LSD (P = 0.05) 188*			
	S.E. 35.4 LSD (P = 0.05) 98**					S.E. 37.9 LSD (P = 0.05) 108**			

* for comparing two figures in the body of the table
** for comparing two figures in the margins of the table

To investigate whether the yield increases resulting from fertilizer applications are borne by low or high yielding trees, the yields of plots not receiving phosphate and of those receiving 60 lb P_2O_5 per acre per annum (treatment P 2) at Iddo were analyzed for the 1964–65 season in which the P 2 treatment increased the yield by 45 per cent. From the distribution of trees over the yield classes, shown in figure 13, it can be seen that applied phosphate mainly increased the yield of the low bearing trees. Evidently one of the main causes of low yield in the cacao tree population at Iddo is phosphate deficiency in the soil which is at least partly rectified by phosphate application. Similar results have been reported by HARDY (1939b) in Trinidad.

6.2.2.2 The effect of fertilizers on the pod content

An analysis of the number of pods that yield one pound of dry beans was carried out for all 8 sites of the series I experiments for the 1963–64 season, considering the main crop and light crop separately. This showed no consistent treatment effects but differences between sites and the main and light crop. At almost all sites bean weights in the pods from the light crop are lower than in the pods produced during the main crop (*Half yearly Progress Report W.A.C.R.I., Nigeria 1964*).

Further investigations have shown that this seasonal effect on bean size is related to differences in rainfall during the first four months of pod development (TOXOPEUS and WESSEL 1970).

An analysis of the fat content of beans harvested in October and November 1967 from all experimental plots at Aponmu and Oke-Irun revealed that N, P and K fertilizers had no effect on the fat content. The mean percentages of fat were for these sites 56.6 and 57.3 respectively, figures which are normally found in Amelonado beans harvested in the main-crop season.

7. THE USE OF LEAF AND SOIL ANALYSIS IN DETERMINING THE FERTILIZER REQUIREMENTS OF CACAO

In the preceding chapter it has been shown that fertilizer responses occur at certain sites and not at others and that degrees of response vary from site to site. In this chapter the possible use of leaf and soil analysis for assessment of the fertilizer requirements of cacao at the individual sites will be investigated.

The role of leaf analysis as a diagnostic method and advisory aid in crop nutrition has been reviewed by BOULD (1968). Its application in the humid tropics has recently been discussed by DE WAARD (1969).

In 1933 leaf analysis was introduced to cacao by McDONALD (1934) and since then many research workers have tried to use it as a diagnostic aid in the nutrition of cacao. Literature reviews (MURRAY and MALIPHANT 1967, WESSEL 1970d) show that the main problem in applying leaf analysis to cacao lies in the fact that leaf age and light intensity usually over-ride the nutritional effects on leaf composition except when marked deficiencies exist in the soil or other growing media. EERNSTMAN (1968) ascribes the lack of success in applying leaf analysis to cacao mainly to incomplete understanding of the physiology of cacao, especially of yield determining processes (fruit setting and cherelle wilt) and of the role which the various elements play in these processes.

The main factors influencing the mineral composition of the leaf can be subdivided into leaf age, leaf position, development of new leaves and cropping as internal factors, and nutrition, light intensity (shade) and season as external factors. The effects of these factors will be briefly discussed.

7.1 INTERNAL FACTORS AFFECTING THE MINERAL COMPOSITION OF CACAO LEAVES

7.1.1 *Age*

The age of a cacao leaf cannot be determined from its position on twigs or branches. Young leaves are found near the apex and older leaves towards the base of the branch, but not all branches flush simultaneously while differences in flush rhythm also exist between individual trees and groups of trees. Fruits are formed on older branches and on the main stem and their position does not help in the age determination of leaves.

The young developing leaves are soft and usually coloured with anthocyanic pigment which masks the colour of the chlorophyll. In the third week after bud opening the leaf expansion stops and the leaf turns green and hardens. From that moment onwards the leaf darkens and a few weeks later young and older leaves can no longer be distinguished from each other. The possible use of the colour of the leaf petiole in distinguishing leaves of different ages will be discussed later.

The effect of age on the nutritional composition of the leaf was first studied by HUMPHRIES (1940) in Trinidad and later by FENNAH (1954). HUMPHRIES labelled young flushes of mature trees as they expanded (altogether 600 flushes were labelled!) and took leaf samples at weekly intervals over a period of 16 weeks. Some of his slightly modified results are presented in table 25. The percentage of dry weight increases rapidly during the first 9 weeks of development and at a slower rate afterwards. The N percentage drops during the first 4 weeks and then increases gradually to reach a peak in the 8th and 9th weeks and declines afterwards. Potassium decreases with time but the K level is nearly constant between the 4th and 9th week. The P percentage decreases and the Ca percentage increases throughout with increasing leaf age while the Mg percentage first decreases and later increases. The fast increase and the high final level of Ca is most likely due to the low percentage of K in the leaves; this, in turn, might reflect the rather wide-spread K deficiency in Trinidad soils. The changes in the absolute quantities of the elements (not given here) show a slightly different trend. N, P and K increase till the 9th or 10th week, after which there is a progressive decrease which Humphries attributes to transport of elements from these leaves to leaves of new flushes which started to develop in the 9th week.

Fennah studying the partition of nitrogen in cacao leaves under 5 light intensities also gives some data of age effects on dry matter and N content of the leaf (table 26). They show a much faster increase in dry matter, except under the lowest light intensity, than HUMPHRIES' data. This is connected

TABLE 25

Changes in mineral components of cacao leaves during the first 14 weeks of development (modified and summarized after* HUMPHRIES *1940)*

age (days after bud opening)	% dry matter	% ash	% N	% P	% K	% Ca	% Mg	N/P
14	23.6	7.72	3.78	0.51	2.46	0.46	0.38	7.4
42	33.8	7.13	2.31	0.23	1.85	0.84	0.37	10.0
70	39.4	9.20	2.38	0.17	1.54	1.23	0.43	14.0
98	42.9	11.40	2.32	0.14	1.17	2.09	0.48	16.6

* as percentages of dry matter

TABLE 26

Effect of age and light intensity on the dry matter and nitrogen content of cacao leaves (after FENNAH *1954)*

days after bud opening	percentage light									
	100		75		50		25		15	
	% d.m.	% N	% d.m.	% N	% d.m.	% N	% d.m.	% N	% d.m.	% N*
20	34.23	2.27	31.33	2.39	28.66	2.51	26.05	2.63	24.37	2.70
25	37.78	2.24	35.48	2.31	33.12	2.41	30.84	2.52	29.56	2.57
30	40.65	2.22	38.57	2.30	36.47	2.37	34.31	2.45	33.23	2.50

* nitrogen as percentage of dry matter

with the fact that FENNAH dried leaves at 49°C and HUMPHRIES at 105°C. Nitrogen decreases under all light intensities with age. Because no samples were taken between 30 and 60 days after bud opening, it cannot be seen if fluctuations in N occurred within this period as found by HUMPHRIES. Dry matter and N both decrease with increasing light intensity. This illustrates the general trend that unshaded leaves are physiologically younger than shaded leaves of the same age.

The effect of age and light intensity on the mineral leaf content was also studied in Nigeria (WESSEL 1967d). In this experiment young Amelonado seedlings with only two flushes were used while leaf initials of the third flush were removed to prevent migration of nutrients from older to younger leaves. The results in table 27 show the same trend as that found by HUMPHRIES. The P content of the leaves was little affected by light intensity but K decreased throughout and N initially with increasing light intensity.

TABLE 27

Changes in mineral composition and dry-matter content of cacao leaves during first weeks of development under three different light intensities

age (days after bud opening)	% dry matter	% N	% P	% K	% Ca	% Mg
			33% light			
21	26.9	2.42	0.32	3.33	0.37	0.37
28	27.8	2.31	0.27	3.25	0.39	0.30
35	31.1	2.21	0.20	3.08	0.50	0.30
42	32.0	2.65	0.18	2.83	0.68	0.39
49	32.2	2.38	0.18	2.66	0.60	0.39
63	34.7	2.84	0.15	2.41	0.95	0.43
77	38.4	2.54	0.14	2.10	1.13	0.47
			66% light			
21	29.4	2.19	0.26	2.92	0.36	0.31
28	30.2	2.19	0.24	2.67	0.30	0.29
35	32.4	2.33	0.23	3.00	0.50	0.29
42	34.8	2.47	0.21	2.66	0.68	0.44
49	37.4	2.65	0.19	2.33	0.69	0.36
63	38.7	2.80	0.17	2.24	0.97	0.43
77	42.1	2.59	0.14	2.00	1.10	0.32
			100% light			
21	31.4	1.95	0.25	2.95	0.33	0.38
28	32.1	2.05	0.23	2.75	0.35	0.31
35	32.9	2.19	0.24	2.88	0.60	0.40
42	36.2	2.42	0.20	2.49	0.68	0.35
49	36.9	2.98	0.20	2.49	0.68	0.35
63	40.4	2.75	0.15	2.24	1.07	0.38
77	43.6	2.80	0.15	1.87	1.17	0.39

The N peaks in the 7th to 9th week are higher than found by HUMPHRIES; this might be due to the fact that in this experiment nitrogen could not be transported to younger leaves.

When from the data of HUMPHRIES (1940), HUMPHRIES and McKEE (1944) and those from table 27 the regression of leaf age on the percentages dry matter is calculated, highly significant linear relationships (all r's $\geqslant 0.95$) are

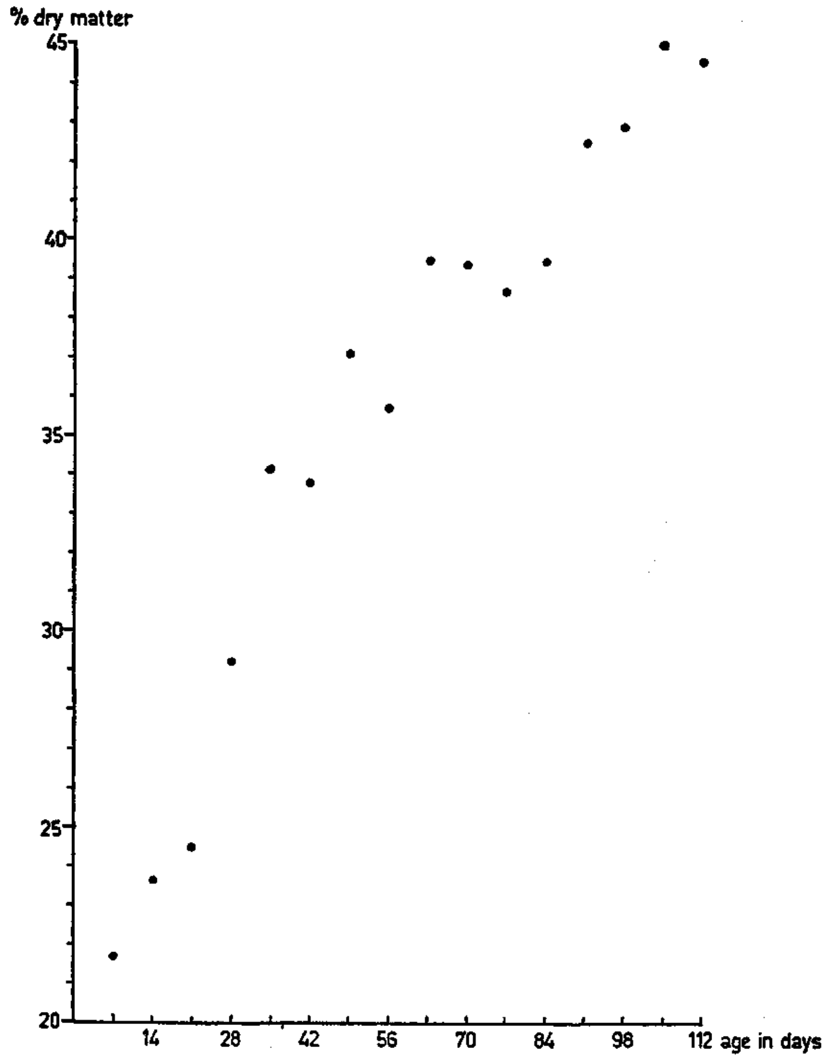


Figure 14
The relation of the percentage of dry matter in cacao leaves to leaf age (based on data of HUMPHRIES 1940)

found. An example of this relationship is shown in figure 14. From this it might be concluded that the percentage dry matter can be used as an age index. The validity of this conclusion is shown in table 28 where it can be seen that the high correlation coefficients between leaf age and the percentages of P, K and Ca are only slightly lower when the age in days is replaced by the dry matter content.

The results of FENNAH and WESSEL show however that the dry-matter content is affected by light intensity; the percentage dry matter decreases with decreasing light intensity. For this reason the percentage dry matter should not only be considered as an index of real age but also as one of physiological age. This can be illustrated using the data of table 26. When the N percentages of 20, 25 and 30 days old leaves are plotted against age in days and the points of the same light intensity are connected, 5 more or less parallel lines are found. When, however, the N percentages are plotted against the percentage dry matter the points fit one straight line as shown in figure 15.

A similar result can be obtained when the K percentages of table 27 are first plotted against age in days and later against percentages dry matter.

The regression equations expressing the relationship between P and dry

TABLE 28

Correlations between some nutrient concentrations in the leaf and leaf age in days and leaf age measured as percentage dry matter (based on* HUMPHRIES *1940)*

	age	% dry matter	period
% P	−0.98	−0.93	28–98 days*
% K	−0.91	−0.89	21–98 days
% Ca	0.99	0.92	28–98 days

* after bud opening

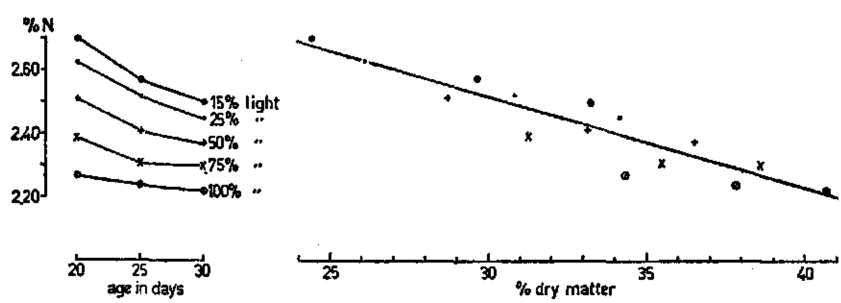


Figure 15

The relation of the nitrogen content in cacao leaves of plants grown under different light intensities to leaf age in days and to leaf age measured as the dry matter content of the leaf matter as calculated from HUMPHRIES' and WESSELS data are almost identical. This is not so for the regression equations for K and dry matter and Ca and dry matter. The K concentrations in Trinidad are much lower than those in Nigeria and a K–Ca antagonism may explain why Ca increases more rapidly with age in Trinidad than in Nigeria.

The percentages of nutrients considered so far were percentages of dry weight. When the concentrations of N, P, K and Ca are converted to percentages of fresh weight, the N percentage is found to increase with age. The Ca percentage increases also but the increase is about half the increase found when the percentage is based on dry weight. The P and K percentages are (with a few exceptions) more or less constant at least during the period from the 4th till the 9th week after bud opening. This, however, does not seem to apply to the P figures in plants under 33 per cent light in table 27.

From these considerations it may be concluded that for those elements which show a clear linear relationship between their concentration in the leaf (expressed as a percentage of dry matter) and leaf age, (e.g. P, K and Ca) the effect of age can at least partly be eliminated by correcting concentrations for regression on dry matter (see 7.4.2). When P and K are expressed as percentages of fresh weight, concentrations are found which are within certain limits more or less independent of age. These corrections for leaf age are only valid as long as an approximately linear relationship exists between age and dry-matter content. This is generally from the 4th till the 11th week after bud opening. The exact length of this period depends on light intensity. It will usually last longer for shaded than for unshaded leaves.

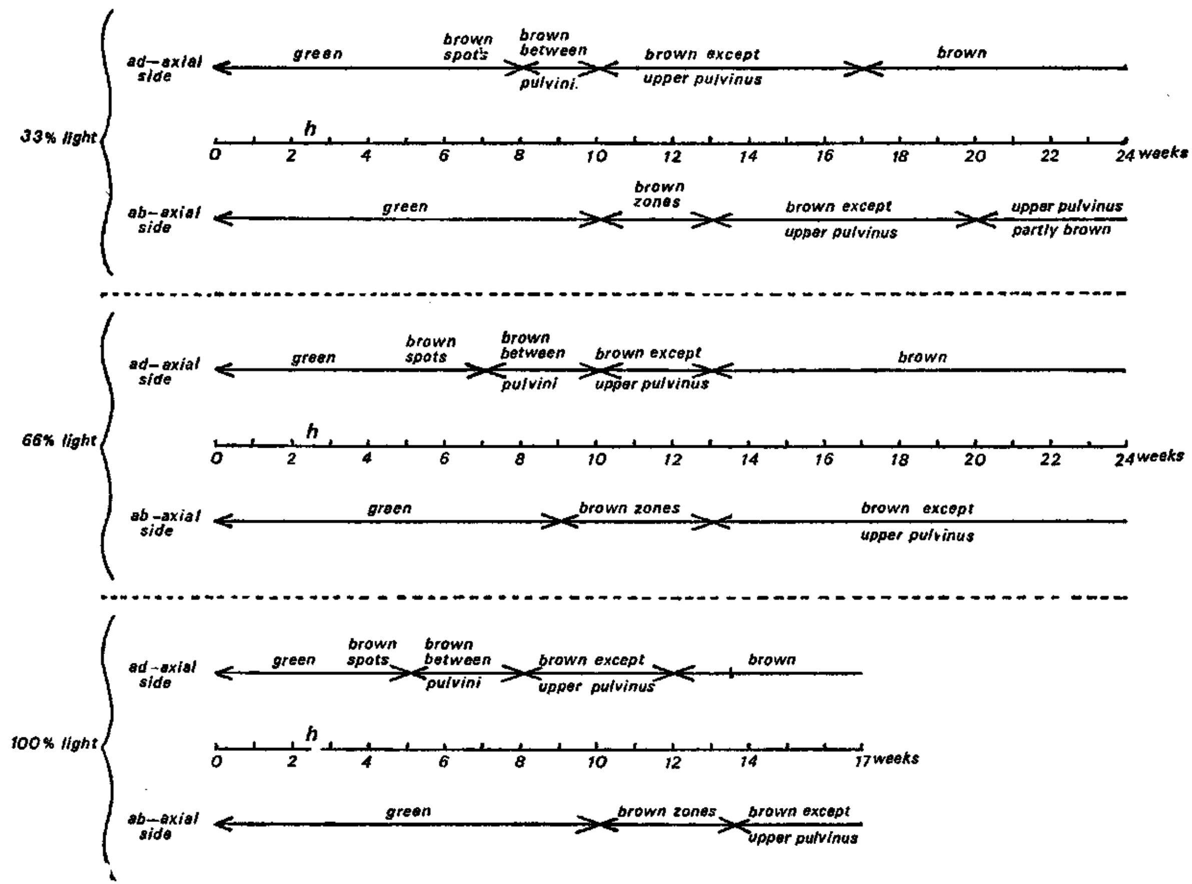
Although leaf age can be estimated from the dry matter content, the problem remains how to sample leaves of the same age. For this reason it has been investigated whether morphological characteristics of the leaf could be used for age determination. The almost hardened leaves have a light green colour corresponding with the 5 GY 5/8 notation of the Munsell colour chart for plant tissue. The leaves darken as time goes on and when they are about 12 weeks old, their colour corresponds to the 7.5 GY 5/6 (or 4/6) notation. Because the leaf colour changes gradually it offers little prospect for age determination. Moreover the procedure of comparing leaf colours with a standard is not practicable for large-scale sampling. Its use is also complicated by differences in light intensity which exist in cacao orchards (shaded and unshaded trees, trees with a thick and a thin canopy).

The colour of the leaf petiole was found to be a more useful criterion as shown in figure 16. Under shaded conditions (33 and 66 per cent daylight) the ad-axial side (upper side) of the petiole is uniformly green during the first 5 or 6 weeks after bud opening. In the next week brown spots start to appear in the area between the pulvini which cover this whole zone when the leaves are about 8 weeks old.* The brown colour spreads over the lower

* The brown discolouring of the petioles is always preceded by a brown discolouring of the internodes between the leaves. These are initially green and turn light brown between the 5th and 7th week after the first buds have opened.

Figure 16

The effect of age and light intensity on the colour of the petiole of the cacao leaf during the first 24 weeks from bud opening; h = time of hardening



pulvinus (attached to the twig) and when the leaves are about 10 weeks old, the ad-axial side of the petiole is brown except for the upper pulvinus (to which the leaf is attached). Three to seven weeks later the entire ad-axial side is brown. Later on, this colour changes to grayish-brown. It can be seen that the colour of the petiole changes more rapidly as the light intensity increases. The ab-axial side (lower side) of the petiole stays uniformly green during the first 10 weeks. The area between the pulvini and the lower pulvinus itself turns brown in the following 3 or 4 weeks while the upper pulvinus stays green for at least several months. Because the ab-axial sides are turned away from the light, the colour change is not greatly influenced by differences in light intensity.

By paying attention to these characteristics of the leaf petiole, leaves of the same age can be recognized. This is of great importance when for example in addition to young leaves the adjacent older leaves are also sampled. Because of differences in flushing rhythm these older leaves may differ in age by several months. The young leaves of the last flush can readily be recognized by a lighter green colour of the laminae, predominantly green petioles and by a green or light brown colour of the part of the twig to which they are attached. The older leaves are more difficult to distinguish from still older leaves. Only after a close observation of the leaf petiole can it be decided whether leaves were formed in the second last or an earlier flushing period. An advantage of this method is that samplers can be instructed to collect leaves of certain, well defined leaf petiole characteristics. Samples brought back to the laboratory can still be checked and leaves with different petioles can be removed from the sample.

TABLE 29

Nutrient concentrations in leaves of successive flushes on a branch of a two year old shaded cacao seedling

leaf order*	% dry matter	% N	% P	% K	% Ca	% Mg	age
1	29.7	1.92	0.23	2.58	0.38	0.32	leaves of the last flush
4	29.2	1.91	0.23	2.92	0.35	0.28	(3 to 4 weeks old)
6	40.5	1.98	0.12	1.13	0.97	0.42	leaves of the second last flush
10	38.4	2.07	0.14	1.33	1.15	0.36	(9 to 10 weeks old)
13	40.3	2.42	0.11	1.33	1.65	0.48	leaves of the third last flush
15	39.3	2.21	0.12	1.40	1.50	0.37	
17	39.5	1.81	0.11	1.25	1.33	0.35	leaves of the fourth last flush
20	40.4	1.91	0.09	1.33	1.30	0.38	
24	42.9	1.77	0.10	1.08	1.50	0.52	leaves of the fifth last flush

* numbered from the apex of the branch.

The importance of keeping apart leaves from different flushes is illustrated in table 29 in which data of the successive flushes on the same branch are given. It is shown that the nutrient concentrations and ratios between concentrations differ greatly in leaves of different flushes. This is especially noticeable when the P, K and Ca concentrations in the leaves of the last and the second last flush are considered.

7.1.2 *Effect of development of new leaves and fruit bearing*

The effect of the development of young leaves on the mineral composition of older leaves has been mentioned already when Humphries attributed losses of N, P and K to migration of these elements from the older to the younger leaves. The author has studied this effect in greater detail in a pot experiment with Amelonado seedlings (WESSEL 1970b). It was found that during the first four weeks of the development of new leaves of the fourth flush, 39 per cent of the P and 25 per cent of the K content were exported from the adjacent older leaves and that the intake of N and Mg in these leaves was reduced by 22 and 50 per cent respectively. The export of K increased the intake of Ca by approximately 72 per cent. Similar migration phenomena can be seen in the data of table 29. It is interesting to observe that the reserves of mobile P and K are found in the youngest fully hardened leaves but that the N reserves are also found in older leaves.

Little information is available on the effect of cropping. BURRIDGE *et alii* (1964) found in Ghana that the percentages of N, P and K gradually decreased during the cropping season and reached a minimum during the peak of crop production. They suggested that these elements were withdrawn from the leaves to supply the developing pods. However, it is likely that the decline of these elements largely reflects an age effect. During the second half of the cropping period few or no young leaves are formed, at least not in the lower part of the canopy from where the samples were taken,* and consequently at each new sampling date older leaves were sampled than on the previous sampling date. That movement of nutrients from leaves into fruits takes place has been demonstrated in an experiment by HURD (1961) in which radio-active phosphate was measured in beans after nearby leaves had been painted with a ^{32}P solution.

Another aspect is the competition for nutrients between young fruits and leaves which is according to HUMPHRIES (1944) one of the reasons for wilting of young pods at the time of or immediately following leaf flushing.

* The annual flushing pattern of mature Amelonado trees in Ghana has been described by GREENWOOD and POSNETTE (1950).

7.2 External factors affecting the mineral composition of cacao leaves

7.2.1 *Effect of nutrient supply*

The effects of nutrient supply have been reported in a great number of experiments in which young cacao has been grown in sand and water cultures with complete and incomplete nutrient supplies (Homès 1953, Murray 1957, Lockard *et alii* 1959. Loué 1961, Wessel 1968a). The results show that reduction in any one element of the nutrient supply not only affects growth and reduces the level of that element in the leaves but also affects uptake and concentrations of other elements. Furthermore it was found that sources of nutrients affect leaf mineral composition (Machicado and Boynton 1960, Asomaning and Lockard 1964).

Fertilizer experiments have also shown that additional nutrients affect the mineral composition of the leaves but that the effects depend on shade (or light) condition. This has been demonstrated in the shade and fertilizer experiment with 5 light regimes in Trinidad which has been mentioned in chapter 6. The main effects of N, P and K manuring were an increase in the corresponding elements in the leaf. In the case of N and K these effects increased with light intensity. Shade (or decrease in light intensity) also increased leaf N and K and thus had a similar effect as the application of these elements to the unshaded cacao. Moreover, it was found that N treatments lowered the K content and both P and K treatments the N content of the leaves at high light intensities (Murray 1953). In other experiments it was shown that both N and K depressed leaf P (Maliphant 1959, Wessel 1967e).

When living shade is used, competition between shade trees and cacao has to be taken into account. In agreement with Murray (1953), Maliphant (1959) reported that both nitrogen fertilizers and shade increased leaf N but that the interaction between the factors was negative as a result of uptake of additional N by shade trees. P fertilizers increased leaf P but additional shade depressed the P content of the leaves because of competition for this element between cacao and shade trees. In this context also should be mentioned the effect of tree spacing. An increase in tree density increases shade and this can result in higher N, P and K levels in the leaves but this effect may, depending on soil conditions, be offset by the increased competition between the trees for nutrients (Wessel 1967e).

7.2.2 *Light intensity*

The factor of light has already been discussed in connection with leaf age and the interaction between light and nutrient supply. An increase in light intensity generally lowers the N and K concentrations and raises the Ca concentration and the dry-matter content of the leaf, but has little effect on the P and Mg concentrations. LOUÉ (1957) has reported very similar effects of light intensity on the nutrient concentrations in coffee leaves.

7.2.3 *Seasonal effects*

The seasonal effect is a complex one depending on internal factors (flushing, age, cropping) and external factors (light, nutrient supply) and on their interactions. It was studied in Ghana (BURRIDGE *et alii* 1964) and in Nigeria (WESSEL 1969b) by taking monthly samples of most recently matured leaves from the lower (shaded) canopy of Amelonado trees. The general pattern in both countries can be summarized as follows: N, P and K concentrations are highest from November/December till May/June and lowest from July till October. Calcium levels varied almost inversely to those of N, P and K while Mg levels varied little in Ghana and followed the trend of calcium in Nigeria.

The pattern for Nigeria is given in figure 17 in which flushing periods and monthly rainfall have also been indicated. The major flushing periods in which all trees flush on all branches are indicated by a continuous line and the periods of minor flush when not all trees flush or flushing is restricted to a limited number of branches by a dotted line. From the graphs it can be seen that because the youngest (fully hardened) leaves are always sampled, the pattern of nutrients mainly reflects the seasonal production of new leaves.

In November new leaves of the September/October flush were available for sampling and this caused a sharp decline in dry matter, ash, Ca and Mg and a marked increase in N, P and K. The leaves sampled in December were four weeks older than at the previous sampling date. This resulted in the usual changes in dry matter and nutrients. As a result of minor and not simultaneous flushing of trees, leaves of various ages but not older than 10 to 12 weeks were sampled in the next months. In April new leaves were again available on all trees. The fact that K reached its highest peak in May might be a true seasonal effect. The much slower increase in dry matter after the May/June flush than after the September/October flush might be again a seasonal effect caused by the fact that the light intensity is much lower during the rainy season than in the dry season.

7.3 TIME OF SAMPLING AND SAMPLING PROCEDURE

The above review shows that many factors influence the mineral composition of the leaf. The effect of a number of them can, however, be eliminated or at least reduced by the choice of a suitable sampling period in which for example no leaves are being formed and only few fruits are present. From figure 17 it can be seen that for leaf age in Nigeria, the best sampling periods seem to be mid-April till mid-May and mid-December till mid-January. In these periods large numbers of young 5 to 10 weeks old leaves are present which are characterized by a dry-matter content between 32 and 38 per cent and which can be distinguished from older leaves by predominantly green

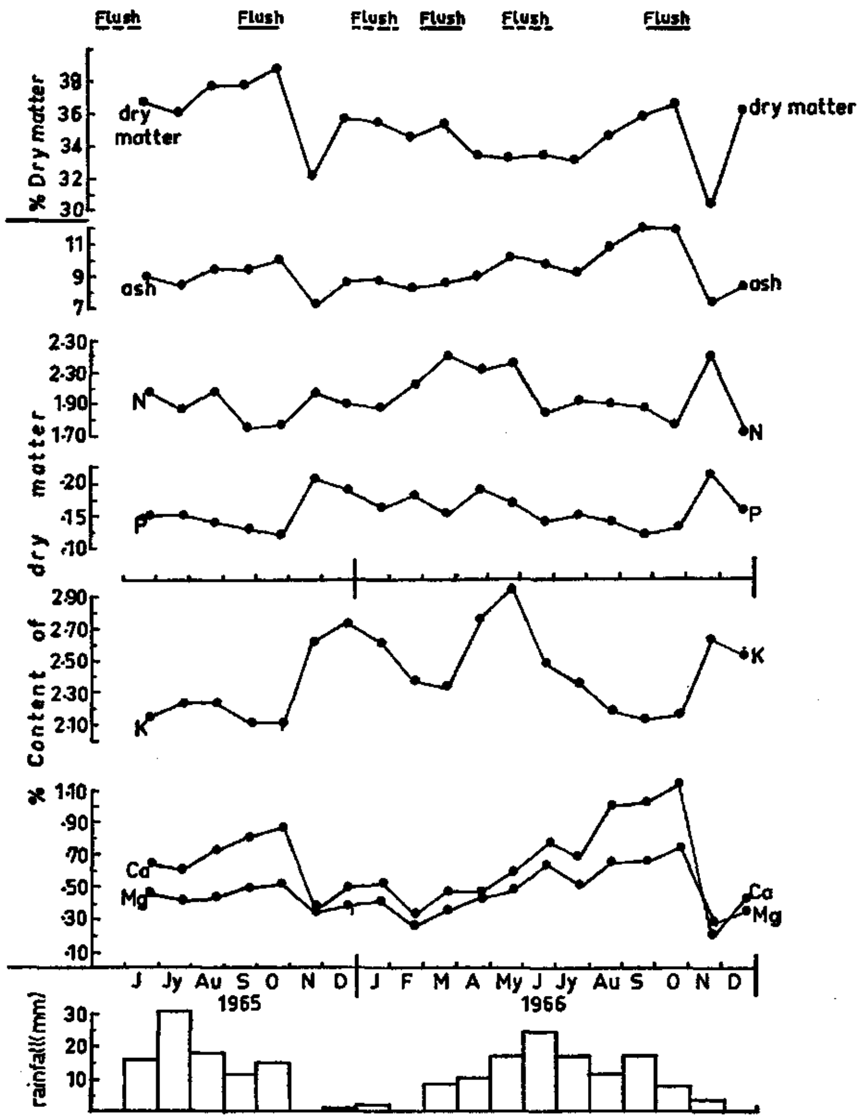


Figure 17
Monthly variation in the mineral content of leaves of mature Amelonado cacao at Gambari Experimental Station

petioles (ad-axial side green with brown spots and ab-axial side green). Differences in age will of course occur because not all fields can be sampled in the same week and because of variations in flushing behaviour between trees and groups of trees. These can, however, be related to the dry-matter content of the leaf. The same applies also to the differences in physiological age introduced by differences in degree of exposure of the leaves and trees sampled.

From the physiological point of view, the second part of the main cropping season e.g. the period August/October is of interest. The fruits have at that stage of their development their greatest demand for nutrients (HUMPHRIES 1940) and elements limiting crop production are likely to show minimum values in the leaves. VERLIÈRE (1967) has recommended this period for studying the relationship between leaf composition and yield on the basis of his work in the Ivory Coast (where cacao has the same cropping cyclus as in Nigeria). Sampling itself is however difficult at that time of the year because leaves of the May/June flush may not be present at all sites and on all trees, while leaves of the previous flush are sometimes too old to be easily distinguished from still older leaves.

On the basis of these considerations leaf samples were taken in April/May (1968), August/September (1968) and in January (1969). The leaves selected were the second and third fully green leaves (of the last flush) below the apex of fan branches as recommended by LOUÉ (1955). In April/May (1968) older leaves directly adjacent to the sampled younger leaves were collected as well. All samples consisted of medium-sized leaves and were taken from the lower shaded part of the canopy where light conditions are usually more uniform than in other parts of the crown. With only a few exceptions leaves were collected before noon on days without rain. The recommendation of ACQUAYE (1964) that sampling should be done between hours of 8 and 10.30 a.m. on a clear sunny day could not be followed since a large number of trees at sites far apart had to be sampled in a short time. ACQUAYE's data show that diurnal variation in nutrient concentrations can be substantial but the recommended hours of sampling seem to be arbitrarily chosen as there appeared to be no consistent pattern of variation.

As the leaf analysis programme was primarily aimed at explaining the differences in fertilizer responses at the various sites, samples were collected at all sites of the series I and series II experiments from trees not receiving fertilizers. Lack of sufficient control plots in these experiments made it necessary to use non experimental trees. Usually 3 or 4 groups of 5 trees per site were chosen on the basis of variability in soil fertility and cacao trees and the accessibility of the lower branches of the trees for sampling. Four pairs of leaves per tree from branches in different parts of the canopy were removed and combined in one sample per group of trees. In the series III trials leaves were collected from trees inside the experimental plots to study the effect of fertilizers on the mineral composition of leaves. In the period August/September trees of one replicate of 8 plots were sampled at all sites

TABLE 30

Mineral composition (percentages of dry weight) of cacao leaves from trees not receiving fertilizer at the sites of the series I, II and III experiments

site	April/May 1968 young leaves						April/May 1968 older leaves adjacent to young leaves						August/September 1968 medium old leaves				January 1969 young leaves			
	% d.m.	N	P	K	Ca	Mg	% d.m.	N	P	K	Ca	Mg	% d.m.	N	P	K	% d.m.	N	P	K
Iddo	37.5	1.83	0.14	1.56	0.77	0.56	39.0	1.77	0.09	1.11	1.14	0.71	36.6	1.67	0.13	1.65	38.0	1.92	0.12	2.11
Aba-Agbo	36.3	1.68	0.18	2.06	0.70	0.53	38.7	1.46	0.11	1.58	1.12	0.70	37.5	1.68	0.15	1.96	35.7	1.63	0.13	2.36
Ayorinde	36.2	1.92	0.23	2.05	0.81	0.62	39.6	1.80	0.13	1.38	1.26	0.80					34.2	1.80	0.19	2.12
Ricket	36.4	1.94	0.15	2.28	0.80	0.61	39.3	1.69	0.10	1.80	1.08	0.69	37.7	1.81	0.13	1.86	35.9	1.78	0.12	2.38
Iroko	33.4	1.76	0.31	2.30	0.43	0.37	39.2	1.66	0.18	1.52	1.11	0.50	35.4	1.54	0.30	1.92	34.8	1.77	0.24	2.73
Akinyele	37.7	1.42	0.21	1.92	0.73	0.49	40.9	1.34	0.14	1.58	1.15	0.60	37.6	1.53	0.22	1.55	36.3	1.83	0.17	2.36
Balogun	33.3	2.00	0.20	2.50	0.71	0.55	37.2	1.62	0.12	1.56	1.28	0.76	34.4	1.56	0.15	2.28	33.5	1.83	0.16	2.51
Aiyetoro	35.3	1.73	0.17	2.20	0.81	0.59	37.9	1.67	0.12	1.72	1.23	0.72	37.4	1.63	0.14	1.93	34.2	1.71	0.17	2.51
Iwo	36.5	1.62	0.17	2.42	0.89	0.50	39.3	1.33	0.09	1.50	1.03	0.67	33.6	1.64	0.17	2.33	34.2	1.94	0.18	2.74
Ilesha	35.1	1.86	0.17	2.04	0.90	0.54	38.6	1.84	0.12	1.34	1.22	0.66	35.3	1.74	0.17	2.03	34.7	1.69	0.21	2.65
Fidiwo	33.9	1.96	0.21	2.17	0.97	0.66	36.6	1.78	0.15	1.71	1.23	0.76	37.4	1.70	0.18	1.86	34.1	1.83	0.19	2.60
Oloba	34.5	1.88	0.16	2.42	0.75	0.52	38.0	1.73	0.10	1.91	0.96	0.59	35.0	1.86	0.15	2.17	34.9	1.93	0.16	2.80
Ife	35.7	2.02	0.15	2.15	0.80	0.61	37.4	1.77	0.10	1.83	1.12	0.77	34.8	1.72	0.15	2.04	33.4	1.86	0.17	2.73
Oke Irun													37.2	1.73	0.11	1.92	33.3	1.84	0.14	2.75
Ikole													32.6	1.89	0.16	1.83	33.3	1.94	0.21	2.68
Aponmu													32.1	1.76	0.13	2.66	34.6	1.91	0.16	2.79
Oda													40.4	1.87	0.10	1.80	36.6	2.15	0.11	2.17

TABLE 31

The relationship between the results of soil and leaf analyses and responses to applied nitrogen

response to applied nitrogen	site	% total N in the soil		April/May				August/Sept.		January		re-sponse to P ferti-lizers	approxi-mate number of trees per acre	mean shade index per plot
		April/May	Jan.	young leaves % N	young leaves N/P	older leaves % N	older leaves N/P	medium old % N	medium old N/P	young leaves % N	young leaves N/P			
response to application of nitrogen	Iroko	0.22	0.19	1.76	5.7	1.66	9.2	1.54	5.1	1.77	7.4	–	360	1.7
	Akinyele	0.19	0.22	1.42	6.8	1.34	9.6	1.53	7.0	1.83	10.8	–	365	0.9
	Ayorinde	0.20	0.15	1.92	8.3	1.80	13.8	–	–	1.80	9.5	–	360	1.6
	Ikole	–	0.20	–	–	–	–	1.89	11.8	1.94	9.2	–	495	1.4
	Aba-Agbo	0.13	0.12	1.68	9.3	1.46	13.3	1.68	11.2	1.63	12.5	+	360	1.6
	Iwo	0.14	0.15	1.62	9.5	1.33	14.8	1.64	9.6	1.94	10.8	+	470	2.0
	Aiyetoro	0.19	0.23	1.73	10.2	1.67	13.9	1.63	11.6	1.71	10.0	+	330	1.0
response to application of nitrogen in certain years	Ilesha	0.15	0.15	1.86	10.9	1.84	15.3	1.74	10.2	1.69	8.0	++	480	1.3
	Ife	0.19	0.17	2.02	13.5	1.77	17.7	1.72	11.5	1.86	10.9	++	440	1.3
	Iddo	0.12	0.11	1.83	13.1	1.77	19.7	1.67	12.8	1.92	16.0	++	380	1.1
	Oloba	0.13	0.14	1.88	11.7	1.73	17.3	1.86	12.4	1.93	12.1	++	580	1.7
	Aponmu	–	0.19	–	–	–	–	1.76	13.5	1.91	11.9	++	425	1.8
	Fidiwo	0.18	0.19	1.96	9.3	1.78	11.9	1.70	9.4	1.83	9.6	–	510	1.5
no response to application of nitrogen	Ricket	0.19	0.16	1.94	12.9	1.69	16.9	1.81	13.9	1.78	14.8	++	310	0.8
	Balogun	0.17	0.15	2.00	10.0	1.62	13.5	1.56	10.4	1.83	11.4	+	595	1.0
	Oke-Irun	–	0.16	–	–	–	–	1.73	15.7	1.84	13.1	+	390	3.0
	Oda	–	0.16	–	–	–		1.87	18.7	2.15	19.5	++	865	0.7

while in January all 24 plots were sampled except at Oda where again plots of one replicate were sampled.

In April/May soil samples were taken from the 0–6 inch and 6–12 inch layers in the "plots" of non experimental trees from which the leaf samples had been collected. In January 1969 a second sampling took place. This time samples from the 0–6 inch layer only were collected around each experimental plot and combined in one composite sample per site.

7.4 Results of leaf and soil analyses

The results of the leaf analyses have been summarized in table 30. All figures are means per site except for those of the August/September leaves from the series III experiments which are based on one single sample from the control plot of one replicate. As the results of the analysis of the soil samples taken in April/May did not differ greatly from those of the January samples already given in chapter 3, they have not been presented. The N and P figures have, however, been listed in table 31 and 33 while the K figures have been used in calculating the correlation between leaf and soil K.

7.4.1 *The relationship between the nutrient status of the soil and cacao leaves and responses to fertilizers*

7.4.1.1 Responses to nitrogen

A summary of the N results is given in table 31 in which the sites have been grouped together according to the degree of their response to applied nitrogen. The first group comprises sites on which large and/or continuous responses to nitrogen have been obtained. Aiyetoro has been placed in this group on the basis of a linear response to N when this element is applied without P. Iwo and Ikole have been included despite the fact that responses have not always been significant. The second group consists of sites which have shown a response to nitrogen in certain years only. Sites with a positive interaction between N and P have also been included in this group. The sites Aponmu and Fidiwo, where N had a positive effect in one year only, are transitional to the third group which consists of four sites which have not shown any response to N.

Four of the sites in the first group are the only ones on soils with a medium high or high phosphorus status (see below), while 3 of the 4 sites in the third group are located on soils which rank among the most P deficient ones (Liebigs' Law of the Minimum). This indicates a certain relationship between the N and P nutrition of the cacao trees and for this reason the N:P ratios have been calculated.

The figures of Humphries (1940) reveal that the N:P ratio increases from values between 7 and 9 in 2 to 4 weeks old leaves to values between 12 and 17 in leaves older than 10 weeks. As LOCKARD *et alii* (1959) and WESSEL (1968a) found ratios of 10.8 and 10.2 respectively in young leaves of plants grown in a complete nutrient solution and HARDY *et alii* (1935) gave a ratio of 10.8 as the ideal equilibrium between N and P, it may be assumed that ratios between 10 and 11 will be normally found in 5 to 10 weeks old leaves of plants which are neither deficient in N nor P.

Furthermore it should be mentioned that three sites in group 1 (Akinyele, Iroko and Ikole) lie in the zone of transition between rain forest and savannah. In this zone visual symptoms of nitrogen deficiency are commonly found in unshaded cacao. N deficiency symptoms were, however, not found in the cacao on the experimental sites except in a few isolated trees.

The analyses of the young April/May leaves show that nitrogen percentages below 1.80 are associated with very N deficient cacao and that percentages between 1.80 and 2.00 are found in moderately deficient and non-N deficient trees. The only exception is Ayorinde where the N percentage does not indicate a marked N deficiency but the N:P ratio of 8.3 means that the N content is too low in relation to phosphorus. The results of the older April/May leaves give a less clear picture. N percentages below 1.60 seem, however, to indicate distinct N deficiency. For N percentages in the leaves sampled in August/September the critical value seems to be 1.70 per cent. The N % at Balogun where N fertilizers have no effect is 1.62, however. The N percentages in the January leaves vary on most sites between 1.80 and 2.00 per cent. Lower values are found only at Aba-Agbo and Aiyetoro and higher values only at Oda .These data do not permit the establishment of a critical value. During this sampling period cacao trees suffer from water stress on most sites and this might have a stabilizing effect on the N content of the leaves.

Values for the N:P ratio < 9, between 9 and 10 and between 10 and 11 can be regarded as indications of severe, moderate and no deficiency respectively. As values within the "normal" range can also be found in leaves which are both N and P deficient, the N:P ratio can only be used as an index of N deficiency on sites with an adequate P supply (available $P > 12$ ppm). These figures, however, only refer to the young April/May leaves.

Both LOUÉ (1961) and MURRAY (1967) have given critical levels for deficiency of major elements in cacao. These have been summarized in table 32. Although the authors do not specify the age of the leaves for which these critical levels have been established, the figures and ratios between elements suggest that MURRAY's figures refer to young (5 to 10 weeks old) and LOUÉ's figures to medium old (possibly 10 to 15 weeks old) cacao leaves. It can be seen that the critical value of 1.80 per cent as found in the April/May leaves has a general validity and that values below this figure indicate severe N deficiency. Furthermore, it can be seen that all the cacao on the sites of the second and third group (table 31) falls in the category which LOUÉ describes as "moderately deficient" and MURRAY as "low in nitrogen." The fact that this moderately deficient cacao responds little or not at all to N seems mainly to be connected with the inadequate phosphate nutrition of this cacao. The response to N at Ayorinde favours this view but the absence of positive NP interactions on many sites does not seem to support it.

Because interactions to N fertilizers are known to depend on light conditions it was investigated if the responses of the moderately deficient cacao could be related to shade conditions. For this purpose the number of trees per acre (as a degree of mutual shading) and the mean shade index per plot have been included in table 31. This shade index is based on a visual assessment of the shaded area plot using the figures 0, 1, 2, 3 and 4 for unshaded, 1/4 shaded, 1/2 shaded, 3/4 shaded and completely shaded plots respectively. From table 31 it can be seen that the high tree density might possibly explain the low degree of response at Oloba (only a positive NP interaction) and the absence of response at Balogun and Oda, while the very high shade index for Oke-Irun might explain the absence of response on that site. As not only the number of trees per acre but also the size and the shape of the trees and furthermore not only the shaded area but also the intensity of the shade determine the light conditions in a cacao farm, not too much value can be attached to this interpretation.

The determination of total N in the soil does not help in explaining the responses of cacao to N fertilizers. This is not surprising because most of the nitrogen measured by the total N has first to be mineralized before it becomes available.*

7.4.1.2 Responses to phosphate

The results of phosphate analyses in soil and leaves have been summarized in table 33. As in the previous table, sites have been classified in three groups according to their reaction to applied phosphate. The linear responses to P range in the first group from 3.5 to 6.0 lb dry beans per lb applied P_2O_5, in the second group from 1.4 to 3.0 while sites in the third group do not react to P.

TABLE 32

Nutrient concentrations in normal and deficient cacao leaves

nutrient	criteria according to Loué (1961)			criteria according to Murray (1967)		
	normal	moderately deficient	severely deficient	normal	low	deficient
N	2.35–2.50	1.80–2.00	<1.80	>2.00	1.80–2.00	<1.80
P	>0.18	0.10–0.13	0.08–0.10	>0.20	0.13–0.20	<0.13
K	>1.20	1.00–1.20	<1.00	>2.00	1.20–2.00	<1.20
Ca				>0.40	0.30–0.40	<0.30
Mg				>0.45	0.20–0.45	<0.20

* Incubation experiments to measure mineralizable nitrogen were started in 1969 but had to be discontinued due to technical problems with the incubators.

TABLE 33

Relationship between the results of soil and leaf analyses and responses to applied phosphate

mean linear response per annum to applied phosphate	site	available P (ppm)* in the 0–6 inch soil layer April/May	Jan.	April/May young leaves % P d.m.	% P f.m.	N/P	April/May older leaves % P d.m.	% P f.m.	N/P	August/September medium old leaves % P d.m.	% P f.m.	N/P	January young leaves % P d.m.	% P f.m.	N/P
3.5–6.0 lb	Ife	3	3	0.15	0.053	13.5	0.10	0.039	17.7	0.15	0.052	11.5	0.17	0.057	10.9
dry beans	Oda	–	4	–	–	–	–	–	–	0.10	0.040	18.7	0.11	0.040	19.5
per lb P_2O_5	Oloba	6	4	0.16	0.055	11.7	0.10	0.038	17,3	0.15	0.053	12.4	0.16	0.056	12.1
applied	Iddo	6	4	0.14	0.056	13.1	0.09	0.035	19.7	0.13	0.048	12.8	0.12	0.046	16.0
per acre	Ricket	6	5	0.15	0.055	12.9	0.10	0.039	16.9	0.13	0.049	13.9	0.12	0.043	14.8
	Ilesha	5	9	0.17	0.060	10.9	0.12	0.048	15.3	0.17	0.060	10.2	0.21	0.073	8.0
	Aponmu	–	7	–	–	–	–	–	–	0.13	0.042	13.5	0.16	0.045	11.9
1.4–3.0 lb	Oke-Irun	–	2	–	–	–	–	–	–	0.11	0.041	15.7	0.14	0.055	14.6
dry beans	Aba-Agbo	7	6	0.18	0.065	9.3	0.11	0.042	13.3	0.15	0.056	11.2	0.13	0.046	12.5
per lb P_2O_5	Balogun	7	7	0.20	0.067	10.0	0.12	0.045	13.5	0.15	0.052	10.4	0.16	0.054	11.4
applied	Aiyetoro	8	8	0.17	0.060	10.2	0.12	0.045	13.9	0.14	0.052	11.6	0.17	0.058	10.0
per acre	Iwo	5	8	0.17	0.062	9.5	0.09	0.035	14.8	0.17	0.057	9.6	0.18	0.061	10.8
no	Fidiwo	8	6	0.21	0.066	9.3	0.15	0.055	11.9	0.18	0.067	9.4	0.19	0.065	9.6
response	Ayorinde	12	12	0.23	0.083	8.3	0.13	0.052	13.8	–	–	–	0.19	0.065	9.5
to applied	Ikole	–	23	–	–	–	–	–	–	0.16	0.052	11.8	0.21	0.070	9.2
P_2O_5	Akinyele	22	24	0.21	0.079	6.8	0.14	0.057	9.6	0.22	0.083	7.0	0.17	0.064	10.8
	Iroko	58	40	0.31	0.104	5.7	0.18	0.071	9.2	0.30	0.106	5.1	0.24	0.083	7.4

* Bray and Kurtz method nr. 1

The sites of the series III experiments have only two levels of P. Their place in one of the three groups is thus not based on a linear response but on response to one level of P only which corresponds with level 1 in the series I and II experiments. Within each group sites have been placed in an order of increasing soil phosphate using the results of the soil samples collected in January 1969 (already presented in table 7). By doing so, a sequence of increasing P figures is obtained starting in group 1 and ending in group 3. The order is, however, disrupted by the figures of Oke-Irun, Ilesha and Fidiwo. On the basis of the results of both soil and leaf analysis Oke-Irun fits in the first group and Ilesha in the second group.

Despite these exceptions the results of table 33 permit the broad conclusion to be drawn that an available P content in the soil below 7 ppm indicates severe deficiency, between 7 and 12 ppm a moderate deficiency and above 12 ppm no deficiency. The figure of 40 ppm at Iroko should be considered as very high.

From the results of leaf analysis the critical levels for severely, moderately and not deficient seem in the April/May leaves to be 0.16 and 0.20 as percentage of dry weight and 0.060 and 0.070 as percentage of fresh weight. In the adjacent older leaves the critical values are 0.11 and 0.13 or 0.040 and 0.050. It is, however, important to consider the results of the young and adjacent older leaves in relation to each other. In the August/September and January leaves no distinct critical value can be found to differentiate the moderately deficient and the severely deficient cacao. The value above which no deficiency occurs lies in both sampling periods probably between 0.18 and 0.19% or expressed as percentage fresh weight between 0.060 and 0.065%.

An N:P ratio > 11 on sites which are not severely N deficient seems to be an indication of P deficiency in all three sampling periods. In the older April/May leaves the critical N:P ratio appears to be 14.

The critical concentrations found in the April/May leaves agree very well with those given by Murray but are higher than those reported by Loué.

The above results indicate that both soil and leaf analysis can be used not only to detect P deficiency in cacao but also to indicate the degree of deficiency. This is not a surprising result in view of the high degree of correlation between phosphate in the soil and in the leaves as shown in table 34. Furthermore, it is shown that when soil P is determined by the method of Olsen *et alii*, a slightly higher correlation coefficient is obtained than when P is determined according to the Bray and Kurtz no. 1 procedure. In later determinations, however, preference has been given to the second method which is more rapid and avoids the treatment with activated charcoal (see chapter 5).

The correlation coefficients for the relationship between leaf P and soil P in the 0–6 inch layer and between leaf P and soil P in the 6–12 inch layer were the same ($r = 0.84$) while only a slightly higher correlation coefficient was found ($r = 0.85$) when the mean P figure of the 0–6 inch layer and 6–12 inch layer is used. From this observation it may be concluded that samples of the 0–6 inch layer give an equally good picture of the available P content of the soil as the samples of the 0–12 inch layer.

Soil and leaf analysis do not explain the fact that the cacao at Oke-Irun shows little response to P application. The results of leaf analyses indicate however that P application at Oke-Irun raised the P concentration in the leaves to a lesser extent than at the sites Ikole and Oda and also at Araromi. The presence of a large number of shade trees and the high P sorbing capacity of the soil are likely to be the reasons that insufficient quantities of the applied P are available to the cacao trees.

Owing to the fact that the P concentrations of the leaves closely reflect the differences in the available P status of the soil the previously found linear relationship between leaf P and leaf dry matter has largely disappeared when the results of all sites are considered together. The correlation coefficients for the young April/May and January leaves are respectively − 0.56* and − 0.49 while those for the older April/May and August/September leaves are of the order of − 0.1. When, however, the correlations were calculated

TABLE 34

Correlations between phosphate concentrations in cacao leaves and available phosphate in the soil (0–6 inch layer; P determined according to Bray and Kurtz nr. 1 procedure)

samples	leaf P	April/May		August/ September	January
		young leaves	older leaves	medium old leaves	young leaves
means per site	% dry weight	0.88***	0.81***	0.88***	0.70**
	% fresh weight	0.90***	0.84***	0.85***	0.73**
single samples	% dry weight	0.80***	0.68***	–	–
		0.84***†	–	–	–

† available soil P determined according to the alkaline extraction method of Olsen *et alii*.

TABLE 35

Summarized relationship between the phosphate content of cacao leaves and soils and the responses to phosphate fertilizers (based on table 33)

young leaves*		older leaves* adjacent to the young leaves		ppm P in the 0–6 inch soil layer	mean linear response in lb dry beans/acre per applied lb P_2O_5/acre
% P d.m.	% P f.m.	% P d.m.	% P f.m.		
<0.16	<0.060	<0.11	<0.040	< 7	>3
0.17–0.20	0.060–0.070	0.11–0.13	0.040–0.050	7–10	1–3
>0.20	>0.070	>0.13	>0.050	>12	no response

* sampled in April/May

separately for some P deficient and some non-P deficient sites high degrees of correlation were found provided that the analyses of the January leaves were omitted. This is shown in figure 18.

Finally the results of this section have been summarized in table 35. Even on the sites with the most P deficient cacao no visual leaf symptoms of P deficiency have been found.

7.4.1.3 Responses to potassium

In chapter 3 it has already been mentioned that almost all sites have a satisfactory high potassium status. This adequate supply of potassium is also reflected* in the K concentrations in the young leaves (table 30) which are on all but two sites in April and on all sites in January above the critical level of 2.00 per cent reported by Murray.

Other indications of a satisfactory K nutrition are the fact that K fertilizers did not raise the K content of the leaves and that when correlations are calculated between the K concentrations and the dry-matter contents of the leaves from all sites in all sampling periods significant negative correlations (r's between -0.6 and -0.8) are found in spite of the large variations in exchangeable K between sites. This last point seems to indicate that at least in the young leaves at all sites enough potassium is present to allow the process of the decrease of K with time to take place at approximately the same rate.

A site with a low K concentration both in the soil and in the leaves is Iddo (see tables 7 and 30), but here also no response to K was recorded. The mean exchangeable K content in the 0–3 inch soil layer at Iddo was 0.23 m.e., just above the 0.20 m.e. limit below which Acquaye *et alii* (1965) found in Ghana potassium deficiency in Amazon cacao which is more demanding for K than Amelonado cacao. As all newly planted cacao is of the Amazon type, future development of potassium deficiency in cacao on the more sandy soils with a rather low K status can be expected.

Widely spread potassium deficiency in cacao has been found on the sedimentary soils in the most South-Western part of the cacao belt. Visual symptoms of acute K deficiency usually appeared at the time of flushing in the (older) leaves directly adjacent to young developing leaves. The symptoms started with inter-veinal chlorosis. Areas between the secondary veins turned yellow and soon afterwards brown. The yellow and brown areas extended gradually and the tissue became necrotic. The dark brown areas had often a shiny appearance. These symptoms resemble the symptoms of K deficiency described by Lockard *et alii* (1959) but differ from the marginal necrosis symptoms which Maskel *et alii* (1953) found in K deficient plants grown in sand cultures and nutrient solutions.

* In none of the sampling periods, however, significant correlations between exchangeable K concentrations in the soil and K concentrations in the leaves were found.

A comparison of the chemical composition of potassium deficient leaves with and without visual symptoms of deficiency and normal leaves is given in table 36. The young, medium-old and old leaves are groups of leaves of subsequent flushes on the same branch. In the K deficient tree without deficiency symptoms enough potassium was stored in the older leaves to give the youngest leaves still a rather high potassium content. Potassium

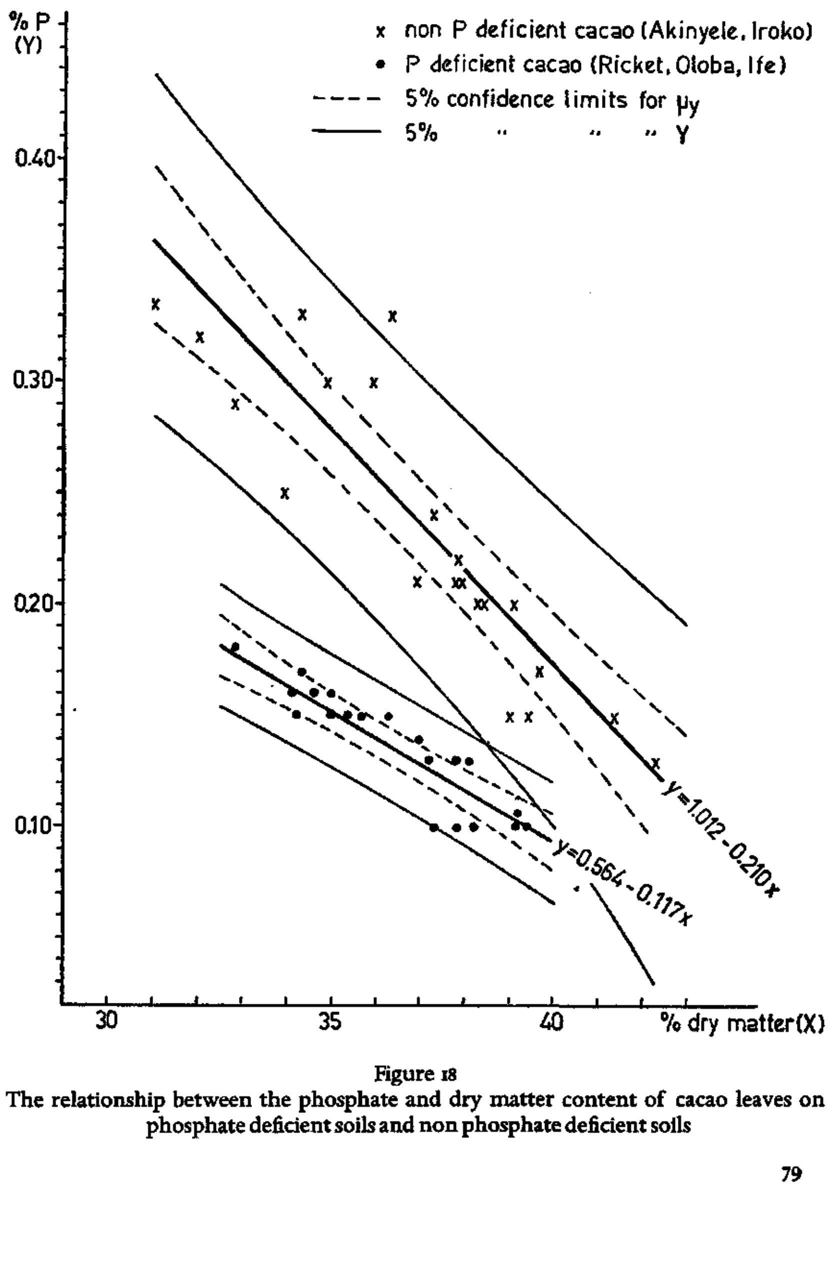


Figure 18
The relationship between the phosphate and dry matter content of cacao leaves on phosphate deficient soils and non phosphate deficient soils

deficiency could in this case only be established by analysing both young and older leaves. In the tree with symptoms in the medium-old leaves, the K content in the young leaves was also low and in these leaves deficiency symptoms started to appear within a few weeks after the leaves had hardened. The leaves with a low potassium content had a very high Mg content and also a high percentage dry matter as a result of necrosis.

7.4.1.4 Responses to calcium and magnesium

A comparison of the Ca and Mg concentrations in the April/May leaves (table 30) with the critical concentrations given by MURRAY indicates that the cacao trees are not deficient in these elements. The results of the soil analyses (table 7) and the results of the fertilizer trials suggest however that at a number of sites Mg may be become a limiting factor when the N and P supply is increased.

7.4.2 *The effect of fertilizers on the mineral composition of leaves*

The results from the August/September leaves revealed that phosphate fertilizers increased leaf phosphate except at Aponmu, that nitrogen increased the nitrogen content of the leaves at Oke-Irun, Ikole and Oda and that potassium fertilizers had no effect on the potassium content of the leaves.

Since in January all experimental plots at three sites were sampled, the

TABLE 36

Comparison of the chemical composition of potassium deficient and normal cacao leaves

	age	% dry matter	% N	% P	% K	% Ca	% Mg	origin of samples	m.e. exchangeable K/100 g s (0–6 inch laye
K deficient tree without leaf symptoms	young*	30.6	2.37	0.24	1.75	0.60	0.48	variety trial Ilaro	
	medium-old	39.6	2.06	0.12	0.54	1.66	0.98	(sampling date 3/4/68)	0.13
	old	41.8	1.86	0.09	0.32	1.88	1.03		
K deficient tree with deficiency symptoms on medium old leaves	young	33.9	2.56	0.30	1.17	0.50	0.41	variety trial Ilaro	
	medium-old	43.8	1.75	0.12	0.23	1.60	1.23	(sampling date 14/6/69)	0.10
"healthy" tree	young	31.8	1.99	0.24	2.34	1.03	0.54	variety trial Ibule	
	medium-old	38.7	1.50	0.10	1.17	1.69	0.62	(near Akure)	0.30
	old	40.7	1.58	0.08	1.10	2.33	0.59	(sampling date 9/4/68)	

* the young, medium-old and old leaves are groups of leaves of subsequent flushes on the same branch

results could be analysed statistically. To eliminate at least some of the variation caused by differences in leaf age, an analysis of covariance was carried out by which the N, P, K, Ca and Mg concentrations were corrected for regression on percentage dry matter. Table 37 shows that correction for age reduced the variance of leaf P and Ca and especially of K but not of Mg and N, elements which have also previously shown not to be related to the dry-matter content of the leaves.

Nitrogen fertilizers did not affect the mineral composition of the leaves while potassium fertilizers only tended to decrease the P content at Ikole and to raise the K content of leaves at Aponmu. The interaction of N and K had, however, a significant positive effect on leaf Ca at Oke-Irun and a negative effect on leaf Ca at Aponmu when for this site the un-adjusted data are considered. P fertilizers increased the P content of the leaves at all three sites (see table 38). They furthermore depressed leaf K and increased leaf

TABLE 37

The effect of correcting nutrient concentrations for dry matter content on the variance of nutrient concentrations in cacao leaves (statistical analysis of results of the 2^3 NPK experiments)

nutrients	ratio of variances without and with regression of nutrients on dry matter			significant regression coefficients		
	Oke-Irun	Ikole	Aponmu	Oke-Irun	Ikole	Aponmu
N	1.04	0.99	0.96			
P	1.81	1.18	2.22	−0.0103**		−0.0113***
K	2.39	6.83	2.99	−0.0991***	−0.1684***	−0.1433***
Ca	1.64	2.48	1.78	+0.0473**	+0.0562***	+0.0592**
Mg	0.94	0.94	1.02			

TABLE 38

The effect of application of phosphate fertilizers on the nutrient concentrations of cacao leaves

sites		effects without correction for dry-matter content					effects with correction for dry-matter content				
		% N	% P	% K	% Ca	% Mg	% N	% P	% K	% Ca	% Mg
ke-Irun	P 0		0.138	2.72	0.84			0.138	2.72	0.84	
	P 1		0.154*	2.53*	0.95*			0.154*	2.53***	0.95**	
	S.E.		0.0055	0.047	0.027			0.0041	0.031	0.021	
ole	P 0		0.197	2.61	0.78	0.302		0.193	2.51	0.81	0.303
	P 1		0.222*	2.38	0.88	0.356***		0.227**	2.47	0.85	0.354***
	S.E.		0.0081	0.093	0.037	0.0098		0.0074	0.036	0.023	0.0101
ponmu	P 0	2.00	0.163				2.00	0.163			
	P 1	1.88	0.183				1.88	0.182**			
	S.E.	0.045	0.0071				0.046	0.0048			

Ca at Oke-Irun. Similar P effects were found at Ikole but the analysis of the adjusted data shows that the differences in K and Ca between Po and P1 plots are partly caused by age effects. P furthermore increased the Mg content of the leaves at Ikole and tended to depress leaf N at Aponmu. The latter effect might explain the positive interaction on yield between N and P treatments at Aponmu.

A positive effect of P fertilizers on the P content was also found in the Araromi fertilizer experiment where P increased the P content in young leaves from 0.17 to 0.25 and in the adjacent older leaves from 0.09 to 0.14 per cent.

These results differ from earlier observations in the 2^3 NPK fertilizer trial at Gambari Experimental Station (WESSEL 1967e). In this experiment N application significantly increased the N content of the leaves and both the N and K treatments significantly lowered the P content of the leaves while P fertilizers had no effect.

All these results indicate however that mutual N-P and P-K "antagonisms" are operative when additional nutrients are given to cacao.

7.4.3 *Relationship between N, P and K concentrations in young leaves and the adjacent older leaves (sampled in April/May)*

For N, P and K (expressed as % of dry matter) correlation coefficients of 0.83, 0.94 and 0.63 were found indicating a close relationship between the concentrations of these elements, in the young leaves and adjacent older leaves of a previous flush. The P and K concentrations are much lower in the older leaves as a result of the migration of these elements from the older leaves to the younger leaves which already starts when the young leaves begin to develop.

7.4.4 *The suitability of the sampling periods*

As to the time of sampling the following conclusion can be drawn. For detecting both N and P deficiency and for determining critical concentrations, the sampling period April/May seems to be more suitable than the January period. Sampling of the additional older leaves does not seem to be necessary when nitrogen levels are studied. It may be useful when phosphate contents are considered and it is essential when potassium levels are studied. Sampling in the August/September period may also give useful information but has the disadvantage that because of differences in leaf age the results of samples from different sites are difficult to compare. The results of the series III experiments (table 30) may clarify this point. At Ikole and Aponmu leaves of flushes which developed in June or July were sampled while at Oda and Oke-Irun leaves from this flushing period were not present and much older leaves probably from the March flush had to be sampled instead. Even when in June new leaves are developed at all sites, their numbers usually will be small and this complicates future sampling. As at this time of the year the dry-matter content of the leaves increases only slowly when the leaves grow older, it has still to be investigated whether the dry-matter percentage can be used to correct for age effects.

7.5 The future of leaf analysis of cacao

It has been shown that leaf analysis makes it possible to detect marked deficiencies and to indicate correcting measures. However, as Murray and Maliphant (1967) have pointed out, within the normal range of concentrations in the leaf no technique yet exists that can provide a quantitative fertilizer programme. In a few cases only (Maliphant 1959, Wessel 1967e) relationships between nutrients and yields have been found while optimum concentrations, related to good growth and high yields, have yet to be established. Moreover, in cacao a range of optimum concentrations has to be determined to cover differences in leaf age and shade. Even when these problems can be solved, the possibilities of large-scale application will be far greater on well organized plantations than on the small farms in West Africa in which trees of all sizes and shapes are grown.

For the moment, however, the main value of leaf analysis in cacao seems to be in detecting and identifying nutrient deficiencies and in helping the interpretation of the results of fertilizer experiments.

8. SUMMARY AND DISCUSSION OF RESULTS

Nigeria is at present the second largest cacao producing country in the world with an annual export of approximately 220,000 tons of dry beans. The main cacao producing area is situated in South-Western Nigeria as shown in figure 2. Most of the cacao is of the West-African Amelonado type. It is grown in small holdings by peasant farmers who planted the cacao at random in between their food crops in small farms cleared from forest. The number of mature trees per acre usually varies between 350 and 700. The cacao is generally grown with little or no shade and without manuring. The average yield is low and estimated to be about 350 lb dry cacao per acre.

and the texture of the surrounding earth. It would appear that any appreciable quantity (exceeding 15 volume per cent) of gravel above 12 inches and below 36 inches is undesirable and that in the layer between these depths the total volume of gravel should not exceed 40 to 50 per cent of the total soil volume.

Monthly moisture determinations in the top 4 ft of the soil have shown that soils dry out to great depth during the dry season. Moisture levels approaching the P.W.P. of the soil were recorded in three successive years during January and February in soils under cacao on the middle and lower slope of a soil catena. In years with normal rainfall F.C. is usually not reached before the middle of June. From that time onwards till the end of October rainfall exceeds the potential evapo-transpiration except in August which is a relatively dry month. During the second half of October and November the actual evapo-transpiration equals approximately the potential evapo-transpiration, to fall below it in December and from then onwards the period of water deficiency starts again. The total amount of water lost by drainage from the top 4 ft of the profile does usually not exceed 8 inches per annum.

The annual precipitation of 45 to 65 inches inside the cacao belt is thus on one hand marginal for cacao but on the other hand the main reason why the soils derived from acid metamorphic rock have not lost all their bases by leaching and can thus successfully support cacao.

The low amounts of available water in the soil make survival of the cacao trees during the 4 to 5 months long dry season the main problem in establishing cacao. Farmers in the drier parts of the cacao belt have tried to solve this problem by removing forest shade trees, which compete with the cacao for the limited soil moisture, and by planting trees close together to compensate for the lack of shade. The fact that the amount of available water is so low that cacao trees cannot survive in the presence of large forest trees has been confirmed in an experiment reported in chapter 4.

It is of interest to mention that similar conditions have been described in the coffee literature. This tree crop is in many countries grown under shade, but in places where shade and coffee cannot survive together because of moisture competition, it is successfully grown without shade at remarkably low soil moisture conditions (WELLMAN 1961).

Growing of cacao in full light requires good soils, a high standard of maintenance and crop protection and manuring. As these conditions are usually not met in Nigeria, lack of shade mainly accounts for the rather short economic life of farmers' cacao.

It is difficult to give a solution for the soil moisture problem in Nigeria. The beneficial effects of mulching on the soil moisture relations of coffee in East Africa are well known. However, appreciable quantities of grass or other mulch are not available in the forest zone while establishment of mulch gardens is likely to be too expensive and does not fit in the present farming system. Irrigation can also be ruled out for economical and technical reasons. Planting of deep rooting shade trees offering only limited competition for water might be a solution for cacao plantations but is not acceptable to the Nigerian farmer who favours a "tree crop" like bananas and plantains, a certain group of starchy cooking bananas which produces marketable products in a short time. Under these conditions the best solution seems to be to plant rows of closely spaced bananas or plantains as permanent side protection at regular intervals (about 60 ft apart) and plant cacao between these rows at a close spacing under some type of temporary shade.

8.2 Soil phosphate studies

The positive reactions to application of P fertilizers was a reason for studying the phosphate status of the cacao soils in greater detail.

It was found that the top 6 inches of forest soils contain relatively high quantities (of the order of 30 ppm) available P. These amounts gradually decrease, after the soils have been planted to cacao, to the low values (averaging 6 ppm) which were found in most farms. This indicates that although only small quantities of P are removed in the annual crop (a yield of 500 lb dry beans removes approximately 3 lb P per acre*, corresponding with 1.5 ppm soil P) cacao depletes available P reserves of the soil in the long run. In the soils low in available P, the total P varies in general between 350 and 550 ppm,* 40 to 60 per cent of which is present in organic form. This organic P fraction was found to be highly positively correlated with the organic carbon content of the soil. Fractionation of the inorganic phosphorus according to the procedure of Chang and Jackson gave the result that on the average about 77 per cent is present as occluded phosphates, 5 per cent as Ca-bound P, 13 per cent as Fe-bound P, 4 per cent as Al-bound P and less than 1 per cent as loosely bound or water-soluble P. The amounts of non-occluded phosphate ranged in the P deficient soils from 25 to 70 ppm but in soils with medium high and high P status from 125 to 325 ppm where they constituted more than 40 per cent of the total inorganic phosphate.

The distribution of P over the different chemical fractions in soil profiles shows an accumulation of total P in the top inches of the soil due to the presence of large quantities of organic P. Below this level organic P drops sharply and continues to decrease with depth but more slowly than might be expected from the fall in total organic matter. The same trend is apparent for extractable or non-occluded P. The Al-P fraction shows a particularly sharp decrease with depth. The drop in the Fe-bound P fraction is more gradual and as a result the proportion of Fe-P increases rapidly with depth. This characteristic pattern is the same for P deficient and non P deficient sites, although the quantities involved differ. Other investigators have shown

* figures for the 0–6 inch layer

that iron concretions which occur in greatly varying quantities in most cacao soils have a very high P content (between 500 and 700 ppm) but this phosphate is locked up and not available to plants.

As part of the P studies, the fate of applied soluble phosphate was studied in cacao plots which had received triple superphosphate for 5 or 6 subsequent years. The P balance sheet shows that on the average 20 per cent of the added P could be accounted for as being removed by the harvested crop. Of the surplus only 55 per cent could be recovered in the top 6 inches of the soil, mainly in non-occluded form. This means that about half of the surplus is leached down to deeper soil layers. Large differences were however observed in the quantities lost from the top soil, the greatest loss being 62 per cent and the smallest 20 per cent. The amount retained in the non-occluded Fe-P fraction was closely correlated with the P sorption capacity of the soil as determined by laboratory methods. These sorption capacities varied between 20 and 65 μg P per gram soil or 92 and 298 lb P_2O_5 per acre and were found to be positively correlated with the clay content of the soil. This relationship however, depends on pH.

The distribution of the added soluble P among the extractable inorganic P fractions revealed that most of it was present as Fe-bound P. On two moderately deficient P sites the added P was distributed in proportions which already existed in the soil but on two other sites which were very deficient in P, the very low Al-P fraction received a relatively larger share than the other fractions. The effects of applied P on yield were far greater at the last two than at the first two sites which seems to support the general concept that the Al-bound P is more available to the plants than the other forms of extractable inorganic P.

The results of these P studies thus show that in the Nigerian cacao soils most of the inorganic P is present in non-soluble or occluded form. Of the non-occluded fraction only a small portion is present in the Al-P fraction. The sharp decrease of this fraction with depth means that the tree can not rely on appreciable quantities of available P in the sub-soil. The largest potentially available P reserves will thus be in the organic P fraction in the top soil. Agricultural practices have to be aimed at preserving this reserve and raising the low available P status of the soil by the addition of soluble phosphates. Due to the low P retaining capacity of the top soil a large portion of the applied P will leach down to deeper layers. As the amount of clay, which was shown to be the main site of P sorption, increases with depth, most P will be retained within the rooting depth of the cacao trees. As the soil volume which can be thoroughly exploited by the cacao roots decreases with depth, only a part of this leached P will be within reach of the plant.

8.3 Fertilizer experiments

The fertilizer experiments have clearly shown that yields are greatly limited by lack of phosphate followed in importance by lack of nitrogen. The positive response to P is not surprising in view of the low amounts of available P in the soil and the fact that fertilizer trials on arable crops have also established that in West Africa in general P is the most serious nutrient deficiency. The response to nitrogen is most likely related to the fact that cacao in Nigeria is grown with little or no permanent shade. Trials elsewhere have shown that cacao in full light requires additional nitrogen for high yields.

The more detailed results show that young cacao established on soil cleared from forest does only require some additional nitrogen. As nitrogen generally stimulates vegetative growth it stimulates early jorquetting in cacao. As a result a closed canopy is obtained soon after planting, the main advantage being that weed growth is suppressed and the soil is protected against deterioration of its physical and chemical properties. The P status of these forest soils is adequate but has to be maintained at a satisfactory level by P fertilizer applications when trees come into bearing. When soils are cleared from cacao or arable crops, their available P reserves have usually been depleted and young cacao will require both N and P. Young trees are very sensitive to fertilizer toxicity (probably because of a low buffering capacity of the soil) and therefore small quantities per application have to be used especially when single fertilizers are used. Mulching of the soils has been shown to have a beneficial effect on uniform establishment and early bearing.

Most of the mature cacao is deficient in P and annual applications of 60 to 90 lb P_2O_5 per acre seem to be required to raise the production adequately. Once a reserve of available P has been built up, this quantity might be reduced to half of the amounts mentioned above while strong residual effects seem to indicate that after a period of annual applications, P has only to be applied every other year. Both points need, however, further investigations.

Cacao on soils with a high P status is usually very deficient in N. On these soils annual applications of the order of 120 lb N per acre are required. On soils with a low P status N rates can be lower, probably of the same order as the P_2O_5 quantities.

The experiments have shown that in general there is no need for application of K. The amounts of exchangeable K under mature cacao are still rather high despite the fact that annually considerable amounts of K are removed from the soil by the crop. On some of the more sandy soils the K concentration may not be high enough to meet the demands of Amazon cacao especially when grown without shade. In view of the fact that responses to Mg have been recorded in certain years on a few sites, it seems advisable that Mg is applied along with K. The sedimentary soils are very low in exchangeable and total K. Application of this element seems to be a prerequisite for successful cacao cultivation on these soils.

Fertilizers affected the number of pods but not the content of the pods.

As to the technique of the field experimentation on farmers' cacao, the need of pre-treatment yield recording should be stressed. The cacao trees are extremely variable in yield, mainly because of a long history of insect attacks and replanting of missing stands. The statistical analyses have shown that standard errors are considerably reduced when pre-treatment data are used in an analysis of covariance. A two year period was found to be sufficiently long to record the existing differences in yield between the experimental plots.

8.4 Soil and leaf analyses

When the preliminary results of the fertilizer trials became available, the next step was to investigate whether soil and leaf analysis could be used in assessing the fertilizer requirements of cacao. For soil phosphate, determinations of available P from the Bray and Kurz no. 1 extractant and Olsens alkaline extractant were found to give very similar results.

The results of both determinations made it possible to classify the soils in the following categories: P deficient, moderately P deficient, non P deficient and soils with a high P status. This classification corresponds very well to the responses to P fertilizers on these soils. For technical reasons the Bray and Kurtz procedure was preferred to the Olsen method. As could be expected the determinations of total N did not yield useful information on N availability to cacao.

Applications of leaf analysis to cacao have so far been very limited. The main problem has been and still is that effects of light and age on leaf composition are often more pronounced than nutritional effects. The age of leaves cannot be determined from the position of the leaf itself or fruits on the branches. The problem of light intensity is connected with the fact that cacao trees are grown under widely varying shade conditions and at different, often irregular, spacings. Apart from these two factors many other factors such as interaction between shade and nutrients, competition for nutrients between shade trees and cacao, fruit production and formation of young leaves, affect the mineral composition of the leaves. The effects of these factors have been reviewed in chapter 7.

A critical study of chemical data obtained by Humphries and Fennah in Trinidad has shown that a clear linear relationship exists between the percentage dry matter in the leaf and its age and that the concentrations of the elements P, K and Ca which are highly significantly correlated with leaf age, show about the same degree of correlation with the dry-matter content of the leaf. From this finding it was concluded that the dry-matter content could be used as an index of age. Further investigations revealed that the dry-matter content is not only an indication of real age but also of physiological age. This dry-matter index can only be used as long as these relationships stay linear. This is usually from the 4th till the 10th week after bud opening, the exact length of the period depending on light conditions. Furthermore, it was found that during the same period the P and K concentrations remain almost constant when expressed on a fresh-weight basis. There are thus two ways of at least partly overcoming the age problem when studying the nutrient concentrations in young leaves:

1. elimination of age effect by correcting nutrient concentrations for regression on dry matter;
2. expressing results as percentages of fresh weight.

The first method is applicable to P, K and Ca; the second to P and K only.

Another problem of leaf sampling is how to make sure that leaves of the same age are sampled. This is an important question because large differences exist between nutrient concentrations and ratios in young and older leaves. As has already been mentioned, the age of the leaf cannot be known from its position on the branches and twigs because of the existing differences in flushing rhythm between branches of the same tree and branches of different trees.

Observations on the changes in the morphology of the leaves which take place after hardening have shown, however, that the green colour of the petiole darkens in a characteristic way with time and that this colour change makes it possible to estimate the approximate absolute age of young leaves and the relative age of older leaves. The main advantage of the examination of leaf petioles is that samples of the same age can be collected.

After these considerations on leaf age the results of the leaf analyses will be discussed. First it should be mentioned that the main aim of the programme was to see if foliar analysis could be used in explaining the differences in response to fertilizers as found on the various experimental sites. For this purpose trees not receiving fertilizers were sampled in three periods: April/May 1968, August/September 1968 and January 1969.

In the first and last periods many young leaves are available for sampling because they follow the two main annual periods of flushing. The second period was chosen because it coincides with the stage when the developing main crop exercizes its greatest demands for nutrients. When nutrient deficiencies exist, they are likely to be more pronounced at this time of the year.

The results have demonstrated that the nutrient concentrations in the April/May leaves reflect the differences in the nutrient status of cacao on the various sites better than those in the January leaves. It is thought that conditions of water stress in January might have a stabilizing effect on the nutrient concentrations which makes them less "sensitive." In the August/September period sampling itself gave problems because in the preceding months trees formed new leaves at some sites and not at others. The differences in leaf age caused by these variations in flushing are so large that age effects seriously hamper the interpretation of the results when comparing the data of different sites.

It must thus be concluded that April and the beginning of May is the best sampling period when results of different sites have to be compared.

For this reason only the results of the April/May leaves will be used when discussing the concentrations of the nutrients.

For nitrogen it was found that in young leaves percentages of N < 1.80 were associated with cacao showing a large response to N applications and percentages between 1.80 and 2.00 with cacao showing small or no responses to applied N. According to the criteria of LOUÉ and MURRAY cacao with N concentrations between 1.80 and 2.00 per cent should be considered as N deficient, albeit a moderate degree of deficiency. The fact that the N percentages in the cacao leaves do not exceed the 2.00 per cent limit at any site and that nevertheless a part of this cacao does not respond to applications of N fertilizers does not seem to be in agreement with these criteria. A distinct relationship between the N and P nutrition of cacao was found however in the general trend that the responses to N fertilizers decreased and the N/P ratio increased with decreasing amounts of available P in the soil.

This indicates that the P concentrations in the growing medium have a profound effect on the N concentrations in the leaves. HOMÈS goes even further in saying that the N concentration in cacao may even be more influenced by the P than the N concentration in the growing medium (in Homès' experiment nutrient solutions in a sand culture were used). It could thus be that cacao is N deficient at all the experimental sites in an absolute sense but that the response to N fertilizers depends on a relative deficiency in regard to P. This should imply that once the P status of the soils has been raised, responses to N can be expected. Unfortunately the absence of positive N-P interactions on many sites does not support this view.

The main conclusion is that in predicting the N requirements of cacao not only the N concentrations have to be considered but also the equilibrium between N and P. In young non deficient leaves N:P ratios usually range between 10 and 11, but a value within this range can also be found in leaves which are equally N and P deficient. An N:P ratio < 10 is however an indication of N deficiency while a ratio > 11 usually indicates P deficiency.

The results of the P analyses are more straightforward than those of nitrogen. The most probable reason is that while leaf N and also leaf K are greatly affected by light intensity conditions, P concentrations are only affected to a much smaller extent. In addition more sites responded to P and as a result of this more data were available from which conclusions could be drawn. These can be summarized as follows. The P concentrations in the leaves were closely related to the amounts of available P in the top 0–6 inches of the soil. On the basis of leaf analysis cacao can be classified as P deficient, moderately P deficient and not P deficient, while furthermore the degree of response to P fertilizers for each of these categories can be indicated.

A summary of the relationship between soil and leaf analyses and responses to phosphate fertilizers has been given in table 35.

The results of the K analyses confirm that lack of K does not limit cacao production on the soils derived from metamorphic igneous rock. On the sedimentary soils, however, very low K figures have been found which reflect the low K status of these soils.

It has already been mentioned that in general a close linear relationship exists between the P and K concentrations and the dry-matter content in the leaves. This relationship was found on individual sites and on groups of sites with approximately the same P status. When the results of all sites were considered together this relationship had largely disappeared as a result of the differences in the P concentrations in the soils at the various sites. In the case of K the relationship was maintained when all results were considered together despite the rather large variations in exchangeable K between soils. This seems to be another indication that the cacao trees have an adequate K supply.

Lastly the influence of N, P and K fertilizers on leaf concentrations was investigated. The present and a previous study showed that dressings of N and P raised the concentrations of leaf N and leaf P respectively. Simultaneously mutual N-P and P-K "antagonisms" were operative. In this study leaf concentrations were corrected for the effect of age by means of their regression on dry matter. This greatly reduced the error in the analysis of variance of the P, K and Ca concentrations indicating that this technique provides a good practical means of eliminating at least some of the variations due to age.

8.5 Fertilizer use

The ultimate goal of the fertilizer and soil and leaf analysis studies was to arrive at a preliminary fertilizer recommendation which is presented in table 39.

As only few leaf analysis data are available for young cacao, the recommendations for young trees are based on the experimental results and the differences in chemical status usually observed between cleared forest soils and soils with a recent cropping history. The P status of forest soils is usually high and for this reason P fertilizers do not have to be applied before trees come into bearing and the depletion of available P reserves in the soil by crop removal starts. As high yielding Amazon cacao is likely to exhaust gradually the available K reserve, the nutrition of the trees on light textured soils calls for special attention.

TABLE 39

Preliminary fertilizer recommendation for cacao on soils derived from metamorphic igneous rock

young cacao (established according to modern planting and maintenance methods)

year	soils cleared from forest		soil cleared from cacao and arable crops	time of application		remarks
year of planting	10 g N/tree		10 g N + 10 g P_2O_5/tree	one half in July	one half in September	apply fertilizers on the soil surface in circular bands starting at 6 inches from the stem
1st to 3rd year after planting	20 to 30 g N/tree		20 to 30 g N + 20 to 30 g P_2O_5/tree	one half in April	one half in August	
4th and 5th year after planting	45 to 60 lb N	+	30 lb P_2O_5/acre	one half in April	one half in August	annual broadcast application of fertilizers
6th and following years	60 to 90 lb N	+	45 lb P_2O_5/acre*	one half in April	one half in August	annual maintenance fertilizer treatment for bearing cacao

existing mature Amelonado cacao

cacao	nutritional status soil	nutritional status leaf**	recommended fertilizer rate	time of application		remarks
severely N deficient	–	% N<1.80 or 1.80<% N<2.00 and N/P<9	120 lb N/acre	one half in April	one half in August	annual broadcast application
moderately N deficient	–	1.80<% N<2.00 and N/P>9	60 to 90 lb N/acre	one half in April	one half in August	annual broadcast application
not N deficient	–	%N>2.00	no N fertilizer			
P deficient	available P<10 ppm	% P(dm)<20 %P (fm)<0.070	45 to 60 lb P_2O_5/acre	one half in April	one half in August	annual broadcast application
not P deficient	available P>12 ppm	% P(dm)>20 % P (fm)>0.070	no P fertilizer			

* these rates have to be adjusted according to the criteria given for mature cacao

** 5 to 10 weeks old leaves sampled in April/May

The recommendations for mature cacao have been based on the soil and leaf analysis criteria as previously discussed.

As large scale soil and crop testing facilities are not yet available in Nigeria a simplified recommendation is made for the farmers, recommending the use of an NP compound (20% N and 20% P_2O_5) for cacao on metamorphic rock soils and of an NPK compound for cacao on sedimentary soils. The rates for young cacao increase from 2 ounces (56 grammes) per tree in the year of planting to 4 ounces in the fourth year after planting. From the 4th to the 6th year 2 cwt (100 kg) NP compound should be applied annually and from then onwards 3 cwt, which is the same rate as recommended for the existing mature cacao.

As a result of fertilizer application yield increases of the order of 30 per cent can be expected on soils physically suitable for cacao provided that pest and disease control form an integrated part of cacao farming. Calculations of the economic returns of fertilizer application on mature cacao (WESSEL 1970c) have shown that on well maintained farms value to costs ratios of 3 and higher can be obtained when the above recommendations are followed.

I. METHODS OF ANALYSIS

1. Soil samples

1.1 Pre-treatment of samples

The soil samples were air-dried in trays. The air-dry soils were lightly crushed and passed through a 2 mm sieve. The fractions retained by and passed through the sieve were weighed to calculate gravel percentages. The fine earth was checked for rootlets and organic debris. Sub-samples were taken for moisture determinations and mechanical and chemical analysis.

1.2 Physical methods

1.2.1 Mechanical analysis

Silt and clay determined by the hydrometer method (Bouyoucos, G. J. Soil Sci. 23, pp. 319–27 (1924)), coarse sand by sieving and fine sand by difference. Size limits of soil separates according to the International System:

> 2 mm	gravel
2.0 — 0.2 mm	coarse sand
0.2 — 0.02 mm	fine sand
0.02 — 0.002 mm	silt
< 0.002 mm	clay

Determination of basic soil textural classes in terms of the International System for soil separates according to a modified graphical chart (Loxton, R. F., S. Afr. J. Agric. Sci. 4, pp. 507–12 (1961).

1.2.2 pF determinations

Air-dry soils which had passed through a 2 mm sieve were transferred to a cellophane membrane of a pressure membrane apparatus. After the samples had been saturated with moisture for 24 hours, pressures of ⅓, 1, 4, 10 and 15 atmosphere were applied for 24 to 72 hours and the moisture contents at equilibrium were determined gravimetrically.

1.2.3 Field-capacity and bulk-density determinations

Sufficient water was applied to each soil horizon to wet the soil completely. Areas of two square feet of wet soil were covered with polythene sheeting to prevent losses by evaporation. Samples were taken after 48 hours when excess drainage had stopped. In gravel-free and almost gravel-free soils cylinders of 100 ml volume were used, in gravelly soils wide cylinders of 600 ml volume. As the soils could not be sieved in the wet state, the wet samples were weighed, oven-dried and reweighed. The dry soils were passed through a 2 mm sieve and the weights of the fractions larger and smaller than 2 mm recorded. The moisture content at field capacity and the bulk density of the soil were calculated both for the whole soil mass and the fraction smaller than 2 mm.

Because in gravelly soils different samples of the same horizon contained greatly varying proportions of gravel, it was impossible to obtain reproducible figures for the bulk densities of gravelly soils. The figures presented have been obtained by calculating the mean of three samples per horizon.

1.3 Chemical analysis

pH: determined by a glass electrode in soil suspension of 1 N KCl using a soil:solution ratio of 1:2.5.

Organic carbon: estimated by the chromic-acid-oxidation method (Walkley, A. and I. A. Black, Soil Sci. 37 pp. 29–38 (1934)).

Total nitrogen: determined by the usual macro-Kjeldahl digestion method using sodium sulphate and copper sulphate as catalysts and micro-Kjeldahl distillation.

Exchangeable bases: determined in a 1 N ammonium acetate (pH 7) extraction solution. Potassium by flame photometer, calcium and magnesium by an E.D.T.A. method involving a calcium and magnesium separation (Barrows, H. L. and E. C. Simpson, Soil Sci. Soc. Am. Proc. 26, pp. 443–45 (1962)).

Exchange capacity: calculated from values for total exchangeable bases and exchangeable hydrogen determined by the calcium p-nitrophenol method of Woodruff (Jackson, M. L., Soil Chemical Analysis, 1960).

Available phosphate: determined in 0.03 N NH_4F in 0.025 NHCl (Bray and Kurtz solution nr. 1) according to Jackson (1960) employing a shaking time of 10 minutes and a soil to extractant ratio of 1 : 10.

Available phosphate: determined in 0.5 N $NaHCO_3$ adjusted to pH 8.5 according to Olsen *et alii* (Jackson, 1960).

Organic phosphate: extraction of P with acid before and after ignition (Jackson, 1960).

Total phosphate: $HClO_4$ digestion of the sample followed by vanadomolybdophosphoric colour development (Jackson 1960).

Phosphate fractionation: according to Chang and Jackson, Soil Sci. 84, pp. 133–14 (1957).

Phosphate sorption capacity: measured according to Kurz, T. *et alii*, Soil Sci. 61, pp. 111–24 (1946). A 2 g sample was shaken for 24 h. with 50 ml of a KH_2PO_4 solution (pH 7) containing 4 µg P/ml. (in samples from Iddo and Ricket also solutions of 2, 6 and 8 µg P/ml were used). After centrifugation the P concentration in the supernatant was determined and the amount sorbed obtained by difference.

2. Leaf samples

2.1 Pre-treatment of samples

The collected leaves were stored in polythene bags and the fresh weight was recorded as soon as possible after the description and the removal of the petioles. Leaves were wiped with wet cotton-wool and rinsed in demineralized water to remove the dust. After drying at 85°C dry weights were recorded. Samples were ground in a micro-hammermill before sub-sampling for analysis.

2.2 Chemical analysis

Wet digestion of the sample according to Lindner and Harley (Schuffelen A. C. *et alii*, Neth. J. Agric. Sci. 9, pp. 2–16 (1961)).

Nitrogen: micro-distillation according to Kjeldahl

Phosphate: chlorostannous-reduced molybdophosphoric blue colour method in a sulphuric acid system (Jackson, 1960)

Potassium, calcium and magnesium: see methods of analysis for soil samples.

3. Butter fat determinations in cacao beans according to Analytical Methods of the Office International du Cacao et du Chocolat, pp. 8a–b.

II. SUMMARIZED ANALYSES OF VARIANCE[1]

Series I experiments: analysis of variance over all 8 sites (pods/plot). Yields 1962–67 adjusted by yields 1960–62.

Source		D.F.	Mean Square
sites		7	2.553.096***
(blocks within sites)		(8)	—
treatments:	N	3	2.561.664***
	P	3	2.182.818***
	K	1	192.832
	Ca	1	766.924
	Mg	1	727.137
	NxP	9	590.017
	NxK	3	167.424
	NxCa	3	703.297
	NxMg	3	5.469
	PxK	3	80.419
	PxCa	3	191.121
	PxMg	3	256.860
	KxCa	1	1.242.189
	KxMg	1	0
	CaxMg	1	256.522
	Error	200	454.749
	Total	254	—

Series II experiments: analysis of variance over all 5 sites (lb dry beans per acre). Yields 1964–69 adjusted by yields 1961–64.

Source		D.F.	Mean Square
sites (S)		4	1.489.190***
treatments:	N	2	513.390
	P	2	1.545.018**
	KMg	2	126.917
	NxP	4	126.139
	Nx(KMg)	4	189.937
	Px(KMg)	4	107.680
	SxN	8	159.051
	SxP	8	225.408
	Sx(KMg)	8	145.902
	SxNxP	16	104.133
	SxNx(KMg)	16	112.237
	SxPx(KMg)	16	211.945
	Error	39	226.412
	Total	133	226.725

[1] These analyses were carried out by Mr. P. Walker of Rothamsted Experimental Station, England.

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