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Titel

Soils and crop yields of rainfed coffee on the southeastern slopes of Mount Kenya

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CONTENTS

Preface

This report contains the results of a fieldwork carried out as a part of a six-month post-graduate course in tropical soil science of the Agricultural University of Wageningen.
The fieldwork took place in the period from March to May, 1986. It was a part of the Training Project In Pedology of the Agricultural University of Wageningen, in Chuka, Embu District, Kenya.
The object of the Training Project In Pedology (TPIP) is to prepare a soil map of the Chuka area, scale 1:100,000, and a report for the Kenya Soil Survey.
A broader objective is to obtain a better knowledge of the soils and the agricultural conditions in the area to provide a basis for the further agricultural development in the area.
Land evaluations have been carried out for different crops.

This report concerns the land evaluation for arabica coffee.
The research aims at a quantitative land evaluation; describing the actual yields in different zones of the survey area as a function of different land characteristics.
The attention is focussed on the determination of the influence of soil, climate and slope on crop yields to provide an answer to the question: "Can a quantitative land evaluation be based on these land characteristics"?

The tutor was Mr. D. Legger.
I wish to express my gratitude to Mr. T. de Meester and Mr. J. Dijkerman of the TPIP staff, personnel and students at the TPIP camp, all the farmers and personnel of the Farmers' Cooperative Societies and coffee factories in the survey area for their kind cooperation, the personnel of the Kenya Soil Survey in Nairobi and of the routine lab. of the National Agricultural Laboratories who prepared the soil test reports, the personnel of the Liquoring Department of the Coffee Board of Kenya and Mr. C.N. Mwongi and Mr. J. Mburu of the Coffee Research Foundation in Ruiru.

SUMMARY

This report concerns the land evaluation for arabica coffee in the coffee zone of the Kyeni area, Embu District, Kenya. The research aimed at the determination of the relation between actual crop yields and characteristics of climate, soil and slope.

Methods

In a sample strip across the coffee zone augerhole and profile pit observations have been made at regular intervals in pairs, consisting of a shamba on a slope and a shamba on nearly flat terrain. Soil samples have been analysed and the information about augerholes and profile pits has been summarized in two computer databases.
Statistical tests have been carried out to determine the nature (positive or negative) and significance of linear relationships between the variables in the databases. Two separate tests were carried out to decide whether the population of yields of shambas on slopes and the population of yields of shambas on nearly flat terrain must be considered as separate populations or as samples from the same population of yields in the survey area.
The land evaluation has been based on the results of the statistical tests and on a comparison of crop requirements and land qualities in the survey area.

Results and conclusions

The most significant positive correlation exists between yield and altitude. Altitude can easily be translated into climate.
The difference between yields on slopes and on nearly level terrain is not significant.
Shallow soils are less favourable for yields than deep soils. The first soils are orthic, ferric and humic Acrisols, the latter are dystric Nitisols and one humic Nitisol.
Nutrient levels in the soils are deficient. Especially shortages of available phosphates limit yields.
Soil erosion occurs on nearly every sloping coffee shamba. Soil erosion does not yet limit yields, but it probably will in the near future if no appropriate measures are taken.

The land mapping units or zones of the land evaluation are derived from figure 8, showing the average yields of the surveyed shambas as a function of the range of altitudes. From 1150 to 1600 m the maximum average yields increase from about 1 to 12 kg and decrease steeply above 1600 m.
Six zones are recognized and they are characterized by a certain range of yields and a range of altitudes. Factors which limit production are described for every zone separately.
The yield differences which exist between zones are in the first place a result of differences in rainfall.
The yield differences within a zone are in the first place a result of differences in management by the individual farmers, in the second place of poor physical conditions, such as Acrisols with limited rooting depths.

GLOSSARY AND ABBREVIATIONS

average yield	- average annual yield of berries per coffee stem on a certain shamba, calculated from total yields of berries in three consecutive financial years (1982/1983, 1983/1984 and 1984/1985) on that shamba and the number of stems on that shamba
coffee: berry or cherry	- ripe fruit of coffee tree which has been picked but not pulped
buni coffee	- fruit of coffee tree which has been dried without removing pulp and parchment, produces coffee of low quality
parchment coffee	- coffee which has been pulped but which has its parchment still intact. It is sent to mills in this form after fermenting and drying
clean coffee	- coffee which has been milled, to remove the parchment and silverskin from the bean
debe	- a unit of measurement equivalent to a 20 litre kerosene tin
jembe	- a broad bladed hoe
panga	- single edged matchet
shamba	- field
CBK	- Coffee Board of Kenya
mm	- millimetres
cm	- centimetres
m	- metres
km	- kilometres
ha	- hectares
kg	- kilograms
KPCU	- Kenya Planters Cooperative Union
Ksh	- Kenya shilling
TPIP	- Training Project In Pedology

1 GENERAL INFORMATION

The survey area is located in the coffee zone of the Kyeni area, Embu District, Kenya, see figure 1. This zone forms a coffeebelt on the southeastern slopes of Mount Kenya and runs from an altitude of about 1150 to 1840 m above sealevel. A wide range of rainfall, temperature and soils is found in this zone. The survey area is a cross-section of this coffeebelt which is approximately 24 kilometres wide in the Kyeni area.
The survey area corresponds with the coffee zone part of the southern sample strip of the Chuka-South soil survey (De Meester and Legger, 1988) and covers the ISC/ICRA survey area.

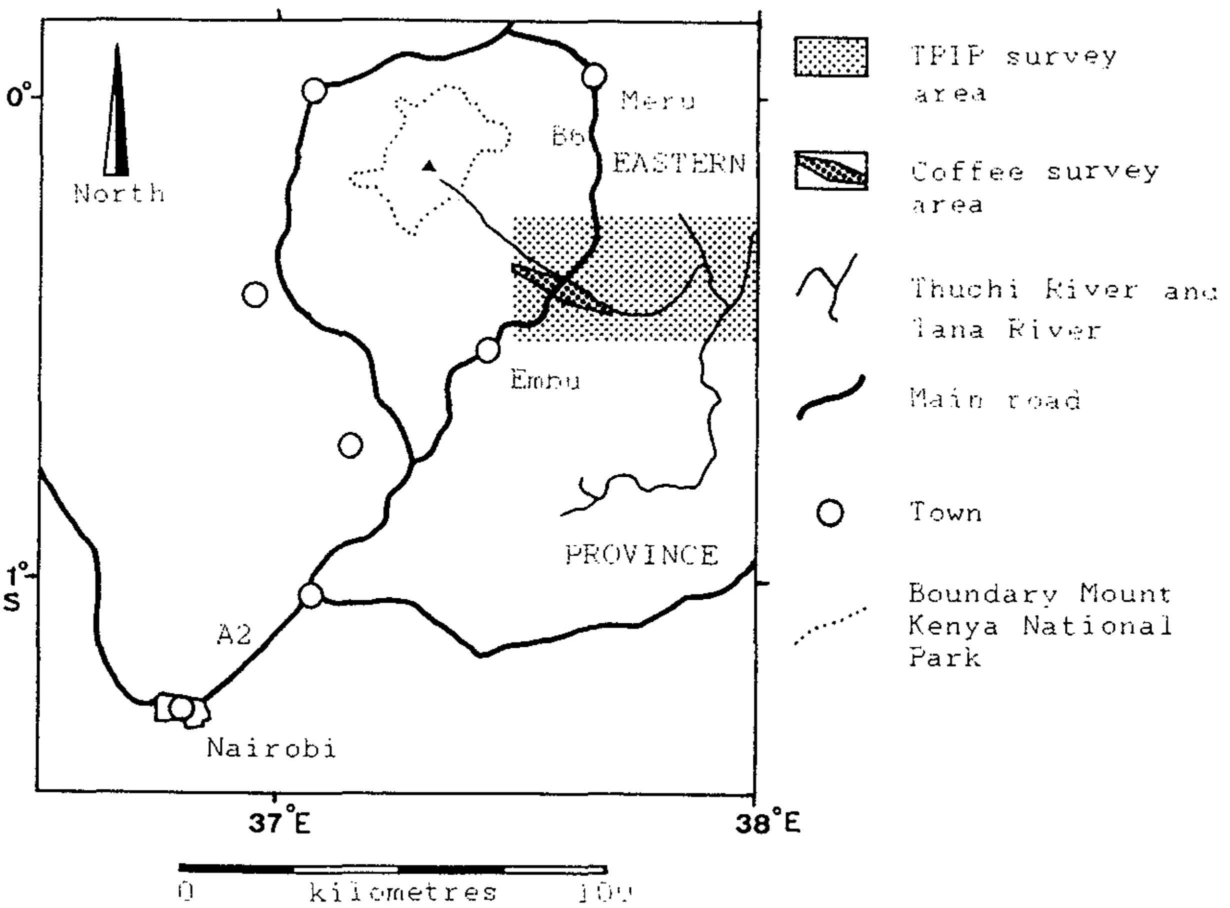

Figure 1. Location of survey area

The area is situated on the Mountain Footridges of Mount Kenya. The ridges are caused by the minor and major incisions of streams and rivers. The valley of the Thuchi River is the only major incision in the survey area, the other valleys are less than 100 metres deep. The general direction of drainage is from the north-west down to the southeast.
From summit to slopes of the Footridges, the meso-relief varies from gently undulating with mean slope percentages of 2 to 5%, to hilly, 16 to 30%. Locally in major valleys, slopes of up to 100% are found. The average slope of the survey area from 1840 m down to 1150 m is only 3.5% .

The bimodal rainfall pattern results in two growing seasons per year. The first is from March to July and the second season is from October to January. Average annual rainfall is approximately 1100 mm at an altitude of 1200 m and 1800 mm at 1800m. The relation between altitude and rainfall is linear, compare maps 1 and 2, appendix 1.

The following information is a summary of the ISC/ICRA report (ISC/ICRA, 1986), about the farming system in part of the coffee-belt between 1250 and 1500 m.
Most farms have a size of only one to five hectares, in private freehold titles. The average farm size is approximately 2.5 hectares. The average family size is nine persons.
Sub-division of holdings is occurring to provide land for male children, reducing the average farm size still further.
The main food crops are maize and beans, and cattle, usually 2 or 3 heads, is kept in a zero-grazing system due to the shortage of land. Land cultivation is permanent, intensive and any land not under perennial crops is double-cropped. Predominantly, cultivation is carried out with manual labour.
On average 19% of the total area of a farm is under coffee, 40% is used for maize and beans, 12% for bananas, 3% is under Napier grass for fodder production and 26% is used for other crops. These figures concern the low rainfall area from 1250 to 1500 m, at higher altitudes the cultivation of tea is expanding ever since the introduction around the year 1960.

Coffee growing was introduced in the survey area before 1940 and expanded during the fifties. The dominant varieties of Coffea arabica grown in the area are K7, SL28 and SL34 and the proportion of bearing trees is almost 90%.
Activities of the coffee enterprise in order of labour intensiveness are picking of berries, weeding, pruning, manuring, spraying of herbicides, fungicides and pesticides and communal labour at the coffee factory. On slopes the labour involved in the construction and maintenance of benched terraces, is important.
Pesticides and fungicides are applied by the majority of the farmers but at rates below these recommended by extension. In spite of the use of pesticides and fungicides, pests and diseases such as Coffee Berry Disease and thrips, cause large losses of yield.
Herbicides are applied by approximately 30% of the farmers. Most weeding is still done with the panga.
Chemical fertilizers are applied by about 90% of the farmers. The fertilizer most commonly used is Calcium Ammonium Nitrate, applied at a reported rate of about 280 kg per hectare. This rate is less than one tenth of the rates recommended by extension.
98% Of the farmers use animal manure at a reported rate of approximately 15 debes per ten trees.

ISC/ICRA reports an average yield of 4.8 kg per bearing stem in the upper part of their survey area above 1400 m and 6.0 kg in the part below 1400 m. This is surprising, because the climate in the upper part (Main coffee zone) is more favourable for coffee than in the lower part (Marginal coffee zone).
The upper part is more incised by streams and rivers, and coffee stems are growing on generally steeper slopes than in the lower part of the ISC/ICRA survey area. Steeper slopes are more eroded and possibly less favourable for coffee, possibly overshadowing the advantage of climate and explaining the differences in average yields reported by ISC/ICRA.
Therefore, an important hypothesis to be tested is that coffee stems on slopes yield less than coffee stems on nearly flat terrain.

2 METHODS

2.1 Selection of locations

The research started with a reconnaissance survey of a sample strip, covering the coffeebelt which is approximately 24 kilometres wide.
In a west-east direction, pairs of observation sites, numbering 1 and 2, 3 and 4 etc. to 22, were selected at two kilometre intervals. Each pair consists of a coffee shamba with a slope of more than 10% and another with a slope of less than 8%, sloping to the South. Care was taken that each coffee field was the only one of the farmer concerned so that yield data, available at the farmers' cooperatives, could be related to the yield of this particular field.
In every selected shamba one auger observation was made, approximately in the middle of the field and between two trees standing in a row (see map 1, appendix 1). Data about the soil profile and the environment of every selected shamba were noted (see specimen of description form 1, appendix 1). Special attention was given to signs of soil erosion and measures to control it.

The next step was to make a more detailed soil survey in the Kyeni-Kathunguri area. This area was selected since coffee is the most important source of income for the farmers in this part of the coffee belt and a vast amount of research had already been carried out by the ISC/ICRA group.
Eleven soil profile pits, numbered 1 to 11, are located in coffee shambas in this area. Soil profile descriptions are presented in appendix 6.
Seven locations for soil profile pits were chosen from the random sample of 80 shambas made by the ISC/ICRA group. The pits were chosen to the south of the reconnaissance strip.
Again, pairs of a nearly level shamba and a shamba on a slope were selected at regular intervals (see map 1, appendix 1).
One more soil pit was selected in the main coffee zone. The crop performance of several shambas in that part of the main zone is strikingly poor, which had to be investigated.
Three more soil profile pits were selected from 130 soil profile pits studied by other TPIP students. Those pits were added to the coffee survey because they are located in coffee shambas in the southern sample strip. Data about the soil profile and the environment of every selected shamba were noted (see specimen of description form 2, appendix 1).

2.2 Soil description

Soil profile descriptions of the profile pits were made according to the "Guidelines for soil profile description" (FAO, 1977) and the "Field guidelines for the annotation of the soil profile description form" (Kenya Soil Survey Staff, 1978), see appendix 6.
All profiles from auger observations and soil profile pits have been classified using the "Legend of the FAO-Unesco Soil map of the world" (FAO-Unesco, 1974), supplemented with "The application of the FAO/Unesco terminology of the soil map of the world legend

for soil classification in Kenya" (Siderius, W. and Van der Pouw, B.J.A., 1980).

2.3 Soil analyses

Soil samples were taken from augerings and profile pits. The samples were taken separately from every soil horizon. Soil material for the samples was gathered along the complete depth of every horizon to represent the mean composition of the horizon. Samples from augerings have only been tested for pH-H2O at the TPIP field laboratory. This test was carried out because the value of pH is an indicator for the base saturation and therefore of nutrient availability for the crop. pH-H2O of topsoil and subsoil is presented in the databases (appendices 2&3).

The soil horizon samples from the profile pits were also tested for gravel %, sand %, silt %, clay %, pH-KCl, Electrical Conductivity, Carbon %, Cation Exchange Capacity, the exchangeable cations calcium, magnesium, potassium and sodium, and the presence of qualitative calciumcarbonate. These tests were carried out by the National Agricultural Laboratories in Nairobi. The same laboratories have also tested fertility samples taken at standard depths of 0-20 cm and 40-60 cm in every profile pit. The soil test reports are presented in Appendix 8.

Farmers' Cooperative Society	Name of factory and registration number		altitude in metres
Kagari North	Kanja	01	1720
Kiangagwa	Mururiri	02	1620
	Ivurori	03	1530
Kanjugu Kamurai	Gitwa	01	1450
	Kathugu	02	1400
New Kyeni	Gakwegori	01	1470
	Kashagori	03	1400

Table 1. Cooperative Societies and coffee factories in the survey area.

2.4 Yield figures

All coffee farmers are members of Cooperative Societies. The latter buy the coffee berries and process them in factories (table 1). Each Cooperative keeps a register of the amount supplied by each farmer during a year. Every year has two picking seasons (except Kagari North Society which has only one) and the financial year ranges from September to August. Membership number and number of coffee stems were noted at all the farms visited.
The total amount of berries produced by every farm in the survey was noted at the cooperatives for three consecutive financial years: 1982/1983, 1983/1984 and 1984/1985.
These figures were converted into the mean yield per stem, to

enable comparisons between shambas of different sizes.
The mean yields per stem per year are presented in the databases (appendices 2&3).

If necessary, mean yield per stem can easily be converted into yield per hectare or per acre. Traditional coffee spacing is used everywhere. This means that the spacing is 9 ft * 9 ft, giving approximately 1330 plants per hectare. On benched terraces the distance between the rows is increased, but the spacing within the rows is reduced to give the same density per hectare.

Due to several reasons, the figures of some farms and the figures for the year 1982/1983 of Kanjugu Kamurai were not available.

For comparison, some farmers were asked for their own estimate of their average annual production.

Apart from the quantity of berries, the quality had to be studied. Payment for high-quality beans is much better. The quality of berries is not determined for each farmer seperately, but for the total production of all farmers who deliver to the same factory. The quality can vary considerably during the season.
For instance, many light beans are produced during the beginning of the season.
The berries and beans are graded for quality and size at five different stages of the production.

- The farmers select the berries before delivery to the factory: red and yellow beans are suitable for the factory and green and dark brown berries are dried at home for buni coffee. Buni coffee is only a small part of the total production and is much less profitable than the parchment coffee produced in the factory. Buni coffee production has been excluded from the enquiry.
- The parchment coffee is graded for weight and size at the factory in three classes.
- On the drying tables, the parchment beans are checked for discolouring and bad beans are discarded.
- Grading for size is again carried out in Nairobi by the KPCU, where the hulling of parchment into clean coffee is done.
- Finally, the quality of every "lot" of coffee is rated by the Liquoring Department of the Coffee Board of Kenya in Nairobi. There are ten different classes (appendix 11). The first six are export quality. The value of a "lot" of export quality coffee is determined by the world market, and is quite variable. Large beans are generally preferred, but relatively small beans have the same average quality and value. Beans from Coffea arabica which grows in the survey area, fetch better prices than beans from Coffea robusta, which grows in lowland areas.

The final price paid to the farmer for a kilogram of berries is the total value of all the berries delivered by all the farmers to one factory in one year, minus the costs for running the factory and the cooperative, and divided by the total weight of the berries delivered at the factory.
The final price and the quality class attained by a factory can serve as an indicator for the suitability of an area for growing coffee and was therefore recorded.

The Societies were also asked the names of their "best farmers", to find out the maximal production per stem in the surroundings of every factory. These farmers were visited to check the number of stems.

2.5 Computer databases

Two computer databases are made to summarize the variables which probably influence the production of coffee.
The first database contains the data that were gathered in all the coffee shambas with augerhole or profile pit, without the data from the soil test reports (appendix 2).
The second database contains the data for the profile pits plus the data from the soil test reports (appendix 3).

The databases have been made with the help of the ABSTAT statistical program on an MS/DOS personal computer.
Many data had to be coded because the program does only accept numerical data. The titles of the variables had to be limited to eight signs.
The explanation of the codes, units of measurement and description of the variables are presented in the legends that accompany the printed databases in the appendices.

Besides the purpose of summarizing the data, the databases do enable statistical analyses to be prepared by computer.

2.6 Statistical analyses

The ABSTAT program and the databases were used for testing different variables for their relation with each other and for comparing the sample population of yields of shambas on slopes with the sample population of yields on nearly flat shambas.

Plots have been made to illustrate the relationship between some variables.

Non-parametric tests were usually preferred because these do not require that the sample values are taken from a normally distributed population.
One important assumption must be satisfied: the yield data and data of other variables must come from random samples.
The locations themselves, from which the variables originate, are the result of the systematic sampling procedure described in paragraph 2.1. These are not chosen completely at random, but in clusters of two or three shambas, at regular distances.
Usually random samples meet the demands for statistical tests better than systematic samples as used in the tests. In the survey it was decided that the systematic sampling procedure would provide the best possible description of the population of coffee shambas as a whole, considering the number of samples which could be collected.
For detailed information on the tests used, the reader is referred to textbooks on statistics (e.g. Ebdon, D., 1977).

The analysis started with a calculation of the Pearsons correlation coefficients of most pairs of variables in each database. This resulted in two correlation matrices which are presented in appendices 4 and 5.
ABSTAT excludes cases with missing values in one or more variables from the calculation. Therefore, the coefficients for

variables with many missing values are calculated separately.
The correlation coefficients may or may not show that there may be a real association between two variables. These results do not in themselves prove the nature of the relationship: it may be a causal relationship or merely an association.
The tests used, are tests for proving linear relationships.

The attention was focussed on the correlation of average yields with other variables.

The set of sample values of every variable has first been ranked in order of magnitude. The resemblance of a series of ranks of one variable is compared to that of another. The degree of resemblance or correlation is expressed in the coefficient. The coefficient can vary from -1.0 to +1.0.

Some variables with a relatively high correlation with yields were tested for the significance of the correlation coefficients. On the other hand, some correlations were tested because a low value of correlation was found where a strong relationship between two variables could be expected.

The coefficient may either signify there is a relationship between two variables or the coefficient may be due to chance in the sampling process.
In order to be able to decide whether the coefficients show that variables are correlated or not, the significance of the value of the coefficient must be judged.
The significance level of for example 0.05 is the chance that on the basis of the correlation coefficient of the sample sets of values of two variables in the matrix, the false decision is made that the total populations of the two variables are correlated.
The chance that the decision that the two variables are correlated is true, is 0.95.

The two possible decisions can be summarized in the following hypotheses, in which Rs is the rank correlation coefficient of the populations of the variables and rs is the correlation coefficient calculated from the samples of the variables, shown in the matrices.

H0: Rs = 0. There is no rank correlation between the two variables. If the sample rank correlation coefficient (rs) is not zero, this is due to chance in the sampling process

H1: Rs $\neq$ 0. There is a relation, either positive or negative, between the two variables

Levels of significance correspond to different critical values of rs, depending on the significance level chosen and the number of values in the sample of the variable.

The critical values of rs which are relevant for the evaluation of the matrices, are given in table 5.
The significance of the correlation coefficients in the matrices has been tested by comparing them to the critical values presented in table 2.
The critical values for the coefficients of the matrix on profile pits are much higher, because the numbers of valid cases are only ten and eleven.

degrees of freedom (number of valid cases)	significance level (two-tailed) 0.1	0.05	0.02	0.01
10	0.564	0.648	0.745	0.794
11	0.523	0.623	0.736	0.818
30	0.305	0.364	0.432	0.478
33	0.291	0.346	-	0.455

If the degrees of freedom are 10, and 0.05 is the significance level that is chosen, then a value of rs in the matrix of more than 0.648 will lead to rejection of the H0 hypothesis. The H1 hypothesis is accepted. The chance of rejecting H0 by mistake, is less than 0.05.
If the H1 hypothesis is accepted, the correlation is either positive or negative, depending on the sign of rs in the matrix.

Table 2. Critical values of Spearman's rank correlation coefficients at different levels of significance (Ebdon, D., 1977).

The sample population of yield figures on slopes of more than 9% has been tested against the sample population of yield figures on flat areas and gentle slopes of less than 10%, to decide whether they are both sample populations from the same population of all yield figures, or the sample populations come from separate populations. This test was carried out to provide the answer to the question whether shambas on relatively steep slopes yield less than on flat or gently sloping shambas. Simple comparisons of means are not sufficient to answer this question, except when a very large part of all yield figures are known in the surveyed area. That is not the case, however. Every cooperative society has hundreds or even thousands of members, of whom only a small sample was taken.

Two statistical tests are suitable for this comparison: Student's T test for two independent samples and Mann-Whitney's U test. Student's T test is the more precise test, but it is parametric and therefore it requires that the populations from which the samples have been taken are normally distributed and the values must be measured on an interval scale.
The second requirement is satisfied, but the first may be disputed, see paragraph 3.2. Therefore, both tests have been carried out.
First, the set of values of average yields was divided into a set of values belonging to slopes of less than 10% and a set of values belonging to values of 10% or more.
The difference between the mean of the yields on steep slopes and the mean of the yields on gently sloping to nearly level shambas can be expressed in a value T. Depending on the value of T, the following hypotheses can either be rejected or accepted:
H0: there is no difference between the means of the populations from which the two samples were taken
H1: the two samples are taken from two different populations with different means

H0 is rejected if the calculated value of T is greater than the critical value at a chosen significance level.

The Mann-Whitney U test is a test for deciding whether there is a significant difference between the medians of two sample sets of data. It is nonparametric, so it is not restricted by any assumptions about the nature of the population(s) from which the samples have been taken.

HO: the two samples are taken from a common population, there is no consistent difference between the two sets of values, any observed difference such that the median of one set of values is consistently larger than the other, is due to chance
H1: the two samples are taken from two different populations with different medians

HO is rejected if the calculated value of U is less than or equal to the critical value at the chosen significance level.

2.7 Land evaluation

The land evaluation aims at describing and explaining the spatial variation of the actual crop production in the surveyed shambas. Average annual yield per stem from 1982 to 1985 was used to represent the actual crop production.
No attempt was made to incorporate different management levels or to calculate maximum yield levels with high level management. Therefore all conclusions about yields bear only on the management levels which are currently used in the surveyed shambas.

First, information on the crop requirements was gathered from interviews with Mr C.N. Mwongi, Head of Research of the Coffee Research Foundation in Ruiru, and Mr. Joseph Mburu, Assistant-director of the chemistry and nutrition section of the same institute. Additional information was obtained from literature.

Than it was attempted to translate the variables of the database into land qualities and to compare them with the crop requirements.
If all land qualities match the crop requirements and management factors are also favourable, yields will be high.
Not every variable, c.q. land quality, has the same significance to crop production in the area. The results from the statistical analyses have been used to find the variables which have the strongest and most significant negative or positive correlation with yields.
The variables can not yet be used to explain the differences in yields in the shambas in a mathematical way. Therefore, the boundaries of the land mapping units for the land evaluation are not based on these variables, but solely on the average yields of the surveyed shambas.
The variable altitude, closely related to climate, has a strong positive correlation with yields and was therefore used for defining suitability zones.

The variation of yields on shambas which are near to each other is high, therefore the yield levels of the suitability zones are defined as broad, overlapping intervals of actual yield levels at certain altitude intervals.
These intervals define six suitability classes which are depicted as land mapping units on map 3.

Than it was checked whether the differences in yield of different land mapping units can be explained by differences in their land qualities. It was also checked whether differences in yield of shambas within the land mapping units can be explained by differences in their land qualities.
A short description of the suitability zones, c.q. land mapping units is based on those comparisons.

Finally the general suitability of the area for the cultivation of coffee is discussed.

3. RESULTS

3.1 Soil description

3.1.1 Environment

All soils are developed in parent material consisting of weathered pyroclastic agglomerates, belonging to the Mount Kenya Series.

The slopes on which the profiles of the survey are situated, vary from 2 to 52 %. The sloping soils under coffee are generally situated on the upper to middle part of the slope of minor valleys with a difference in relief of 20 to 100 metres.
All slopes of more than 10 % which are under coffee, have benched terraces.
The pattern of the slope is usually convex at the upper slope and predominantly linear at the middle and lower parts of the slope.
The bottoms of the valleys are relatively narrow and no coffee is cultivated there.
Most soils on summits and slopes are well drained and the ground-water table is deep.
Only 4 out of 33 profiles are fairly stony at the surface.
Small cracks are visible on the surface of bare soils, mostly on the slopes.

The natural vegetation has been cleared and is replaced by permanent crop cultivation on small farms. There are small shambas for the production of annual food crops like maize and beans in a crop rotation system, and for different kinds of vegetables. Banana trees are quite common, as well as fruit trees such as mango, passion fruit, avocado and citrus. Trees are also planted for timber and firewood. Napier grass is grown for cattle, which is kept in a zero-grazing system.
The most important cash crops are coffee and tea above approximately 1550 m and only coffee below that limit. The coffee is growing in pure stands of 100 to 2500 stems and an average of 480 stems per farm.
For coffee, the tillage practices are weeding with the panga, construction of terraces with the jembe and digging of plant holes.

3.1.2 Soil erosion

The risk of erosion is relatively high in the survey area. During the rainy seasons high intensity showers give rise to potentially

erosive overland flow, especially on slopes.
The foliage of the coffee trees does not sufficiently protect the soil from the impact of raindrops and the soil surface is usually bare because weeds are regularly removed.
However, the relatively high infiltration capacity of the friable topsoil reduces the risk of erosion.

Out of 15 shambas on slopes of more than 10%, 4 show slight sheet erosion, 6 show moderate sheet erosion, 2 show slight rill erosion and 1 shows gully erosion. All 15 shambas have benched terraces.
After construction, the benched terraces deteriorate due to erosion. Especially rill and gully erosion can ruin the terraces very quickly.

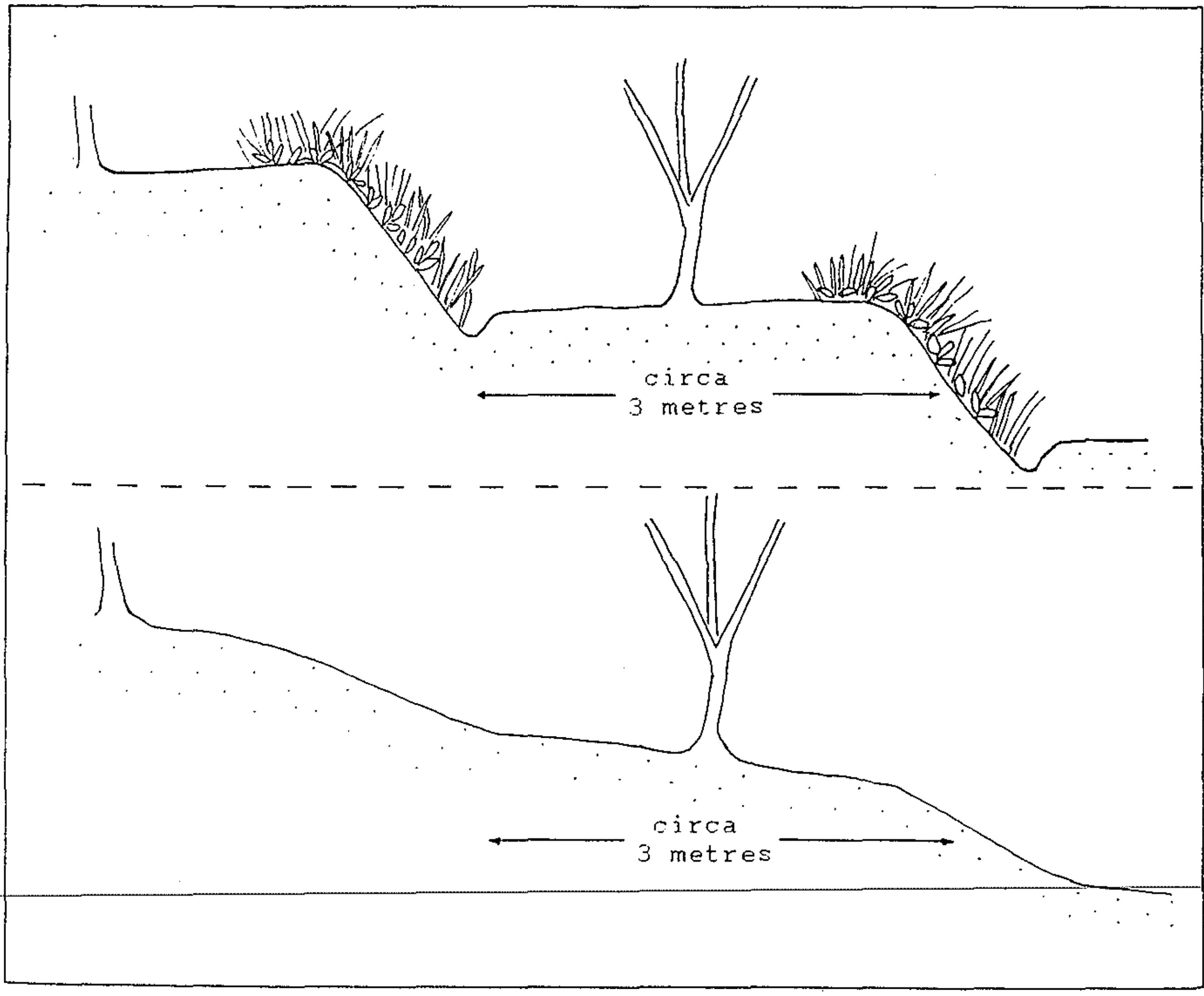

Figure 2. Differences between well-maintained benched terraces (top) and severely eroded, neglected benched terraces (bottom)

Gullies of about 0.5 m deep develop sometimes in the footpaths which lead downhill along the coffee shambas, because runoff rainwater is channelled from the terraces onto the footpath.

Appropriate measures, like grassed waterways downhill and storm-drains along the contours, are missing.
Another cause of the deterioration of the terraces is the impact of people working in the shamba and walking along the edges of the terraces.

The best terraces found in the survey area are those which are well-maintained, which are laid out exactly along the contours, are gently sloping backwards and have the stems planted in the middle of the terrace. The edges are planted with herbs and grasses, to reinforce them with roots, to slow down overland flow, to increase infiltration and to protect the soil from the impact of rainfall. The differences between a well-maintained and a severely eroded, neglected terrace are displayed in figure 2. Only one terraced shamba in the survey showed all the features of perfect terracing, all the others were deficient in one way or another.

3.1.3 Soil horizons

Two to five different horizons have been recognised in the soil profiles.

The top horizon is always an Ap-horizon of approximately 25 cm deep, with a friable or very friable consistency when moist and a clay texture.
The Munsell colour when moist is usually 7.5YR or 5YR with values and chromas of less than 3.
The structure of the topsoil is generally crumb or granular, fine, with many pores.
Sometimes an A-horizon is present below the Ap-horizon. A-horizons have a different structure, colour and consistency than the Ap-horizons. They are firmer, have a subangular blocky structure and soil colours are often lighter, indicating less organic matter. Often a transitional horizon occurs below the A-horizon; usually AB-horizons.

All 33 soil profiles, except those from augerhole 12 and 20, have a B-horizon. The B-horizons have a clay texture in which a faint rock structure may be visible.
Nearly all B-horizons have an illuvial concentration of silicate clay.
The colour of the B-horizon is generally 5YR or 2.5YR with values of 2.5 and 3 and chromas of 2 to 6.
The structure of the B-horizons is usually angular or subangular blocky and size is medium or coarse. Pores are common.
Roots are fine and usually there are only few.
In a few cases the horizon is slightly gravelly, or there are very few very small iron or ironmanganese concretions.
The Bt-horizon is often subdivided into a Bt1 and a Bt2-horizon. The quantity and grade of the clay cutans in the Bt2-horizon is less than in the Bt1.
The B-horizon of profile pit number 10 contains very frequent large ironmanganese concretions. The concretions form a murram layer which is positioned below the surface. Depth and extend of the layer were tested with the auger and a cross-section is presented in figure 3, profile A. Other slope situations are also shown in figure 3.

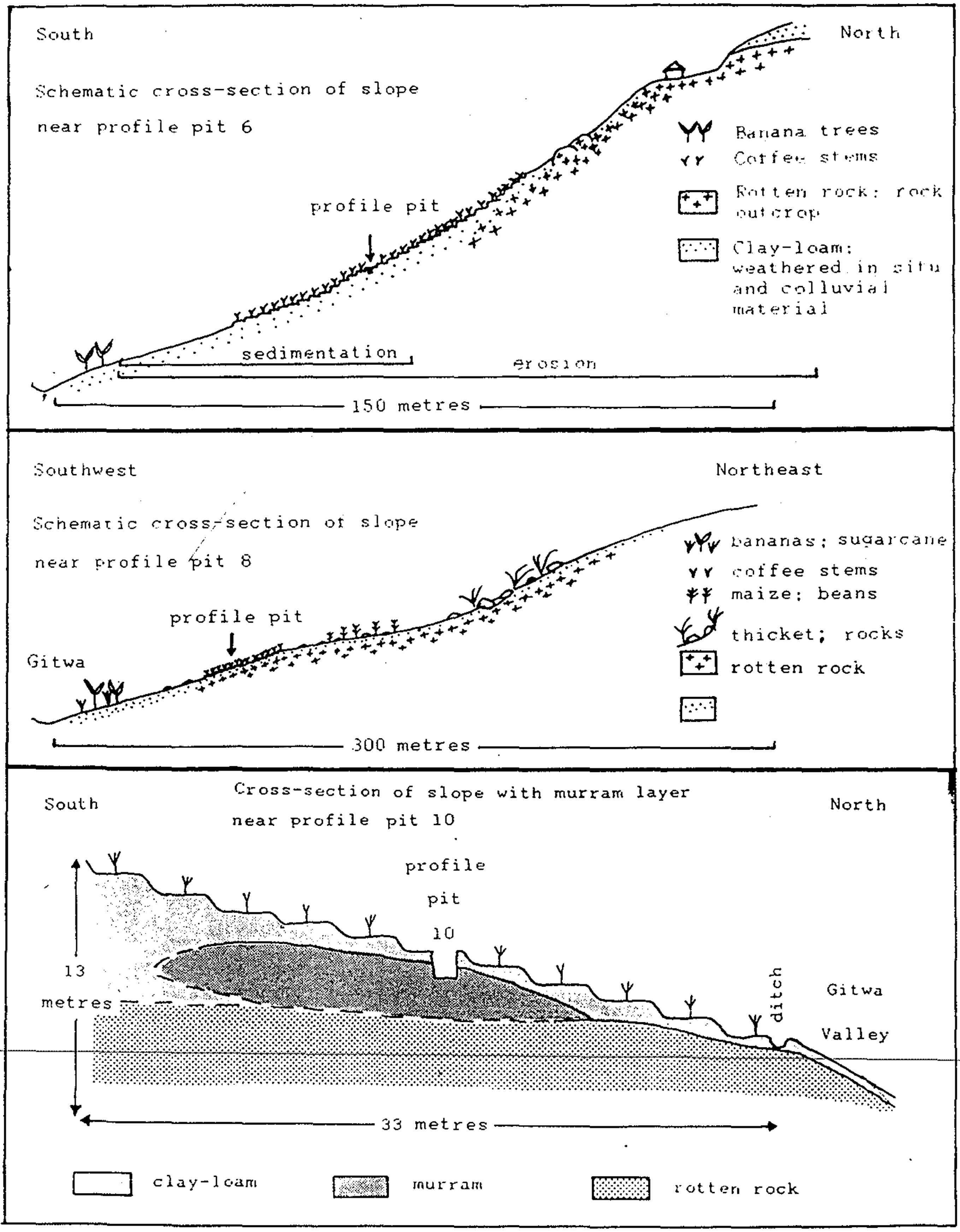

Figure 3. Slope profiles near profile pits 6, 8 and 10

Twenty-nine of the profiles in the soil survey have a Bt-horizon

or a Bt2-horizon as deepest horizon in the profile pit or augerhole.

Only the profiles of augerhole 12 and 20 and the profile pits 8 and 10 have different deepest horizons.

Augerhole 12 has a CR-horizon below the Ap-horizon which consists of clay, which is the parent material of the soil, rotten rock and a gradual transition to continuous indurated rock.

Augerhole 20 has C and CR-horizons containing clay and rotten rock immediately below an AC-horizon.

Profile pit 8 has a CR-horizon containing clay, rotten rock and clay cutans in the top of the horizon.

These three soils are relatively shallow: 80 cm, 100 cm and 100 cm respectively. They limit root development because they are shallow and contain rotten rock. Root development is also limited in the soil at profile pit 10 by a murram layer.

The expected rooting depths of the other soils, with profiles ending at a Bt or Bt2-horizon, are much more favourable to plant growth.

3.1.4 Soil analyses in relation to altitude and slope percentage

The results of the pH-H2O tests are shown in figure 4. The acidity of the soils decreases from pH 6.7 at an altitude of 1210 m, to pH 4.4 at an altitude of 1680 m. The topsoils at high altitudes have lower values of pH than the subsoils.

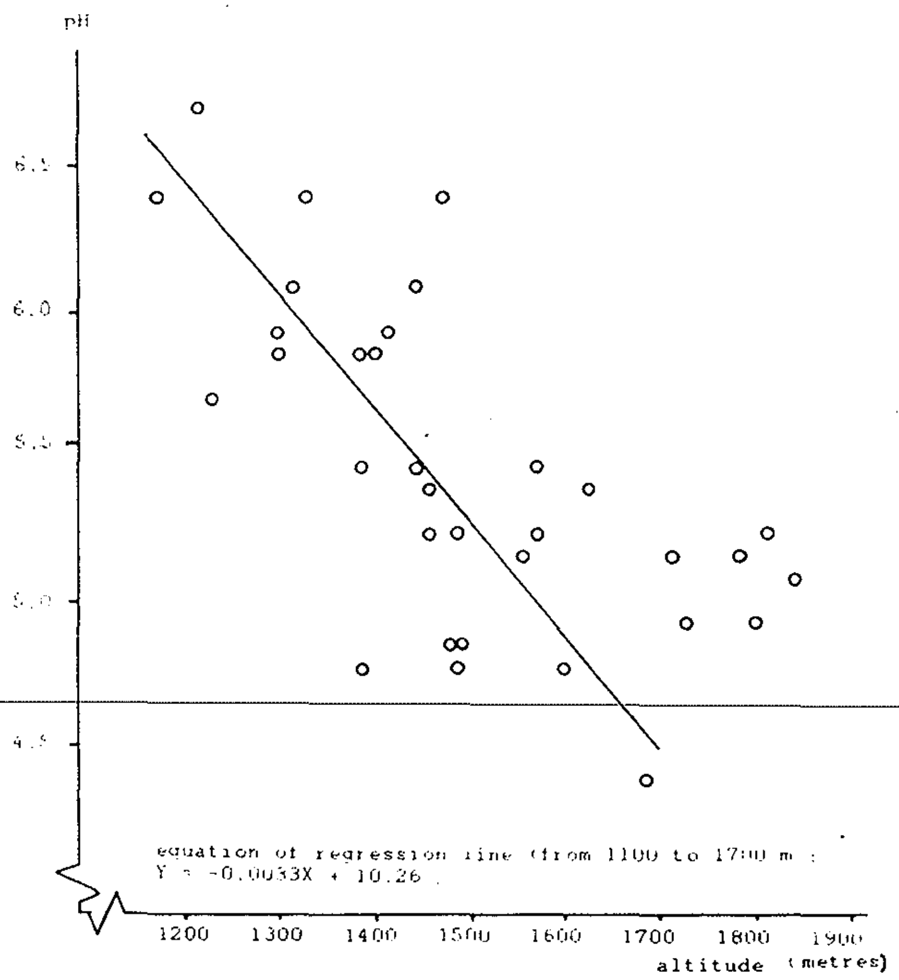

Figure 4. pH-H2O of the topsoil at different altitudes

A precise measure for the relative concentration of exchangeable cations calcium, magnesium, potassium and sodium in the soil, is the % of base saturation. The base saturation of the topsoil of the profile pits in relation with altitude, is shown in figure 5. The three lowest values of base saturation are at relatively high altitudes of 1570 and 1480 metres, which shows that the availability of cations for plant growth decreases when altitude increases. The level of base saturation is always less than 50%.

The Cation Exchange Capacity seems to decrease with increase of altitude, too (see appendix 3).

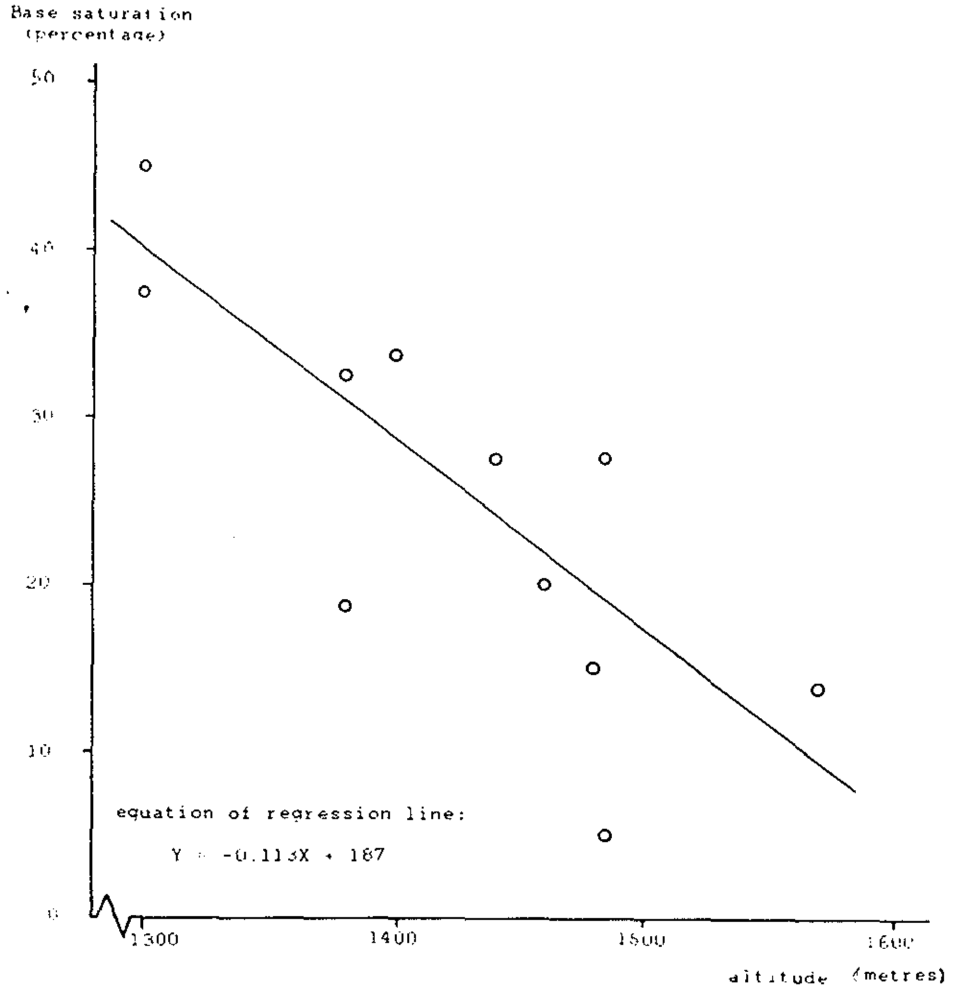

Figure 5. Percentage of Base Saturation of the topsoil at different altitudes

Figure 6 shows the relation of carbon percentage of the topsoil and altitude. No tendency is visible.
Figure 7 shows the relation of slope percentage and carbon percentage. Carbon percentages decrease when slope percentage increases.

3.1.5 Soil classification

The most common soil type on which coffee is grown, is the dystric Nitisol. 29 Out of 33 soils are classified as dystric Nitisols.
One humic Nitisol was found and there are two orthic Acrisols, one humic Acrisol and one ferric Acrisol.

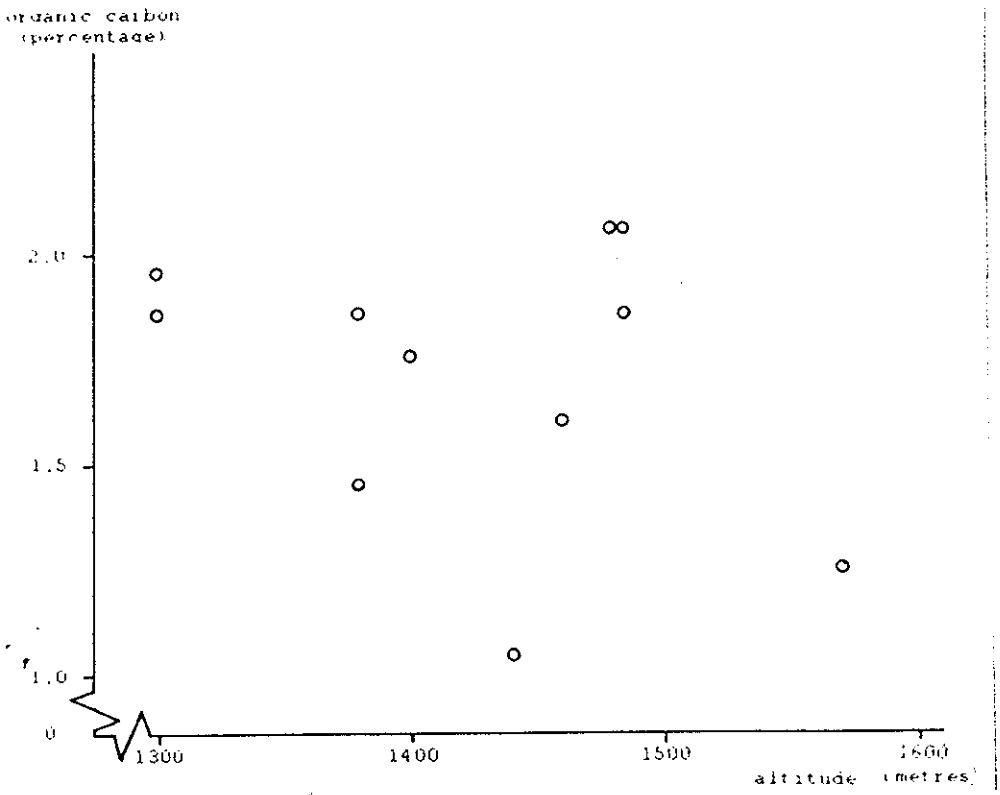

Figure 6. Organic carbon percentage of the topsoil at different altitudes

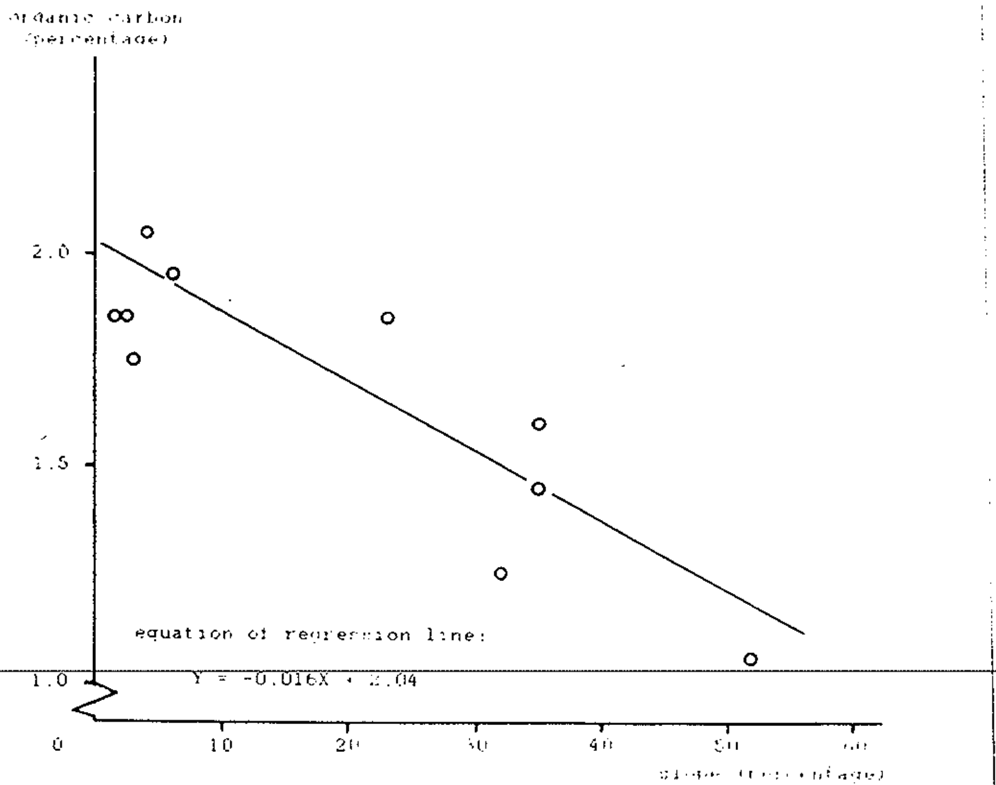

Figure 7. Organic carbon percentage of the topsoil at different slope percentages

3.2 Yield figures and quality classification

The average yield was 3.5 kg per stem per year from 1982 to 1985.
The year 1983/1984 was best at 3.9 kg. The lowest yield, 3.2 kg, was attained in 1984/1985.
The poor yield in 1984/1985 did not occur on every shamba. Some shambas attained their maximum yield in this year.

The differences between shambas are much greater than those between years.
The minimum yield found on any shamba was 0.4 kg per stem in 1982/1983 and the maximum yield was 10.9 on another shamba in 1984/1985.

The distributions of the yield values in different years have a positive skewness, which proves that the bulk of the values are less than the mean values. See appendix 2, Statistical description.
The kurtosis of the distribution of yield values is much higher than 3.0 in the year 1984/1985 and for the distribution of average yield values per stem from 1982 to 1985 the kurtosis is also higher than 3.0. For 1982/1983 and 1983/1984 the kurtoses are about 3.0.

The greatest differences of mean yield per stem between shambas were found when the shambas are situated at different altitudes. For example, the maximum yield was noted on a shamba at 1600 m, while minima of 0.4 to 0.7 were recorded at altitudes of 1820 and 1220 m.
This corresponds with a model of yield per stem being primarily controlled by climatic variables, which is described in paragraph 3.4 on land evaluation.

Differences in yields between shambas at approximately the same altitude and hence climatic conditions, were studied by comparing the columns on altitude and mean yield per stem in the database, summarized in table 3.

altitude in m	augerhole and profile pit numbers in order of average yield (average yields between brackets)		difference between maximum and minimum average yield per stem (expressed in % of maximum yield)
1820-1840	2>1	(3.7>1.1)	70%
1785-1805	3>4	(5.5>2.8)	49%
1680-1725	6>7>5	(9.2>2.4>2.2)	76%
1600-1630	9>8	(10.1>3.6)	64%
1455-1465	13>14	(3.9>3.4)	13%
1385-1440	16>17>15	(2.8>2.4>1.6)	43%
1210-1230	20>21	(1.4>1.0)	29%
1440-1485	P5>P2>P6	(4.9>2.4>1.8)	63%
1380	P9>P8	(2.2>1.1)	50%
1300	P10>P11	(3.6>3.0)	17%

Table 3. Differences in average yield between shambas at similar altitude.

Finally, the differences in yield per stem from year to year on the same shamba can be important. From one year to another, yield figures can double or triple, or decrease sharply.
From 1982 to 1985, 11 out of 29 shambas showed a yield variation from year to year of at least 100%.

The estimates that were made by farmers of their own average yield, show important differences with the averages from 1982 to 1985. Some farmers overestimated their yield while others underestimated it. See appendix 2.

The results of the separate "best farmers survey" are presented in table 4.
Member number 36 of Kiangagwa Farmers' Cooperative Society located at 1620 metres has the best yield, at the highest altitude. The other farmer at this altitude has the same mean yield as member number 310 of New Kyeni at a much lower altitude. This illustrates again that climate is only one of several variables which influence yields.
The mean yields also vary from year to year.
The "best farmers" are located on nearly flat shambas as well as on slopes.

no.*	member no.	number of stems	82/83	83/84	84/85	average
1	36	600	7.0	8.4	11.2	8.8
1	1023	660	3.8	5.6	4.8	4.7
2	1342	1500	3.6	7.5	3.5	4.9
2	229	2500	3.0	1.7	1.8	2.1
3	310	3750	4.4	6.1	3.7	4.7
4	511	1000	3.7	4.1	3.2	3.7
4	434	572	5.6	7.8	3.1	5.5
4	312	654	2.8	3.7	5.1	3.8

* 1. Kiangagwa Farmers' Cooperative Society; factory 02 (1620 m)
2. Kiangagwa Farmers' Cooperative Society; factory 03 (1530 m)
3. New Kyeni Farmers' Cooperative Society; factory 01 (1470 m)
4. New Kyeni Farmers' Cooperative Society; factory 03 (1400 m)

Table 4. Mean yields of berries per stem of the "best farmers".

The quality classification and final payment to the farmer in different years are presented in table 5.

no.*	1982/1983		1983/1984		1984/1985	
	Ksh/kg	quality	Ksh/kg	quality	Ksh/kg	quality
1	3.85	3 to 7	5.16	2 to 6	6.58	3 to 6
2	-	-	4.88	-	5.38	-
3	3.85	-	4.56	-	5.05	-
4	3.55	-	4.35	-	5.00	-
5	4.26	4 to 6	4.08	4 to 6	4.74	4 to 6
6	4.29	4 to 6	3.94	4 to 6	5.59	4 to 6

* 1. Kagari North Farmers' Cooperative Society; factory 01 (1720 m)
2. Kiangagwa Farmers' Cooperative Society; factory 01 (1580 m)
3. Kiangagwa Farmers' Cooperative Society; factory 02 (1620 m)
4. Kiangagwa Farmers' Cooperative Society; factory 03 (1530 m)
5. New Kyeni Farmers' Cooperative Society; factory 01 (1470 m)
6. New Kyeni Farmers' Cooperative Society; factory 03 (1400 m)

Table 5. Payments to farmers per kg of berries and quality ratings of different factories and cooperatives.

The best classification possible, class 1, was never attained in the years 1982 to 1985. However, nearly in all cases the factories produced coffee of export quality.
Differences of payment and quality between different factories are relatively small.

3.3 Correlations of environment, soil and yield

The values of skewness and kurtosis of the distributions of yield values in paragraph 3.2 prove that the values are not distributed in normal distributions, which should have a skewness of 0.0 and a kurtosis of 3.0. Therefore, only non-parametric statistical tests may be used.
The Spearman's rank correlation coefficients of many pairs of variables of the two databases are presented in two correlation matrices, see appendix 4 and 5.
The attention was at first focussed on the significant correlations of average yields per stem with other variables, see appendix 4.

Significant positive correlations:
- There is a strong correlation of average yields with relative altitude, even surpassing the 0.01 significance level.
  The relation means that average yields tend to increase up to an altitude of 1600 metres and decrease from 1600 metres upwards.
- There is a strong correlation of average yields with crop cover percentage, also surpassing the 0.01 significance level. Average yields tend to increase when crop cover percentages increase.
- The correlation of average yields with the yields in the year 1984 to 1985 is very high but is rather trivial, because the average yields are not an independent sample, but calculated from the yields in 1984 to 1985 and other years.

Significant negative correlations:
The negative correlations are only just above the 0.1 significance level for the variables soil classification, surface stoniness, crop performance and pH-H2O of the subsoil;

- The average yields of shambas on Acrisols tend to be less than on Nitisols.
- The average yields on shambas with gravel at the surface tend to be less than on shambas with fine textured surfaces.
- The average yields on soils with a high pH of the subsoil tend to be less than on soils with low pH of the subsoil.
- The coefficient for the estimates of crop performance shows a negative correlation with average yield, because the original ranking from 1, excellent, to 5, very poor, is reversed during the calculation of the rank correlation coefficient. In fact, the relationship of crop performance estimates and average yields is positive: favourable estimates are correlated with high yields and unfavorable estimates indicate low yields.

Noteworthy are the correlation coefficients of average yields with erosion, slope percentage and possible rooting depth. The values are below the 0.1 significance level, so these three variables are not the most significant for crop production, but the signs of their correlation values show that erosion and slope percentage tend to have negative effects on average yields and deep rooting depths tend to have a positive effect on average yields.
Soils with deep umbric horizons, do not seem to be favourable for high average yields.
The subjective judgements of management levels do not show significant correlation with average yields.

Secondly, the attention was focussed on correlations of the average yields of profile pits with other variables, appendix 5.

- Average yields have positive correlations, at a 0.1 level of significance, with the variables number of stems, management level estimate 1 and with yields in other years (trivial).
- The significance of the positive correlation of average yields with available phosphate concentrations in topsoils and subsoils, is 0.05.
- The only negative significant correlation of average yields is with the modulus value of the % difference between the actual and desired concentrations of available phosphates in the topsoil. This means that deviations from the desired available phosphate concentrations are correlated with low average yields.

The following results are a summary of the correlations of concentrations of plant nutrients and other chemical variables, see appendix 5.

- The available phosphate concentrations have significant, positive correlations with the concentrations of calcium in the topsoil (F20CA), with the modulus value of % differences between the actual and desired ratios of calcium, magnesium and potassium in the topsoil (F20CAMG+) and with the concentrations of available phosphate. It has a significant negative correlation to the modulus value of % differences between the actual and desired concentrations of available phosphates in the topsoil (F20P+).
- The Cation Exchange Capacity has negative significant

correlation with altitude and positive with pH, exchangeable calcium and potassium, and with Base Saturation.
- Base Saturation shows nearly the same correlations as the Cation Exchange Capacity. The absorption complex of the soil is dominated by exchangeable calcium.
- The correlation of the Cation Exchange Capacity of the topsoil with the organic carbon percentages of the topsoil is low.

The results of the statistical tests for the significance of the difference between the average yields on slopes of 10% or more and average yields on shambas with slope percentages of less than 10%, are shown in table 6.
- The value of T of approximately 0.3 means that the absolute difference of the means of the two sets of values is approximately one third of the standard error of the difference between the two.
  With 28 degrees of freedom the critical value of T varies from 1.70 to 3.67 for significance levels of 0.1 to 0.001. This means that the H0 hypothesis of Student's T-test can not be rejected at any significance level.
- Since the calculated value of U is 98.5 and the critical values vary from 71 to 39 at significance levels of 0.1 to 0.002, the H0 hypothesis can not be rejected at any significance level.

Student's T-test

variables	mean	standard deviations	number of values
average yields on slopes of less than 10%	3.66	1.96	16
average yields on slopes of more than 9%	3.42	2.35	14

T statistic = 0.30
degrees of freedom = 28
one-tailed probability = 0.38
two-tailed probability = 0.77

Mann-Whitney's U-test

variables	sample size	U	mean	standard deviation
average yields on slopes of less than 10%	16	98.5	112	24
average yields on slopes of more than 9%	14	125.5		

Z-score = 0.56
one tailed probability = 0.29

Table 6. Results of Student's T-test and Mann-Whitney's U-test comparing average yields on slopes and on nearly level shambas.

3.4.1 Physical crop requirements and limitations

Most of the information about the crop requirements of coffee is qualitative. The most desirable state of some variables for growing coffee can be described, but the consequences of any deviation from this optimum can not be expressed in quantitative terms of limitation of yield. Even the requirements that are defined as quantities, such as nutrient requirements, can not yet be translated into quantitative limitations of yield.
Some requirements, such as the availability of moisture, are still defined by several variables; altitude, average rainfall, texture and moisture retention capacity of the soil. These variables are no crop requirements but land characteristics and qualities.
However, the description of the physical requirements of coffee can be used to see which land characteristics of the survey area are favourable and which limit yield.
The description is based on Acland (1971), Jaetzhold (1983), Sombroek (1982), Williams (1970) and interviews with personnel of the Coffee Research Foundation in Ruiru, acknowledged in the preface.

The water requirement of coffee is relatively high; Acland states a lower limit of about 900 to 1000 mm average rainfall per year on coffee estates east of the Rift Valley. In such conditions mulching and good weed control are necessary to conserve moisture.
In most parts of the world, about 1800 mm average annual rainfall is considered ideal. Jaetzhold considers an average of 1500 mm six out of ten years, well distributed rainfall during the growing period, to be ideal. Such rainfall only leads to better yields if the accompanying problems, such as increased weed growth, diseases and leaching of nutrients, are dealt with. Diseases which flourish in humid conditions, such as Coffee Berry Disease, are potentially the most severe limitations in high rainfall areas.
The rainfall needs to be fairly well distributed throughout the year, with the exception of a 1.5 to 2.5 month dry period. Such a dry spell is generally regarded as beneficial because it hardens the wood and gets the tree into a cycle of flowering and bearing. There should be a good moisture supply until about four months after flowering. A severe moisture shortage during the third and fourth month limits the size of the beans. Moisture stress can also limit yields because this condition favours the pest "thrips".

The information about temperature requirements of arabica coffee is limited.
The decrease of average annual temperature with increase of altitude, causes an increase of the ripening period, continuous small flowerings, stunted growth and an excessive incidence of the "hot and cold" condition and crinkle leaf. Therefore, temperature requirements seem to be met better at low altitudes. A possible explanation is that photosynthesis increases with the increase of temperature and insolation at low altitudes. The importance of photosynthesis is stressed by Williams, who states that "...the highest production (of coffee flowers) occurs under hot and dry conditions, when irrigation is available" (Williams & Joseph, 1970).

Soil requirements of coffee include the availability of moisture,

oxygen and nutrients.
Moisture and oxygen availability are controlled by soil structure, texture and depth. Ideally the soil must allow free drainage, but it must also allow reasonable water retention.
Depending on rainfall and topography the ideal balance of the requirements will be different. E.g. in areas with low rainfall, a high water retention capacity of the soil is very desirable. The same high water retention can cause a shortage of oxygen in high rainfall areas and in depressions.
Generally a soil texture of medium loams is ideal; heavy loams and clays are less suitable because they are poorly aerated, especially in areas with high rainfall.
Sandy soils are equally undesirable because they dry out rapidly, especially in areas with low rainfall.
Deep soils are considered essential as an insurance against drought and 180 cm is usually quoted as the minimum depth. This depth requirement is more important in areas with low rainfall. The vertical and axial roots and their branches are most important for water absorption. They can reach a depth of 240 to 300 cm in deep soils.
The presence of a murram hardpan seldom allows healthy growth although roots can penetrate a thin or uncompacted layer.

	desired level or concentration	
pH-$CaCl_2$ 1:2.5	4.4 - 5.4	
pH-H_2O suspension	5.3 - 6.0	
Exchangeable acidity	< 0.5	
Na (Mehlig)	< 0.2	cmol/l
K	0.4 - 2.0	cmol/l
Ca	1.6 - 10.0	cmol/l
Mg	0.8 - 4.0	cmol/l
Mn	< 1.0	cmol/l
P (Mehlig)	20 - 100	mg/kg
(Ca + Mg)/K (to ensure a balanced absorption of these nutrients)	4 - 10	
$CaCO_3$	< 1%	
$CaSO_4$	< 0.5%	

Sources: Coffee Research Foundation Ruiru and Jaetzhold, 1983.

Table 7. Desired levels and concentrations of nutrients and acidity in the soil, for Coffea arabica.

The main feeding roots of coffee stems are a mass of ramifying lateral roots which form a surface mat seldom deeper than about 30 cm. The nutrient status of this top layer must be high.

The Coffee Research Foundation carries out tests of soil samples taken from depths of 0 to 15 cm, representing the topsoil, and from 15 to 50 cm, representing the subsoil.
The results are compared with the optimal nutrient concentrations and acidity levels, quoted in table 7, to recognize shortages and potentially harmful surplusses in the soil. Recommendations are prepared for the use of fertilizers to overcome these problems and increase yield.

The shade provided by trees can limit insolation and can have other effects, mainly the change of the micro-climate. The net effects on yields are still discussed. It has been proven that in East Africa bananas interplanted with coffee reduce the coffee yields considerably, not as a result of shade but because the feeder roots of both crops compete at the same depth and the banana plant requires large quantities of nutrients.
Weed growth is stated to reduce the yield of coffee, as a result of the competition for nutrients and water. The competition for nitrogen is considered to be severe. However, research in Kisii (V.d. Torren, 1977) has shown that weed growth does not affect the leaf nitrogen percentage in the leaves of coffee stems, so the effect of weed growth might be overestimated.

3.4.2 Land qualities

The fulfilment of the water requirements of coffee depends among others on average annual rainfall, the variability of rainfall and the distribution of rainfall over the two growing seasons. An overview is given in table 8.
Average annual rainfall is best in the highest part of the Coffee-tea zone. In the other zones it is probably limiting crop yield. Some signs of moisture stress are visible in the shambas of the Marginal zone; many coffee stems suffer from thrips, have yellow leaves or the laterals are nearly defoliated. Only two farmers in the survey use mulch such as clippings of trees and maize stalks and leaves, to reduce moisture stress, thrips and weed growth.
A negative side-effect of high rainfall is the incidence of Coffee Berry Disease in the Main Coffee zone and even more in the Coffee-Tea zone. There are problems in the upper part of the Coffee-tea zone because the temperature requirements of coffee are not met. The ripening period is very long; approximately 12 months, so there is only one crop per year instead of two.
The lengths of the growing seasons are defined by Jaetzhold as the number of days in a row, when rainfall is 0.4 times the potential evapo-transpiration. Coffee flowering starts with the onset of rains and than needs a growing season of about 4 months to develop the berries, which eventually are ripe after 8 to 12 months in the next rainy season. The growing periods of the first rains in all zones satisfy this requirement nearly every year.
The second rains are shorter and they are only sufficient in most of the years in the Coffee-tea and Main Coffee zone.
On the other hand a dry spell of 1.5 to 2.5 months is beneficial. The upper part of the Coffee-tea zone possibly lacks this dry spell in some years, when rainfall is more than average.

	altitude (m)	average annual rainfall (mm)	60% reliability rainfall (mm) 1st rains	2nd rains
Coffee-Tea zone (1)	1590-1830	1400-1800 (1640-1880)*	700-950 growing 155-174 days	450-550 seasons 115-134 days
Main Coffee zone (2)	1400-1590	1200-1500 (1450-1640)*	580-720 135-154 days	380-450 115-134 days
Marginal Coffee zone (3)	1280-1460	1000-1250 (1330-1510)*	480-600 135-154 days	350-400 105-114 days

* Annual average rainfall by Ooms is placed between brackets

ad (1)
climatic conditions good to fair for arabica coffee, tea. Temperate and humid; annual average precipitation at least 80% of the potential evapo-transpiration (or more to store enough soil moisture for dry seasons affecting tea)

ad (2)
climatic conditions good for arabica and maize. Temperate and subhumid; annual average precipitation 65-80% of the potential evapo-transpiration (or more to store enough soil moisture for dry seasons affecting coffee)

ad (3)
moisture conditions fair to poor for coffee, than irrigation profitable; fair for maize depending on soils. Temperate and semi-humid; annual average precipitation 50-65% of the potential evapo-transpiration (or more to store enough soil moisture for survival of coffee in dry seasons)

Table 8. Description of agro-ecological zones after Jaetzold, 1983 and Ooms (TPIP) 1986.

The moisture availability requirement of coffee can be translated into the moisture retention capacity of the soil. The oxygen availability can be translated into the "aeration " of the soil. Both are determined by soil structure, texture, content of organic matter and depth of the profile.
The topsoil structure is generally crumb or granular and favourable for infiltration of rainwater, aeration and the penetration of roots. Runoff losses of rainwater on slopes are small. Subsoil structure and consistency are less favourable: they are hard when dry with a generally coarse angular blocky structure. The activity of soil fauna improves the aeration of most soils, however. Organic matter in the soil improves soil structure and moisture retention capacity. The organic carbon percentages of the topsoils vary from 1.0 to 2.1 and the organic matter percentages are approximately 2.3 times the organic carbon percentage.
The soils contain 60 to 90% clay, increasing from topsoil to subsoil. Silt percentages vary from 4 to 25%, with a high content

in the topsoil. The sand fraction ranges from 4 to 20%, slightly more in the topsoil than in the subsoil. The soils are classified as heavy or clay soils, so they can not be considered as ideal for coffee.
However, the high clay content gives a high moisture retention capacity, prolonging the growing season. The free drainage requirement is still met because soil structure is well developed and the profile is generally deep. No signs of waterlogged conditions were found in all but one of the shambas. Farmers do not plant coffee on soils where waterlogging is likely to occur; such as soils situated in valley bottoms and dambos.
The rooting depth of the majority of soils which are classified as Nitisols, is more than 180 cm and they are considered to be ideal for coffee in this respect.
Exceptions are the shallow soil profiles which have a smaller moisture retention capacity. Some of the moisture is retained in the rotten rock where roots are scarce. Moisture availability and rooting depth are less favourable for coffee in some soil profiles on slopes which are classified as orthic, humic and ferric Acrisols.
The lengths of growing seasons may well be longer than those shown in table 8. Jaetzold calculated the lengths of growing seasons for medium textured soils with a depth of 60 cm, whereas the soils in the survey area are much deeper clay soils. Besides, the average annual rainfall figures described by Ooms are much higher than those used by Jaetzold.

Nearly 50% of the shambas in the surveys have a level of pH-H2O within the limits of the desired interval from 5.3 to 6.0. This can be seen in figure 4.
A comparison between the actual and the desired levels of nutrients and other elements in the top 20 cm of the soil has been made. It contains eleven profiles from altitudes between 1300 and 1570 m and is presented in the database on soil profiles, appendix 3. The results are given below:
- 1 topsoil has a small excess of sodium
- 2 topsoils have a small shortage of potassium
- 3 topsoils have a shortage of calcium, one of which contains only a trace of calcium
- 5 topsoils have a small excess of magnesium and 1 a shortage
- 1 topsoil has a small excess of manganese
- 7 topsoils have a shortage of phosphates
- 3 topsoils have a ratio of calcium magnesium and potassium which is too high, 1 has a ratio which is too low

All profiles, except profile pit 2, show one or more deviations from the desired levels of nutrients and acidity of the soil. The differences between shambas on slopes and shambas on nearly level terrain, are not significant. The concentrations of some nutrients decrease at higher altitudes because of the intensity of the leaching process. The percentage of base saturation in the top horizon declines with altitude, figure 5, mainly because calcium content of the soil decreases with increase of altitude.

Coffee stems are cultivated in pure stands in the survey area. Sometimes grass is grown between the rows for cattle feed, or there are rows of trees planted around the coffee stems or an occasional fruit tree in the middle of the coffee shamba. So far, shadow trees are rarely used to improve micro-climate or provide materials for mulching.

3.4.3 Suitability

The yield figures of all the surveyed shambas are plotted against their altitude, showing the relationship of altitude and yield, see figure 8.
Altitude and yield are strongly correlated, see paragraph 3.3.

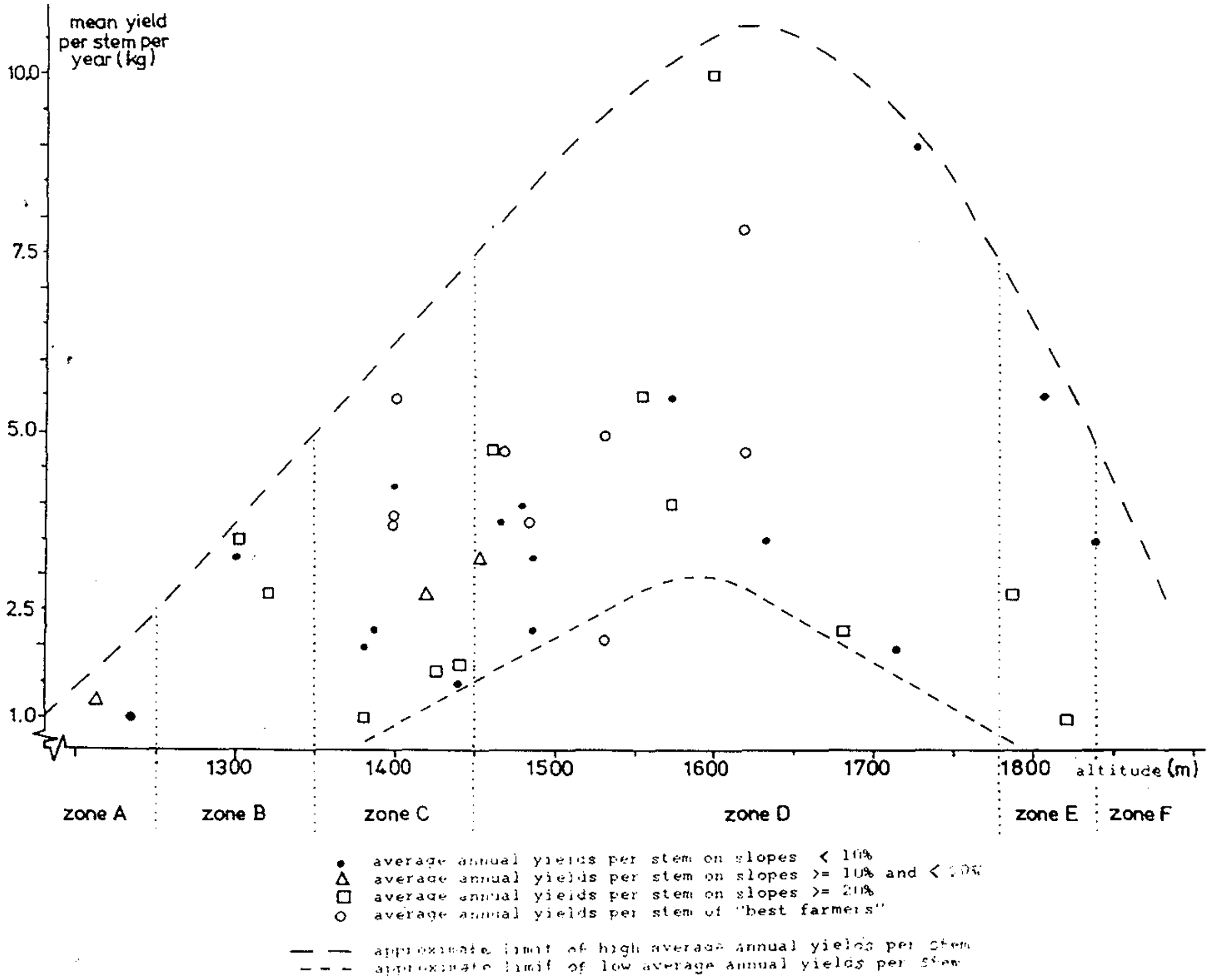

Figure 8. Average annual yields per stem at different altitudes

Two curves have been drawn in the figure to delineate the approximate range of yields which can be expected at different altitudes. This range is quite broad.
The ecological boundary of rainfed coffee is situated at about 1100 m, at the low rainfall end. Average yields rise to a maximum of approximately 10 kg per stem per year and than decreases again, to an ecological boundary outside the survey area.
Lines have been drawn to delineate the boundaries of yield intervals related to altitude intervals, or zones.
The choice of the boundaries is of course arbitrary and approximate, but it serves the purpose of describing the yield potential in the survey area, at current management levels.

The factors which pose limitations to yield and the factors which are particularly favourable in the different zones, are described below. The locations of the zones in the survey area, are presented in map 3.

Zone A: altitude of about 1150 to 1250 m; yield potential below 2.5 kg per stem per year but still above approximately 0.5 kg
Crop is limited by severe moisture stress in all years, thrips and defoliation occur frequently
Base saturation better than average, pH too high
Acrisols are unsuitable for growing coffee

Zone B: altitude of about 1250 to 1350 m; yield potential below 5 kg per stem per year but still above 1.0 kg
Crop limited by severe moisture stress in most years, thrips is a major problem
Crops on Acrisols suffer more from moisture stress
pH is often too high

Zone C: altitude of about 1350 to 1450 m; yield potential below 7.5 kg per stem per year but still above 1.0 kg
Crop limited by moisture stress in the growing season of the second rains, and sometimes during first rains
Moisture stress is more severe in crops on Acrisols
pH generally good, base saturation decreases

Zone D: altitude of about 1450 to 1780 m; yield potential below 12 kg but usually above 2.0 kg
No limitation by moisture stress above 1600 m but occasionally below 1600 m, especially in crops grown on Acrisols. Most important crop limitations are posed by Coffee Berry Disease and poor nutrient status of the soil, pH is often too low. CBD and poor nutrient status grow worse with increase of altitude

Zone E: altitude of about 1780 to 1850 m; yield potential below 7,5 kg but above 1.0 kg
Crop is limited by low temperatures, low nutrient status of the soil and CBD.

Zone F: altitude above about 1850 m; yield potential 5.0 kg decreasing very fast with increase of altitude.
Same problems as Zone E but more severe

A limitation in all zones is probably the low concentration of available phosphates in most soils.
The nutrient status of the soil is deficient in every zone. The deficiencies are more severe at greater altitudes.
Zone D has the best yield potential but there are many limitations that suppress the effect of the ideal rainfall.

4 DISCUSSION

Methods

The method of asking the cooperatives for their "best farmers" was of limited use because the cooperative societies do not have systematic information on mean yields per stem. Their information about total production per farm is very accurate, but information about the number of stems is not accurate or not available. The number of stems can only be determined by asking the farmer and by estimating and counting in the field.

The correlation coefficients are generally not very strong. An explanation is that the systematic sampling method described in paragraph 2.1 is well suited for finding ranges of the different variables, which means that the database is not so well suited for finding correlations of only two variables at a time, since the other variables are not stable and influence the result.
The advantage of the systematic sampling method is that apart from showing the ranges of the variables, a good comparison is made possible between yields on slopes and yields on nearly flat terrain, in all growing conditions of the coffee zone.
If a more limited approach would have been chosen, for example limited to shambas at similar altitude, results would have been more precise but less meaningful to the land evaluation of the coffee zone at large.

Soil acidity and altitude

Although the variation is large, there seems to be a linear relationship between altitude and pH. The explanation is that the intensity of leaching of the soil by rainwater, increases when rainfall increases. Rainfall increases with altitude, so leaching of the soil is more intense at high altitudes.

The topsoils at high altitudes have lower values of pH than the subsoils, because the leaching effect of rainwater is most effective in the topsoil. When it reaches the subsoil, it contains a higher concentration of cations already, and a proportion of the protons is already absorbed in the topsoil.

The correlation coefficients for pH-H2O and altitude, thus rainfall, are negative and significant. The correlation coefficient for the topsoil is -0.68, higher than for the subsoil; -0.52. The stronger correlation of altitude with pH-H2O of the topsoil than with pH-H2O of the subsoil, indicates that the leaching process is more effective in the topsoil.

The correlation coefficient of pH-H2O and yields is negative and significant. When pH-H2O increases, yields decrease. This may be caused by the fact that pH-H2O is high in areas with low rainfall.
Yields in low rainfall areas are probably more limited by moisture stress than by high pH of the soil. The high correlation coefficient of yields and altitude, which is closely related to rainfall, proves this.

Carbon percentage, altitude and slope

In other research in Kenya it has been proved that carbon percentage in the soil tends to increase with altitude. At high altitude, the more humid and colder conditions slow down the decomposition of organic matter and therefore carbon content will increase. This effect is not visible in figure 6, so perhaps the number of cases and range of altitudes studied are not large enough, or the effect does not take place in the survey area.

The percentage of carbon in the topsoil decreases when the percentage of slope increases. This can be the result of soil erosion taking place on slopes. Material of the topsoil which has a relatively high percentage of organic matter is gradually removed, leaving soil material with less organic matter behind. In nearly level terrain, organic matter can accumulate much more easily, resulting in a higher organic matter content in the top-soil, than in the topsoil of slopes.

Variations of yield

The lowest average yield in 1984/1985 was probably the result of the drought which occurred in 1984.
This drought affected the yield in 1984 as well as in 1985.
Coffee is a perennial crop and a decrease in growth of tree and berries is strongest in the cropping season after the moisture stress has occurred.

The differences in yield per stem from year to year on the same shamba can be important. From one year to another, yield figures can double or triple, or decrease sharply.
This effect is mainly a result of overbearing of berries on stems which are pruned inadequately in relation to the development of the tree and the availability of nutrients. Inadequate pruning means that too many flowering laterals are present. They cause a bumper harvest in one year, but the stem can not sustain this for many years. All the carbohydrates are used for the berries and the development of new laterals which should bear flowers and berries in the next season, is severely limited. In bad cases, the result of overbearing is defoliation and die-back of the laterals. The berries, if any are present at all, can not ripen, resulting in a poor cropyield.
The average yield of overbearing trees is less over a series of years, than that of a tree with a more stable pattern of bearing berries. Besides, the overbearing may cause a shortage of labour in one year and a surplus in another. Another disadvantage is the instability of the cash income of the individual farmer.

In the drier areas, mulching would be beneficial for coffee because it prevents moisture stress and thrips. According to Acland (1971), mulched coffee can produce almost double the yields of unmulched coffee, in dry areas.
Mulching has two drawbacks: the land needed to produce the mulch and the labour and the expense involved in producing and applying mulch.
For example one acre of well managed Napier grass is sufficient for one acre of coffee. In the survey area mulching material can not be produced in this way. Land use is already intensive and there is a lack of space.
Perhaps agroforestry of coffee and tree species with suitable foliage for mulch can provide an answer.
The shade of these trees can be beneficial to coffee in the low rainfall area.

The large differences in yield per stem on different shambas at nearly the same altitude and hence climatic conditions, see figure 8, prove that yield is not only a function of climate. Other variables must also influence the yield.
The importance of management on yields is proven by a number of cases of neighbouring shambas where different farmers have quite different yields although physical conditions of climate, soil and slope are nearly the same.
Unfortunately, the differences in management levels and which management practices for pruning, fertilizing etc. are favourable, are difficult to judge.

Soil erosion and yields

Soil erosion causes visible losses of soil on slopes, but yield losses are not yet significant. This will probably change in the near future because progressive soil erosion can damage coffee trees and will gradually reduce soil and rooting depths.
Acrisols with limited soil depths have shown a significant negative correlation with yields already, so the reduction of soil depths by erosion will probably lead to an ever increasing reduction of yields on slopes.

Comparison of Kenya and the survey area

Six to seven kg of berries from the survey area produce one kg of clean coffee.
In some other areas of Kenya the ratio is much higher. In the Kisii highlands for example, the ratio was found to be 1 to 8.7 (V.d. Torren, 1977).
This shows that weight and density of the beans produced in the survey area is high in comparison to the weight of the pulp and parchment of the berries, which is a characteristic of high quality coffee.

The average yield per stem per year is 3.55 kg in the survey area, slightly more than the mean yield for Kenya, which is 3.4 kg per stem (ISC/ICRA, 1986).
The average yield per stem of the survey area would have been higher, if more samples had been taken in the high rainfall zones of the survey area. Besides, the yield figures of the "best farmers" were not counted in the average.

The maximum yield in the survey area, about 11 kg per stem in one year is still much less than the maximum of 20 kg per stem which can be attained in ideal conditions for growing coffee (Acland, 1971).
Several farmers who were selected by the cooperative societies as their "best farmers", do not have very remarkable crop yields at all.
An explanation is that the cooperatives do not collect information about mean yields per stem, but only the total yields per farmer.

5 CONCLUSIONS AND RECOMMENDATIONS

Methods

Evaluation of the suitability for coffee can not be accomplished with the information about "best farmers" alone.

Analysis of yields must be carried out on the basis of figures from the cooperatives and not on the basis of interviews with the farmers alone, because they have no written records.

The estimate of crop performance does not give a good indication of yields and neither do the estimates of management levels.

Statistical analyses

The most significant positive correlation exists between yield and altitude. Average yields tend to increase up to 1600 m and decrease steeply above that altitude.

The correlation between yields and Acrisols is negative and significant. The average yields of coffee grown on Acrisols tend to be less than the yields on Nitisols.

There is a positive significant correlation of yields and concentrations of available phosphates in the soil.

The nutrient status and the acidity of the majority of the soils shows important deviations from the levels of nutrients and acidity which are desirable for coffee, especially at greater altitudes.

The results of the Student's T test and the Mann- Whitney U test show that it is highly probable that the two sets of values representing the average yields of coffee stems on slopes and on relatively flat terrain respectively, are samples taken from one population of all yield figures in the survey area.
There is no reason to suppose that slopes of 10% to 52% are less or more suitable for crop production than land with slopes of less than 10%.
The hypothesis that coffee stems on slopes yield less than coffee stems on nearly flat terrain, must be rejected.

Yield can not be described as a simple and precise function of the characteristics of soil, climate and slope. The correlation coefficients show that many variables influence yield and that none is of paramount importance.

The suitability zones show a large variation of actual yields on shambas.
The differences of yields which exist between zones are in the first place a result of differences in rainfall.
The differences of yields within every zone are in the first place a result of differences in management by the individual farmers and in the second place of the variation of physical conditions other than rainfall. For example, relatively low yields occur on Acrisols with limited rooting depths.

Quantity and quality of coffee yields

Differences of payment and quality between cooperatives and

factories are relatively small.
The mean final counts of all factories and areas are comparable, so approximately the same quality of coffee is produced at different altitudes. Nearly always, coffee of export quality is produced. Both the quality of the berries and the processing at the factories must therefore be good.

Another proof of the quality of coffee in the survey area is the favourable ratio of the number of kilogrammes of berries needed to produce one kilogram of clean coffee.

The above average quantity and quality of yields, shows that the suitability of the survey area for the production of arabica coffee, is good.

Recommendations

Coffee yields can be increased by improving management, mainly pruning methods and the use of fertilizers, manure and mulch.
Capped multiple stem pruning can limit Coffee Berry Disease and reduce the risk of overbearing.
Effective use of fungicides can improve yields in the high rainfall area.
Some farmers in the survey show the potential of improving coffee yields through better management already.

Agroforestry must be encouraged to provide mulching material, erosion control and shade to limit evapo-transpiration of coffee trees in low rainfall areas. Multi-purpose trees used for agroforestry yield more useful products, examples of tree species and products are presented in appendix 8. Tree species must be chosen that do not compete too much with coffee trees.
Integrated control of coffee pests is possible and desirable because it is less harmful to the environment and it is often less expensive.

An ever increasing limitation of yields on slopes will occur if soil erosion, which is already taking place, is not controlled by improved soil management, see paragraph 3.1.2. On slopes of about 30% and steeper, the construction of storm drains along the contours and grassed waterways downhill is necessary.
Strip cropping of coffee and cattle fodder can be increased to limit erosion. Persistent chemicals can not be used on coffee trees in this situation.

BIBLIOGRAPHY

Acland, J.D.	1971	East African crops. FAO, Longman Group Ltd., London.
FAO	1977	Guidelines for soil profile description. By Soil Resources Development and Conservation Service, FAO, Rome.
FAO-Unesco	1974	Soil Map of the World 1:5,000,000. Volume I Legend. Paris.
ISC/ICRA	1986	The farming system in the Coffee Area, Kyeni South Location, Embu District, Kenya. Preliminary Report. International Student Course for development Research in Agriculture, Wageningen.
Jaetzhold, R. and Schmidt, H.	1983	Farm management Handbook of Kenya. Volume IIA and IIC. Ministry of Agriculture, Kenya.
Janssen, B.H., Guiking, F.C.T. and Eijk, D. van der	1979	Soil fertility aspects of the Kisii soils. Preliminary report No. 6, TPIP, Kisii, Kenya. Agricultural University Wageningen, the Netherlands.
Kenya Soil Survey	1980	The application of the FAO-Unesco terminology of the soil map of the world legend for soil classification in Kenya. By W. Siderius and B.J.A. van der Pouw. Miscellaneous Soil Paper M15, Nairobi.
Kenya Soil Survey	1982	Exploratory soil map and agro-climatic zone map of Kenya, scale 1:1,000,000. By W.G. Sombroek, H.M.H. Braun and B.J.A. van der Pouw. Exploratory Soil Survey Report No. E1, Nairobi.
Kenya Soil Survey	1978	Field guidelines for the annotation of the soil profile description form. Internal communication No. 17.
Meester, T. de and Legger, D.	1988	Chuka soil survey report. Kenya Soil Survey and TPIP, Agricultural University, the Netherlands.
Ooms, B.	1986	Student report. TPIP, Chuka, Embu District, Kenya. Agricultural University, the

		Netherlands.
Torren, K. van der	1977	Cash crops in the Kisii District (coffee and pyrethrum). Preliminary Report No. 25, Training Project in Pedology, Agricultural University Wageningen, the Netherlands.
Williams, C.N. and Joseph, K.T.	1970	Climate, soil and crop production in the humid tropics. Oxford University Press.