SOIL INORGANIC NITROGEN AND MOISTURE IN RELATION TO EIGHT CROPS GROWN ON A RED FRIABLE CLAY SOIL OF KABETE, KENYA

by

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This thesis is my original work and has not been presented for a degree in any other University.

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ABSTRACT

The soils of the Station on which the trials were carried out are deep well drained red friable clays belonging to the Nitosol soil taxonomic group in the F.A.O. classification. The plough layer of the plots was moderately acid (p^H 5.85) and had an average C.E.C. of 25.6 me/100 g, average carbon and nitrogen contents of 3.22 and 0.286% and bulk density of 1.09 gm/cc. Water held at field capacity and wilting point averages 35.64% and 27.73% giving 7.91% (dry weight basis) available water in this horizon, though available water stored (storage capacity) in the top 180 cm of the soil averages 136.6 mm.

The investigations on soil inorganic nitrogen were carried out during the long rains (March -

October 1978) and during the following short rains of November 1978 - February 1979. During the two seasons, rainfall was above average, being 758.2 and 519.8 mm as compared with averages of 584.6 and 343.5 mm.

During the study period, it was found that inorganic nitrogen (the sum of NO_3, NH_4 and NO_2 nitrogen) in the top 30 cm of the soil investigated:

a) accumulated rather steadily during the dry periods. During this period, it increased from about 29 ppm in mid July to about 64 ppm early in October 1978.

b) increased rather sharply from about 21 ppm on the 11 January 1979 to about 26 ppm on the 26th January 1979, dropped to about 18 ppm during early February 1979 then rose again.

c) decreased as the rains continued from about 64 ppm in October 1978 to about 21 ppm during the first half of January 1979 and from about 26 ppm late in January 1979 to about 18 ppm early in February 1979.

Accumulation of inorganic N in the top 30 cm of the soil during the dry period was ascribed mainly to continued mineralisation of organic N. Rather sharp increases of inorganic N noticed during the period 11th January - 26th January 1979 and after 7th February 1979 were attributed to the flush of decomposition of organic matter and subsequent mineralisation of organic N at the onset of rains (Birch effect).

Rapid declines of inorganic N during the periods 16 - 22nd August 1978, 3rd October 1978 - 11th January 1979 and 26th January - 7th February 1979 were due mainly to leaching of inorganic N when there was enough moisture to wet the profile above field capacity.

This general pattern of inorganic nitrogen levels during the two seasons investigated was further found to vary according to the crop, significant differences being found between levels under the eight crops planted in the trials. These eight crops were Irish potatoes, maize, wheat, linseed, soya beans, field beans, sunflower and sweet potatoes. During short cropping periods when all crops were fertilised with nitrogen except sunflower and sweet potatoes, it was concluded that inorganic nitrogen levels were relatively high below Irish potatoes and maize and relatively low under linseed and wheat. Although the amounts of inorganic N below the various crops varied more or less according to the sampling date, the crops can be ranked according to the levels of inorganic N under them as follows:

linseed $<$ wheat $<$ field beans $<$ sunflower $<$ soyabeans $<$ sweet potatoes $<$ maize $<$ Irish potatoes.

Significant differences in organic nitrogen content were found between Irish potatoes and all other crops; maize and linseed; maize and soya beans; sweet potatoes and wheat and sweet potatoes and sunflower. The differences in the soil inorganic N between crops were mainly due to uptake of inorganic N from the soil though it is possible that the influence of the crops on mineralisation rates was a contributory factor. The high inorganic N below Irish potatoes was possibly due to low rates of nitrogen uptake, and due to the effects of weeding, earthing up and wide spacing on mineralisation rates. The low inorganic N below linseed and wheat on the other hand was due to high rates of N uptake, and the fact that they were weeded only once and covered the soil well.

Since nitrogen movements, transformations and uptake by the crops are much influenced by the soil moisture levels, subsidiary investigations monitored soil moisture levels below the eight crops studied. Soil moisture investigations covered the long rains 1977, short rains 1977/78 and the long rains 1978.

Stronger drying conditions were experienced during long rains 1977 than during the remaining two seasons (1977/78 short rains and 1979 long rains) but in none of the three seasons did the soil dry out to wilting point to more than a depth of 70 cm at which depth moisture was continuously available to crops so that none of the crops wilted permanently. During the 3 seasons the deepest layer the soil was dried below wilting point was about 60 cm depth. Drying the soil below wilting point was due to upward movement of water mainly in the vapour phase and evaporation of water from the soil surface.

In general, total soil moisture in the profile to a depth of 180 cm throughout the growing period seemed to be:

a) lowest under sunflower

and

b) highest under Irish potatoes

However, marked differences between water content of specific sampling horizons were found to occur between crops as follows:

Horizon	Least moisture	Most moisture
0 - 10 cm	linseed	maize
	field beans	sunflower
10 - 30 cm	linseed	Irish potatoes
	wheat	sweet potatoes
		maize
30 - 70 cm	linseed	Irish potatoes
	sweet potatoes	soya beans
		field beans
70 - 120 cm	sunflower	Irish potatoes
	sweet potatoes	wheat
		linseed
120- 180 cm	sunflower	Irish potatoes
	maize	linseed
		wheat

The moisture use of the various crops was related to the rooting habit (rooting depth and intensity) whereas the moisture in the whole profile down to 180 cm throughout the growing season was related to rooting depth and uptake, duration on the ground and evapotranspiration.

The basic agronomic trial, within which the soil nitrogen and moisture studies reported took place, was concerned with finding out the extent to which the growth and yield of each of the eight crops planted was influenced by the nature of the preceding crop. Within the trials, each crop was followed first by each of the eight crops, to give 64 treatment combination, and then by a test crop of maize. The yield of the eight crops and the test crop during the three seasons covered by the investigations did not appear to be significantly influenced by the preceding crop, but was related more to the rainfall of each season.

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CHAPTER I

1. INTRODUCTION

Much work has been done in the past on the effects of crops on the soil on which they grow under different conditions ranging from pot experiments to field trials. Investigators who have been involved in this work include Pickering (1919), Schreiner (1910), Thatcher (1923), Saunder, Ellis and Hall (1937), Bray (1949), Ingham (1950b), Woodruff (1950), Jones (1956), Nye and Greenland (1960), Stevenson (1964), Bennison and Evans (1968), Bloomfield (1969), Sullia (1972), Claudius (1973), Kimber (1973), Russell (1973) and Rice (1974).

However, little work has been done on the effects of crops on the soil when they are grown in association (Mixed cropping systems) and when they are grown successively in rotations with reference to soil inorganic nitrogen and moisture. Of all the workers who have been involved in this work, only a few, including Bennison and Evans (1968), Jones (1956) and Saunder, Ellis and Hall (1937) have addressed themselves to the effects of different crops on the soil inorganic N (especially NO_3-N) during cropping periods of rotations.

Consequently, much work still remains to be done on the effects of crops on the soil inorganic N in rotations including many crops on different soils and different climatic conditions. The effects of crops on the soil moisture and its behaviour also need to be investigated since soil moisture influences transformations and utilisation of soil nitrogen (Wild, 1972; Arnon, 1972; Colman and Lozenby, 1975).

It is with this in mind that investigations for this thesis were carried out on the soil inorganic nitrogen (NO_3-N, NH_4-N and NO_2-N) and soil moisture. This work was an integral part of the crop sequence trial project which is basically concerned with finding out the extent to which the growth and yield of each of the eight crops planted were influenced by the nature of the preceding crop. The project is currently being carried out at the University of Nairobi Field Station, Kabete, latitude 1^{o} 15' S and longitude 36^{o} 44' E. The altitude of the Field Station is 1941.76 metres (63969 feet) above sea level. The soils of the Station are deep red Kikuyu friable clays developed over underlying Kabete trachytes. The soils belong to the Nitosol soil taxonomic group (FAO classification).

The aim of the project is to obtain fundamental information on the soil, and on the effects of specific crops on the growth of subsequent crops planted in the same field. The eight crops on which work was done were maize (M), wheat (W), linseed (LS), sweet potatoes (SP), Irish potatoes (IP), sunflower (SF), field beans (FB) and soya beans (SB). These crops fit well into the rotations that would be suitable to the highland areas of Kenya. All these crops except sunflower, linseed and soya beans are already of major importance in the East African highlands.

Investigations have been carried out on the changes that take place in the soil as effected by the eight crops during the cropping phase, with special reference to:

a) soil inorganic nitrogen in the top 30 cm of the soil which is the main feeding zone of most crops, and,

b) soil moisture down to 180 cm.

Work on soil inorganic N covered two cropping seasons (1978 long rains and 1978/79 short rains) while work on soil moisture covered three cropping seasons, starting in the 1977 long rains and ending in the 1978 long rains. From the point of view of maintaining fertility of the soil and increasing the productivity of the land, it was thought that attention should be focused on the cropping phases and on rotations with short fallows since in many areas of Kenya where agriculture is possible, increasing land pressure will not in future allow long fallowing as was practical in shifting cultivation.

The information obtained on soil inorganic nitrogen and moisture can be extrapolated to explain possible sequential effects, as evidenced mainly by crop yields, in the area of the trials and in other areas with similar soil and ecological conditions.

The objectives of the soil investigations were therefore to obtain information on:

a) fluctuations of inorganic N in the top 30 cm of the soil as caused by the eight crops and by meteorological factors such as rainfall, soil temperature, radiation and humidity.

b) soil moisture movements, seasonal moisture fluctuations and carryover as influenced by crop uptake and by meteorological factors.

c) the relationship between the amount of soil inorganic nitrogen and soil moisture in the soil profile at harvest and the sequential effects with reference to crop yields.

Besides the above mentioned investigations, the soil on which the trials were carried out were characterised with respect to initial organic carbon content, phosphorus content, mineralogy, reaction (p^H), cation exchange capacity, texture, moisture retention characteristics (wilting coefficient and field capacity), bulk density, previous cultivation histroy and natural heterogeneity. Changes which take place in the soil during the cropping period with respect to soil organic carbon and soil reaction were also monitored.

CHAPTER 2

2. LITERATURE REVIEW

2.1. The effect of a crop on the soil and on succeeding crops

A crop may influence a succeeding crop in a number of ways. A crop may have several effects on soil in which it grows. The influences might be beneficial or deleterious, the effects being due to a variety of factors or inter-relationships. These effects if long lasting may affect the growth of succeeding crops. The effects might be through the microclimate a crop creates, through the soil organisms it supports, through the cultural agronomic practices associated with it, through the soil moisture carryover from one season to the next, through the residues and soil nutrient it leaves behind, through diseases and pests in the soil and through allelochemicals a crop leaves in the soil (allelopathy).

Allelopathy is any direct or indirect harmful effect that one plant has on another through the production of chemical compounds (allelochemicals) that escape into the environment. Sources of allelochemicals are living roots, living leaves and dead and decaying plant parts. The concept of allelopathy has been investigated and examined by several workers including Schreiner and his collaborators (1910), Bedford and Pickering (1919), Thatcher (1923), Jenny (1941), McCalla and Hoskins (1964), Stevenson (1964), Guenzi and McCalla (1966) Bloomfield (1969), Kimber (1973), Russell (1973) and Rice (1974). Among the allelochemicals they identified are phenolic acids such as protocatechuic acids, vanillic acid, p-hydroxybenzoic acid, alumina soluble in normal ammonium chloride and dihydroxystearic acid.

The effects of crops on the soil through the soil organisms have been examined and investigated by several workers including Jenny and Leonard (1934), Jenny *et al.* (1948), Krasilnikov (1958), Jenny and Rachaudhuri (1960), Sullia (1972), Claudius and Mehrotra (1973) and Russell (1973). They found that substances (allelochemicals) such as carbohydrates, sucrose, polythienyl, allyl thiourea, histidine, prussic acid, dithio and thiocarbamates, hydrazines and chlorates produced by higher plants apart from inhibiting the activity of nitrifying bacteria may interfere with uptake of nitrogen or may even lock up soil nitrates on decomposition. Savanna grasses of andropogon family (e.g. *Andropogon saracinas*) have been found to inhibit nitrification even after clearing. The roots of Crotalaria and Lentil species have been found to produce allelochemicals among them amino acids and sugars which either inhibit or stimulate the growth of certain important soil fungi (Sullia, 1972).

The effects of crops on the soil through the microclimate has been investigated by Stevenson (1964) among others while the effect of crops on the soil physical properties has been examined by Emerson (1955), Clark (1971) and Russell (1971) among others.

Despite the fact crops can change the soil with respect to total nitrogen, organic matter, p^H, cation exchange capacity, freedom from deleterious substances (allellochemicals) and physical characteristics, these changes are not likely to be important in rotations with short cropping periods. Work by Bartholomew and Kirkham (1960), Nye and Greenland (1960) and others show that the levels of total N and organic carbon are not subject to large changes within short cropping period. Work done at Rothamsted, U.K., casts doubt on the allelopathy hypothesis since it was proved that no long lasting toxic effect is produced in the soil by any common farm crops and that if anything is actually produced by roots, the amount of it which accumulates during long periods is insufficient to cause any appreciable depression in the next crop. Russell (1973) also argues that decomposition products of crop residues are of no practical consequences because they are either present in too dilute solutions to have any effects on plant roots or because they are absorbed by clays.

However, levels of soil inorganic N (especially NO_3-N) may vary according to different crops grown in a season or in the previous season and to climatic conditions in the cropping periods of rotations (Saunder, Ellis and Hall, 1937; Jones, 1956; Bennison and Evans, 1968). Likewise a preceding crop may have a profound effect on the growth and development of a succeeding crop through the soil moisture carry-over from one season to the next, particularly in deeper layers when there is little moisture loss by drainage (when the soil is below field capacity) and little moisture loss by upward capillary movement and evaporation in the absence of plant roots.

2.2. Soil inorganic nitrogen

The work of Bennison and Evans (1968) on a tropical red earth in Katumani Kenya, Jones (1956) on sandy soils of Gezira, Sudan and Saunder, Ellis and Hall (1937) on sandy soils in Rhodesia indicate that levels of soil inorganic N (especially NO_3-N) may vary according to different crops and according to climatic conditions in cropping periods of rotations.

Available forms of inorganic N are the NO_3-N, NH_4-N and simple organic compounds, mainly those containing amide or amino groups such as urea (Bartholomew and Clark, 1965). At any one time, the available N in the soil does not usually exceed 1% of the total N and is usually very much less than that. However, it is the inorganic fraction of N, mainly the NO_3-N and NH_4-N that is important when available N is talked of, the NO_2-N and the organic available forms being relatively unimportant because of their transient nature.

The available N in the soil is controlled by the factors of addition and the factors of loss of inorganic N. Factors of gain include build up of organic matter in the top soil during the fallow periods (nutrient cycle), mineralisation of organic N in the upper layers of the soil, N fixation, addition in precipitation, upward capillary movement of inorganic N and its subsequent accumulation in the upper layers of the soil and the sorption of NH_4-N from the atmosphere.

Additions of N in precipitation are small and insignificant as compared to other factors of addition. Leland (1952) estimated the annual addition of N (as NH_3 and NO_3 from dust, atmospheric discharges and trails of meteorites) to the soil in precipitation at about 6 kg ha^{-1} at Cornell and between 2 and 22 kg ha^{-1} elsewhere in the world. Eriksson (1952) estimated it at about 7 kg $ha^{-1}y^{-1}$ in tropical regions while Jones and Bromfield (1970) estimated it at 4.6 kg $ha^{-1}y^{-1}$ mineral N in the tropics.

Factors of loss of inorganic N include crop uptake, denitrification of inorganic N, loss by volatilisation, microbial immobilisation (assimilatory N reduction), leaching, runoff and fixation of NH_4-N by clay minerals (though reversible).

A Sources of soil inorganic N (factors of gain)

(i) Build up of organic matter in the top soil during the fallow periods (nutrient cycle)

Fallows are important in maintaining or increasing the fertility of cropped land. The beneficial effects of the fallow can be combined with the effects of rotation to maintain or increase soil fertility.

Nye and Greenland (1960) and Sanchez (1973) noted that during fallowing, there is a transfer of N with water and other nutrients from the subsoil to the top soil tending to make good losses from the top soil that might have occurred during the cropping period. It is partly in this connection that fallows are important in maintaining or restoring fertility in rotations. Nye and Greenland observed also that the changes that take place in the soil during fallow and cropping periods are closely linked to increases and decreases in the soil humus which help to hold N in organic form. Nye and Greenland calculated average increases of total N during fallows to be 38.2 kg/ha and 10.9 kg/ha per annum under tropical forest and high grass savanna respectively.

(ii) Mineralisation of organic nitrogen

According to Bear (1964),Ahn(1973-TC2)and Russell (1973), it is the organic fraction of the soil which supplies almost all the nitrogen of the soil.

Humus is added to the soil through the partial decomposition of leaf litter, root sloughs, root exudates, dead plant roots and parts, dead soil fauna, microfauna and microflora and is removed by mineralisation, soil erosion and by leaching in both cropped and fallow land (Nye and Greenland, 1960).

Through the processes of decomposition (Mineralisation) carried out by soil micro-organisms, humus N is converted to inorganic forms of N, NO_3-N and NH_4-N (Nye and Greenland, 1960), Investigations reveal that there is a flush of decomposition of organic matter at the onset of rains which results in mineralisation of organic N (Griffith and Manning, 1949; Griffith, 1951; Mills, 1953b; Greenland, 1958; Birch, 1958, 1959, 1960, 1964; Kabaara, 1964; Agarawal, Singh and Kanehiro, 1971; Laura, 1975).

(a) Nitrogen flushes (Birch effect)

Birch and Friend (1958, 1959) in their respirometer studies found that drying a soil (or heating it) and rewetting it resulted in a flush of decomposition of humus and subsequent mineralisation of organic N. They further observed that a soil can be dried and rewetted a number of times and on each rewetting another flush occurs of only slightly less magnitude than the previous one. Similar observations were made by Agarwal, Singh and Kanehiro

(1971) and Laura (1975). Birch and Friend found that a single flush lasted for 5 to 10 days and that the laboratory phenomenon was comparable to the changes that take place under field conditions, although these would be complicated by the fluctuations in the field soil temperature, soil moisture and by concurrent decomposition of leaf litter. They also found that the magnitude of the flush reflected the length of time the soil had been dry.

Semb and Robinson (1968) investigating the magnitude of flush in 13 sites in East Africa, found that the magnitude of a single flush in the top 0 - 40 cm of soil ranged from 13 kg/ha to 183.3 kg/ha mineral nitrogen. Griffith (1951) and Mills (1953b) working in Kwanda and Serere in Uganda, found that at both places there was a steep rise in soil nitrate from about 10 ppm at the onset of the rainy season which was quickly followed by a fall of about 2 - 6 ppm NO_3-N in the top 15 cm soil layer under mulch. Under bare fallow they found that the corresponding value continued rising to 30 - 50 ppm NO_3-N. They also found that at both places, the soil NO_3-N was only about 1 ppm under grass and remained low (2 - 5 ppm NO_3-N) on opening throughout the following season possibly because of the depressing effect of the grass on mineralisation.

Birch and Friend (1960, 1964) found that the amount of mineral N produced in the respirometer during the first flush was equivalent to 2471 kg/ha of ammonium sulphate fertiliser for a high humic soil and 336 kg/ha of ammonium sulphate fertiliser for a low humic soil. In general, they concluded that each cycle of drying and wetting effected an increment of about 20 ppm of NO_3-N equivalent to 218 kg/ha of ammonium sulphate fertiliser. Saunder, Ellis and Hall (1937) found that when red brown clay soil taken from cropped then ploughed area was incubated at 35^{o}C for 2 weeks at a moisture near field capacity, 25 ppm NO_3-N was released but when incubation went on for 4 weeks, 30 ppm NO_3-N was released. The results compared well with those found with lysimeters kept in the field.

Birch and Friend attributed the flush of decompositon to the physical and chemical changes that take place in soil organic matter during drying which make it more exposed to microbial attack, to the activities of strains of bacterial (Nitrosomonas and Nitrobacter) and possibly other organisms which survive the drying through resistant forms such as spores, to the many dead microbial cells available for decomposition and to the predominance of young cells still in their logarithmic phase of growth. Lededjanter (1924) and Jager (1961) also made similar observations. Agarwal, Singh and Kanehiro (1971) concluded that in addition to microbial stimulation through drying, heat was directly responsible for the major amount of N and C released by chemical alteration of otherwise unavailable organic matter and by killing off organisms. Laura (1975) concluded that drying of a soil increases the proton supply from the "residual water" and this increases the mineralisation of soil organic matter.

Birch and Friend (1958, 1959) found that the mechanism (the flush) is very sensitive to short but pronounced soil moisture changes and that the rate of decomposition declined as the wet period progressed (possibly due to the behaviour of bacteria and enzymes they produce, the availability of substrate and to the narrowing of the C:N ratio as decomposition proceeded since drying promotes faster carbon than N mineralisation). These flushes are typical of ustic soil moisture regimes although they occur to a lesser extent in udic soil moisture regimes. However, Chew, Williams and Ramli (1980) found that in peats the phenomenon is affected by failure of the peat to reabsorb moisture on rewetting. They further observed that to optimise N mineralisation, watering at intervals not exceeding four days is necessary.

Birth (1958), Greenland (1958), Nye and Greenland (1960) all observed that the course of soil organic matter decomposition was related to rainfall, cropping pattern, extent of dry periods and the intensity of dryness, the carbon content of the soil, the soil p^H and the type of crop residues and root exudates. Most of these factors can be influenced by the presence of growing crops. The possible effects of crop residues and root exudates has been discussed in Section 2.1. The effects of the other factors on mineralisation of organic N are discussed in turn in the following sections.

(b) The influence of soil temperature on mineralisation

Mineralisation (ammonification and nitrification) rates are higher in warm regions than in cool regions because just like other chemical and biological reactions, the rate of mineralisation increases with increasing temperature according to the Q_{10} rule. Thiagalingam and Kanehiro (1973) found that the rate of nitrification of added ammonium .

nitrogen in four soils incubated at 5, 15, 25 and 40°C in the laboratory increased with increase in temperature upto 25°C in 3 out of 4 soils. In the 4th soil, they found that nitrification was as active at 40°C as at 25°C. They further observed that mineralisation of organic N occurred to a greater extent at 40°C than at 5,15 and 25°C temperatures. Gerretsen (1931) showed that in the temperature range of 5° - 30°C the rate of decomposition of crop residues increased with increasing temperature while Hulpoi (1939) showed that in the temperature range of 45 - 75°C, both loss of organic matter and organic N of compost decreased with increasing temperature.

However, in the range 30°C - 45°C, increasing temperature may not have an effect on the loss of organic matter but may allow an increase in the inorganic N content of the soil (Hulpoi, 1939). Several workers including Russell *et al.* (1925), Meiklejohn (1953b) and McIntosh and Fredrick (1958) studying the effect of temperature on mineralisation noted that nitrification was more sensitive to extremes of temperature than ammonification. Nitrification is practically inhibited above 45°C but ammonification may proceed, while below 25°C to 35°C, nitrification decreases gradually till it practically ceases. NH_4-N may therefore accumulate in the soil under extreme conditions of temperature.

Tyler and Broadbent (1959) in their incubation experiments with clay soils found that under acid conditions at a temperature of 23.9°C, there was a net release of soil NO_3-N of 15 ppm during a 14 day period while at a temperature of 6.7°C, there was an increase of only 7 ppm NO_3-N during the 14 day period. Birch (1959) found that after a Kikuyu red loam soil from Muguga, Kenya, had been dried and wetted 204 times over a period of 4 years, it had lost 63% of its carbon and 46% of its organic N while Eno (1960) by incubating 5 sandy soils in polythene bags maintained in the field, showed that a 18°F variation in soil temperature during a 27 day period resulted in a change in average rate of NO_3-N production of 67 ppm. As a rough guide, drying the soil to 100°C decomposes 1 to 2% of organic matter at each flush of decomposition (Russell, 1973).

In this connection Birch (1958, 1960) and Simpson (1960) both observed that agricultural practices which enhance soil drying such as burning, wide spacing, ploughing and bare fallowing accelerate decomposition of organic matter and mineralisation of organic N, while others which reduce soil temperature such as shading, mulching and watering reduce decomposition of organic matter and mineralisation of organic N on rewetting by main season rains. Birch (1960) further observed that in a long rotation where fertility declines after each cropping period, deficiency symptoms will be more noticeable in crops grown in seasons following the shorter dry periods e.g. the short rains in Kenya.

(c) The effect of soil moisture, aeration and tillage on mineralisation

Calder (1957), Robinson (1957), Greenland (1958) and many others agree that reduced aeration suppresses nitrification but ammonification is less affected. Due to this, NH_4-N in concentrations as high as 100 ppm may be found in waterlogged soils.

Work at Wooster, Ohio, by Salter and Green (1933) which demonstrated the effect of cultivation and aeration on the rate of carbon rundown (mineralisation) showed that continuous maize plots had only 35% of the organic carbon present in the soil 30 years previously while continuous wheat (weeded less frequently than maize) plots had 62% of the organic carbon present 30 years previously. Work by Lal (1973) on tropical Ferric Luvisol of Nigeria showed that the soil temperature at 5 cm depth was 9.8°C lower with no tillage than with tillage and 4.2°C lower with no tillage than with tillage at a depth of 20 cm during a period of two weeks. He further observed that although at the end of the experiment it was found that the no tillage plots had more NO_3-N than the tillage plots, the initial organic carbon decreased from 2.33% to 1.69% for the ploughed plots and from 2.33% to 2.26% for the no tillage plots within a period of 17 months (under maize crop). Agarwal, Singh and Kanehiro (1971) found a highly significant correlation between rates of N and carbon mineralisation in incubation experiments. Pokorky, Burda and Flegr (1980) studying the effects of cultivation methods on wheat yield found that shallow ploughing after clover and spring wheat were not advantageous but after potatoes, ploughing increased wheat yield. This was attributed to the effects of crops and cultivation on soil N.

Soil moisture may influence mineralisation through its effects on soil aeration. There is a .

controversy over the optimum moisture in the soil for mineralisation. Most investigators report moisture contents around 40% of the water holding capacity of the soil. Calder (1957) and Semb and Robinson (1969) noted that mineralisation may take place at moisture tensions greater than 15 bars in well aggregated soils. Greaves and Carter (1920) found that nitrification is inhibited at a moisture content corresponding to 10% of the water holding capacity (3 - 8% moisture content); Greenland found nitrification at 4% moisture while Robinson (1957) found nitrification at wilting point ($p^F = 4.2$). Ammonification may, however, occur at even lower moisture contents and ammonia may consequently accumulate under air dry conditions (Robinson, 1957; Greenland, 1958; Dommerques, 1959).

(d) The effect of soil pH on meneralisation

The optimum p^H level for mineralisation of organic N seems to be slightly on the alkaline side. This has been recognised by Schachtschabel (1953) and Russel (1973) among other workers. The generally accepted opinion is however that little nitrification takes place below p^H5. Fraps and Sterges (1947), Drounineau *et al.* (1948), Morrill

(1959) and Tyler *et al.* (1959) found that p^H values around 7.5 to 8 may retard change of NO_2-N to NO_3-N with resultant accumulation of NO_2-N. However, this rarely occurs and is only possible in calcareous soils or in heavily limed soils or in rich soils supplied with urea (Soulides and Clark, 1958).

Chapman and Liebig (1952) working with an orchard soil of p^H 7.7 which was heavily dressed with urea in California, U.S.A., found that upto 90 ppm NO_2-N accumulated in the soil for several months when the soil temperature was below 10 to 15^oC, and Cornfield (1972) incubating two Tea soils for 12 weeks at a temperature of 30^oC found that accumulation of mineral N increased with p^H and that maximum accumulation occured at p^H 5.0 whilst at higher p^H levels, N accumulated as NH_3. Ammonium oxidisers are however less sensitive to extremes of acidity and alkalinity, therefore ammonia does not accumulate in most soils.

(e) The effect of soil organic matter levels on mineralisation

Under field conditions, for a given drying time, the amount of N mineralised is proportional to the carbon content of the soil. Agarwal, Singh and Kanehiro (1971) and Thiagalingam and Kahehiro

(1973) in their incubation experiments found that active mineralisation was associated with high levels of organic matter and high C/N ratio of soils. Russell (1973) observed that the rate of decrease in the humus content of the soil whether measured by fall in organic carbon or N content, is a linear function of the carbon content of the soil (rates of N and carbon mineralisation are highly correlated). Thus if C is the soil organic carbon content t years after ploughing, the relationship is described by the equations:

$$\frac{dc}{dt} = a - bC \text{------------} (i)$$

and

$$bC = a - (a - bC_o)_e^{-bt} \text{-------} (ii)$$

where a = annual addition of organic carbon to the soil

b = fraction of carbon decomposed each year

C_o = initial carbon content of the soil

C = the soil organic carbon content t years after ploughing

The higher the carbon content of the soil (for a given temperature and soil moisture), the higher the rate of mineralisation. Thus the soils ability to supply mineral N decreases during the cropping period till an equilibrium level typical of a particular ecosystem is reached (when gains in organic carbon are equal to losses). Milne (1937) working on forest laterized red earth of Usambara Highlands of Tanzania, found that when the organic matter content and the C:N ratio of the top 10 cm of the soil were 4% and about 12 - 15:1 respectively, land which was cleared and planted to coffee for 35 to 45 years had an organic carbon content of the order of 2.5% (about 5% organic matter). Nye and Greenland (1959) on the other hand calculated that the rate of decomposition of humus carbon in the 0.3 cm layer of the soil is between 2 and 5% per annum for tropical lowland forest soils and between 0.5 and 1.2% per annum for savanna soils.

Kononova (1929) in his respirometer work with light soils of Russia, found that under irrigated conditions, the amount of soil NO_3-N mineralised from ploughed virgin land (when conditions were ideal) was 22 mg/kg soil (22 ppm) in 20 days. Under cotton during the first year 13.6 mg/kg soil (13.6 ppm NO_3-N) were mineralised while during the 4th year under cotton, only 10.4 mg/kg soil (10.4 ppm NO_3-N) were mineralised in 20 days.

(f) The influence of decomposing material. nitrification inhibitors. root exudates and levels of soil inorganic N on mineralisation

The type of decomposing material and the levels of soil inorganic N may also affect mineralisation. Doryland and Warksman (1927) and Nye and Greenland (1960) found that the C:N ratio of the decomposing material must be below 20 to 25 for a net release of inorganic N. This corresponds to total N content of 1.5 to 2%. Investigations by Parberry (1942), Archarya (1946) and Bartholomew and Clark (1963) confirmed this finding. Birch, however, found that the critical C:N ratio below which mineralisation takes place depends on whether or not the soil is being alternately dried and wetted. Birth found that a residue containing 1.5%N, N was mineralised under alternate wetting and drying conditions but immobilised under constant moisture.

Decomposing humus might influence mineralisation of organic matter through their decomposability and their associated N factors (the number of grammes of N in the form of NH_4+ ions immobilised during decomposition of 100 g of the material), their phosphorus contents (Mamchenko, 1941) and their cation contents (Broadfoot and Pierre, 1939). Bartholomew (1965) calculated that ordinary crop residues immobilise 9 to 13 kg of organic nitrogen per ton of original residue decomposed under aerobic conditions. Chew, Williams and Ramli (1980) found that when an oligotrophic peat was air dried (moisture of 15% v/v basis), N was not available to Napier grass because the peat was unable to reabsorb moisture on wetting (irreversible dryness). This affected the mechanism of the N flush.

The effect of root exudates (allelochemicals) which might have some influence on mineralisation had been discussed in section 2.1 of this chapter. Several other compounds have been shown to inhibit nitrification in soils. Verstraeten and Vlassak (1973) investigating the influence of some chlorinated hydrocarbon insecticides on mineralisation of N fertilisers and plant growth, found that lindane (hexachlorocyclohexane) inhibits nitrification in soils.

Fresh organic matter has been shown by Löhnis (1947) and other workers to accelerate mineralisation of humus and subsequent release of N. By the same reasoning, excretions of plant roots, root sloughs and even dying roots can also provide organic matter which has some "priming effect" on the soil microflora. This has been observed by Goring and Clark (1949) and Bartholomew and Clark (1950).

Levels of inorganic N are also important in influencing mineralisation. Harnsen and Lindersberg (1949) and Birch (1960, 1964) indicate that high levels of inorganic N suppress mineralisation in most soils. Kaila et al. (1953) and Kivekes and Kivinen (1959) showed that concentrations of inorganic N of 100 to 200 ppm suppress mineralisation.

(iii) Nitrogen fixation

Nitrogen fixation, the process by which atmospheric N is converted to organic N, may be important in crop rotations from the point of view of addition of N to the soil during the cropping periods when legumes are included, the sequential effects of specific crops and additions of N to the fallows when they include leguminous and non-leguminous plants which grow in symbiotic association with N-fixing eukaryotes.

The effects of legumes in fixing atmospheric N and additing N to the soil system has been observed for a long time and in fact is the only reliable way of adding N to the soil outside the nutrient cycle excluding additions by fertilisers and manures (Kass and Drosdoff, 1970). Graham and Hubbel (1975) estimated that biological N fixation contributes about 100 to 500 x 10^6 ton/year N to the biosphere.

Atmospheric N can be fixed by groups of organisms including bacteria (particularly rhizobia), fungi, algae, and actinomycetes living either freely or in symbiotic association with leguminous or non-leguminous plants. The nitrogen is later released to the soil system as inorganic N after mineralisation of the fixed organic N (Stewart, 1970). It can also be secreted into the soil in organic forms such as aspartic acid and β-alanine (Nico, 1934; Nowotnowna, 1937; Virtanene, 1938; Wilson, 1940; Holmes and Macllusky, 1955).

(a) Nitrogen fixation and soil conditions

The fixation of atmospheric N by symbiotic or non-symbiotic organisms is only possible when there is a source of energy (carbonaceous material) and when the C:N ratio of the soil organic matter exceeds 5 (Greenland, 1962). While fixation by blue green algae takes place mainly in rice fields (Kass and Drosdoff, 1970; Fogg, 1973), fixation by other non symbiotic organisms takes place under special conditions and is limited because of high energy requirement of the fixing organisms (Kass et al., 1971; Döbereiner et al. 1972). For every 10 kg N fixed per hectare, 100 kg of energy are consumed by the non-symbiotic organisms.

The conditions necessary for fixation are adequate supply of mineral elements necessary for the growth of the fixing organisms, especially molybdenum, phosphorus, cobalt, boron, magnesium, calcium; optimal p^H and low levels of N (Russell, 1973). High aluminium in the soil may inhibit the activity of fixing organisms (Sanchez, 1976). However, the requirements depend on species of organisms and legumes. Jensen (1947) concluded that the p^H tolerance of legumes probably depends partly on their tolerance to the AI^{+++} ion and partly on the Ca^{++} ion requirement. However, a p^H of 4 seems to be the lowest limit for N fixation and/or nodulation.

(b) Nitrogen fixation during the cropping period

Many cultivated leguminous and non leguminous food crops may fix N when growing in symbiotic association with N-fixing organisms. Besides nitrogen is fixed by non symbionts, algae and fungi during the cropping period.

Fixation by symbiotic bacteria (the best known of which are bacteria of the genus Rhizobium) on cultivated legumes is common in soils low in nitrogen and in leached soils. Many legumes grown in the tropics for the purpose of raising the nitrogen status of the soil are not nodulated for most of the season or even if they nodulate, they do not fix N or still may nodulate in one habitat and fail to do so in another (Bonnier, 1957). Associations between commonly cultivated legumes and bacteria of the genus rhizobium have been known for a long time. Field beans in symbiotic association with Rhizobium phaseoli have been shown by Bond (1957) to fix about 700 mg N per gramme dry matter while soya beans in association with Rhizobium japonica have been shown to fix about 250 mg N per gramme dry matter.

Döbereiner (1972a , 1972b) has shown that sugar cane growing in pseudosymbiotic association possibly with the bacterium Azotobacter paspali may fix N. There is also a possibility that fixation in the roots of sugar cane may be due to a pseudosymbiotic association with the bacterial strain Beijerinckia indica. Other non leguminous crops may also play a role in the nitrogen economy of soils. Ruinen (1961) found that tropical and subtropical plants including cotton and coffee fix N while growing in symbiotic association possibly with phyllosphere organisms such as Azotobacter, Beijerinckia and Pseudomonas. Dioscorea species have likewise been shown to fix N.

Non symbiotic N fixation may also take place during the cropping period and may account for 4 to 20 kg $Nha^{-1}y^{-1}$ (Keya, 1979). The bacteria largely responsible for non symbiotic N fixation are bacteria of genera Azotobacteraceae and Beijer-inckia in aerobic soils and clostridium in anaerobic soils. Meiklejohn (1954) however found that clostridium was always present in over 40 East African soils while she found Azotobacter and Beijerinckia in one out of over 40 East African soils which she studied. Bacteria of the genera Bacillus, spirillum, Derxia, Klebsiella, Acromobacter and Pseudomonas have also been shown to fix N while living freely.

Blue green algae and fungi (Pullularia spp) also fix nitrogen during the cropping period. In rice soils subjected to periodic flooding, N is fixed by blue green algae and photosynthetic bacteria (Yamato, 1971). The genera of blue green algae responsible for N fixation include Anabaena, Calothrix, Cylindrospermum, Nostoc and Tolypothrix. While rates of fixation as high as 276 kgN/ha/yr and as low as 55 kgNha/ha/yr have been reported for paddy soils, maximal algal fixation rates vary from 2.5 kgN/ha/yr to 51 kgN/ha/yr in different habitats.

(c) Nitrogen fixation during the fallow period

Fallows can increase the levels of inorganic N if they contain legumes, non leguminous plants which fix N and N-fixing algae. Non symbiotic nitrogen fixation also takes place during the fallow period.

Apart from the common fodder legumes grown during the fallow period, agro-forestry legumes such as Acacia mearnsii (Sherry, 1971) and Leucaena leucocephala and many nodulated legume weeds such as Indigofera, Crotolaria, Stizolobium, Pueraria

Aeschynomene and Vigna species also fix nitrogen. Derby cited by Sherry (1971) calculated that Acacia mearnsii fixed 160 kgN/ha/yr.

Clark and Paul (1970) have observed that associations involving non legumes (among them gymnosperms and angiosperms) play a role in the N economy of the soil. Available data show that symbiotic N fixation by non legumes vary from 3.4 kg/ha/yr in sand dune culture to 125 - 625 kg/ha/yr in other pot experiments. On average the rate of N fixation by non legumes can be taken to be 50 kgN/ha/yr. It has been shown that many non-leguminous tree and shrub genera in symbiotic association possibly with actinomycetes fix N (Gartner and Gardner, 1970). Such genera include Alnus, Myrica, Casuarina, Hippophae, Shephardia, Aleagnus, Coriaria and Coenothus (Silver, 1969). Silver (1969) also showed the presence of N-fixing bacteria - Klebsiella in the leaves of certain tropical plants such as Psychotria bacteriophila and Pavelta-zimmermanniana. Jones (1970) has also shown that Douglas fir in symbiotic association with phyllosphere populations fix nitrogen.

Greenland (1971) and Döbereiner et al. (1972, 1978) have shown that C_4 grasses fix nitrogen when growing in symbiotic association with nitrogen fixing organisms. Data accumulated in the past point out that rates of N fixation of 160 kgN/ha/yr are possible in grassland soils. Greenland reported gains in soil N of the order of 50 kgN/ha/yr when arable Australian soils were put down to grass containing no legumes. Döbereiner found that the tropical grass _Paspalum notatum_ fixed upto 90 kgN/ha/yr when growing in association with the bacterium _Azotobacter paspali_. Recent work of Döbereiner (1978) suggests that grasses also fix N in association with the bacteria of the genus _Spirillum_. Russel (1973) observed that the grasses _Panicum maximum_ and _Pennisetum purpureum_ may also fix appreciable amounts of nitrogen when growing in association possibly with _Beijerinckia indica_.

Besides fixing N when living freely in rice fields, some blue green algae also fix N when in symbiotic association with non leguminous plants. Cycads have been shown to possess N fixing ability when growing in association with the blue green algae belonging to the genus _Anabaena_. Chu (1978) has also reported that in Vietnam and China, the symbiosis between the alga _Anabaena_ and the water fern _Azolla_ results in appreciable fixation of N. Azolla was found to have about 425 kgN in 160 tons per ha of dry matter in 3 to 4 months.

(d) Enrichment of the soil with the fixed nitrogen

Two factors seem to be important in connection with enrichment of the soil with nitrogen fixed by legumes. First is the fate of the fixed N (whether or not there is nutrient export from the soil in which the legume is grown), second is the rate of mineralisation of the legume residue.

Bonnier (1957) working in Yangambi, Zaire, observed that a large proportion of N fixed by large seeded crops such as peas, beans, soya beans and groundnuts is removed from the land in the seed crop and nearly all the rest in vines or straw is removed at harvest. Greaves and Jones (1942) also observed that a legume need not enrich the soil in N because it fixes N and that legume crops grown for their seed (peas, field beans, soya beans and groundnuts) tend to reduce the N content of the soil whereas legumes grown for leaf (clover, sweet clovers and lucerne) tend to increase the N content, though not necessarily. Russell (1973) reported that soyabeans, field beans and peas harvested for grain depleted the soil N as much as ordinary cereal crops although they fixed between 120 and 240 khN/ha/yr.

On the contrary, Schrader et al. (1966) found that a crop that followed a good legume crop in a rotation received upto about 110 kgN/ha while the second crop following the legume received from 1/3 to ½ of the amount obtained by the first crop. Jones (1942) also found that land rested under the legume Glycine javanica which was not harvested, increased the N content of a Kikuyu red loam soil near Nairobi, Kenya, at the rate of 180 kgN/ha/yr for the first 5 years of the rest and at the rate of 110 kgN/ha/yr for the second five year period.

When considering availability of the fixed N to crops succeeding a legume, decomposability of a crop residue is also important since it influences the rate of leaching which may occur before a succeeding crop is established (Karraker, Bartner and Fergus, 1950).

(iv) Upward movement of inorganic N, its continued production during the dry periods and subsequent accumulation in the top soil

Results from Trinidad (Hardy, 1946a), Ghana (Greenland, 1958) and Nigeria (Wild, 1972) show that seasonal fluctuations in inorganic N are sensitive to short but pronounced soil moisture changes .

showing a slow build up during the dry seasons followed by large but short lived increases in inorganic nitrogen at the onset of rains and then rapid decreases as the wet season progresses. Accumulation during the dry season was attributed to continued nitrification and upward movement of nitrates in solution which was present in the lower layers or which was leached there during the wet season (Hardy, 1946a; Stephens, 1960b; Wetselaar, 1961; Simpsons, 1961; Robinson, 1969).

Accumulation of soil inorganic N in the top soil is determined by mineralisation of organic N, additions due to N in precipitation (though small), upward movement of inorganic N (particularly NO_3-N) in solution or in suspension by capillary movement and evaporation. Rainfall (Hall, 1924), temperature (Russell, Jones and Dhar, 1931) and insolation (Batham and Nigram, 1930; Rao and Dhar, 1931; Dhar et al., 1933) have been separately and in combination invoked as affecting nitrate accumulation in most tropical and subtropical soils.

Fluctuations of inorganic N are related to seasonal rhythms, more specifically to wet and dry periods in tropical climates. Batham and Nigram (1930) and Dhar and his colleagues, claim a relationship between the nitrate status of soils and insolation on the basis of world data. They suggest that sunlight in the presence of photocatalysts bring about purely chemical changes leading to an increase in soil nitrates, but this is open to question. On the other hand Fraps and Sterges (1935) report that the effect of light on nitrification is strongly inhibitory.

Calder (1957) working with a non laterised red earth of Uganda whose field capacity was 25% and wilting point 12.5% found that between 45% and 55% moisture content (oven dry soil basis), soil nitrate was much depressed but between 20 - 35% moisture, it was not influenced by moisture content. Hardy (1946a), Simpson (1960), Wetselaar (1961) Semb and Robinson (1969) and Wild (1972) found that mineral N (NO_3-N and NH_4-N) produced by mineralisation at soil moisture tensions of 15 to 80 bars accumulated in the top soil during the dry season.

Harmsen and Kolenbrander (1965) wrote that mineral N contents of the soil vary markedly among soils, and between seasons of the year in the same soil. The same writers reviewing literature on inorganic N observed that work indicated that the content of inorganic N varies from plot to plot and from day to day. Wild (1972) reported a coefficient of variability of 100% for samples taken from 0 - 15 cm layer of the soil. Beckett and Webster (1971) have also reported similarly high variability of soluble ions in soils.

Baumann and Maasz (1957), Vanstallen (1959) and Ogata and Caldwell (1960) all reported that in winter when no fertilisers are applied, the level of inorganic N seldom exceeds 10 ppm and often remains below 5 ppm in the top soil. However, during summer and spring in the temperate regions, the content can rise to around 40 - 60 ppm in fertile top soils. Rheinwald (1933) contended that even higher levels can be reached with high levels of organic matter. In tropical and subtropical climates, the levels of inorganic N may generally be higher than those in the temperate regions. Scofield (1945) working in Queensland, reported concentrations of mineral N as high as 100 ppm without additions of fertilisers in the top soil of fallow plots, but when green manure was ploughed in, as much as 400 ppm mineral N accumulated.

Jewit (1945, 1950) working with heavy soils of Gezira, Sudan, (extreme arid tropical conditions) where leaching was insignificant, reported concentrations of 40 ppm NO_3-N in the top soil Hardy (1946a) working with soils of the humid tropical climate of Trinidad, found values of NO_3-N of about 60 ppm in the top soil during the dry season due to upward movement and continued nitrification. Griffith and Manning (1949), Griffith (1951) and Mills (1953, 1954) working in relatively heavy soils of Uganda in tropical climate with 2 dry seasons and 2 wet seasons, found amounts upto 70 ppm NO_3-N in the top soil due to upward movement and mineralisation.

The amounts of NH_4-N and NO_2-N accumulating in the top soil are low except under adverse conditions. Griffith (1951) found levels of NH_4-N of 1ppm from unfertilised soil in Uganda while Simpson and Mills (unpublished) found levels of about 8 - 9 ppm NH_4-N from plots receiving ammonium sulphate fertiliser. Bennison and Evans (1968) found that the amounts of NH_4-N produced and accumulated in tropical red soils under semi arid conditions of Katumani, Kenya, were low while those of NO_2-N were negligible.

Wetselaar (1961) working on tropical soils of Australia, found that most of the nitrate during the dry season accumulated below surface crust where physical continuity (capillary conductivity) was broken. Wetselaars work also seems to support the fact that very little soil nitrate was affected by upward capillary movement below 40 cm depth. Wild

(1972) working in northern Nigeria, showed that differences in NO_3-N content of the soil due to crop uptake would be expected in the region of 45 - 90 cm depth late in the growing season since it was found that it is at this depth at which greatest accumulation took place.

(v) Sorption of atmospheric N by the soil

Sorption of N from the stmosphere is also a source of inorganic N. Ingham (1950b) noted that cellulose and organic colloids play the part of catalysts adsorbing ammonia and mineral matter from the air and transfering them in aqueous solution by the agency of rain to the roots of growing crops. Mattson and Koulter-Andersson (1943, 1944) also asserted that in soils of high base status, atmospheric oxygen is adsorbed and this leads to fixation of atmospheric NH_4 by lignin or lignin-nitrogenous constituents of organic matter.

In view of the foregoing, it can be said that crops may influence the inorganic N content of the soil in different ways in long term rotations. However, in most cultivated soils, the quantity of NH_4-N apart from that which is fixed by clay minerals is insignificant compared with NO_3-N (Nelson, 1953; Ray *et al*, 1957; Sanchez, 1976).

B Factors of loss of soil inorganic N

(i) Uptake of inorganic N by crops

Of all the factors of loss, crop uptake is the most important. Harmsen and Kolenbrander (1965) observed that plant uptake is the chief source of loss of inorganic N and each kind of crop and soil situation results in a unique removal pattern. The work of Viets (1960) and Rogers (1961) showed that plant recovery of available N ranges on average between 50% and 60% while Alessi and Power (1978) working with continuous spring wheat systems in Northern Great Plains, U.S.A., found that two thirds of the applied N was removed in the crop or remained in the subsoil.

There has been a general agreement among investigators that immobilisation is much higher under cropped land than under fallow. Bennison and Evans (1968) working on a tropical red earth in the semi arid climates of Katumani, Kenya, found that the quantity of soil nitrates left by crops of maize, short term maize, silage maize and beans, was generally related to their vegetative bulks, rooting habits and the duration on the ground.

Crops may depress the level of soil available N through their effects on nitrification, through actual uptake and through temporary locking up by the rhizosphere organisms they support (Russell, 1973). Extracts from an unpublished compilation by Publio Santiago, Cornell University, and from Wrigley (1961); Ochse et al. (1961), given in table 1 show the amounts of N removed by different crops of corn, potatoes, sweet potatoes, soyabeans and field beans at different yield levels. Pokorky, Burda and Flegr (1980) found that after suitable preceding crops (red clover, fodder beet and potatoes), grain yield of winter wheat was markedly higher than after an unsuitable crops (spring barley) and that in order to equalise yields, it was necessary to increase applied N by 40 kg/ha after unsuitable crops. Grasslands are characterised by low levels of inorganic N throughout the seasons possibly because of their inhibitory effects on nitrification. Concentrations of inorganic N found in grassland soils are of the order of 5 ppm. In this connection, grassland soils may be expected to accumulate nitrogen in the NH_4-N form (Moore and Waid, 1971).

Table 1: Nitrogen requirement of different crops at different yield levels (dry-weight basis)

Crop	Part	Yield tons/ha	Nitrogen removal in kg/ha
Corn	Grain	1.0	25
	Stover	1.5	15
	Total	2.5	40
	Grain	4.0	63
	Stover	4.0	37
	Total	8.0	100
	Grain	7.0	128
	Stover	7.0	72
	Total	14.0	200
Wheat	Grain	0.6	12
	Straw	1.0	3
	Total	1.6	15
	Grain	5.0	80
	Straw	5.0	38
	Total	10.0	118
Potatoes	Roots	12.0	52
	Roots	22.0	120
	Roots	40.0	172
	Whole part	62.0	147
Sweet potatoes	Roots	16.5	72
Beans	Beans	1.0	31
Soya beans	beans	1.0	49

Source: Unpublished compitation by Publio Santiago, Cornell University; Wrigley (1961); Ochse *et al* (1961), adopted by Sanchez (1973).

Mineralisable N (the inorganic N released after incubating the soil) which is a measure of potentially available N or the N which may become available for growth of crops in subsequent periods may also vary within each season according to the various crops grown. Stanford, Legg and Smith (1973) found that soil N mineralisation potential (estimated by the method of Stanford and Smith) offered a basis for reliably estimating amounts of N mineralised during a crops growth and that amounts of soil organic N mineralised during cropping plus the mineral N present initially in the soils correlated highly with the N uptake by the whole plant.

Saunder, Ellis and Hall (1937) working with red brown clays of Rhodesia, found that when the soil was incubated at $35^{o}C$ and at a moisture near field capacity for 2 weeks, the amount of NO_3-N produced from samples taken after one year of maize was 30 ppm and the yield of a test crop of maize grown after one year of maize was 33.6 bags/ha. When the soil samples for incubation were taken after one year of potatoes, the amount of NO_3-N produced on incubation was 43 ppm and the yield of a test crop of maize grown after the potatoes was 48 bags/ha. When the soil samples for incubation were taken after one year of green legume manure, the amount of NO_3-N produced was 48 ppm and the yield of maize test crop grown after the legume was 60 bags/ha.

The work of Saunder, Ellis and Hall showed that the N mineralised during incubation was of the order of N mineralised in miniature lysimeters maintained under bare fallow conditions. They found a correlation coefficient of +0.83 between mineralisable N and the yield of maize and tobacco at zero fertiliser - N levels in the field during a season of good rainfall.

(ii) Leaching and movements of inorganic N

Gardner (1956) contended that if evapotranspiration losses exceed precipitation, there can be no leaching of inorganic N if the soil was not above field capacity, but if on the other hand precipitation exceeds evapotranspiration then there may or may not be leaching losses depending on the amount of water required to bring the soil to field capacity. Leaching of inorganic N can be important during wet periods and may start as soon as the profile is wetted to field capacity after the flush of N at the onset of the main rains.

Leaching of inorganic N may vary in one season in the same area according to the different crops grown. Cfops may influence the leaching rates of inorganic N by the extent to which they intercept rainfall, influence the soil physical properties such as drainage (through cracks) and porosity, by the extent to which they influence the moisture regimes of soils and by the extent to which they remove the soil N.

Leaching of soil inorganic N is also influenced by the following:

a) water movement in the soil, since in a given area of similar rainfall, water movements tend to be inversely proportional to the amount of water held by different soils at field capacity,

b) moisture content throughout the soil profile,

c) the amount of soluble and adsorbed N present or added,

d) the extent of upward movement of inorganic N in the soil during the periods of drought,

e) the amount and duration of rainfall,

f) infiltration and percolation of water which in turn depend on soil composition, texture, structure, depth of the profile and surface treatment.

Wild (1972) working with soils of Nigeria, found that the extent of leaching of soil inorganic N depends on the amount of water entering the soil, the rate at which it enters the soil and the hydraulic conductivity of the soil. The latter in turn depends on the soil structure, texture and the driving force (gravity and diffusion gradients). Hardy (1946a) working on sandy soils of a humid area of Trinidad, showed that as the soil he studied dried to moisture content below 6% (oven dry weight basis), accumulation of soil inorganic N took place, as the soil was wetted above field capacity (13% moisture), diffusion within the non-capillary pores took place but as the moisture content of the soil approached 21%, downward deep percolation took place accompanied by leaching and loss of nitrates.

Movement of N in the soil may be vertical or lateral. The main forms that move either in solution or attached to particles in suspension are NO_3-N and soluble amino compounds such as urea. The NH_4+ ion is not leached to any extent since it is adsorbed by the exchange sites of the soil colloids and within the lattices of clay minerals. However, Smith (1952) and Linser <u>et al.</u>(1959) asserted that a slow leaching of NH_4-N is possible where there are other cations to replace it from the exchange sites. On the other hand Nelson (1953) and Ray <u>et al.</u>(1957) argue that this would be unimportant in cultivated soils since the concentration of NH_4-N in those soils apart from that which is fixed (native NH_4+) and N applied in fertilisers is insignificant.

Gardner (1962) observed that substances including soil inorganic N move in the soil by convection of soil solution due to mass flow, by molecular of ionic diffusion due to concentration gradients, by movement of ions due to concentration gradients, by movement of ions due to electric fields and mass flow due to density gradients arising from concentration gradients. He also observed that diffusion occurs in both liquid and gaseous phases and that the direction and extent of flow depends on the gradients and their direction and that both diffusion and mass flow can simultaneously occur either in the same or opposite direction.

Wild (1972) also noted that the driving forces for the NO_3-N movement are gravity, diffusion gradients and absorption by positive charges in the lower horizons. Apart from vertical movements, nitrates and water also move laterally by hydrodynamic dispersion. Movements are facilitated by the presence of large pores, cracks, insect tunnels, root trees and interstices between large structures in the soil. Kolenbrander (1970) also made similar observations.

Greene (1935) working on soils of the Sudan, found an accumulation of NO_3-N of about 150 kg ha^{-1} in a layer between 100 and 150 cm from the soil surface late in the growing period while Mills (1953) working on clay soils of Uganda, found amounts as high as 400 ppm NO_3-N at 90 cm depth. Accumulation at these depths were due to downward leaching of NO_3 from the top soil. Lysimeter work at Cornell, U.S.A., by Bizzell (1949) showed that leaching losses were 45 kg NO_3-N per hectare for a high N soil and 20 kg NO_3-N per hectare for a low N soil for a 9 year period under a crop of Timothy. Under garden crops he found leaching losses to be 710 kg NO_3-N per hectare when the crops were fertilised with sulphate of ammonia and 780 kg NO_3-N per hectare when fertilised with sodium nitrate for a period of 15 years. Russell (1950) calculated that under tropical forest condition of the Amazon, where annual rainfall exceeds 1,750 mm, the annual rate of leaching of inorganic N from the solum was 430 gm ha^{-1}. Figures which would be expected for cultivation systems are higher than Russell's figures since under closed forest systems, leaching is reduced by interception of nutrients being leached by deep tree roots and also by increased transpiration. Cassell (1970) found maximum NO_3 concentration at a depth of 30 cm in covered and uncovered soil when 22 cm of water was cumulatively applied by irrigation (loamy soil). When 30 and 50 cm of water were applied to covered and bare soils respectively, maximum concentration occurred at 61 cm.

Stephens (1962) found that when sodium chloride whose movement resembles that of nitrates, was applied to bare heavy clay loam soils of Kawanda, Uganda, only a half of it was leached below 45 cm, 3½ months later after receiving 325 mm of rain. Terry and McCants (1970) found leaching rates of 1 to 5 mm in Sandy ultisols of north Carolina, U.S.A., while Wild (1972) working on ferruginous sandy soils of Nigeria whose field capacity and hydraulic conductivity were 26.2% (volume basis) and 43 mm/hour respectively, found that during a period of 2 years when a total of 2,172 mm of rain fell, the leaching rate on average was 0.5 mm/mm rain. Rates reported from elsewhere range from 1 to 4 mm/mm rain. Watanabe and Padre (1979) using labelled N found that in a fallow clay with good drainage, 20% and 40% of applied N were recovered from 0.75 cm soil in uncovered and covered soil after 850 mm of rain in 4 months.

In well structured loams and clays, appreciable quantities of nitrates can be held against gravity possibly because percolating water moves down mainly through cracks and pores between crumbs while most nitrates are found in crumbs so that they can get into this water only by diffusion which is a slow process. The holding of soil nitrates gainst gravity is important for it means that a part of the nitrates produced in a previous fallow is available for a succeeding crop. Crowther (1935) working in the Sudan and using indirect evidence showed that most of these nitrates must be held in the subsoil rather than the surface crumbs possibly because surface nitrates are lost by denitrification in surface crumbs well supplied with decomposable organic matter.

Leaching of nitrates to the subsoil is important in rotations since it preserves the soil N (particularly N from fertilisers). This residual N is used by a succeeding crop in the following season. Widdowson and Penny (1965) at Rothamsted, found that the average residual effect (due to leaching and preservation of inorganic N) of 190 kg ha^{-1} N as sulphate of ammonia given to potatoes for the following wheat crop was equivalent to 63 kg ha^{-N} as top dressing in spring and that the residual effect of 125 kg ha^{-N} top dressing in winter on wheat was equivalent to 25 kg ha^{-1}N applied to the following potato crop. However residual effects due to leaching and preservation of inorganic N are larger in dry than in wet years.

Recent research has addressed itself to ways of reducing leaching losses and increasing the efficiency of N fertilisers. In relation to leaching, attention has been focused on the use of NH_{4-} fertilisers together with nitrification inhibitors and slow release fertilisers. The use of NH_{4-} fertilisers together with nitrification inhibitors prevent or delay the conversion of ammonium to nitrates, and this reduces leaching losses of inorganic N. Slow release fertilisers include coated granules which dissolve slowly in the soil or granules of N - compounds that are slowly soluble such as magnesium-ammonium-phosphate and subsituted ureas (e.g. iso-butylidene di urea) or insoluble substances which hydrolyse to ammonia only slowly such as cryotylidene and urea-formaldehyde compounds (Hamamoto, 1966; Balba and Sheta, 1973).

Recent work by Singh and Sekhon (1976) has revealed that a balanced fertilisation of sandy soils (p^H 8.5) reduced leaching of nitrates from the rooting zone. In their experiments, there was little loss of NO_3-N when P and K were added to the soil at the rates of 26.2 kg/ha and 24.9 kg/ha respectively while when no P and K were added, much of the NO_3-N was left in the profile unutilised by a crop and therefore leached. Emphasis has also been laid on applying the N fertilisers and planting at specific times to reduce leaching losses. Wild (1973) for example, concluded that at the Samuru, Nigeria, roots of crops should grow down to 45 - 90 cm by late August in order to use the high nitrate concentrations found in both seasons at that depth.

(iii) Denitrification

Denitrification (oxidative N reduction) which is the biological reduction of NO_3-N, NO_2-N and NH_4-N .

to gaseous forms - N_2, N_2O, or NO_2 can or cannot take place depending on the soil conditions and situations obtaining (Bartholomew, 1957). Denitrification depends on soil factors such as soil microbiological activity, level of oxygen in the soil, moisture content of the soil, soil temperature, the presence of an energy source, the nature of substrate and p^H.

Some crops have in the past been suspected of accelerating denitrification. Different crops might either increase or decrease denitrification through their effects on soil, temperature, microbial activity, moisture and aeration. Stefanson (1972) found that in sealed soil-plant systems, large quantities of gaseous nitrogen and nitrous oxide were evolved by denitrification from sealed growth chambers after application of NO_3-N, the final concentration of N_2 and N_2O in the chambers increasing in the presence of growing plants. They found that growing plants increased the proportion of molecular nitrogen and that plants increased denitrification in high fertility soils but reduced it in low fertility soils.

Simpson (1960) working with soils of Uganda, found that in most soils, denitrification takes place when the moisture content rises to about 30%, other factors being ideal. Stefanson (1972) working with sealed soil-plant systems, found that at field capacity, the losses of N as N_2 and N_2O from the soil by denitrification averaged 1 - 3 mgN per kilogramme soil per week (for a 6 week period). Denitrification also takes place under conditions of reduced oxygen supply. Greenwood (1962) found that the concentration of dissolved oxygen in solution bathing the bacteria must fall to about 4×10^{-6} M (0.3 per cent oxygen) before reduction starts.

Bremner and Shaw (1958), Simpson (1960) and Velera and Alexander (1961) found that denitrification does not take place outside the p^H range 4 - 10 and that the optimal p^H was 7 - 7.5. Velera and Alexander (1961) found that denitrification in soils not too acid only takes place when there are active microbial populations and plenty of organic matter. Greenland (1970) and Russell (1973) also concluded that ploughedin organic matter and roots of actively growing crops both increase nitrate reduction. Normmick (1956), Gilmour <u>et al.</u> (1957) and Bremner and Shaw (1958) found that denitrification does not occur below 10°C while Simpson (1960), working with the soils of Uganda, found that it does not take place at temperatures above 40°C.

However, Greenland (1962) working in Ghana, concluded that in cultivated soils, it would seem that losses of soil NO_3-N due to denitrification are not very great because NO_3-N would be lost by assimilation, by crop uptake, by leaching when it is wet and moreover there would not be sufficient energy source and substrate (levels of soil NO_3-N on average would be expected to be in the region of 6 - 60 ppm). Greenland maintained that it is possible that at times when the organic matter mineralisation is maximal and the soil is waterlogged enough to create anaerobic conditions, dentrification may occur simultaneously with nitrification in soils with enough substrate and enough carbonaceous material to supply energy as long as leaching and crop uptake are not pronounced. This supports the concept of a micromosaic of aerobic and anaerobic spots in wet soil put forward by Jansson and Clark (1952).

Allison (1955b) in his lysimeter studies, showed that denitrification takes place but in many instances the magnitude of loss has been of the order of magnitude of analytical errors. Laboratory experiment with sandy loam soil fertilised with nitrate salts, by Allison, Carter and Sterling (1960) showed that only trace losses of soil inorganic N occured by denitrification when small samples were kept air-free at approximately 1/3 atmosphere in the presence or absence of upto 1% glucose or 2% wheat straw. However, when oxygen partial pressure was only 0.46%, they found losses of N as high as 10% of the nitrate in the absence of any energy source and 50% of the added NO_3 in the presence of 0.5% glucose.

In sandy loam arable English soils, Arnold (1954) found denitrification losses upto about 3kg/ha/day inorganic N. Bartholomew (1964) and Allison (1966) estimated that from 5 to 15% of the available N could be lost by denitrification in the course of a single cropping season. Burford and Millington (1968) working at Adelaide, Australia, calculated that the soil would lose upto 1.2 kg/ha N as N_2O per day by denitrification under wheat when the soil received 1,100 kg/ha as sodium nitrate.

Low levels of inorganic N have generally been noticed in grassland soils. Woldendrop (1962, 1963) found that grass culture induced denitrification by producing sufficient oxygen accepting substances which reduce the oxygen content of the soil thereby permitting denitrification.

(iv) other types of inorganic N losses

Other sources of loss of inorganic N are non-biological N reduction (volatilisation, erosion, temporary and reversible microbial immobiliation (assimilatory N reduction) and fixation of NH_4-N in soil colloids.

(a) Non-biological reduction (volatilisation)

Evidence of chemical N reduction or volatilisation and denitrification was afforded by Allison (1965) in his lysimeter studies in which he found that the total loss of inorganic N in the soil could only be accounted for by leaching, erosion, crop removal together with denitrification and volatilisation of N. Indirect evidence of gaseous loss of N from the soil has been obtained by Shankaracharya and Mehta (1971) among others. Alessi and Power (1978) working with continuous spring wheat systems in the Great plains, U.S.A., found that 1/3 of the applied fertiliser N was lost by volatilisation or adsorption by organic matter.

There is increasing evidence of purely chemical pathways involving the conversion of nitrates to nitrogen gas particularly in acid soils adequately supplied with organic matter. In this pathway, nitrates are reduced in acid solutions by chemical processes to nitric oxide and nitrogen peroxide (NO_2). The nitric oxide so produced reacts with oxygen to form nitrous acids, so there is no loss of N from the system (Russell, 1973). Allison and Sterling (1948) and Nelson and Bremner (1969) have shown a non biological pathway in which nitrogen gas is formed by the reaction between nitrites, polyphenols, lignins, amino groups, ammonia or humic acid (van Slyke reaction) in slightly acid soils rich in humus. The work of Gerretsen (1946, 1949, 1950), Gerretsen and Doetsch (1951), Allison et al. (1952), Wijler and Detwiche (1954) and Gerretsen and de Hoop (1957) support this but there is no evidence that such changes take place under field conditions. Moreover, the work of Bartholomew and Cady (1961) discount the importance of van Slyke reaction and proposes the direct disintegration of NO_2-N.

Ammonia can be lost from the soil provided the p^H is sufficiently high, as in calcareous soils.

Gandhi and Paliwal (1976) incubating clay loam, sandy clay loam and sandy loam soils, whose electrical conductivities ranged from 1.1 to 50 mmhos/cm, found that gaseous losses of NH_4-N increased with salinity. They found that when the soils were incubated for 6 weeks with ammonium sulphate there was 67.8% loss of NH_4-N (due to denitrification and volatilisation) and when the soils were incubated with urea, 70.6% NH_4-N was lost during the same period. Work by Hargrove, Kissel and Fenn (1977) on calcareous montmorillonitic clay soil of Houston to which nitrogen had been applied as ammonium sulphate and ammonium nitrate, showed that in the field, volatile losses ranged from 3% to 50% of the applied N. Their work also showed that volatilisation was increased by high soil temperature, low atmospheric humidity and by high rates of N application. Studies of Craswell and Vlek (1978) and Vlek and Craswell (1979) have also shown that in warm countries, irrigation water used in rice growing commonly has a p^H of more than 7 and that much ammonia is lost by volatilisation when ammonium salts or urea are applied.

Ammonia can also be lost when it is being formed near the soil surface or when the absorption capacity of the soil is not sufficiently large to hold it (Bartholomew and Clark, 1965). Moreover, ammonia in excess of acidic onions such as is found in decomposing proteins (Lindhard, 1954) and during the hydrolysis of urea, results in high p^H which may permit the loss of ammonia from the soil (Kresge and Satchell, 1960).

However, the extent to which crops influence the volatilisation of NH_4-N by changing the soil p^H and soil organic matter may be negligible in practice, since the soil p^H (particularly in well buffered soils) and the soil organic matter in short cropping period are not subject to appreciable changes. Crops may however influence volatilisation through their effects on soil temperature since high soil temperatures have been reported to increase ammonia volatilisation.

(b) Fixation of ammonia by soil colloids

Bartholomew and Clark (1965) wrote that NH_4^+ ions can be removed from the plant pool through fixation by minerals mainly micaceous ones such as illite and vermiculite. The process is reversible however, so the ammonia finally becomes available for plants. The release of fixed NH_4^+ is accelerated by additions of cations which cause crystal lattices to expand (Barshed, 1954) whereas high concentrations of K+ together with root exudates prevent release of fixed NH_4^+ by causing lattices to contfact (Dräke *et al.*, 1951; Nommick, 1957). Besides fixation at crystal lattices and at exchange complexes, NH_4^+ ions can be physically adsorbed in mineral praticles and in organic matter.

Said (1973) found that for montmorillonitic heavy alkaline vertisols of Gezira, Sudan, from 0.25 to 0.30 me/100 g soil of NH_4-N were fixed in the surface soil while at a depth of about 70 to 140 cm, from 0.28 to 0.4 me/100 g soil of NH_4-N were fixed. Alessi and Power (1978) contended that about 1/3 of the applied N is lost by absorption by organic matter.

Fixation of NH_4-N by soil colloids has agricultural importance. First, in rice fields, fixation of NH_3 supplied as fertilisers prevent its nitrification so prevents loss by denitrification (Cooke, 1964). Secondly, fixation of NH_3 by soil colloids (when N is supplied in the ammonium form) reduces the loss of N by leaching. In the past ammonium fertilisers have been mixed with nitrification inhibitors to prevent the change of ammonium nitrogen to nitrate-nitrogen and to prevent leaching of NO_3-N. An example of such inhibitors is 2-chloro-6-(trichloromethyl)-pyridine(N-serve). However, field trials have not demonstrated its efficiency in promoting retention of N in the soil by fixation and in reducing N losses through leaching (Gasser, 1970).

(c) Soil inorganic N, crop growth and yield

A relationship between soil inorganic N and crop growth and yield has been demonstrated by many workers. Saunder, Ellis and Hall (1937) working with red clays of Rhodesian soils, found in incubation experiments that the yield of crops were related to the soil mineralisable N under crops of maize, tobacco, potatoes and legumes. Bartholomew and Clark (1965) noticed that soil N was related to many crop parameters such as yield, quality, toxicity of forage to animals, uptake and many others when moisture was not limiting. Robinson (1968) and Colman and Lozenby (1975) found correlations between available N and crop removals. Bennison and Evans (1968) working on a tropical red earth in a semi arid climate of Katumani, Kenya, showed that the yield of crops growing in the second season was related more to the soil nitrates remaining at all depths in the soil than to soil water. Smika and

Greb (1973) working with winter wheat in Colorado and Nebraska, U.S.A., showed that combined effect of rainfall and temperature measurements, available water in the soil and total nitrate measured at seeding at a depth of 180 cm accounted for 16% of the variability in protein levels in wheat.

Whether or not a crop responds to changes in soil inorganic N depends on the levels of total N in the soil and the climatic conditions which in turn control the factors of loss and gain of inorganic N. Crops will not respond to changes in inorganic N if the amount of inorganic N in the soil is enough to cause maximal responses of crops (when crop yields reach a plateau). Above levels of inorganic N which cause maximal crop yields, any decreases or increases in soil inorganic N will not cause yield responses.

Birch and Friend (1956) found that in the Kenya Highlands, consistent significant responses to N were only found in shallow soils where continuous cultivation and burning of crop residues had reduced the soil organic matter and total N to 2.3 - 4% and 0.1 - 0.2% respectively. Birch and Friend further observed that soils in the more temperate parts of East Africa are not deficient in available N except when organic matter status for one reason or another is low (assuming a linear relationship between soil organic matter and total N).

Olson, Frank, Deibert, Drier, Johnson and Sander (1976) also observed that the effect of soil inorganic N on the yield of crops depended on the level of residual mineral N and the environmental conditions and that above some optimal value of mineral N, no responses to added mineral N were found. When working in Nebraska, U.S.A., they found that grain yield response of wheat to applied N was unlikely when the soil residual mineral N exceeded 120 kg/ha and for irrigated corn around 240 kg/ha at yield levels of approximately 25 to 30 quintals per hectare of wheat and 85 to 90 quintals per hectare of corn.

Studies of Olson et al. (1976) revealed that the depth at which the soil mineral N remains might also determine whether a crop responds to the soil N or not. Olson working with winter wheat and maize in Nebraska, U.S.A., found that for both crops, residual N in the subsoil had a major effect on percentage grain protein irrespective of the fresh fertiliser N applied. This possibly is because of the fact that root activity declined in the surface soil as it dried. The subsoil N taken up late in the season therefore became important in grain development.

A crop may respond to additions of N with a decrease or an increase or no change in yield, the.

factors affecting the response to an increment of N in addition to the ones discussed above are, the soil supply of N in relation to the crop needs and the availability of moisture (Rockefeller foundation, 1963 - 64; Bartholomew and Clark, 1965). It seems that whether or not a particular crop responds to an increment in soil N (other factors being constant) depends on the yield component that is being studied. For example, work on sugar beet by Campell and Viets (unpublished) indicates that too much soil N results in excessive expansion of leaves at the expense of sugar accumulation. Bartholomew and Clark (1965) observed variable crop responses to soil nitrogen from one season to the next on the same area due to climatic variations. More N may be needed in some years than in others because of climatic differences.

2.3. Soil moisture

Soil water which includes capillary water and absorbed water is a critical factor in the growth of crops. Most growing crops need water throughout the growing period. Soil water is supplied mainly by rainfall although where possible it is supplied by irrigation. Soil acts as an absorbent which takes water and stores it. Stored soil water is important for agriculture since variation in rainfall makes continuous recharge impossible unless irrigation is practised. Soil moisture stored in the profile is used <u>in situ</u> by crops. Stored soil water might be sufficient for the growth of certain crops without recharge, but for most agricultural crops, periodic recharge is necessary to maintain good growth. Nwe (1979) studying the frequency and amount of irrigation for maize on well drained clayey fine sand (classified as being Ferric Luvisol) of Western Nigeria, concluded that a mosture level of approximately 70% of the field capacity throughout the growing season was sufficient to produce a good yield.

Although crop growth in the tropics as elsewhere is influenced by a wide range of physical, chemical and biological factors, soil water availability is a major control. Soil water is necessary for many soil processes and interactions. Soil water influences the availability and uptake of nutrients, influences transformations of soil N and in general is the medium in which many soil reactions take place. Several workers including Wild (1972), Colman and Lozenby (1975) and Walia (1980) found that soil nitrogen recovery and utilisation are closely related to the soil water. Consequently a study of other soil factors and inter-relationships without an understanding of the behaviour of water in the soil might be misleading.

Water balance (budget) studies are necessary for crop development purposes, determining irrigation requirements of crops and for assessing the impact of land use changes on the hydrological cycle among other purposes. For crop development purposes, evapotranspiration (the combined transfer of water by evaporation from the soil and transpiration from vegetation surfaces), precipitation, surface runoff, total profile water change and profile drainage have all to be considered (Cater, Bondurant and Robbins, 1970; Wangati, 1972; Singh and Russel, 1978; Sen and Rajpurohit, 1980). The relationship is described by the equation:

$$P = E_t + \triangle G + R + \triangle S \qquad \text{(iii)}$$

Where P = Precipitation

E_t = Evapotranspiration

$\triangle G$ = Profile drainage

R = Surface runoof

$\triangle S$ = Total profile water change.

In working out water budgets for hydrological studies however, precipitation, evapotranspiration from the catchment, stream flow, water storage change in the root zone, outflow/inflow other than past stream flow measurement points and water change beyond root range have to be considered. The relationship is described by the identity:

$$E_t = P - (Q + \Delta S + \Delta G + L) \text{ ---------------------- (iv)}$$

Where E_t = Evapotranspiration

P = Precipitation

ΔQ = Stream flow

ΔS = Water Storage change in the root zone

G = Water change beyond root range

L = Outflow/inflow other than past stream flow measurement point

The amount of water under each crop at any depth and at any one time is determined by the factors in the water balance equation. A part from water from precipitation, soil may gain water by water movement from soil water reserves (when suction and vapour pressure gradients occur). Water use of a crop represents the total evapotranspiration for the whole period of growth. Water budgets can be calculated on weekly, fortnightly or monthly basis throughout the period under review but the commonly used time interval is ten days.. Each item in the water balance equation is considered in turn and in detail in the following sections.

A. Runoff, infiltration and drainage of soil water

Runoff occurs when rainfall intensity exceeds infiltration rates. Such a condition is likely to obtain when rainfall intensity is high (particularly in heavy textured soils such as montmorillonitic clays) and gradients are steep. In such situations losses of water by runoff are high. Jackson (1977) wrote that:

> "Rainfall intensities tend to be high in the tropics and a considerable proportion of the rain is concentrated in a comparatively small number of very heavy storms. This means that much of the rainfall may therefore not be effective in the agricultural sense since it never becomes available to plants. Instead of contributing to the build-up of soil moisture reserves which can be drawn on in dry spells, surface runoff is considerable, creating problems of flooding and soil erosion".

Fabrother and Manning (1952) found that in an agricultural flat land at Namulonge, Uganda, with a 2% slope, 39 - 64% of the 576 mm rain that fell was lost by runoff from a bare soil.

Infiltration of water into the soil takes place when the soil surface is not sealed as is the case with heavy textured soils after the effect of drain drops. As soil moisture increases infiltration capacity decreases (depending on the soil type and condition) and falls off with time after the onset of rains (Stayter, 1962). Slayter later reports infiltration rates of many clay loams to be 3.8 - 1.3 mm/hr.

Drainage of soil water takes place when total rainfall plus antecedent profile moisture exceed the storage capacity of the soil to a specified depth (Singh and Russell, 1978). Soil water drains by gravity if the soil is wetted above field capacity. Drainage water (gravitational) is available to plants though is transient in nature. Experiments have revealed that upto 5 cm of gravitational water can be used by crops. The rate of downward movement depends on the amount of water in the soil, the amount received and its rate of addition, presence of large pores and cracks, the hydraulic conductivity of the soil and the presence of a shallow water table. The presence of large pores and cracks increase drainage rate while large amounts of water and high hydraulic conductivity of the soil will increase the drainage rate. The rate of downward movement of soil water can either be increased or reduced by a shallow water table.

Morh and van Baren (1959) cited by Jackson (1977) observed that continuous downward movement of water occur in regions with no dry season with continuous rainfall of over 60 mm per month accompanied by continuous leaching. Alternating downward movement of water and cessation occur in regions with alternating wet and dry seasons with ground water level well below the soil surface so that capillary rise cannot bring water to the surface. Singh and Russell (1978) found that evaporation from a fine clay mixed with udic Rhodustalf constituted 29% of the total seasonal available water to 127 cm depth in a semi arid tropical region of India.

Crops can influence runoff, infiltration and drainage through interception of rainfall, uptake of soil water, through their modification of surface roughness and through the extent to which they produce cracks in the soil and modify the soil structure and porosity (Clark, 1971). McGinty, Smeins and Merrill (1979) found that infiltration rate was significantly influenced by plant biomass, bulkdensity, presence of depressions in the surface and soil depth. For pasture deferred-rotation grazing system and a 27 year exclosure system, they found infiltration rates of 10.40 and 10.24 cm/hr respectively while for a heavily grazed pasture, they found a rate of 4.41 cm/hr. A vegetation cover tends to increase the proportion of rainfall that infiltrates not only by reducing surface runoff but also by reducing the impact of raindrop splash, thereby reducing soil compaction effects (Jackson, 1977). The cultural practices that accompany a particular crop such as weeding, ridging and harvesting may also change the physical properties of the soil in a way which may either favour or reduce water infiltration, drainage, runoff and retention. The effects of crops through interception of rainfall are discussed below.

B. Upward movement and evaporation of water

Upward movement of water is important in supplying water to crops in the field. The phenomenon of upward movement of water in the soil was investigated by Wild (1955) who found that upward movement of water was 48% of the water lost by evaporation under dry tropical conditions of northern Nigeria.

Water can move in the soil by liquid flow under a pressure gradient, under gravity (drainage) or under a suction gradient (capillarity) or as vapour. The gradients can be caused by drying by evaporation, crop uptake or by soil solutes. Water movements may also be caused by soil temperature gradients causing the water to move from warm to cooler regions in the soil (Russell, 1973). Capillary conductivity is dependent on the continuity of the water films in the soil and for loam and clay soils, it can be maintained at suctions exceeding 50 bars while for sandy soils, the films may become discontinuous at suctions as low as 10 bars (Jackson, 1965).

However, at high suctions water moves in the soil mainly by vapour transfer since as the suction increases, the vapour pressure decreases. Rose (1963) found that vapour movement is the only means of transfer of water in moderately dry soil and that above suctions of 15 bars, it predominates but below 15 bars, water moves mainly in the liquid form. Jackson (1964) using a combination of theory and experience concluded that above suctions of 144 bars, water moves only in the vapour phase.

The extent of upward movement of water in the soil depends on the suction gradient between the dry layer at the top and the wet soil below, texture of the soil and the depth of the water table. Suction gradients are caused by crops through their effects of drying the soil and by evaporation of water from the soil. Morh and van Baren (1959) cited by Jackson (1977) observed that alternate downward and upward movement of water will take place in regions with alternating dry and wet periods when capillary water is able to reach the surface layers and to evaporate. In these regions also surface soil receives water from below in the dry season allowing an alternating process of leaching and accumulation. In areas of very low rainfall with high evaporation rates and a supply of capillary water however, upward movement of water will result in an accumulation of salts in the upper surface.

Russell (1973) reported that at Muguga, Kenya, seasonal variation (lag between the upper and lower soil layers) in soil temperature may go as deep as 1 metre. These may cause temperature gradients which if high enough might cause vertical moisture movements in the soil. Van Bawel, Brust and Stirk (1968) have shown that as much as 4 mm per day of water can move from the subsoil into the root zone as the soil dries out. Gardner and Foreman (1958) investigating the relationship between the evaporative rate of water in bulk and that in different soils, found that upward movement of water by capillarity continued from free water (which was 60 cm deep) in sand loam and fine sany soil. Fox and Lipps (1956) working with four soils in Nebraska, U.S.A., where natural rainfall is inadequate for the production of good yields by crops on the contrary found that, upward movement of water in the soil from the free water surface would be effective over distances as great as 2 metres. Russell (1973) observed that when there exists a suction gradient in the soil above a water table after drainage, water may rise by capillarity from the water table in the above capillary fringe to the surface.

Black (1968) however urgues that upward movement of soil water would be less important in high rainfall areas because of the preferential use of the rain water in the top layers of the soil by plants, reduction of suction gradients in the soil upwards by rain water and the subsequent reduction in upward movement of water by downward displacement of water caused by rain water.

Water loss by evaporation from the soil constituted 21% of the total seasonal available water (rainfall + irrigation + profile available water) down to 127 cm in Alfisols (fine clay mixed udic Rhodustalf) of semi-arid tropical region of India. As the soil dries out, the dry layer at the top of the soil protects the soil below from further water loss by evaporation. Water movement through such a dry layer occurs mainly by vapour diffusion (Hillel, 1973). Penman (1941) found that even a dry layer of soil 1 to 2 millimetres thick was effective in reducing evaporation. Oliver (1969) as a rough guide however, cites 10 cm for surface layers of clays and 20 cm for surface layers of sands.

Several workers have found that cultivation by disrupting capillary continuity reduces evaporation. Farbrother and Munro (1970) reported that any disturbance of the soil by cultivation increases the depth to which drying out can take place in dry weather while Kollar, Kovac, Pilat and Zigo (1980) found that soil moisture content at emergence under winter wheat was increased by conventional ploughing followed by disc harrowing. Willis and Bond (1971) found that tillage effectively terminated first stage drying and evaporative losses when 60 cm columns of soil were initially wetted from the top to about 33% (by volume), covered for 2 days then tilled to depths of 2.5 and 7.5 cm after uncovering. The highest reduction of evaporation was associated with earliest tilling which showed over 50% reduction in evaporative losses for more than 22 days after tilling. The effect was attributed to the disruption of capillary continuity during the first stage (constant rate stage) of evaporation after wetting.

Cassell (1970) pointed out that a lower potential evaporation rate will dry the soil surface less rapidly thus allowing water conduction upward from below the soil surface for a long period of time while a higher potential evaporation rate will dry the soil surface rapidly and present a barrier to water conduction in the liquid phase. Experiments at Rothamsted by Schofield (1870) on fallow and cropped land with barley after prolonged drought showed that no water was lost from the soil by evaporation below 45 cm from the fallow while in cropped land, water was removed from a layer 135 cm deep. Pereira and Wood (1958) found that at Kongwa, Tanzania, after the rainy season in two successive years when the mean monthly temperature at 7.5 cm depth exceeded 33^{o}C towards the end of the dry season, it took about 1 month for soil at 15 cm and 3 or 4 months for soil at 30 cm to be dried to 15 bar suction. At the end of a seven month dry season, the soil had been dried to about 7 bar suction at 45 cm depth and to about 1 bar suction at 60 cm depth.

Cassell (1970) working with a covered and bare loam soils in a sub humid environment of North Dakota, U.S.A., found upward movement of water from the 61 cm depth eleven days after irrigation from an uncovered soil.(Russell (1973) argues that under tropical and subtropical conditions involving prolonged dry seasons, water may be lost by upward movement and evaporation from deeper layers than would be the case in cool climates. In soils with a high water table (within 2 metres of the surface), the water table may influence capillary movements of water. The effects of the water table would be more pronounced in soils whose capillary conductivities fall at high suctions such as clays and loams than in soils such as sandy soils. Moore (1939) suggested loss of water of the order of 0.5 millimetres a day from a water table 2 metres below the surface of certain soils under strong drying conditions. It is only by evaporation that the soil can be dried to suctions greater than those corresponding to wilting-point.

C. Soil water reserves

In deeper layers where there is no evaporation, no upward capillary movement of the soil water, and where there are no plant roots, water may stay for long periods of time in a metastable state after the drainage of excess water (after coming to field capacity). This is the basis of dry farming. Soil moisture reserves are used whenever potential evaporation exceeds rainfall.

Though Richards (1960), Black (1968), Hillel (1973), Pidgeon (1972) and many others observe that field capacity is not a well defined characteristic water retaining property of the soil since it is not reproducible in the field, values of soil water reached at 0.33 bar suction (p^F 2.7) are usually used as laboratory estimates of field capacity. Wilting coefficient of the soil is always reached at a suction of 15 bars (p^F 4.2) though this also varies with the various crops. At suctions higher than 7 bars, the roots of most agricultural crops appear unable to keep the whole plant turgid when kept in a saturated atmosphere.

Urrutia (1977) using barley and maize to determine the moisture retention of a red clay latosol, found the wilting coefficient was between 22 and 23% for both species while the field capacity was between 62% and 66% for both species. In general field capacity determined by using 0.33 bar suctions range from 10% moisture in coarse textured soils to more than 30% in fine textured soils. Field capacity water content is commonly 1.8 times water held at permanent wilting point (Black, 1968).

Available water is the water held between field capacity and wilting point and it was described by Veihmeyer (1927) as the amount of water a crop can take from the soil before its yield is seriously affected by drought. Miller and Aarstad (1970) concluded that under summer environmental conditions, evapotranspiration reduced deep drainage sufficiently to allow reasonable estimates of actual available water to be made from conventional field capacity data. Miller and Aarstad applying their results to methods used by Miller (1967), established that available water can be correctly estimated by adding water used in evapotranspiration to the time of sampling to determine available water values for cropped land and by adding 40% of the total evapotranspiration for covered soils.

Soil moisture retention is influenced by soil treatment, organic matter contents, texture, previous history of wetting and drying and the nature of the underlying soil. England (1970) found that in Mollisols and Alfisols with a texture of silt loam, row crop cultivation for 3 years resulted in 40% more water being retained in cultivated Mollisols than in corresponding pastured soils while Alfisols retained 25% more water than the corresponding pastured soils at suctions below 1/3 bar. At tensions above 1/3 bar, cultivated soils of both orders held less water. This effect was attributed to increasing the total pore space (decreasing bulk density) and increasing the hydraulic conductivity. Goldberg, Rinot and Karu (1970) and Hudson (1969) also noticed that cultivation increased the water holding capacity of alluvial soil developed over sandy loam subsoil and stony montmorillonitic clays. Bradford and Blanchar (1976) found that trenching a fragindalf (silt loam) underlain by brown clay loam increased available water storage.

Jadhav (1978) found that moisture retained at 1/3 and 15 bar showed a significant positive correlation with silt plus clay, organic carbon and exchangeable Na while Russell and Balcerek (1944) and Salter and Williams found that organic matter increased available water content of the plough layer of a clay loam soil from 5 to 6.8% and increased the field capacity (F.C.) and permanent wilting point of a sandy loam soil at the 0 - 15 cm layer by 0.5 cm. Pidgeon (1972) working with Ugandan Ferrallitic soils whose texture ranged from loamy sands to clays found that F.C. depends on the previous moisture conditions. Moisture retention can differ between horizons due to hysteresis effects such as can ensue when different soil horizons are subjected to sequential wetting and drying (Hillel and Mottes, 1964). Pidgeon (1972) also found that field capacity, permanent wilting point and available water capacity vary more or less according to soil texture and organic matter contents.

While Khosla, Gupta and Abrol (1979) found that water held at field capacity was highest in the top 0 - 15 cm of a sand loamy hyperthemic soil whose water table was below 1.5 metres but decreased inconsistently down the profile to 90 cm, several workers including Bomba (1968) observed that loss of structure due to compaction increased the amount of water held at moderate suctions. Hudson (1969) found that the water storage capacity of a deep montmorillonitic clay was 200 mm in the 80 cm profile. For sandy or stony montmorillonitic clays derived from Kaolinitic clays, the storage capacity was less than 110 mm. Singh and Russell (1978) found that 300 mm and 120 mm of water were retained at field capacity and wilting point by a fine clayey deep Alfisol of a semi-arid tropical area of India.

Retention of water at field capacity is important from the point of view of moisture carry-over from one season to the next, particularly in deep layers when there is little loss by upward capillary movement and evaporation in the absence of plant roots. Veihmeyer (1927) demonstrated this in a column of soil 122 cm deep in a tank which was protected from losses except evaporation at the surface. His results show that little loss of water occurred during a period of 4 years. However, the efficiency of fallowing over a summer season in conserving water can be rather poor. At Adelaide, Australia, Bulter and Prescott (1955) noticed that evaporative losses from bare fallow in a month was equivalent at approximately half the sum of the rainfall and available water stored in the top 61 cm of the soil.

D. Water use by crops

Bennison and Evans (1968) working in Katumani, Kenya, observed that moisture use by crops was related to their rooting habits, vegetative bulks and duration on the ground. These factors are the main ones determining crop water use although soil water use is a complicated and dynamic process which is affected by other factors including, water movements in the soil, soil temperatures, soil osmotic pressures (solute suction) and root activities (Hillel, 1973).

(ii) Rooting habits of crops

Rooting intensity (the amount of root mass per volume of soil) and rooting depth along with other factors determine crop water use. Besides, plants have varying abilities to extract soil water (Russell, 1961).

Plant roots may live in soil layers at wilting point if water is available in other parts of the soil. Pereira (1957) found that during drought the roots of arabica coffee growing in deep red loam soil in Kenya, removed water from more than

3 metres depth but had only dried the top 1.5 metres of the soil to 15 bar suction, without wilting permanently. Similar results have been found at Muguga, Kenya, on similar soils. Russell (1973) reported that in Great Britain, in dry summers, roots of annual crops and grasses go as deep as 120 cm but dry the soil to 15 bar suction to depths not exceeding 50 cm. Cole and Mathews (1939) working in Northern Nebraska, U.S.A., on an area planted to wheat each year observed that the soil was dried below permanent wilting percentage at 60 cm to 150 cm. They also found available moisture at a depth of 150 cm under a crop in another season, while in others, they found that the soil was depleted of water to permenent wilting percentage or below throughout the profile at a depth of 210 cm. Singh and Russell (1978) pointed out that in Alfisols of semi arid tropical region of India, water was lost from layers below 90 cm by transpiration (due to upward acting gradient) although the major contribution to water loss was from the top 90 cm.

Although the rooting habits of crops is influenced by soil moisture regimes, it is possible to make broad generalisations on rooting habits of various crops in the light of past work. At Muguga, Kenya, Dagg (1965a) and Russell (1973) have reported maize to be rooting down to 150 - 200 cm. Pillsbury (1968) has reported maize to be extracting available water to 150 cm. However most of the roots of maize are concentrated in the top 70 - 75 cm (at maturity only 2% of the roots occur below 60 cm; Foth, 1962). Irish potatoes have been reported to be extracting available water to 60 cm depth (Pillsbury, 1968) but Chapman and Carter (1976) have observed that most roots of Irish potatoes are between 30 - 64 cm. Sweet potatoes have been reported to be taking water down to 120 cm depth while beans have been reported by Pillsbury (1968) to be drawing water from 60 cm depth, although most of its roots are concentrated in the top soil.

Linseed have been reported by Chapman and Carter (1976) to be rooting down to 61 cm although Pillsbury (1968) reported it as rooting down to 150 cm. Arnon (1972) also observed that most roots of linseed were found in the top soil. Hurd and Spratt (1975) found that under wet and dry conditions wheat roots grew as deep as 12o cm, although the majority were in the top 30 cm. Musick et al. (1963) found that about 70% of the water extracted by wheat was from depths down to 90 cm. Arnon (1972) however remarked that 60% of the root system of wheat is in the top soil. Sunflower has been reported to be rooting as deep as 300 cm while soya beans roots are mainly found in the top soil (Arnon, 1972). Most workers use an assumed average rooting depth of 1 metre.

Russell (1961) asserted that small grains and luccerne should extract more water than maize and potatoes. However at osmotic pressures (of soil solution) of 2 bars, the growth of most agricultural plants is affected while at pressures of 10 bars, no agricultural plants would make appreciable growth depending on the moisture content of the soil.

(ii) Evapotranspiration

In the past crop water use has been related to crop transpiration coefficients (the weight of water that must be transpired by a plant in order to produce a unit weight of dry matter by its aerial parts) and duration on the ground. Recently the concept of transpiration coefficients has been replaced by the concept of evapotranspiration which is a meteorological quantity rather than a biological one. Sharkawi and El Monayeri (1976) concluded that total water loss was a function of foliage amount carried by trees rather than the transpiration rate. Fisher (1977) stressing the physical rather than the biological approach to crop water use, pointed out that the difference in water use per day between any two crops is unlikely to differ by more than 10% whereas the daily meteorological conditions might easily differ by 200%. In this connection, it is important to note that transpiration per unit area per unit time is largely independent of the nature of the crop under adequate moisture supply and developed canopy. Wangati (1972) studying the water use of maize and beans at Mwea irrigation scheme, found that the moisture use of these two crops was closely related to evapotranspiration.

Singh and Russell (1978) found that under semi arid tropical climate of India, transpiration throughout the growing season was 35% of the total seasonal available water down to 127 cm depth of fine clayey soil mixed with udic Rhodustalf. Scholl (1975) found that evapotranspiration accounted for 98% of precipitation during the dry period while during the wet period, it accounted for 80% of the precipitation in an area in Arizona, U.S.A., of gravelly loamy sand covered with stands of Chaparral shrubs.

Evaporation from crops, particularly in the tropics, is likely to be higher than the open pan evaporation because of high leaf area indices (Williams and Joseph, 1971). Jackson (1977) citing Thornthwaite and Mather (1955) pointed out that evapotranspiration is proportional to available water and that if only 60% of water is available between field capacity and wilting point, then evapotranspiration will drop to 50% of its potential value. In silty clay loam soil of Iowa, Denmead and Shaw (1962) found that capillary conductivity of soil can almost maintain its rate until a suction of the soil water exceeds 12 bar if the transpiration rate of maize is 1.4 mm/day but if the transpiration rate was 6.4 mm/day, capillary conductivity was unable to maintain the rate at suctions exceeding 0.3 bar.

Water requirement of a crop is determined by potential evapotranspiration, soil moisture regime and nature of the crop and its physiological reactions to moisture stress. Evapotranspiration of a crop is dependent on availability of soil water, meteorological conditions of the air (evaporative demand of the air), leaf area, stomatal aperture, crop resistance to water movement, display of leaves, density and height of foliage, absorptive and reflective (albedo) properties of foliage (Williams and Joseph, 1971; Kowal and Kassam, 1978). Of these factors, leaf area index, and absorptive and reflective properties of foliage are lergely responsible for variation in evapotranspiration between various crops (Wangati, 1972; Singh and Russell, 1978). Jackson (1977) pointed out that interception (which is a function of the leaf area index) affects the spatial distribution of water reaching the ground and hence the pattern of moisture variation under a vegetation canopy and the significance of evaporation of intercepted water (which is accelerated). Figures from Wolluy (1890) quoted by Jackson (1977) show that when rainfall was 175 mm in 30 days, the difference between crops of maize and soya beans due to interception were of the order of 15% while when 65 mm of rain fell in 25 days, the difference was of the order of 30%.

Although crop water use data do not exist because crop water use varies from place to place according to the evaporative demand and because of difficulties with lysimeter work, it is possible to calculate crop water use from easily obtainable meteorological data and formulae which have been developed. If evapotranspiration values of a specific crop have been determined in one locality, these can be used to determine the water use of that particular crop if potential evaporation values are available in that locality.

Several methods have been developed for assessing evapotranspiration and crop water use. These include the potential evaporation (open pan and atmometer), lysimeter, aerodynamic, energy budget, combination (Penman), empirical formulae (Thornthwaite and Blaney-Criddle) and the moisture/water budget methods. Some of these methods estimate evapotranspiration directly by difference between the items of the water balance equation, others derive it directly from potential evaporation (either empirically found by open pan or atmometer methods or derived from meteorological formulae) values, others derive it by relating it to potential evapotranspiration of a reference crop by crop coefficients (Doorenbos and Pruitt, 1975), yet others estimate crop consumptive use from crop coefficients, mean monthly temperature and monthly percentages of daytime hours in the year. These methods are discussed in detail in several references e.g. Ward (1971), Chang, 1968), Weisner (1970), Penman (1963) and Doorenbos and Pruitt (1975).

Crop coefficients have been worked out for some crops at specific stages of growth under specified climatic conditions since evapotranspiration varies according to a crop's development stage, and climatic conditions. Wangati (1972) reports some coefficients for maize, potato, soyabeans, beans, sunflower and wheat for different climatic conditions for the mid season phase. The data is given in table 2.

Table 2: Crop coefficients for the mid season phase

Crop	Climate:	Wet		Dry	
	Wind:	light	moderate	light	moderate
Beans		1.05	1.1	1.15	1.2
Maize		1.05	1.1	1.15	1.2
Potato		1.05	1.1	1.15	1.2
Soyabeans		1.0	1.0	1.1	1.1
Sunflower		1.05	1.1	1.15	1.2
Wheat		1.05	1.1	1.15	1.2

Adopted from Wangati, F. J. (1972)

Attempts have been made by several people to estimate water use of various crops in different places.

Nwa (1979) found that on well drained clayey fine sand (Ferric Luvisol) of W. Nigeria, maize needed about 330 mm of irrigation water to produce a good crop. Shimshi (1966) found that for near maximum yield, maize requires approximately 500 to 800 mm of water depending on environmental factors. Shimshi and Ephrat (1970) found that the total seasonal evapotranspiration of wheat in a Mediterranean climate was 380 mm. Wheats total irrigation requirement is estimated at 100 - 150 mm of water. Arnon (1972) reported that field beans grown under irrigation required from 300 - 350 mm of water. However the assumed average maximum water use by a crop with a fully developed canopy is about 5 to 6 mm/day (Pillsbury, 1968).

CHAPTER 3

3. MATERIALS AND METHODS

3.1. Experimental design

The investigations were started in the long rains of 1977 and were carried out in two parts, the 3 year sequences and the 18 month sequences. For the 3 year sequences, planting was done only during the long rains, while during the short rains the plots were left under fallow. The 18 month planting was done during both the short and long rains. The experiment was designed such that each sequence was carried out in overlapping cycles, each cycle consisting of 3 plantings and having 128 plots in all.

Each cycle of both sequences had 2 blocks each of 64 plots in a randomised block design. In each block, each of the 8 crops was replicated eight times making altogether 64 plots. In effect each crop was replicated 16 times in a cycle. Each of the 128 plots in a cycle was planted three times in three seasons. In each cycle, each of the 8 crops was succeeded by itself and by the other crops in the second season and by a test crop of maize in the third (last) season. Thus the effect of a crop on the soil and on the next crop could be shown in the second planting, the effect of a sequence of two crops on a test crop of maize could show in the third planting season of each cycle.

Blocking was done such that the blocks ran orthogonal to the slope and possible fertility gradients since the experiment covered a wide area of land (Bailey, 1959). Each plot measured 8 by 8 metres. The margins of the plots were planted with guard rows of maize which act as shelter against wind and pests and which also create a condition similar to actual field conditions. The 3 trial sites were all in close proximity with the main field station building so that they were assumed to be very similar with respect to rainfall, temperature, radiation and soil.

A. The 18 month sequences

For the 18 month sequences, a new cycle was started during the long rains 1977 in field 6, its second planting was during the short rains 1977 and its third and last planting was during the long rains 1978. During the long rains 1978, another cycle was started in an area broken from grass in field 14. This was planted for the first time during the long rains 1978 and planted for the second time in the short rains 1978. The trial sites were ploughed and disc harrowed at least once.

Spacing was as given in table 3 below. Weeding was done twice in a season for all the crops except for linseed and wheat which were weeded once. Earthing up was carried out for sweet potatoes and Irish potatoes. The stover of all crops except Irish potatoes (whose aerial parts withered and were incorporated into the soil before harvesting) was removed from the plots during harvesting time and was not returned in any form.

B. The 3 year sequences

The 3 year sequences were the same as the 18 month sequences in all respects except that for the 3 year sequences, planting was done only during the long rains. For the 3 year sequences, an area was broken from grass in field 14 during

Table 3: Crop varieties/clones, fertilisers and rates, spacing and pesticides

Crop	Variety/ clone	Fertiliser: Name	Fertiliser: Amounts in kgs/64m^2	Fertiliser: Equivalent in kgs/hectare	Spacing (cm)	Pesticide
Maize	Hybrid 512	46% TSP 26% CAN	0.884 1.97	138 308	75 x 30	DDT powder
Wheat	Kiboko	46% TSP 26% CAN	0.557 0.492	87 77	15 x 2	-
Linseed	Mixed varieties	46% TSP 26% CAN	0.557 0.492	87 77	15 x 2	DDT powder
Sunflower	Kensun	46% TSP	0.557	87	75 x 40	-
Field beans	Canadian wonder	46% TSP 26% CAN 60% KCl	0.696 0.5 0.427	109 78 67	60 x 5	Dimethoate (Rogor E), DDT powder
Soya beans	Hill	46% TSP 26% CAN 60% KCl	0.696 0.5 0.427	109 78 67	60 x 5	-
Sweet potatoes	Mixed clone	NIL	-	-	90 x 30	DDT powder
Irish potatoes	Ex-Meru	46% TSP 26% CAN	0.835 0.984	130 154	75 x 25	Dithane M-45

TSP - Triple superphosphate; CAN - Calcium ammonium nitrate; KCl - Potassium Chloride (Muriate of Potash) the long rains 1977 and planted for the first time. Its second planting was done during the long rains 1978 and the test crop was planted during the long rains 1979. Figure 1 is a diagrammatic presentation of the rotation scheme.

C. Fertiliser and pesticides used

Fertilisers were applied to crops only in the first and the second seasons. The test crop was not fertilised so that differences between crops could be better brought out. All fertilisers were broadcast and raked into the soil immediately after the first soil sampling for plot characterisation and before planting. Phosphate as 46% Triple Superphosphate (T.S.P.) was given to sunflower, to Irish potatoes, to wheat, to soyabeans, to field beans, to linseed and to maize. Nitrogen as 26% calcium ammoniumium nitrate (C.A.N.) was given to Irish potatoes, to wheat, to maize, to linseed, to soyabeans and to field beans. Potash as 60% Muriate of Potash (KCl) was given to field beans and soyabeans only. Sweet potatoes was not fertilised. The rates at which the fertilisers were applied are given in table 3.

For protection against pests and diseases, maize was dusted with DDT powder, field beans were dusted with DDT powder and sprayed with Dimethoate (Rogor E), Irish potatoes were sprayed with Dithane M-45 while sweet potatoes and linseed were dusted with DDT powder.

3.2. Field observations and soil sampling

A. Field observations

Since there is patchiness in the soil even within short distances due to variation in vegetation, topography, hard pans, concretions, termite mounds and tree stumps (Nye and Greenland, 1960; Ahn, 1973), it was necessary to observe the trial sites initially with respect to the features mentioned above. These were combined with mapping of the growth pattern of a test crop of maize. Initial observation of the soil and mapping of the soil revealed differences in the soil which are either as a result of crops planted previously on the soil or due to the natural heterogeneity in the soil (the experimental sites were broken from grass to give

Figure 1: Diagrammatic presentation of the rotation scheme

	1977 long rains	1977 short rains	1978 long rains	1978 short rains	1979 long rains
1st cycle 18 month sequence (field 6)	First crop (128 plots)	Second crop	Test crop (maize)		
2nd cycle 18 month sequence (field 14)			Crop 1 (128 plots)	Second crop	Test crop (maize
1st cycle 3 year sequence (field 14)	First crop (128 plots)	Fallow (predominantly grass)	Second crop	Fallow (predominantly grass	Test crop (maize)
2nd cycle 3 year sequence (field 14)			First crop (128 plots)	Fallow (predominantly grass)	Second crop

them a relative uniformity at the start of the experiment).

B. Meteorological observations

Since meterorological factors influence the soil processes and plant growth, it was necessary to collect data on parameters such as rainfall, radiation, ambient temperature, potential evaporation, windspeeds and relative humidity. These were abstracted for Kabete meteorological station.

The data for rainfall for the period of the experiment were rain gauge values, those for radiation were daily total radiation values measured by the Gunn-Bellani radiation integrator, those for ambient temperatures were averages of daily maximum and minimum temperatures measured by an ordinary thermometer, soil temperatures were also averages of maximum and minimum daily temperatures measured by thermistors, those for potential evaporation were daily open pan values while those for windspeeds were anaemometer values on a daily basis. The data is presented in the appendices 11, 13a, 136 and 14

C. Sampling for soil organic carbon and soil pH

In addition to the field observations and soil mapping, the plots were characterised by laboratory determinations of soil organic carbon, soil reaction, cation exchange capacity, bulk density, field capacity percentage and wilting coefficient. Sampling for initial soil organic carbon and reaction was started on the 3rd April 1977 in field 6 and field 14, just after harrowing and before fertilisation of the plots and the 1977 long rains planting. Sampling was carried out by taking 20 core samples from the top 15 cm of the soil of each plot using a core sampler and then compositing the 20 cores from one plot in a polythene bag. Altogether 152 plots from field 6 and field 14 were sampled in this manner. Sampling for organic carbon and pH was also carried out in pits 1 and 2 at nine depths down to 180 cm. Results are given in tables 4 and 5 and appendices 1a to 1d

Soil samples for investigations on the possible effects of the crops on the soil pH were taken in October 1977 just after harvesting of the first season crops in field 6. Sampling for this investigation was also done by taking 20 core samples from the top 15 cm of each plot and bulking them in one polythene bag. At least 12 composite samples were taken in this manner under each of the eight crops for pH checking. Results are given in appendix 3.

Parallel samples from the samples used for inorganic N determinations taken in a similar manner to the ones used for pH checking but from the top 30 cm of the soil were used for checking the soil organic carbon as influenced by the 8 crops. The samples were taken on the 17th July, 7th August, 15th August and 21st August 1978. The results of their analysis are given in appendices 2a, 2b, 2c and 2d

D. Sampling for bulk density, cation exchange capacity and moisture retention characteristics

Sampling for bulk density, field capacity, wilting coefficient and cation exchange capacity was carried out in pit 1 (field 14) and pit 2 (field 6) at 9 depth intervals down to 180 cm. Sampling for bulk density, field capacity and wilting coefficient determinations was done according to the method used by Pidgeon (1972). Four undisturbed soil samples per depth were used for bulk density, field capacity and wilting point determinations while those samples on which C.E.C. was determined were samples weighing about 3 kg for each depth of each pit. Sampling for bulk density and moisture retention characteristics was carried out at the sides of the profile pits using the short sampler and the small ring. Results are given in table 4.

E. Sampling for soil moisture

Planting during the long rains 1977 started on the 4th April 1977 in field 6 and field 14. Sampling for soil moisture under each of the eight crops down to 180 cm started on the 3rd August 1977 in field 6. Sampling for moisture was carried out at least once a week at depth intervals of 0-10, 10-20, 20-30, 30-50, 50-70, 70-90, 90-120, 120-150 and 150-180 cm using 45 cm diameter Jarret auger pairs. Samples were taken at one point in each plot of each crop and whenever possible, 3 plots of each crop were sampled in this way each sampling day. Field moist soil samples from different depths and under different crops were put in polythene bags whose tops were securely tied to prevent moisture loss and analysed for moisture within a few hours of sampling.

During the second planting of the 18 month sequences in field 6, soil samples at 9 depths down to 180 cm were also taken under each of the 8 crops for moisture determination. Sampling commenced on the 23rd January 1978 and ended on the 22nd March 1978. During the 1978 long rains, sampling for soil moisture under the 8 crops started on the 12th June 1978 and ended on the 14th August 1978 in field 14.

F. Sampling for soil inorganic nitrogen

In April 1978 before investigations on soil inorganic nitrogen as influenced by the 8 crops started, investigations into methodology with particular reference to amount of soil to be used, shaking time and natural variability in the top soil were carried out. Soil samples for this purpose weighing approximately 3 kg were taken from points 40 metres apart, from guard rows of field 14 just before the onset of main rains 1978.

During that season in the same field, sampling for soil inorganic nitrogen as influenced by the

8 crops was also carried out. It started on the 17th July 1978 and ended on the 26th October 1978. Sampling was done by taking 20 core samples from the top 30 cm of the soil of each plot at least once a week. At least 4 plots of each of the 8 crops were sampled this way each week using core samplers. The 20 core samples from each plot were bulked in one polythene bag and air dried for analysis.

In the 1978 short rains, sampling for soil inorganic nitrogen was carried out in the same way it was done during the long rains. Sampling started on the 29th November 1978 and ended in the month of February 1979.

3.3. Laboratory methods

A. Soil inorganic nitrogen determination

Soil inorganic N was determined by Bremner's steam distillation method on composite soil samples which were air dried and homogenised by mixing then ground to pass through 500μ mesh. According to the method, 100 gm of thoroughly homogenised soil samples were extracted for their inorganic N by shaking for one hour with 2N KCl using a soil/

solution ratio of 1:2. An aliquot of the decanted extract was then steam distilled with ball milled Devardas alloy and heavy magnesium oxide for 7 minutes in a Markham's steam distillation apparatus.

The Devardas alloy (a mixture of copper, aluminium and zinc) reduced the NO_3-N and NO_2-N in the extract to NH_4-N which was liberated together with the exchangeable NH_3 in the extract by MgO on distillation. The method therefore combines the nitrogen in the NO_3, NH_4 and NO_2 forms. The NH_3 so liberated was collected over 2% boric acid and determined by titration with 0.005 N sulphuric acid using as indicator bromcresol green mixed with methyl red. During extraction and before analysis, samples were preserved with the KCl itself and phenylmercuric acetate or chloroform. Results were expressed as ppm inorganic N as NH_3.

The steam distillation method was chosen because it has the advantage that it is simple, convenient, yields highly accurate and reproducible results, its extraction method is applicable for NH_4-N, NO_3-N and NO_2-N, it yields extracts that can be stored for a time before analysis (no enzymatic or chemical reactions leading to nitrogen transformations are observed with preparations of extract by 2N KCl - Black, 1965), it effects quantitative recovery (99%) of the nitrate, nitrite and ammonia, it is applicable to acidic, neutral and calcerous soils, it is not affected by various organic compounds (e.g. glucosamine, fluvic acid) and inorganic compounds which interfere in other methods (Bremner, 1960, Black, 1965).

B. Soil moisture determination

Soil moisture was determined on field moist samples (well protected from moisture loss) by the gravimetric method (conventional oven method) described by Gardner (1964). Soil samples in metal containers were dried in a forced draft oven at 105°C for at least 24 hours. The moisture content was found by difference between the weight of the wet and the oven dry soil (p^F 6.9) and the results were expressed as percentage of the oven dry weight of the soil.

The temperature of 105°C was chosen because it is well above the temperature at which water is dispelled from the soil samples while not permitting excessive water loss from organic matter by oxidation and decomposition (Gardner, 1965).

The gravimetric method was chosen because if the procedure is carefully followed, it produces reproducible results, it is fairly accurate, simple, does not need special apparatus, it is suitable for work which involves a large number of samples to be analysed routinely and it gives results which can be converted to inches (or centimetres) of water per depth of soil and moisture on a volume basis if the bulk density of the soil taken from the same area and same depth is known.

C. Field capacity determination

Field capacity percentages of various soil depths were determined by the method fof Richards (1948) reviewed by several workers including Peters (1964), Childs (1969), Pidgeon (1972), Hillel (1973) and McIntyre (1974). Water retained at field capacity was determined by extracting the soil water from small, soaked, undisturbed samples under a suction of 0.33 bar (p^F 2.7) in a pressure chamber with a ceramic plate and then determining the moisture retained after extraction gravimetrically.

D. Wilting coefficient determination

Wilting coefficients of the various soil depths were also determined by the method similar to that used for field capacity. Soil moisture in small, soaked, undisturbed soil samples was extracted under a suction of 15 bars (p^F 4.2) in a pressure plate with a ceramic plate. The moisture retained after extraction was determined gravimetrically.

E. Moisture at air dry state determination

Moisture of air dried soil samples was determined by spreading soil samples in metal trays and drying them for over 10 days indoors and then determining the moisture retained after air drying gravimetrically. This was expressed as a percentage of oven dry soil.

F. Soil organic carbon determination

Soil organic carbon was determined by the Walkley-Black method described by Allisons (1964) and modified by Ahn (1973). Air dry soil samples (about 13% moisture) were homogenised and sieved to pass through 500μ mesh before weighing 0.5 grammes for determination of organic carbon. The method involves oxidising the carbon of the organic matter with Potassium dichromate ($K_2Cr_2O_7$) in the presence of 36 N H_2SO_4 and then determining the amount of chromic acid not used by titrating with 0.5N ferrous sulphate using diphenylamine sulphonate as indicator. The organic carbon is expressed as a percentage of the air dry soil.

The method was chosen because it yields reproducible results, it has a high percentage recovery(77%), it attacks carbon in easily oxidised organic matter leaving other forms of carbon such as graphite and charcoal unattacked.

G. Soil pH determination

Soil pH was determined by the glass electrode, pH meter method described by Peech (1964). Soil pH was measured on air dried samples, homogenised and passed through a 2 mm sieve in water-soil and 0.01 M $CaCl_2$-soil suspensions using pH electrodes and meter. The soil/solution ratio used in all cases was 1:2. The pH was measured in salt solution suspension to avoid seasonal pH variations due to fluctuations in the salt content of the soil.

H. Cation exchange capacity (C.E.C.) determination

Cation exchange capacity of the soil was determined by Chapmans (1964) ammonium saturation method modified by Ahn (1973). C.E.C. of the various soil depths was determined on air dried soil samples passed through 2000μ mesh using neutral ammonium acetate as the displacing cation. The method involves saturating the exchange sites in the soil with the NH_4+ cation then determining the amount of NH_3 by distillation with MgO, collection over boric acid and titrating with 0.1N HCl. The amount of soil used was 5 gm and the soil-solution ratio was 1:10. Results are given in milliequivalents per 100 grammes of soil.

I. Bulk density determination

Bulk density of the various soil depths was determined by the method described by Blakes (1964).

The method involves drying undisturbed soil samples of constant volume in an oven at 105°C (p^F 6.9) to a constant weight then determining the dry weight of the samples and the weight of the same volume of water.

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1. Climate of the trial area

The rainfall distribution in Kabete area is bimodal in nature with two rainy seasons per year; April-June (362.31 mm) and November-December (182.72 mm). Each rainy season corresponds to a cropping season. The mean monthly and annual rainfall, monthly rainfall totals for the years 1977 and 1978 and monthly totals for the months of January and February, 1979 are given in Appendix 12 and shown in Figures 2a, 2b, 2c and 2d

The data suggest that the mean annual rainfall for the station is 928 $\pm$ 243 mm. However, it varies over the years as indicated by the large standard deviation. Out of 6 years, (1972-1979) 3 years including two years of the trial had rainfall exceeding the mean annual rainfall. About 40% of the total annual rain falls furing November-December. Figure 2a shows that the wettest months are April (mean monthly rainfall of 204.18 mm) and November (124.22 mm). The dry periods are January-February and June-October.

FIG.2a MEAN MONTHLY RAINFALL

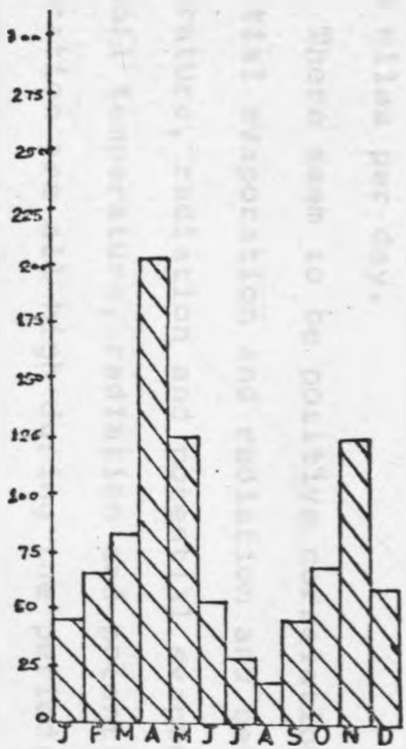


FIG. 2b. MONTHLY TOTALS FOR THE YEAR 1977

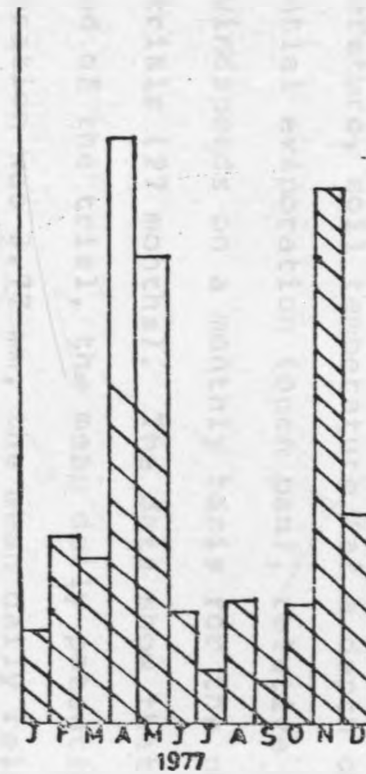


FIG. 2c MONTHLY TOTALS FOR THE YEAR 1978

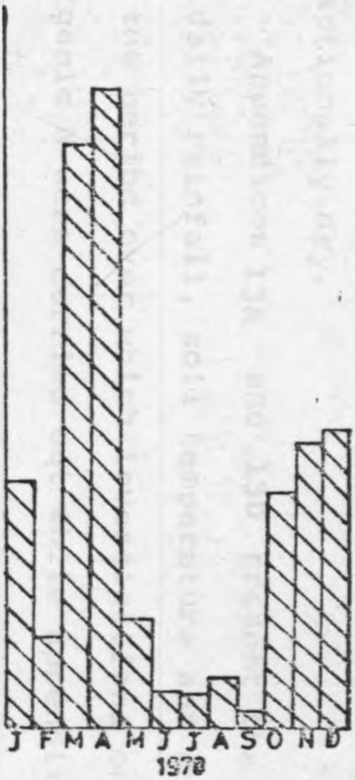
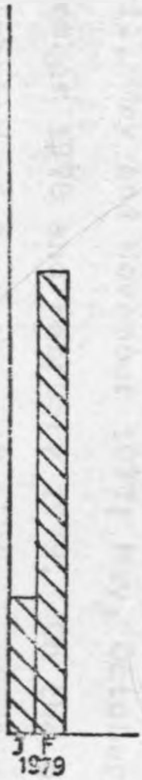


FIG. 2d MONTHLY TOTALS FOR THE YEAR 1979



Appendix 12 and Figures 2a, 2b, 2c, and 2d show that above average rain fell during the months of April, May and November 1977; May, October and December 1978 and February 1979. On the other hand the months of September of both 1977 and 1978 were exceptionally dry.

Appendices 13a and 13b present the data on the daily rainfall, soil temperature and radiation for the period over which investigations on soil inorganic N were carried out while appendix 14 gives the data on the mean daily radiation, air temperature, soil temperature (at a depth of 10 cm), potential evaporation (open pan), relative humidity and windspeeds on a monthly basis for the period of the trials (27 months). The data show that for the period of the trial, the mean daily potential evaporation was 3.77 mm, the mean daily relative humidity was 71.2% and the mean daily windspeed was 59.39 miles per day.

There seem to be positive correlations between potential evaporation and radiation and between soil temperature, radiation and potential evaporation. The soil temperature, radiation and potential evaporation are all high during the periods of January-March and September-October and low during the month of July. The data also suggest that the mean daily temperatures were higher during the wet than during the dry periods.

Variations in soil temperature were small (the variations were of the order of magnitude of 1°C) while the differences between daily air and soil temperatures were of the order of 2.6°C. The soils of the trial area can be described as having an "isothermic" temperature regime since they have a mean soil temperature of more than 15°C but lower than 22°C and the mean soil temperature during the warm and dry periods differs less than 5°C from the mean soil temperature during the cold and wet periods at a depth shallower than 50 cm. The soil moisture regime can be described as being ustic since the soil may be at a moisture tension of 15 bars or more at a depth of 10 - 30 cm for more than 90 cumulative days but less than 180 cumulative days during the year.

4.2. Site characteristics

The experimental area was almost level. In areas where slope approached 8%, bench terraces had been constructed to control soil erosion. The sites were free from surface impediments. However, on augering field 6, occasional clay pans were noticed at a depth of 120 cm. An examination of the two profile pits in fields 14 and 6 revealed that the soil is very deep and well drained (in the pit in field 6, the water table is well below 2 metres). The trial sites had been cultivated some years before the trials but had been left under grass for some time before the experiment.

The vegetation before breaking the field was mainly grass, with Kikuyu grass (Pennisetum clandestinum) and star grass (Cynodon dactylon) being the dominant grass species. Grass was also the dominant vegetation during the fallow periods. The growth patterns of a test crop of maize grown in two different seasons in four different areas (Figures 3a, 3b, 3c and 3d) show that the growth of maize did not conform to the geometry of the plots but was broadly related to drainage patterns. An examination of the growth patterns reveals that field 6a was more uniform in drainage than fields 6b, 10a and 10b.

4.3. Soil characterisation

A. General aspects

The soils of the experimental area are red Kikuyu friable clays developed from underlying volcanic

Figure 3a. Growth pattern of a test crop of maize - field 6a

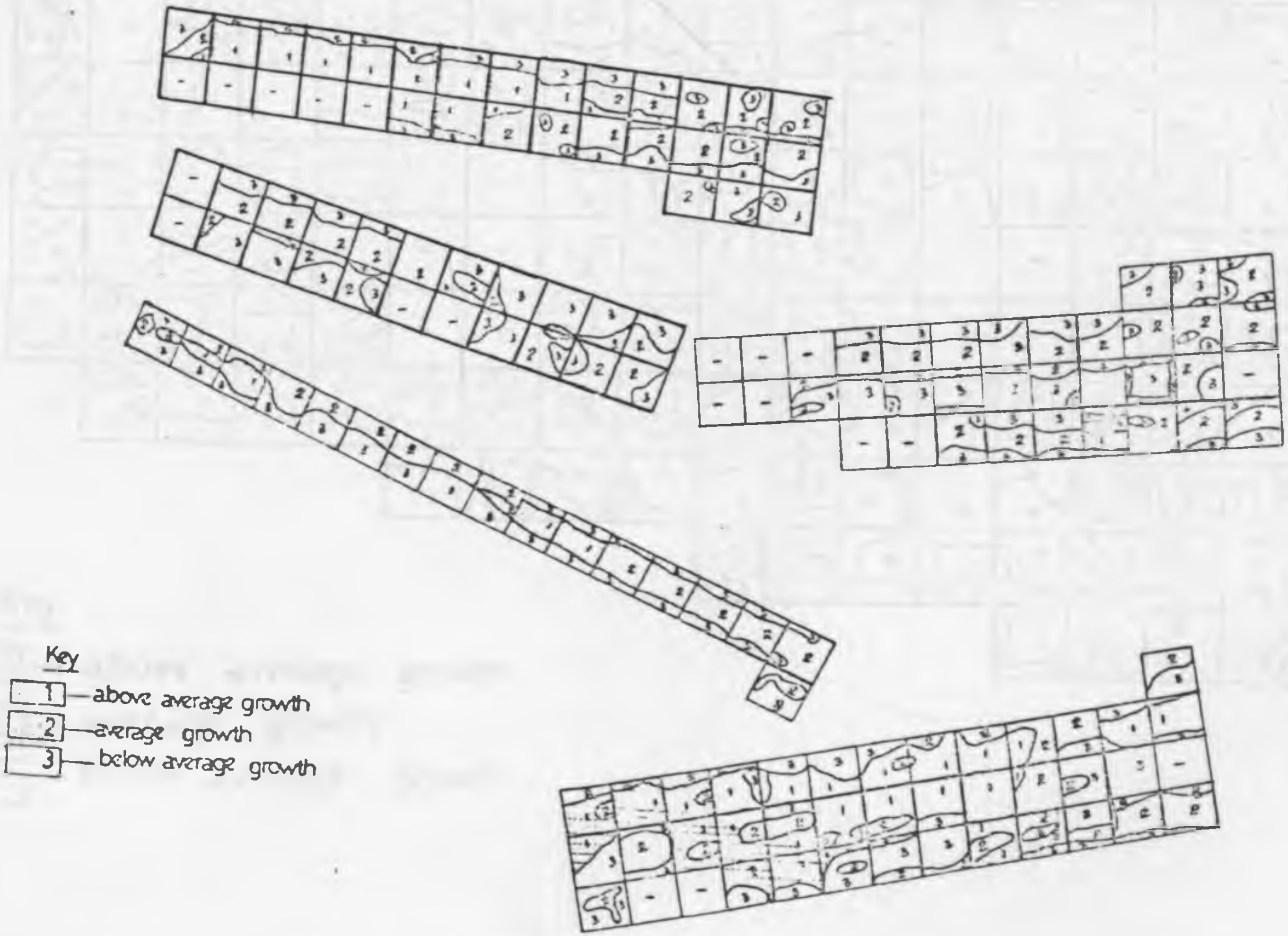


Figure 3b. Growth pattern of a test crop of maize - field 6b

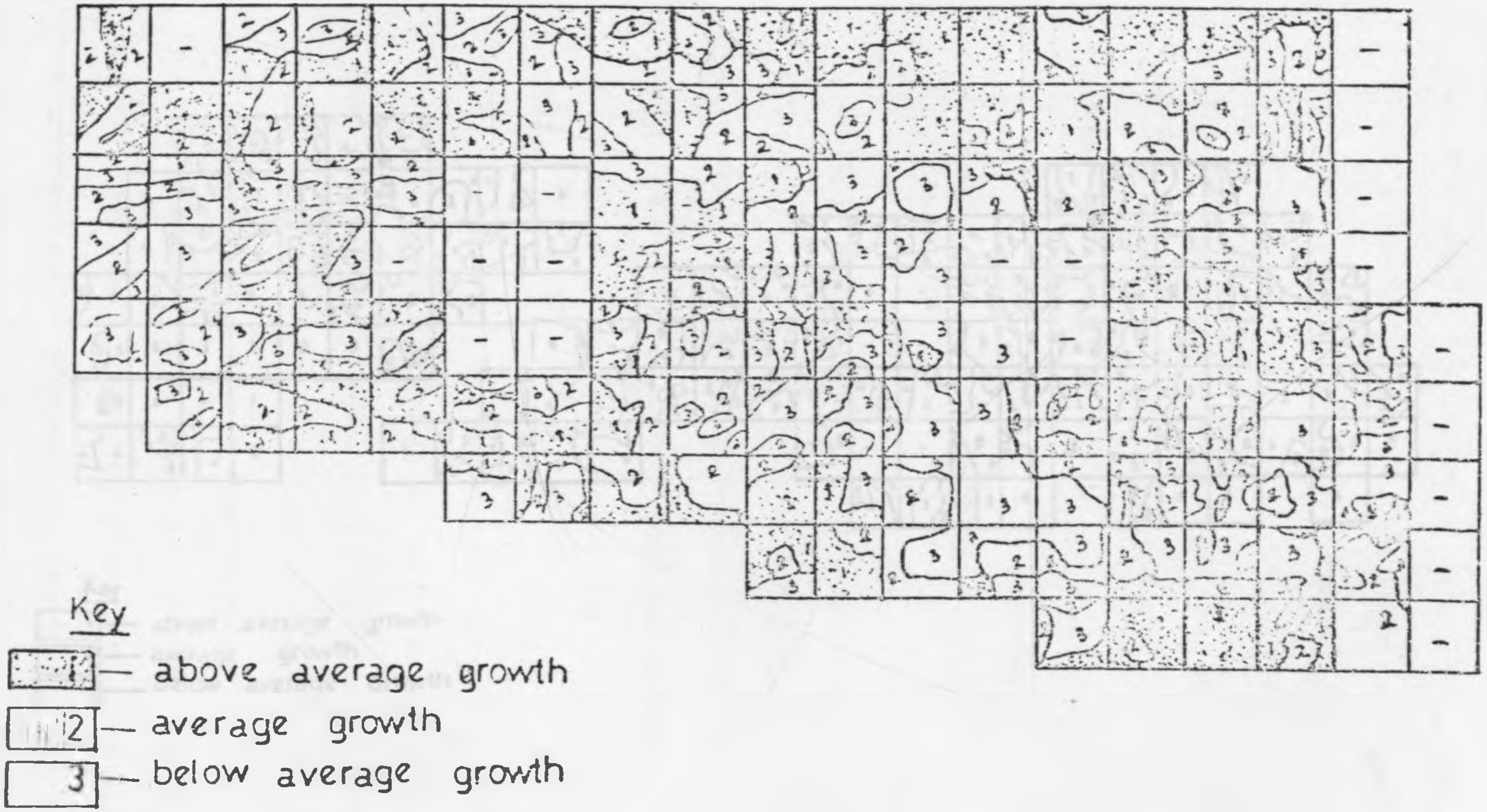


Figure 3c. Growth pattern of a test crop of maize - field 10a

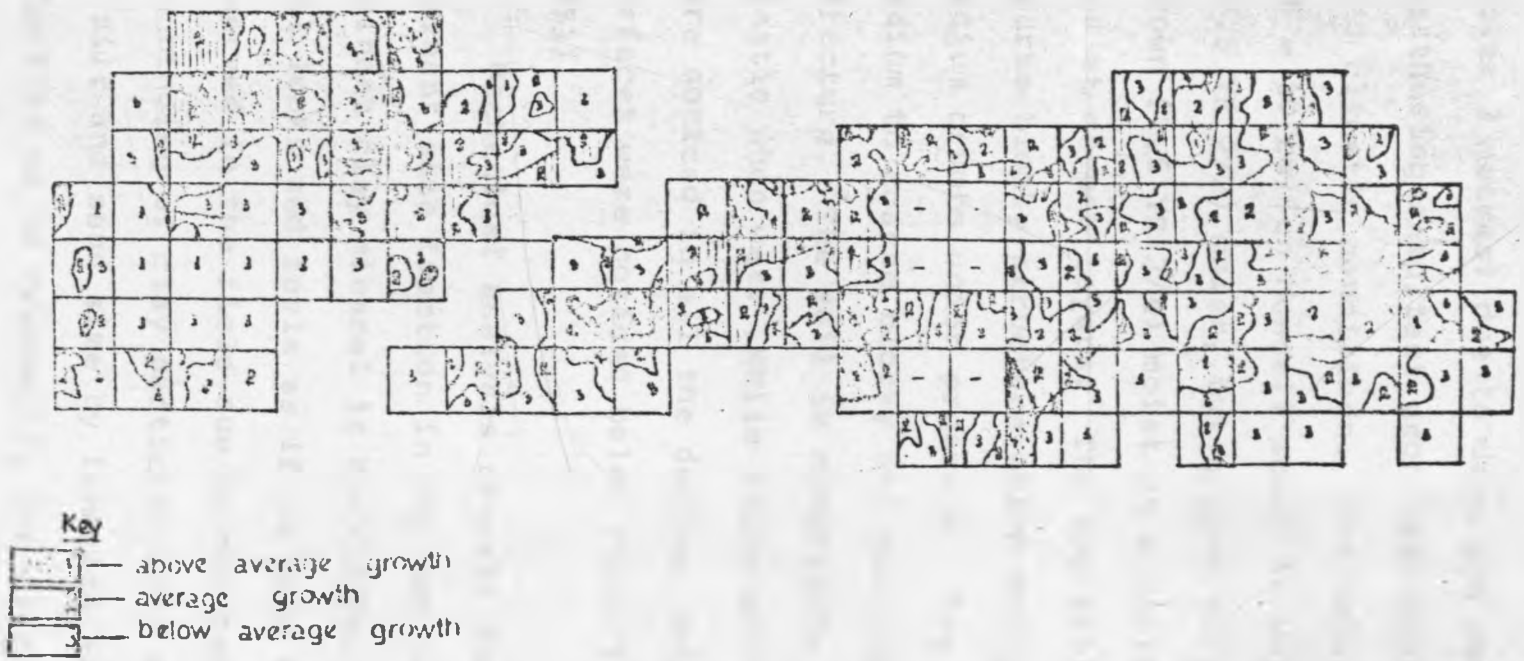


Figure 3d. Growth pattern of a test crop of maize - field 10b

lavas (Kabete trachytes). The soils are deep (over 2 metres) due to deep and relatively rapid weathering resultant upon high rainfall and associated climatic conditions. The colour of the top layer (0 - 10 cm) on Munsell scale is very dusky red (2.5 YR 2/2) moist, but grades to dark reddish brown (2.5 YR 2/4) moist at a depth of 40 - 70 cm and at deeper layers. The top soil has a fine to coarse blocky structure which breaks to fine and medium crumbs under pressure. The subsoil has a medium to coarse blocky and sub-angular blocky structure. The soil is moderately sticky and plastic when wet. While roots and root channels were noticed in all the depths, cutans on ped surfaces were noticed below 90 cm (class results, 1973).

Mechanical analysis reveals that clay is the dominant size fraction in the top soil while the dominant clay mineral is Kaolinite. However, the soil looks and feels as if it were sandy when observed in the field due to microaggregation i.e. the binding of clay particles into microaggregates of silt and sand size by iron and aluminium sesquioxides as is frequently the case in highly weathered Kaolinitic tropical soils rich in sesquioxides (Deshpande, et al., 1968; Greenland et al., 1968; Ahn, 1973).

The soils of the trial area are friable with good tilth, and porous with good aeration and moderate permeability. The total N content of the top 15 cm of the soil on average is 0.286% (Kjeldahl's method) and the available phosphorus content of the top 15 cm of the soil is 77.5 ppm (Mehlich's method). The soils of the trial area fix P and responses to applied N and P are obtained. The soils belong to the Nitosol soil taxonomic group in the F.A.O. classification.

B. p^H, bulk density, cation exchange capacity (C.E.C.) and moisture retention characteristics down the soil profile

Table 4 gives the results of p^H in 0.01 M $CaCl_2$, bulk density, moisture at field capacity and at wilting point, the moisture percentage of air dry soil, cation exchange capacity and the available moisture of the two pits at each of the 9 depths. Values given in the table are averages of four determinations at each of the 9 depths. The data in table 4 is shown graphically in Figures 4 and 5

Table 4: Results of soil profile pit characterisation

Depth (cm)	p^H in 0.01M $CaCl_2$	Bulk density in gm/cc	% moisture at field capacity		% moisture at wilting point		% moisture at air dry state		Moisture storage capacity of the soil			Cation exchange capacity (C.E.C.) meq/100 g soil
			oven dry wt basis	volume/ volume basis	oven dry wt basis	volume/ volume basis	oven dry wt basis	volume/ volume basis	% available water	mm/metre	mm/depth	
0- 10	4.85	1.05	35.64	37.42	27.73	29.12	12.13	13.26	7.91	83.0	8.3	25.6
10- 20	5.22	1.05	35.03	36.79	28.03	29.43	12.22	12.83	7.0	73.5	7.4	25.6
20- 30	5.25	1.11	35.76	39.69	28.34	31.46	13.52	15.01	7.42	82.3	8.2	24.1
30- 50	5.95	1.12	35.74	40.03	28.81	32.27	12.98	14.54	6.93	77.6	15.5	24.2
50- 70	5.90	1.15	36.30	41.75	29.38	33.79	13.27	15.26	6.92	79.5	15.9	21.5
70- 90	5.85	1.08	37.19	40.17	29.99	32.39	13.27	14.33	7.2	77.9	15.6	20.6
90-120	5.65	1.16	36.98	42.90	30.49	35.37	13.49	15.65	6.49	75.6	22.7	18.2
120-150	5.75	1.21	36.34	43.97	30.45	36.84	13.15	15.91	5.89	71.5	21.5	17.2
150-180	6.05	1.19	36.74	43.72	30.72	36.56	14.29	17.01	6.02	71.7	21.5	18.0
Means	5.50	1.12	36.19	40.71	29.32	33.02	13.14	14.86	6.86	76.95		21.86
S.E.	0.0164	0.0033	0.0493	0.6611	0.1292	0.799	0.0433	0.1678	0.0412	1.7782		1.1093
Totals											136.6	

The figures show that the soil p^H increased slightly with depth. The range was 4.85 - 6.05 and the S.E. was 0.0164. Changes in bulk density although slight and non consistent are significant being lowest in the top 20 cm (1.05 gm/cc) and highest at a depth of 150 cm (1.21 gm/cc). The S.E. was 0.0033. The bulk density results are in good agreement with the results found by Lenga (1980) in the same area. They also agree with those of Khosla, Gupta and Abrol (1979) who found that the bulk density was low at the top 15 cm of the soil but increased, though inconsistently down to a depth of 90 cm in a deep sand loamy hyperthermic soil.

The moisture at field capacity, wilting point and of air dry soil all show a slight general increase with depth, the increase down the profile being of the order of 2% (oven dry weight basis) for the three parameters (the S.E. was 0.0493, 0.1292 and 0.0433 for field capacity, wilting point and air dry soil respectively). However on a volume/volume basis the increase with depth becomes greater due to bulk density effects (the S.E. was 0.6611, 0.7990 and 0.1678 for field capacity, wilting point and air dry soil respectively). Water held at field capacity and wilting point averages 35.64 (37.42

FIG. 4. SOIL CATION EXCHANGE CAPACITY, P^H AND BULK DENSITY AT NINE DEPTHS

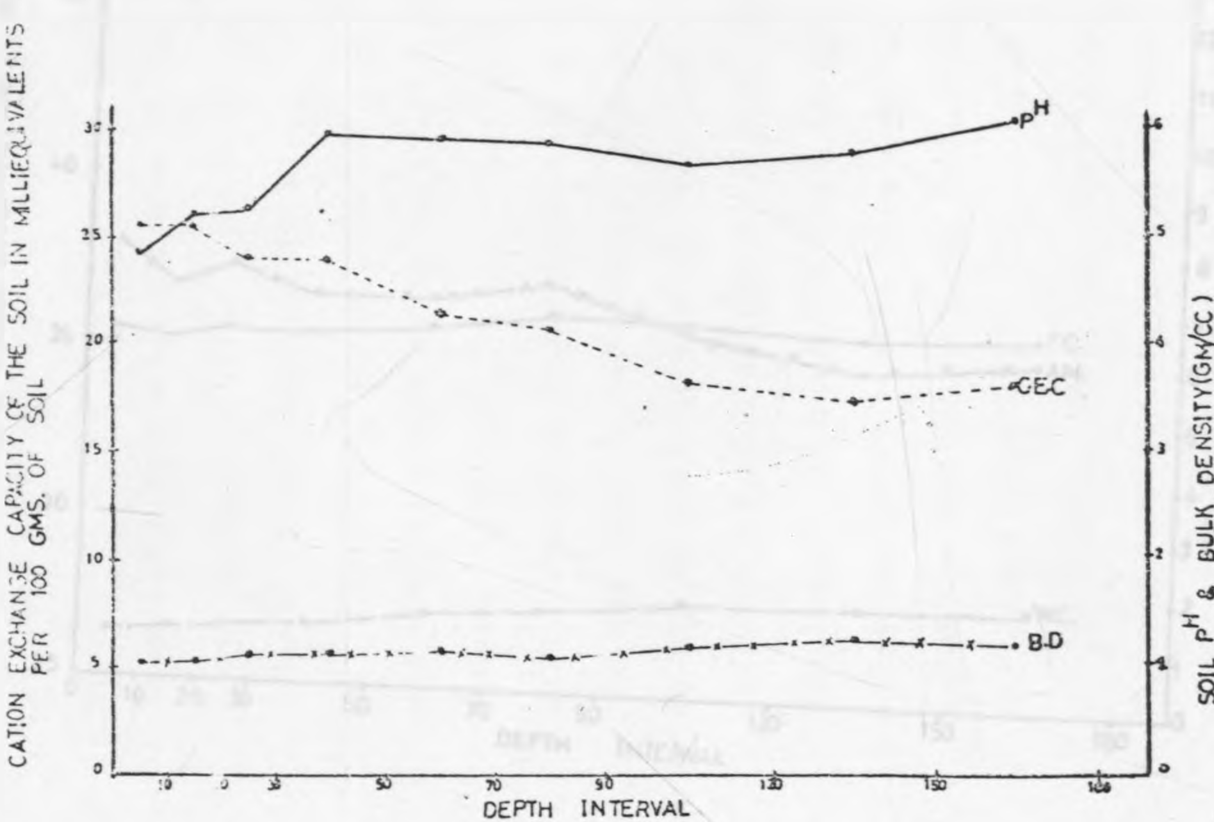
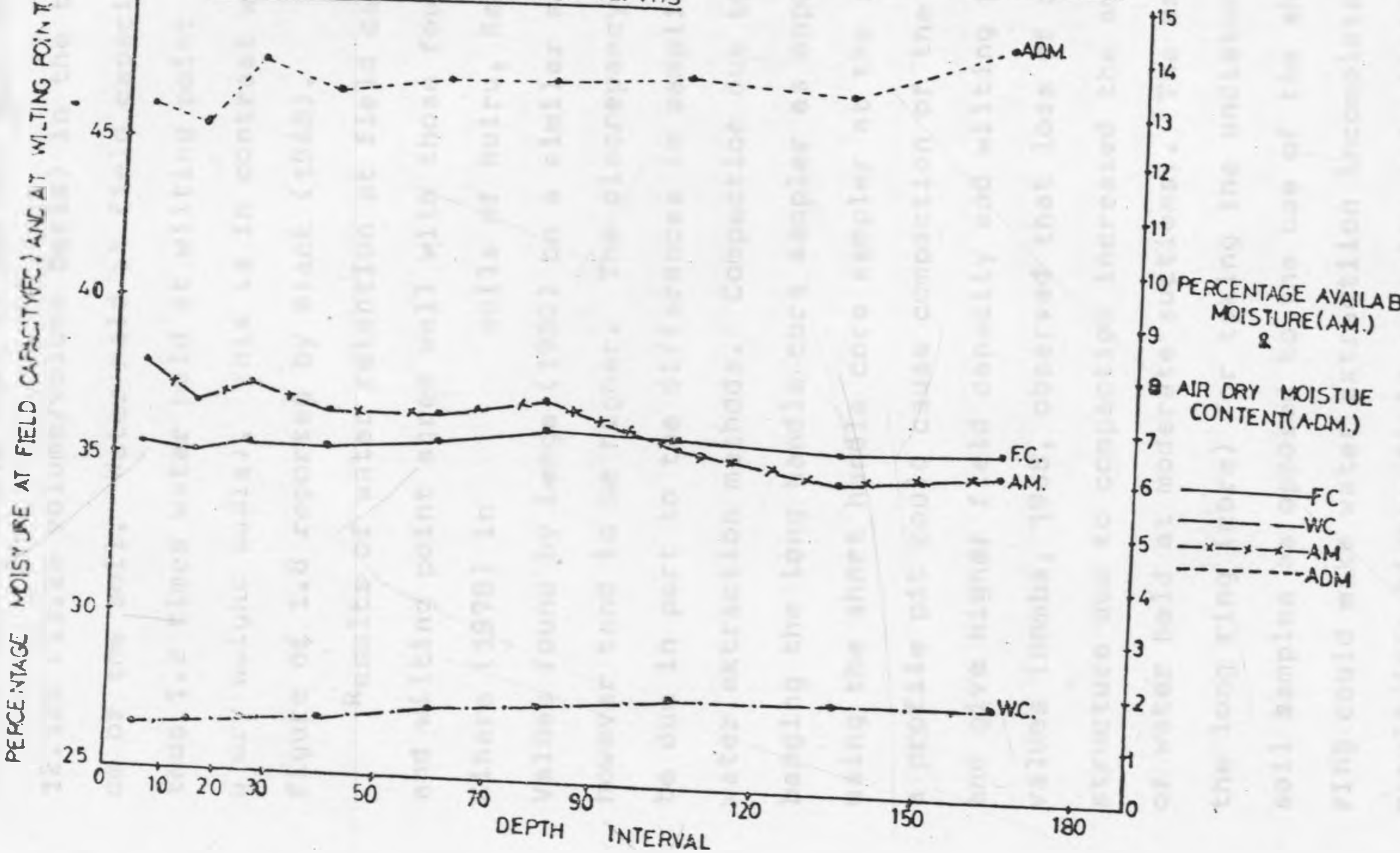


FIG 5 THE RELATIONSHIP BETWEEN SOIL FIELD CAPACITY, WILTING COEFFICIENT AND AIR DRY STATE AT NINE DEPTHS



volume/volume basis) and 27.73% (29.12 volume/volume basis) while that of air dry soil averages 12.13% (13.26 volume/volume basis) in the top 10 cm of the soil. Water held at field capacity is thus 1.2 times water held at wilting point (on a dry weight basis). This is in contrast with a figure of 1.8 reported by Black (1968).

Results of water retention at field capacity and wilting point agree well with those found by Kihara (1978) in soils of Ruiru, Kenya. Values found by Lenga (1980) on a similar area however tend to be higher. The discrepancy might be due in part to the differences in sampling and water extraction methdds. Compaction due to banging the long handle core sampler as opposed to using the short handle core sampler at the sides of a profile pit could cause compaction of the soil and give higher field capacity and wilting point values (Bomba, 1968, observed that loss of soil structure due to compaction increased the amount of water held at moderate suctions). The use of the long ring (core) for taking the undisturbed soil samples as opposed to the use of the short ring could make water extractiion incomplete and result into higher field capacity and wilting point values.

The available water in the top 10 cm of the soil is 7.91% and tends to decrease down the profile (the S.E. is 0.0412). The amount of water held in a given soil depth decreases with depth being 83.0 mm/m in the 0 - 10 cm layer and 71.7 mm/m in the 150 - 180 cm layer. The average amount of moisture stored in a metre of soil is 76.95 mm for the whole profile. The storage capacity of the profile down to 180 cm on average is 136.6 mm of water. This compares well with a storage capacity of 110 mm found by Hudson (1969) from the top 80 cm of a sandy montmorillonitic clay derived from a Kaolinitic clay.

The increase in available water in the top soil is due in part to cultivation in the top soil which increases the total pore space and organic matter effects. England (1970) found that cultivation for 3 years increased the moisture retention of Mollisols by 40% while for Alfisols, the increase was 25% at suctions below 1/3 bar. Similar results were found by Goldberg, Rinot and Karu (1970) and Hudson (1969) who noticed that cultivation increased the water holding capacity of alluvial soil developed over sand loam subsoil and stony montmorillonitic clays. The effect of organic matter in increasing the available water content was noticed by Russell and Balcerek (1944) among others.

The C.E.C. of the soil is high in the top soil and decreases as the depth increases (the C.E.C. of the top 10 cm is 25.6 meq/100 g soil while at 180 cm, the C.E.C. is 18 meq/100 g soil). The standard error for the whole profile is 1.1093.

C. Initial soil reaction (p^H) and organic carbon of the top soil

(i) Variability in the top 15 cm of the soil with respect to organic carbon and soil reaction

Appendices 1a, 1b, 1c and 1d give uncorrected organic carbon and p^H results from composite soil samples (each consisting of 20 core samples) taken from the top 15 cm layer of the soil of each plot, at the start of the long rains (April 1977) before planting and fertilising of fields 6b and 14a. The sample size (n), mean ($\bar{x}$), standard error (S.E.) and coefficient of variability (C.V.) of each of the appendices are given in Table 5.

Table 5: Summary of the analysis of the data in appendices 1a to 1d

Site	Percentage organic carbon				pH in water			
	Sample size	Means	Standard error	Coefficient of variability	Sample size	Means	Standard error	Coefficient of variability
Field 6 block 1	27	2.23	0.045	10.09	27	5.94	0.105	9.41
Field 6 block 2	43	2.51	0.041	10.78	43	6.08	0.073	7.89
Field 14 block 1	48	2.64	0.049	12.88	48	5.68	0.073	8.98
Field 14 block 2	34	2.56	0.085	11.05	34	5.7	0.085	8.77
Means		2.48				5.85		

The data in the table 5 show that the average organic carbon (uncorrected) in the upper 15 cm layer of the soil was 2.48% (5.5% uncorrected organic matter) and that the average p^H in water was 5.85. The plots were relatively homogenous with respect to both the soil organic carbon and p^H at the beginning of the experiment (the S.E. and C.V. values are very low for both organic carbon and p^H in all the 4 blocks). The C:N ratio of the soil averages 11.26.

(ii) Comparison of fields 6 and 14 with respect to the soil organic carbon and p^H

To compare fields 6 and 14 with respect to the soil organic carbon and p^H in water, the d statistic (where d is a normal variate with zero mean and unit standard deviation) is used. Comparing field 6 block 2 (Appendix 1b) and field 14 block 1 (Appendix 1c) at 5% level of significance reveals that the sites are significantly different with respect to both soil p^H and organic carbon. At the 1% probability, however, the sites are significantly different with respect to soil p^H only.

The confidence limits for the difference between the true means with respect to organic carbon and p^H are 0.0099 to 0.2507 and 0.1974 to 0.6026 respectively ($P \angle 0.05$). It seems that field 14 (p^H 5.68) is slightly more acid than field [illegible] (p^H 6.08). It is also interesting to note that the field which is slightly more acid seems to have slightly more organic carbon than the field which is slightly less acid.

4.4. Soil organic carbon and p^H in relation to the crops

A. Soil organic carbon

Appendices 2a, 2b, 2c and 2d present uncorrected organic carbon percentages of composite samples (each composite sample was 20 core samples) taken from the top soil under each of the 8 crops on dates 17th July, 7th and 15th August and 21st August 1978 in field 14. Analysis of variance carried out for all the sampling dates reveals that there were no differences in soil organic carbon due to the crops.

B. Soil reaction

Appendix 3 gives the data on the soil p^H in 0.01M $CaCl_2$ in relation to the 8 crops after the first season planting (1977). The data show that the variability between plots of the same crop and between plots of different crops with respect to soil reaction was low. The standard deviation for individual crops was low (p^H values ranged from 5.29 to 5.11). The overall variance was low (S.E. = 0.0028).

Analysis of variance (F test) shows no significant differences in soil p^H between crops. The crops therefore did not have an effect on the p^H of the top 15 cm layer of the soil after the first season planting (1977).

4.5. Soil Inorganic Nitrogen

A. The soil inorganic nitrogen in the top 30 cm layer of the soil

Preliminary investigations showed that the soil inorganic N in the top 30 cm layer varied from one spot to another (40 metres apart) and between subsamples drawn from one large sample. This confirms what Harmsen and Kolenbrander (1965) observed that inorganic N varies from plot to plot and from day to day in a single spot. Wild (1972) reported a coefficient of variability of 100% for samples taken from 0 - 15 cm layer of the soil. Work of Beckett and Webster (1971) confirms Wild's finding.

However, the variability between 100-g sub-samples was reduced when soil samples weighing about 3 kilogrammes were thoroughly homogenised by mixing and grinding to pass through a 0.5 mm sieve and shaken for one hour with 2 N KCl. Reproducible results were obtained for subsamples from one composite sample in this way.

B. The inorganic N in the top 30 cm of the soil through two growing seasons 1978/79

Table 6, Appendix 4 and Figures 6 and 7 show average levels of inorganic N in the top 30 cm layer of the soil through the long rains 1978 and short rains 1978/79. They show that the soil inorganic N varied in the top soil from plot to plot, from day to day and from season to season in the same spot.

Throughout the growing season the highest within treatment variance was 873.3 on the 3rd October 1978 while the lowest was 0.46 on the 16th August 1978 (refer to Appendix 4). The highest standard error (S.E.) was found on the 3rd October 1978 when the highest average amount was

Table 6: Summary of the inorganic nitrogen results in the top 30 cm of the soil under the eight crops through two growing seasons (1978/79)

Sampling date	Mean soil inorganic nitrogen under the eight crops								Overall mean	Standard error	Rainfall 2 days before sampling	Variance ratio (F value)
	M	SF	LS	IP	SP	FB	SB	W				
18.7.78	39.7	24.25	20.3	41.87	24.3	25.65	29.2	23.8	28.63	6.76	-	9.24**
25.7.78	38.18	29.47	28.35	43.75	32.65	27.65	36.4	27.47	32.99	7.76	3.2	4.55**
2.8.78	37.0	29.99	33.25	38.55	38.33	32.69	33.98	31.6	34.42	6.78	20.3	1.5^{NS}
7.8.78	34.99	33.63	33.6	44.45	41.9	33.89	37.0	34.65	36.76	4.53	1.7	3.82**
9.8.78	48.79	36.05	33.42	61.60	46.22	37.20	40.25	31.15	41.9	13.94	-	7.13**
16.8.78	54.67	37.97	28.82	64.8	54.42	37.10	42.12	35.8	44.4	14.28	1.0	10.39**
22.8.78	45.6	42.66	34.69	53.2	52.88	35.32	41.65	34.30	42.53	19.58	0.3	3.01*
4.9.78	66.85	47.13	40.25	81.2	56.7	43.4	53.6	47.25	44.38	44.38	1.2	4.22**
11.9.78	60.2	62.30	49.7	71.05	63.8	43.75	53.6	47.6	56.47	44.22	-	1.97**
3.10.78	65.8	60.9	41.82	89.95	73.67	58.45	70.0	46.2	63.34	63.36	1.2	3.72**
19.10.78	54.32	55.24	38.64	69.30	56.0	49.84	43.68	44.52	52.03	31.24	-	2.91*
26.10.78	56.35	49.0	40.7	59.15	50.05	57.4	58.8	44.8	51.71	48.83	23.5	1.0^{NS}
30.11.78	66.15	39.20	37.3	61.6	43.75	45.15	54.25	36.05	47.93	53.37	8.1	2.45*
6.12.78	43.75	28.0	27.05	30.45	28.7	31.15	31.45	29.4	31.24	9.875	13.1	2.82*
21.12.78	34.30	27.65	25.02	33.95	30.45	23.60	28.35	23.1	28.32	3.33	11.3	5.82**
4.1.79	26.6	19.60	17.9	24.50	24.15	19.25	20.65	21.4	21.75	3.04	-	3.0*
11.1.79	22.05	17.5	18.55	24.85	24.5	20.65	18.9	17.15	20.56	2.0	2.6	4.4**
19.1.79	25.55	21.35	21.0	30.45	22.75	22.05	20.0	23.8	23.36	3.52	3.7	3.16*
26.1.79	33.3	25.9	21.0	35.0	24.50	22.40	22.4	23.45	25.99	2.95	4.74	9.38**
2.2.79	18.45	20.3	22.4	26.6	22.1	19.85	20.3	23.8	21.72	2.16	80.6	3.10*
7.2.79	19.6	14.70	14.70	20.30	18.90	17.50	18.20	18.9	17.85	3.22	0.6	1.39^{NS}
9.2.79	21.72	17.5	21.7	25.2	21.85	21.0	18.9	21.7	21.19	1.58	3.3	3.24*
Mean	41.57	33.66	29.55	46.89	38.75	32.96	36.07	30.18	35.90			

found, while the lowest S.E. was found on the 9th February 1978. The period between 11 January and 26th January 1979 when rapid increases were prevalent seems to be the period of nitrogen flush since after that period, the amount of inorganic N began to fall as the rainy season progressed.

The amount of inorganic N in a sample replicate ranged from about 123 ppm under Irish potatoes on 3rd October 1978 to about 11 ppm under sunflower on the 7th February 1979 while the averages for replicates of a crop ranged from about 63 ppm on the 3rd October 1978 to about 18 ppm on the 7th February 1979. However, values around 35 - 36 ppm inorganic N were common. The overall mean for all sampling occasions was 35.9 ppm inorganic N. This range of values is reasonable considering what other people found in other areas. Baumann and Maasz (1957), Vanstallen (1959) and Ogata and Caldwell (1960) all reported that in winter when no fertilisers are applied, the level of inorganic N seldom exceed 10 ppm and often remains below 5 ppm in the top soil while during summer and spring in temperate regions, the content can rise to around 40 - 60 ppm in fertile top soils. Scofield (1945) working in a tropical climate of Queensland reported concentrations of mineral N as high as 100 ppm in the top soil without fertilisers in fallow plots. When green manure was ploughed in, however, as much as 400 ppm mineral N was found. While the contribution of NH_4-N to the total mineral N would be small and would not exceed 9 ppm with NH_4-fertiliser additions (Griffith, 1951; Bennison and Evans, 1968; Simpson and Mills, unpublished), the contribution of NO_2-N would be negligible under normal conditions (Bennison and Evans, 1968).

Point to point and time to time variations in inorganic N content can be attributed to leaching, crop uptake, denitrification, mineralisation of organic N, sorption of NH_4-N from the atmosphere, additions in precipitation, immobilisation and possibly volatilisation.

C. Fluctuations of soil inorganic N in general

(i) Seasonal trends

Figures 6 and 7 show fluctuations in the mean soil inorganic N during the two growing seasons. There are deviations from these mean values due to crop effects. This section deals only with average amounts. A consideration of differences between crops is in Section (iii)

FIG. 6 INORGANIC NITROGEN IN THE TOP 30CM. OF THE SOIL THROUGH THE LONG RAIN SEASON 1978

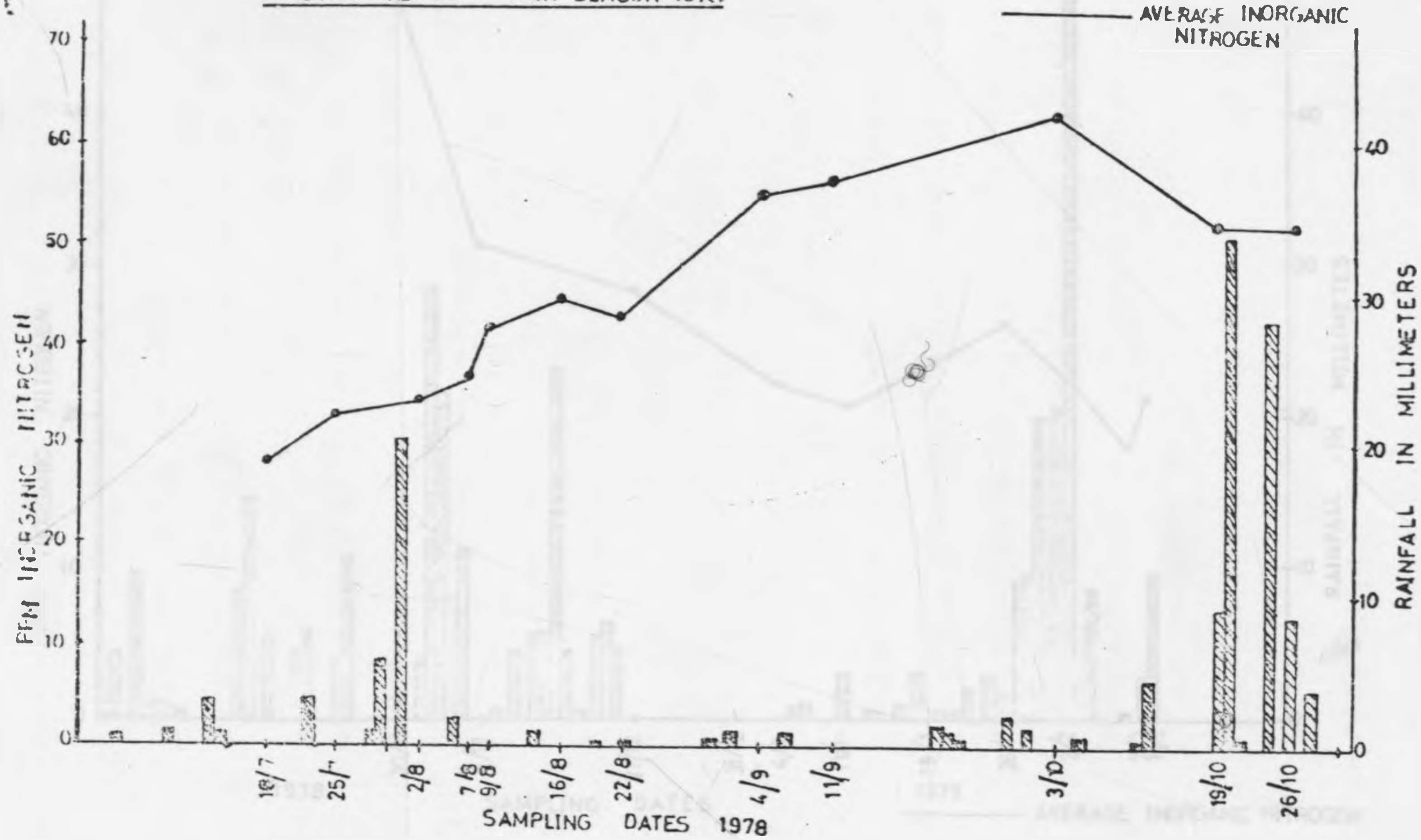
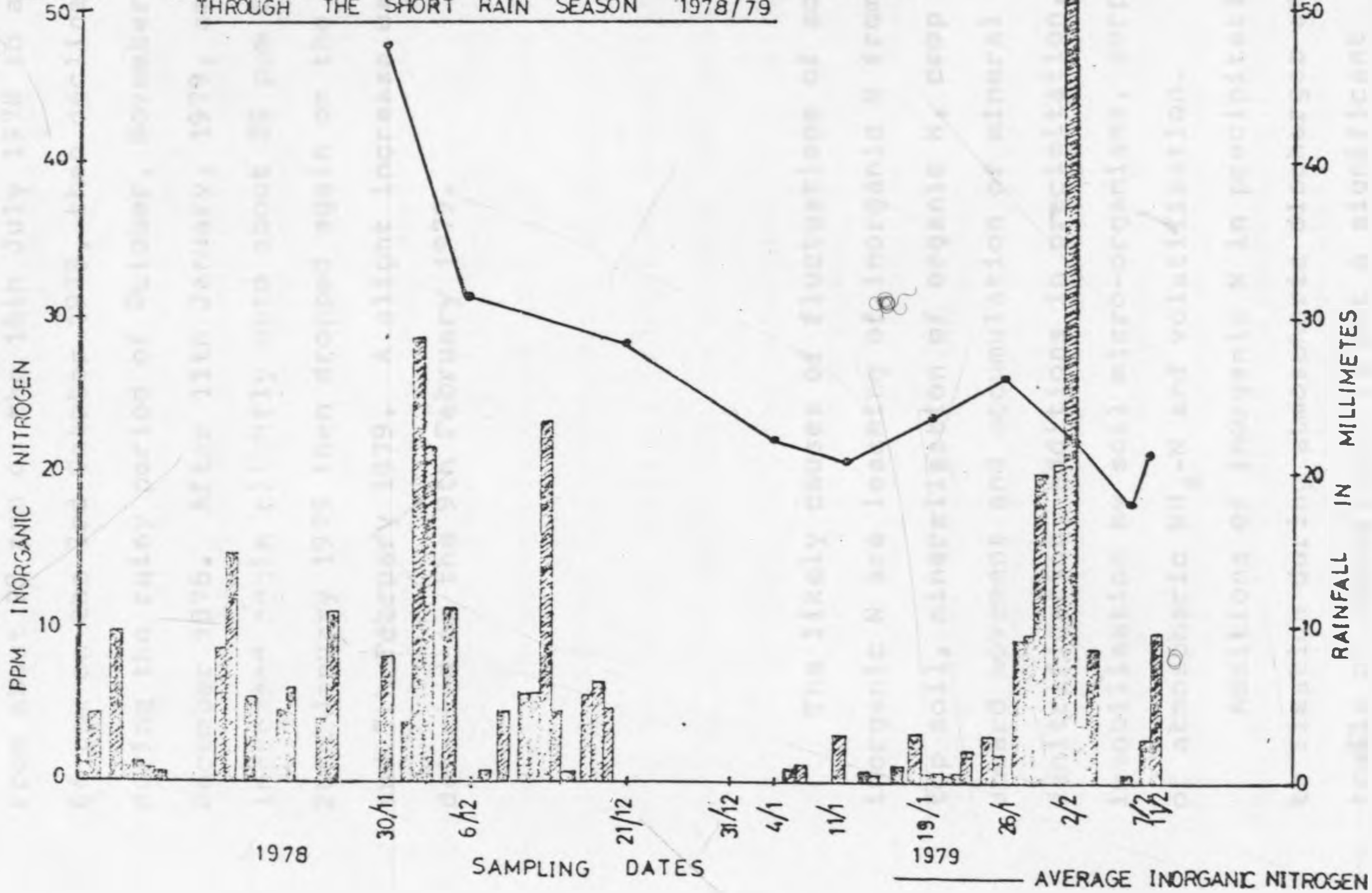


FIG. 7 INORGANIC NITROGEN IN THE TOP 30 CM. OF THE SOIL THROUGH THE SHORT RAIN SEASON 1978/79



In general, the amount of inorganic N increased from about 29 ppm on the 18th July 1978 to about 64 ppm on the 3rd October 1978, then declined during the rainy period of October, November and December 1978. After 11th January, 1979, amount increased again slightly upto about 26 ppm on the 26th January 1979 then dropped again on the 2nd and 7th February 1979. A slight increase was detected on the 9th February 1979.

The likely causes of fluctuations of soil inorganic N are leaching of inorganic N from the top soil, mineralisation of organic N, crop uptake, upward movement and accumulation of mineral N, denitrification, additions in precipitation, immobilisation by soil micro-organisms, sorption of atmospheric NH_4-N and volatilisation.

Additions of inorganic N in precipitation (due to fixation during atmospheric discharges and trails of meteorites) is not a significant contributory factor since the amounts added are low and would be insignificant. Ericksson (1952) estimated it at about 7 kg/ha/yr in tropical regions while Jones and Bromfield (1970) estimated it at 4.6 kg/ha/yr mineral N in the tropics. Moreover thunderstorms are common only at the start of the rains.

Microbial immobilisation (assimilatory N reduction) is also not a likely cause because the levels of inorganic N declined during the periods when the microbes have passed their logarithmic phase of growth and when their activity and numbers are declining (Birch and Friend, 1960, 1964; Jager, 1961). Moreover, it seems that the periods of the nitrogen flush (11th January - 26th January 1979) when microbial activity (therefore immobilisation) should be maximal, are the periods when amounts are high. The fact that the determined C:N ratio of 11.26 is well below the critical value of 20 to 25 (Greenland, 1960) for net mineralisation also rules out microbial immobilisation.

Sorption of atmospheric NH_3 is not a likely cause since there is no reason to suggest that the compounds which cause sorption of NH_3 (cellulose, lignins or lignin nitrogenous constituents) should vary seasonally to cause corresponding fluctuations of inorganic N. Similarly volatilisation of nitrogen as gas such as can occur in acid soils adequately supplied with organic matter or in interactions between nitrites, polyphenols, lignins, amino groups, ammonia or humic acids (van Slyke reaction) in slightly acid soils rich in humus is not likely to be a significant cause since there is no evidence to suggest seasonal changes of the compounds that are responsible for the effect that might cause corresponding seasonal changes in soil inorganic N.

Denitrification might be a possible contributory factor to the fluctuations of soil inorganic N during the periods of heavy rainfall when the soil is well above field capacity and when oxygen supply falls to about 4×10^{-6}M (0.3% O_2) in the soil solution (e.g. on dates 31st July, 2nd August, 30th November and 5th December 1978, 26th January and 2nd February 1979). However, the effects of denitrification would not be great since inorganic N would be lost by both microbial and crop immobilisation, by leaching and moreover energy source would be limiting (Greenland, 1962). Allison (1955b) in his lysimeter studies, showed that denitrification takes place but in many instances the magnitude of loss is of the order of magnitude of analytical errors. Experiments by Allison, Carter and Sterling (1960), Bartholomew (1964), Allison (1966), and Stefanson (1972) confirm Allison's assertion.

Although upward movement of inorganic N has been reported by several workers including Hardy, (1946a), Griffith and Manning (1949), Griffith (1951), Mills (1953, 1954), Wetselaar (1961), Simpson (1961), Robinson (1969) and Wild (1972) in regions of differing climatic conditions including humid tropical climate; it is not likely that upward movement of inorganic N is a major factor contributing to accumulation of inorganic N in the top soil during the dry periods. Although Jackson (1965) reports that in clay and loam soils, capillary conductivity may be maintained at suctions exceeding 50 bars it seems unlikely that in humid tropical conditions of Kabete, inorganic N move up in water by capillarity. This is because as the soil dries out, the dry layer at the top (which is dried below wilting point under ustic soil moisture regimes) protects the lower layers of the soil from water losses (Penman, 1941; Oliver, 1969; Hillel, 1973). Under such dry conditions (suctions above 15 bars) water moves mainly in the vapour phase (Rose, 1963) and inorganic N would not move with it.

Capillary continuity and evaporation of water are further disrupted by cultivation (Fabrother and Munro, 1970; Willis and Bond, 1971). Upward movement of water and solutes is also dependent on the suction gradient at the soil surface (drying conditions). Although Morh and van Baren (1959) cited by Jackson (1977) observed that in regions with alternating dry and wet periods, surface soil receives water from below in the dry season allowing an alternating process of leaching and accumulation, it is not likely that capillary conductivity could be maintained during the dry season (when surface layers were below wilting point) in the trial area since the drying conditions are not so strong as to cause very high suction gradients which can support capillarity.

The most likely causes of fluctuations of soil inorganic N therefore are leaching, mineralisation of organic N and crop uptake.

(ii) Seasonal fluctuations of soil inorganic N as evidence of mineralisation, leaching and accumulation in the top soil

Seasonal fluctuations of soil inorganic N through the two seasons can be ascribed to leaching of inorganic N below the 30 cm layer, mineralisation of organic N and accumulation of inorganic in the top soil.

The slow build-up of inorganic N during the dry period of July, August, September and early October 1978 can therefore be attributed mainly to continued mineralisation of organic N in the top soil and its accumulation there. About 34 ppm inorganic N accumulated between 18th July and 3rd October 1978 (77 days). During that period, the highest average amount was about 63 ppm inorganic N. Scofield (1945) reported as much as 100 ppm mineral N in the top soil of fallow plots (without fertiliser additions) in Queensland, while Griffith and Manning (1949), Griffith (1951) and Mills (1953, 1954) found amounts upto 70 ppm NO_3-N in the top soil of Uganda due to upward movement and continued mineralisation. Amounts of mineral N found by Scofield (1945) were higher than the ones found at Kabete probably because there were no crops to use the nitrogen while those found in Uganda are in good agreement with the highest average level found at Kabete although the amounts in Uganda were for NO_3-N (proportion of NH_4-N is always small).

Similar continued mineralisation of organic nitrogen has also been reported by Hardy (1946a), Stephens (1960b), Simpsons (1961), Robinson (1969) and Wild (1972). Mineralisation was assumed to be either microbial (Birch and Friend 64; Agarwal, Singh and Kanehiro) or photocatalytic (Rao and Dhar, 1931; Dhar _et al._, 1933). During the dry periods, all the conditions necessary for mineralisation were favourable. Throughout the period, the soil did not dry to air dry conditions (approximately 13%). Slight rainfall was received and mineralisation was possible even if the soil was below wilting point. Greaves and Carter (1920), Calder (1957), Semb and Robinson (1969) and Robinson (1957) found mineralisation in conditions ranging from 3 - 8% moisture content to slightly below wilting point (15 bars suction).

Soil temperature was not limiting since during that period, the mean daily soil temperature was 19.21^{o}C. The p^{H} was also not limiting since the soils are acid which permits mineralisation. The C:N ratio of 11.26 also favoured mineralisation (critical ratio 25) and the levels of inorganic N were not so high as to depress mineralisation.

During the dry period small flushes of nitrogen might have occured (though not detectable) as a result of alternate drying at wetting by the light rains that fell during that period. However the main nitrogen flush was noticed during the period 11th January - 26th January 1979. Another flush was also detected after 7th February 1979 after about 5 days without rain. This phenomenon is similar to what was found by Birch and Friend (1958 - 1964), Griffith (1951), Mills (1953b), Semb and Robinson (1968), Agarwal, Singh and Kanehiro (1971), Laura (1975) and Chew, Williams and Ramli (1980) among others. The flush of decomposition at the onset of rains was attributed to the microbes (which survived the drying through spores) which were still in their logarithmic phase of growth (Birch and Friend, 1958 - 1964; Jager, 1961; Agarwal, Singh and Kanehiro, 1971). Just before the flush during the period 11th January - 26th January 1979, there was a dry period of 19 days interrupted by a slight rainfall on the 7th and 8th January 1979. During this flush, about 5 ppm inorganic N were produced in about 2 weeks. The flush was rather short-lived because after that its rate fell and leaching started as the rains progressed.

The value of 5 ppm inorganic N compares well with values of upto 8 ppm (183.3 kg/ha) found by Semb and Robinson (1968) in the top 0 - 40 cm of the soil of 13 sites in East Africa. During the flush, values of inorganic N rose from about 21 ppm on the 11th January 1979 to about 26 ppm on the 26th January 1979. Griffith (1951) and Mills (1953b) working in Kawanda and Serere, Uganda, found that at both places values rose from 10 ppm inorganic N under mulch at the onset of rains and that under bare fallow values continued rising to 30 - 50 ppm inorganic N during a single flush. Their values were higher because there was no crop uptake.

The magnitude of the flush (about 5 ppm inorganic N) seems to be lower than those found in incubation experiments for 2 weeks. Saunder, Ellis and Hall (1937) found that about 25 ppm NO_3-N were released after incubating red brown clay soil from cropped land for 2 weeks at 35^oC and a moisture near field capacity. Birch and Friend (1960, 1964) on the other hand, concluded that on average about 20 ppm of NO_3-N equivalent to 218 kg/ha of ammonium sulphate fertiliser is produced during a single cycle of wetting and drying in a respirometer. The lower value under field conditions might be in part due to the fact that field conditions are not as ideal as incubation conditions and in part due to the fact that the drying prior to the flush was not so intense and was only for a period of 19 days in the field. The 2 week period of the flush is in accord with the period used by many investigators in incubation procedures though Birch and Friend observed that a single flush lasted for 5 to 10 days in laboratory experiments.

Figures 6 and 7 also show that average inorganic N in the top 30 cm of the soil declined during the periods 16th - 22nd August 1978, 3rd October 1978 - 11th January 1979 and 26th January - 7th February 1979. This was assumed due to leaching of inorganic N (particularly NO_3-N) from the top soil by the soil water. The 27 mm of rain that fell in 8 days during 25th July to 2nd August 1978 though much did not cause appreciable leaching possibly because the soil was far below field capacity, so much water was required to wet the soil to field capacity before leaching down the salutes. The potential evaporation during those days was 23.8 mm (at this stage, the average evapotranspiration could have been higher than the potential evaporation).

Appreciable leaching was however caused during the rainy period. Inorganic N decreased in the top 30 cm as the rains continued from about 64 ppm in October 1978 to about 20 ppm during the first half of January 1979 and from about 26 ppm late in January, 1979 to about 18 ppm early in February 1979. Between 3rd and 19th October 1978, the amount of inorganic N decreased in the top 30 cm by 11 ppm. The amount of rain recovered during the 16 days period was 5.3 (4.5 mm fell on a single day) while the potential evaporation of water was 77.8 mm. Leaching losses were heavy during this period because the short duration 4.5 mm rain caused a relatively greater leaching than would otherwise have occured. The heavy rain that fell between 30th November and 6th December 1978 (75.6 mm) leached about 17 ppm inorganic N while 134.6 mm rain that fell between 26th January and 7th February 1979 leached about 8 ppm inorganic N.

It seems that the magnitude of leaching depends on the concentration of the soil inorganic N and the amount and intensity of rainfall in relation to the initial soil moisture contents. This is evidenced by the fact that during the periods when inorganic N amounts were low, large additions of water caused only small decreases in soil inorganic N while during the periods of high inorganic N amounts, even small additions caused large decreases in inorganic N. Similar results were obtained by

Gardner (1962), Kolenbrander (1970) and Wild (1972). However leaching is also influenced by the amount of water removed by the various crops.

(iii) Inorganic N in the top 30 cm layer of the soil in relation to the eight crops through two growing seasons 1978/79

Figure 8 shows that during the long rains 1978, the amounts of inorganic N were highest under Irish potatoes and lowest under linseed and wheat. Values were found to be second highest under maize while the rest of the crops occupied intermediate positions. A similar trend was observed during the 1978/79 short rains although during the early stages of growth, soil inorganic N values were highest under maize, (Fig. 9).

Soil inorganic N under the 8 crops was related to rainfall but variations existed on some dates which suggest differential crop removal. Thus varying amounts of inorganic N were found below different crops on different dates possibly because the amounts of N removed by the various crops at different stages of development varied. Possible explanations for the differences in soil inorganic

FIG. 8 INORGANIC NITROGEN IN THE TOP 30 CM. OF THE SOIL UNDER THE EIGHT CROPS THROUGH LONG RAIN SEASON 1978.

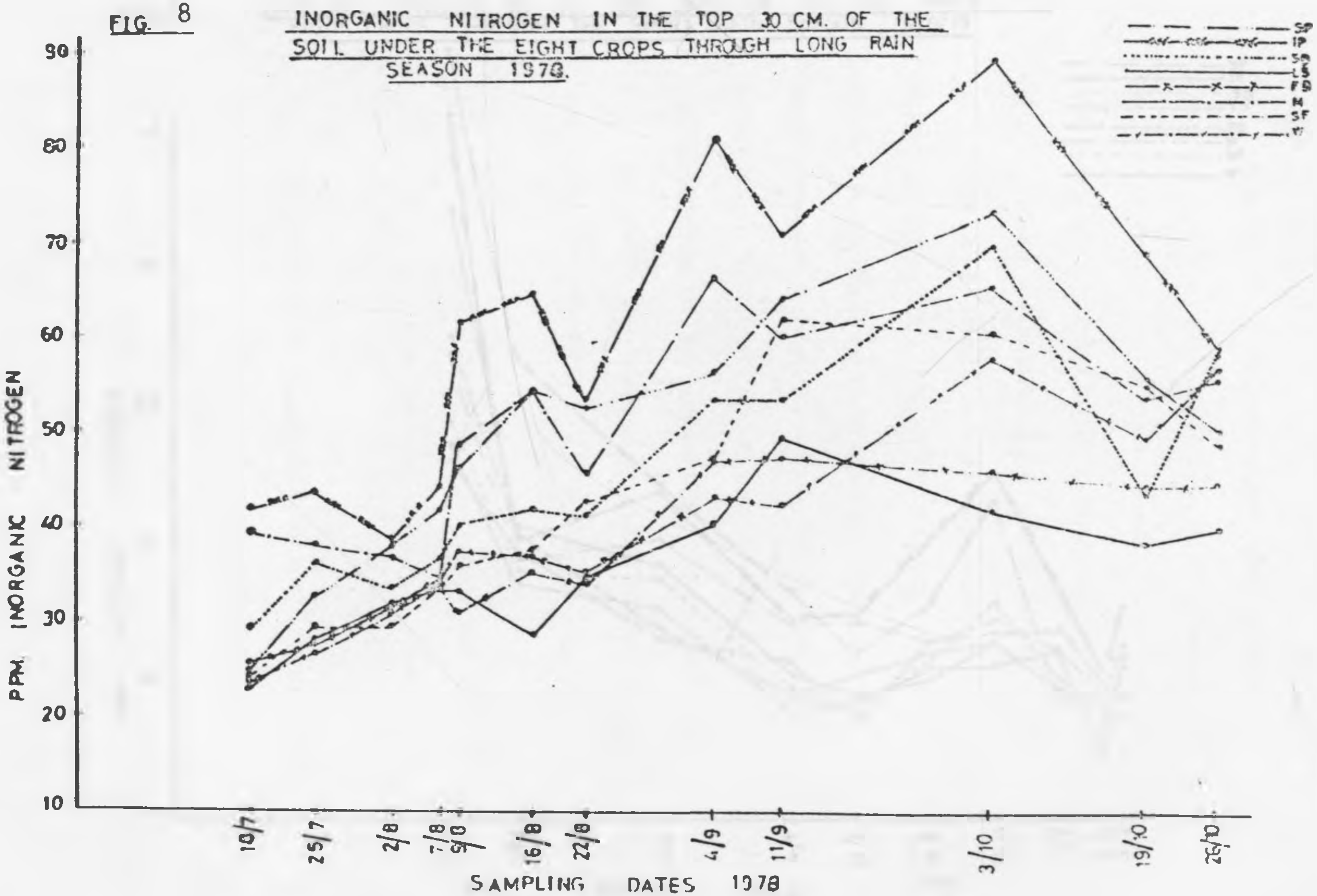
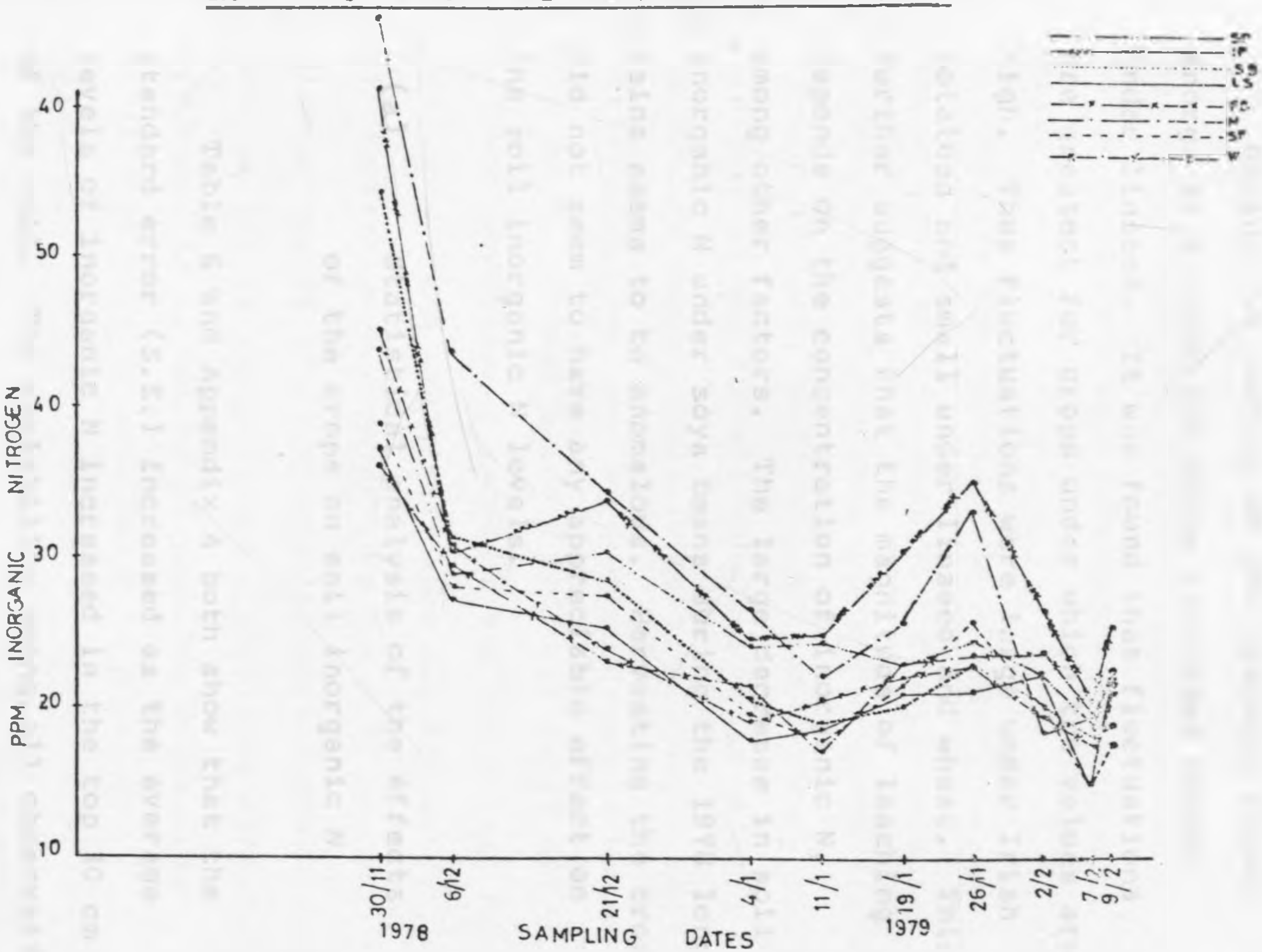


FIG. 9 INORGANIC NITROGEN IN THE TOP 30 CM OF THE SOIL UNDER THE EIGHT CROPS THROUGH THE SHORT RAIN SEASON 1978/79



nitrogen due to crops are discussed in section (b)

During the periods of the nitrogen flush, inorganic N under all crops increased except under linseed. It was found that fluctuations are greatest for crops under which the values are high. Thus fluctuations were large under Irish potatoes and small under linseed and wheat. This further suggests that the magnitude of leaching depends on the concentration of inorganic N, among other factors. The large decrease in soil inorganic N under soya beans during the 1978 long rains seems to be anomalous. Harvesting the crops did not seem to have any appreciable effect on the soil inorganic N levels.

(a) Statistical analysis of the effects of the crops on soil inorganic N

Table 6 and Appendix 4 both show that the standard error (S.E.) increased as the average levels of inorganic N increased in the top 30 cm of the soil. The variability among all observations of sampling dates was highest on the 3rd October 1978 (S.E. = 63.36) and lowest on 9th February 1979 (S.E. = 1.58) which shows that as the soil dried out, variability consistently increased, but as it moistened, the variability decreased. During the 1978/79 short rains when there was more rain than during the preceding period of 1978 long rains, when inorganic N amounts were low, variability was reduced and differences between crops though small were more detectable by statistical tests.

To test the significance of the differences between crops with respect to the soil inorganic N, an analysis of variance and the variance ratio (F) test (Bailey, 1959; Snedcor and Cochran, 1971) were carried out for all sampling dates while the Duncans new multiple range test (Steele and Torrie, 1960) was used to test differences between crop pairs. Tables 6 and 7 and Appendix 4 all show that analysis of variance and the F test (all conditions being satisfied) show significant differences between crops in 8 out of 22 sampling dates at the 5% level of significance (probability) while at the 1% probability, significant differences were found in 11 out of 22 sampling dates. Non significant results were found in 3 out of 22 occasions.

Results of the Duncans new multiple range test are given in Table 7. The test carried out at the 5% probability revealed that there were significant

Table 7: Summary of analysis of variance and Duncan's new multiple range test for all the sampling dates with respect to the soil inorganic N

Sampling date	Analysis of variance (F-value)	Duncan's multiple range test (significantly different pairs)
18.7.78	9.24**	None
25.7.78	4.55**	"
2.8.78	1.5^{NS}	"
7.8.78	3.82**	"
9.8.78	7.13**	"
16.8.78	10.39**	"
22.8.78	3.01*	"
4.9.78	4.22**	"
11.9.78	1.97**	"
3.10.78	3.72**	"
19.10.78	2.91*	"
26.10.78	1.01^{NS}	"
30.11.78	2.45*	"
6.12.78	2.82*	"
21.12.78	5.62**	M-W, M-FB, IP-W
4.1.79	3.0*	None
11.1.79	4.4**	IP-W, IP-SF, SP-W, SP-SF
19.1.79	3.16*	None
26.1.79	9.38**	IP-LS, IP-FB, IP-SB, IP-W, IP-SP, IP-SF, M-LS, M-FB, M-SB, M-W
2.2.79	3.10*	IP-M
7.2.79	1.39^{NS}	None
9.2.79	3.24*	IP-SP, IP-SB

* Computed F value significant at 5% probability

** Computed F value significant at both 5% and 1% probabilities

NS Non significan differences

differences in mean inorganic N values between crop pairs in 5 out of 22 sampling days. The table shows pairs of crops which were significantly different with respect to soil inorganic N below them.

(b) Differences in soil inorganic N due to crops

Table 7 shows that differences between crops with respect to the soil inorganic N were not significant on the 2nd August and 26th October 1978 and 7th February 1979. For the rest of the sampling dates differences between crops were significant at least at the 5% probability. Results also show that the significance of the results was more dependent on the rainfall than on the standard error (variability). Non significant differences were found on days of heavy rain or when heavy rains preceded soil sampling. This is probably because soil water masked any differences between crops by leaching the inorganic N out of the top soil. On all dates when the differences were non significant, the amount of inorganic N decreased due to leaching.

Pairs which were significantly different with respect to soil inorganic N were found on dates 21st December 1978, 11 January, 2nd February and 9th February 1979. On these dates, the pairs which showed significant differences in inorganic N below them were IP-LS, IP-FB, IP-SB, IP-SP, IP-M, IP-SF, IP-W, M-W, M-FB, M-LS, M-SB, SP-W and SP-SF.

The results suggest that during the growing period, the amounts of soil inorganic N under Irish potatoes were significantly different from amounts under each of the remaining crops at some stage while amounts under maize were significantly different from amounts under wheat, field beans, linseed and soyabeans. There seems to be enough evidence to suggest that inorganic N levels were high under Irish potatoes and maize and low under linseed and wheat (Table 6 shows that on most sampling dates, the average inorganic N under Irish potatoes and maize was above average while under linseed and wheat, it was below average).

In general, it seems that throughout the two seasons, the average N was highest below Irish potatoes and lowest below linseed, the remaining crops occupying intermediate positions. The overall mean values of inorganic N can be ranked as follows:

linseed $<$ wheat $<$ field beans $<$
29.55   30.18   32.96

sunflower $<$ soya beans $<$ sweet potatoes
33.66   36.07   38.07

maize $<$ Irish potatoes
41.57   46.89

The causes of differences in soil inorganic N under the various crops could be related to the influence of the crop on any of the following: mineralisation of organic N, leaching of inorganic N, nitrogen fixation, volatilisation of nitrogen and sorption of atmospheric NH_4-N. In addition, differences may be related to differences in crop uptake of inorganic N, the amounts and nature of root exudates and their effects and to the temporary microbial immobilisation. These aspects are discussed in turn in the following paragraphs.

The effects of crops on soil organic carbon which could in turn influence the amount of inorganic N (Kononova, 1929; Milne, 1937; Greenland, 1959) is not a cause since investigations in Section 4.4.A revealed that crops had no effects on the soil organic carbon during short cropping periods.

Crops could influence denitrification of inorganic N through their influence on soil moisture, temperature, microbiological composition of the soil, the supply of energy source and crop residue (Greenland, 1970; Stefanson, 1972) but this is unlikely to cause appreciable differences in soil inorganic N since differences due to crops would be expected to be small and probably of the order of magnitude of analytical and sampling errors (Allison, Carter and Sterling, 1960; Allison, 1966; Stefanson, 1972).

Sorption of atmospheric NH_4 by the soil as influenced by crops is open to question since it is not known whether substances which cause sorption of NH_4 by the soil would vary within short cropping seasons because of the various crops (organic matter is not subject to changes within short cropping periods (Milne, 1937; Greenland, 1959; Birch, 1959; Nye and Greenland, 1960).

The influence of crops on leaching through rainfall interception (Wolluy, 1890, cited by Jackson, 1972), influence on soil moisture regime and modification of soil structure (Clark, 1971) can be a contributory factor, but the differences would be small in situations under which leaching occured (heavy rainfall).

The influence of crops on volatilisation of soil N through their influence on organic matter, polyphenols, lignins, amino groups or humic acids is not a likely cause since variations in all these substances would not be expected in short cropping periods. The influence of crops on volatilisation of NH_3 through changes in p^H (Gandhi and Paliwal, 1976; Hargrove, Kissel and Fenn, 1977; Craswell and Vlek, 1978; Vlek and Craswell, 1979) is not likely since investigations in Section 4.4.B showed that crops did not have significant effects on the soil p^H. The effect of crops on volatilisation (Hargrove, Kissel and Fenn, 1977) is not likely since NH_4-N is produced in the soil only in very small amounts under normal conditions (Bennison and Evans, 1968).

The effects of root exudates which might encourage the growth of organisms which might temporarily lock up soil N is a possibility which needs further investigation.

The effect of the legumes field beans and soya beans on soil inorganic N through fixation of atmospheric N is another possible cause of differences. Field observations revealed that both crops nodulated (though field beans formed more nodules than soya beans) and that N-fixation took place (evidenced by the pink colouration of the inside of nodules indicating the presence of leghaemoglobin). The determined C:N ratio of 11.25 (soil) was well above the critical ratio of 5 for N fixation (Greenland, 1962). Although Bond (1957) reported nodulated field beans to be fixing about 700 mgN per gramme dry matter and nodulated soya beans to be fixing about 250 mgN per gramme dry matter while Russell (1973) reported them to be fixing between 120 and 240 kgN/ha/year, amounts of inorganic N below field beans were below average while amounts under soya beans were nearly average. This suggests that although they fixed N, most of the fixed N was removed at harvest in seed and straw forms (above ground straw was removed from plots at harvest). It further shows that very little if no N was secreted into the soil in organic forms such as aspartic acid and β-alanine as found by Wilson (1940) and Hoolmes and Macklusky (1955) among others.

This finding is in line with the observation that legumes need not enrich the soil with N because they fix N and that many legumes (including field beans and soya beans) grown for their seed actually deplete the soil N (Jones, 1942; Bonnier, 1957;

Russell, 1973). The benefit of a legume in a rotation therefore can only be realised when the legume is not harvested but ploughed in. Shrader et al. (1966) found that a crop which followed a good legume in a rotation received upto about 110 kg/ha while Jones (1942) found that in a place near Nairobi, Kenya, land rested under soya beans (unharvested) increased the N content at the rate of 180 kgN/ha per year for the first 5 years and at the rate of 110 kgN/ha per year for the second five years.

The most likely causes of the differences in inorganic N content of the soil due to crops are crop removals and the effect of crops on mineralisation rates. Mineralisation of organic N could be influenced by crops through their influence on soil temperature, aeration, soil structure, soil moisture, root secretions and microbial populations and by adding fresh organic matter to the soil. Soil temperature, aeration and moisture are factors which influence mineralisation and these in turn can be modified by weeding, earthing up, spacing and amount of crop cover.

While the effect of root exudates on mineralisation is open to question, it seems that the influence of weeding, earthing up, ground coverage (spacing) and the 'priming' effect of fresh organic matter on mineralisation rate together with crop uptake are the likely causes of high inorganic N levels below Irish potatoes and maize. Birch (1958, 1960) and Simpson (1960) both concluded that agricultural practices which enhance soil drying such as wide spacing, ploughing and bare fallowing accelerate decomposition of organic matter and mineralisation of organic N. Lal (1973) found that on tropical Ferric Luvisols of Nigeria the soil temperature at 5 cm depth was 9.8^{o}C lower with no tillage than with tillage and 4.2^{o}C lower with no tillage than with tillage at 20 cm depth during a period of two weeks. Work at Wooster, Ohio, by Salter and Green (1933) also showed that cultivation accelerated mineralisation though over a long period of time.

Tyler and Broadbent (1959) found that when clay soils were incubated at 23.9^{o}C for 14 days the net NO_3-N release was 15 ppm but when the incubation temperature was 6.7^{o}C, the net NO_3-N release was 7 ppm during the same period. Eno (1960) by incubating 5 sandy soils in the field, found that an 18^{o}F variation in soil temperature during a 27day period resulted in a change in average rate of NO_3-N production of 67 ppm. Several workers including

Gerretsen (1931), Birch (1959) and Thiagalingam and Kanehiro (1973) have showed that increase in soil temperature increases the rate of carbon rundown and mineralisation of organic nitrogen. Lal (1973) also found that although at the end of a 17 month experiment no tillage plots had more NO_3-N than the tillage plots under maize, the initial organic carbon decreased from 2.33% to 1.69% for the tillage plots and from 2.33% to 2.26% for the no tillage plots.

In the light of all these, it is possible that crops could influence the rates of mineralisation of organic N during short cropping periods even if they did not change the amount of organic carbon below them in short cropping periods. Hulpoi (1939) found that at certain temperature ranges, temperature may not have an effect on the loss of organic matter but may allow an increase in the inorganic N content of the soil. Irish potatoes which seem to have had the highest amount of inorganic N below it only poorly covered the soil, was weeded twice then earthed up. Moreover, its above ground portions withered early. On the contrary, linseed and wheat which had low amounts of N below them were weeded only once and covered the ground well.

However, of all the factors of loss of inorganic N, crop uptake is the most important. Harmsen and Kolenbrander (1965) observed that plant uptake is the chief source of loss of inorganic N and each kind of crop and soil situation results in a unique removal pattern. Bennison and Evans (1968) found that the amount of inorganic N remaining at all depths below a crop was related to its duration on the ground, vegetative bulk and rooting habit. Work reported by Publio Santiago, Cornell University, and Wrigley (1961); Ochse et al. (1961) showed that at equivalent yield levels, the crops removed N in the following manner.

field beans > soya beans > maize > sweet potatoes > Irish potatoes.

It can therefore be said that the low inorganic N below linseed and wheat was in part due to the fact that they extracted more N from the top 30 cm of the soil than did the other crops. Arnon (1972) reported that most of linseed roots were found in the top soil while Hurd and Spratt (1975) found that under wet and dry conditions wheat roots grew as deep as 120 cm, although the majority were in the top 30 cm of the soil. The high levels under Irish potatoes, maize and sweet potatoes and low levels below field beans and soya beans were in part due to varying extraction of soil inorganic N. Pokorky, Burda and Flegr (1980) found that after suitable preceding crops (red clover, fodder beet and potatoes), grain yield of winter wheat was markedly higher than after unsuitable crops (spring barley) and that in order to equalise yields, it was necessary to increase applied N by 40 kg/ha after unsuitable crops.

The facts that most of the roots of Irish potatoes are reported to be between 30 - 64 cm (Carter, 1976), sweet potatoes have been reported to be rooting down to 120 cm (Pillsbury, 1968) and maize have been reported to be rooting down to 150 - 200 cm (Dagg, 1965a; Pillsbury, 1968; Russell, 1973) at Muguga, Kenya, suggests that rooting habit was also important in determining N extraction.

4.6. The Soil Moisture

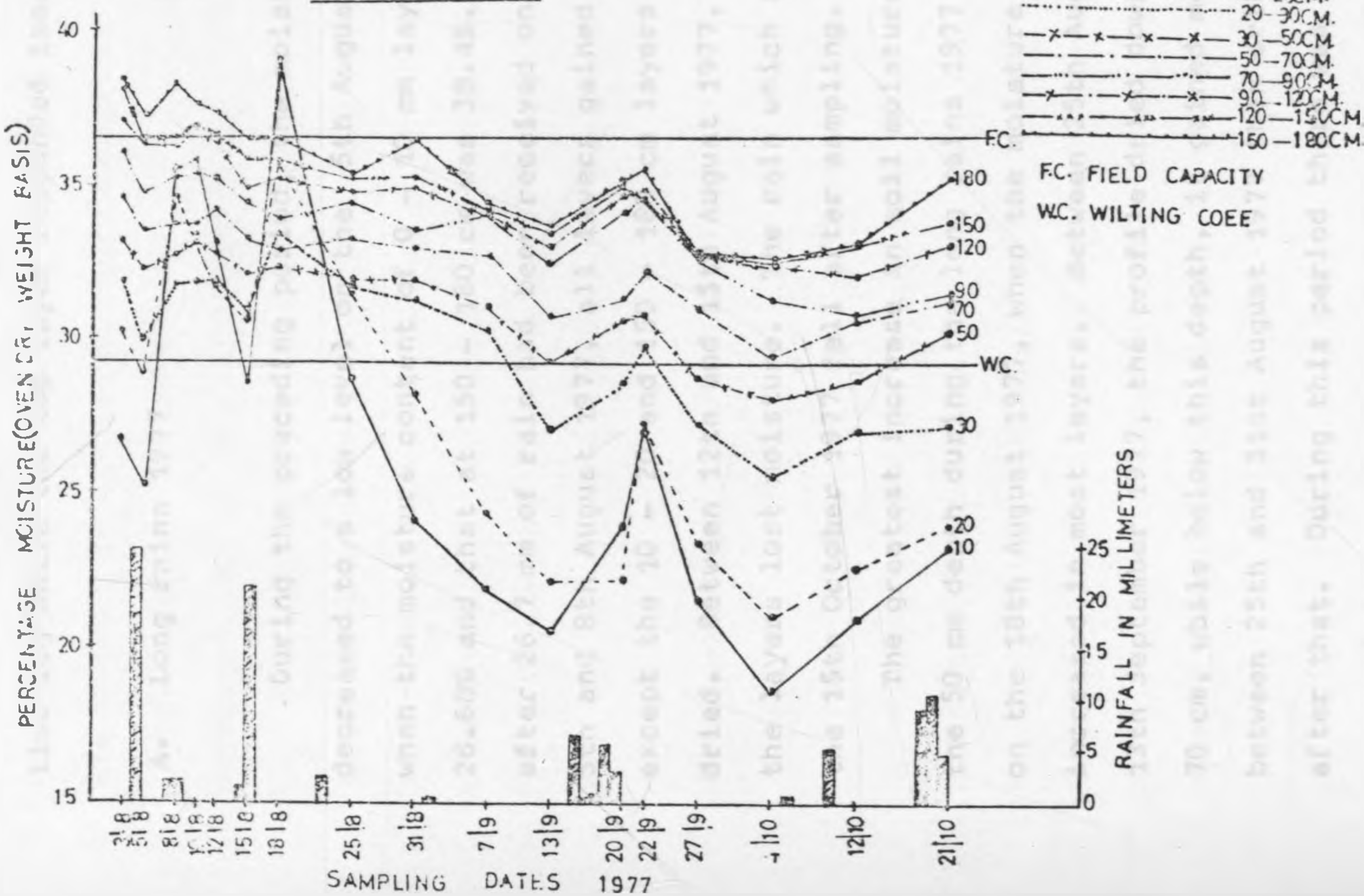
Appendices 5a to 5i present the soil moisture data at nine depths below the 8 crops through 3 seasons while table 9 is a summary of the data in Appendices 5a to 5i Table 10 gives the results of F-test carried out for 3 sampling occasions for the 9 depths. Figures 10, 11a and 12 show the average amounts of moisture in the soil at nine depths through the long rains 1977, short rains 1977/1978 and long rains 1978 while figure 11b represents the soil moisture under the eight crops at a depth interval of 70 - 90 cm during the short rains 1977/78.

The average soil moisture at most of the nine depths (10, 20, 30, 50, 70, 90, 120, 150 and 180 cm) during the month of August 1977 probably was above average levels which would be common in most years (particularly in deep layers) since the rainfall was above average during that month and because the. preceding months of April and May 1977 were exeptionally wet. Appendix 12 and Figures 2a and 2b show that the total rainfall for the month of April, May and August 1977 were 22.5, 203.9 and 53.6 mm respectively.

The average soil moisture levels during the month of March 1978 probably was also above average since the amount of rain (256.0 mm) received during that month was also above average while the soil moisture levels during the month of February, June and July 1978 were probably low compared with other years. With a storage capacity of 138.6 mm in the 180 cm profile, a crop whose roots go as deep as 180 cm (e.g. maize) would make good growth for a period of about 23 days without recharge by rainfall or irrigation if the profile had been wetted to field capacity (assuming an average maximum water use by a crop with a fully developed canopy of 6 mm/day).

Figures 10, 11a and 12 show that soil moisture fluctuations were greatest in the top 0 - 10 cm and least at a depth of 150 - 180 cm through the three seasons and that for all the depths, fluctuations were least during the long rains 1978 (because of relatively moderate rainfall). Fluctuations of 10 - 20 cm depth closely followed those of 0 - 10 cm depth while those of 120 - 150 cm depth closely resembled those of 150 - 180 cm depth. This was due to the fact that rainfall (recharge), drainage of water, evaporation and crop uptake all affected the top layer most and the

FIG. 10. SOIL MOISTURE AT NINE DEPTHS DURING LONG RAINS 1977



deepest layer least. Successive deeper layers responded to periodic recharges of water with a time lag while the top layer responded immediately.

A. Long rains 1977

During the preceding period, the moisture decreased to a low level on the 5th August 1977 when the moisture content of 0 - 10 cm layer was 26.68% and that at 150 - 180 cm was 38.4%. But after 26.7 mm of rain had been received on the 5th and 8th August 1977, all layers gained moisture except the 10 - 20 and 150 - 180 cm layers which dried. Between 12th and 15th August 1977, all the layers lost moisture. The rain which fell on the 15th October 1977 fell after sampling.

The greatest increase in soil moisture above the 50 cm depth during the long rains 1977 was on the 18th August 1977, when the moisture content increased in most layers. Between 25th August and 13th September 1977, the profile dried down to 70 cm, while below this depth, it gained moisture between 25th and 31st August 1977 then dried up after that. During this period there was no rain except 0.3 mm rain on the 2nd September 1977. All layers responded to rainfall between 13th and 22nd

September 1977 with an increase in soil moisture but between 22nd September and 4th October 1977, the layers all lost moisture. Between 4th and 21st October 1977, soil moisture increased in all layers except in the layers 90 - 120 cm where it decreased between 4th and 12th October 1977.

During the long rains 1977, the soil was above field capacity (36.54 % moisture and suction of 0.33 bars) and below wilting point (29.32 % moisture and 15 bars suction) as shown in table 8a On the rest of the sampling dates, the soil was below field capacity and above wilting point.

B. Short rains 1977/78

During the short rains 1977/78, the soil was dried below wilting point only down to 30 cm. On the 2nd February 1978, there was available moisture below the 10 cm depth while on the 7th and 16th February 1978, moisture was only available below the 30 cm depth. The moisture status of the soil on the various sampling dates is given in table 8b

FIG 11a. SOIL MOISTURE AT DIFFERENT DEPTHS DURING SHORT RAINS 1977/78

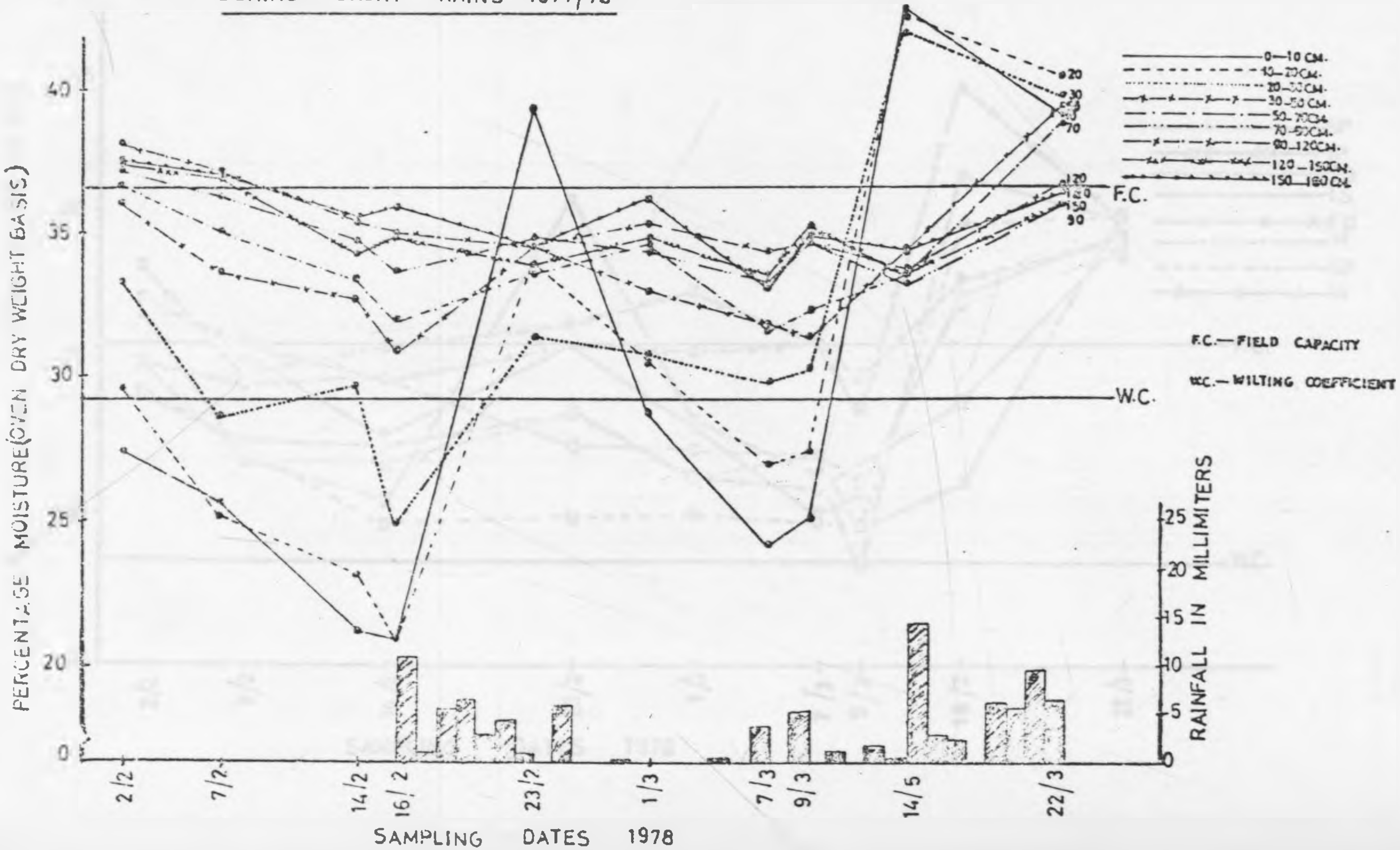


FIG. 11b. SOIL MOISTURE UNDER THE EIGHT CROPS AT A DEPTH OF 30--50CM DURING THE SHORT RAINS 1977/78

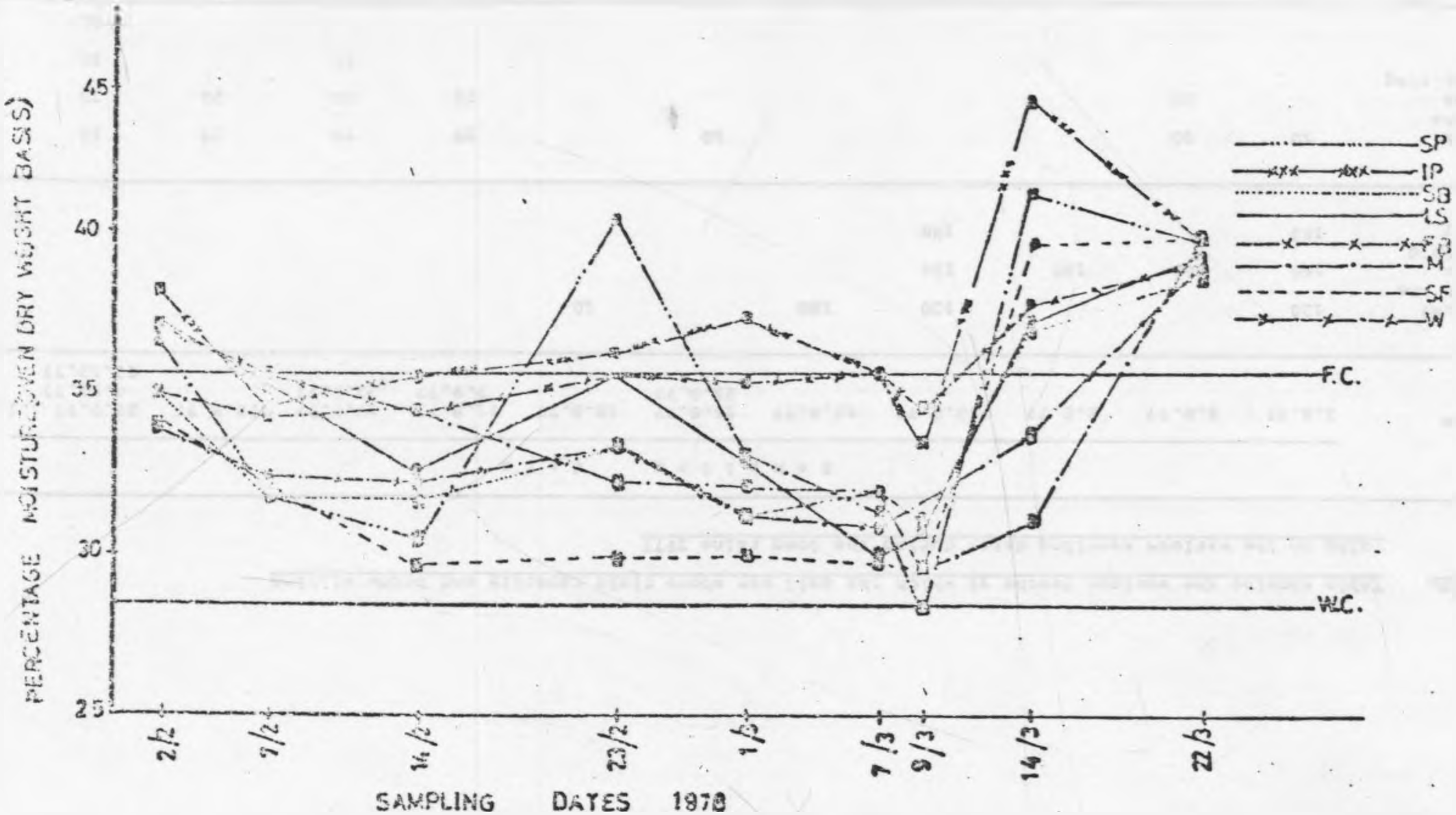


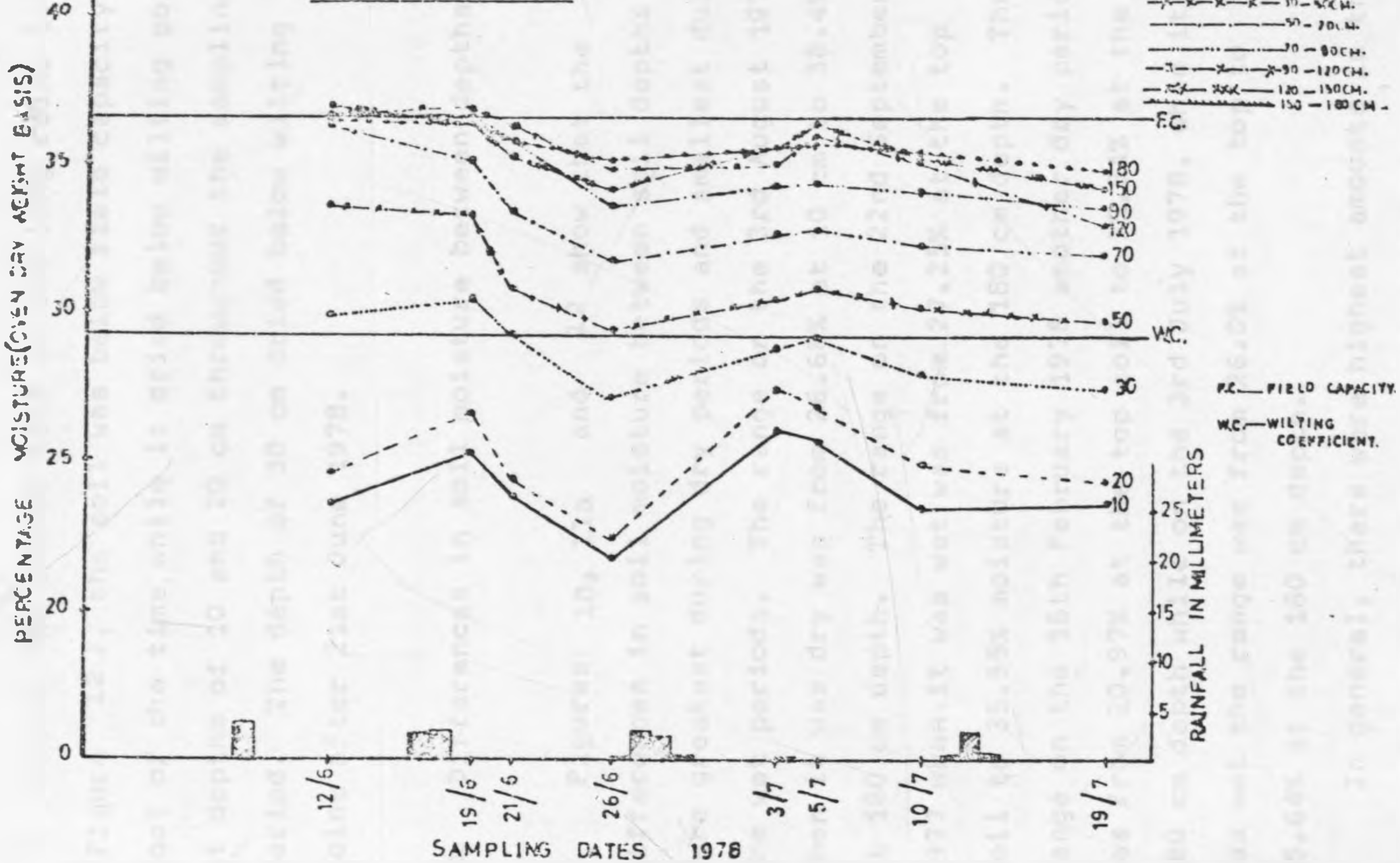
Table 8a. Table showing the various depths at which the soil was above field capacity and below wilting point on the various sampling dates during the long rains 1977

Soil moisture status	Sampling date										
	3.8.77	5.8.77	8.8.77	10.8.77	12.8.77	15.8.77 25.8.77	18.8.77	31.8.77 7.9.77	13.9.77 22.9.77	22.9.77	27.9.77 4.10.77 12.10.77	21.10.77
Depth (cm) at which the soil was above field capacity	120 150 180	180	180	120 150 180	180		10					
Depth at which the soil was below wilting point	10	10 20				10		10 20	10 20 30	10 20	10 20 30 50	10 20 30

Table 8b. Table showing the various depths at which the soil was above field capacity and below wilting point on the various sampling dates during the short rains 1977/78

Soil moisture status	Sampling date								
	2.2.78	7.2.78	14.2.78	16.2.78	23.2.78	1.3.78	7.3.78 9.3.78	14.3.78	22.3.78
Depth in cm at which the soil was above field capacity	90 120 150 180	120 150 180			10			10 20 30	10 20 30 70
Depth at which the soil was below wilting point	10	10 20 30	10 20	10 20 30		10	10 20		

FIG. 12. SOIL MOISTURE AT DIFFERENT DEPTHS DURING LONG RAINS 1978



C. Long rains 1978

During the second half of the long rains 1978 (Figure 12), the soil was below field capacity most of the time while it dried below wilting point at depths of 10 and 20 cm throughout the sampling period. The depth of 30 cm dried below wilting point after 21st June 1978.

D. Differences in soil moisture between depths

Figures 10, 11a and 12 show that the differences in soil moisture between soil depths were greatest during dry periods and smallest during the wet periods. The range on the 3rd August 1977 when it was dry was from 26.68% at 10 cm to 38.4% at 180 cm depth. The range on the 22nd September 1977 when it was wet was from 27.25% at the top soil to 35.55% moisture at the 180 cm depth. The range on the 16th February 1978 another dry period was from 20.97% at the top soil to 35.94% at the 180 cm depth while on the 3rd July 1978, when it was wet the range was from 26.0% at the top to 35.64% at the 180 cm depth.

In general, there were highest amounts in the deepest layer (mean moisture 35.63%) and lowest amounts in the top layer (mean moisture 26.93%) throughout the three growing seasons.

E. Evapotranspiration and water movements in the soil

A trend of increase and decrease in soil moisture due to recharges, drainage and evapotranspiration (Carter, Bondurant and Robbins, 1970; Wangati, 1972; Singh and Russell, 1978; Sen and Rajpurohit, 1980) was observed during the three seasons, though the magnitude of fluctuations was lower during the short rains 1977/78 and long rains 1978 because of lower rainfall during those two seasons.

The amount of water draining through the soil was influenced by evapotranspiration (the total amount of water lost by evaporation from the soil and plant surfaces), lateral movement of water by hydrodynamic dispersion, rainfall and the moisture status of the soil (Wild, 1972; Singh and Russell, 1978). Drainage only took place when total rainfall plus initial soil moisture exceeded the storage capacity of the soil (though modified by crop effects). Due to evaporation, low rainfalls such as were received on the 2nd September 1977 (0.3 mm), 28th March 1978 (0.3 mm) and 5th March 1978 (1.1 mm), did not cause any detectable change in soil moisture even in the upper layers of the soil. Much of the water that was received during these periods appears to have been evaporated either before reaching the soil or from the soil or to have been immediately transpired by crops from the top layers.

The drying of the soil below wilting point can be ascribed only to evaporation and upward movement of water (as vapour) since it is only evaporation which can dry the soil below wilting point. The fact that the soil was dried below wilting point down to about 60 cm during the long rains 1977, suggests that upward movement of water continued down to about 60 cm (see Figures 10, 11a and 12) during the periods of strong drying conditions (September and October 1977) when suction gradients (matric suction) were created in the soil surface by evapotranspiration and when downward displacement of water caused by rain did not counteract upward movement of water.

At times when the soil above 70 cm was at suctions below 15 bars and at a moisture content exceeding 29.32% (wilting coefficient), e.g. on dates 3rd, 5th, 8th, 10th, 12th, 15th, 18th and 25th August 1977, 23rd February, 1st, 14th and 22nd

March 1978, water moved mainly in the liquid form by capillarity when there was enough water in the soil below and when the suction gradient at the surface was steep enough. Fox and Lipps (1956) working with 4 soils in Nebraska, U.S.A., where natural rainfall is inadequate for the production of good yields by crops found upward movement of water in the soil from a free water surface from a depth of 2 metres. Gardner and Foreman (1958) found upward movement of water by capillarity from free water, 60 cm deep in sand loam and fine sandy soils, while Cassell (1970) found upward movement of water from a depth of 61 cm of uncovered loam soils in a sub humid environment. Wild (1972) found that upward movement of water was 48% of the water lost by evaporation under dry tropical conditions while van Bawel, Brust and Stirk (1968) have shown that as much as 4 mm/day of water can move from the subsoil into the root zone as the soil dries out.

Upward movement of water to the soil surface during the dry period was predominantly in the vapour phase although several workers report upward movement by capillarity during dry periods. During the dry periods the soil surface dries out (below wilting point). The dry layer at the top then acts as a mulch and prevents further water loss by upward movement and evaporation. Water movements in such a dry layer is mainly in the vapour form (Hillel, 1973). Penn (1941) observed that even a dry layer of 1 to 2 mm thick is effective in reducing evaporation while Oliver (1969) as a rough guide cites 10 cm for clays and 20 cm for surface layers of sands. Moreover, Farbrother and Munro (1970), Willis and Bond (1971) and Kollar, Kovac, Pilat and Zigo (1980) all observed that cultivation by disrupting capillary continuity during the first stage of evaporation (constant rate stage) reduced upward movement of water and evaporation substantially.

Although Jackson (1964) using a combination of theory and experience, concluded that above suctions of 144 bars, water moves only in the vapour phase and Russell (1973) observed that capillary conductivity can be maintained at suctions exceeding 50 and 10 bars for clay/loam and sandy soil respectively, its unlikely that water moved up by capillary conductivity during the dry season. This is because capillary conductivity would not be continuous under moisture contents below wilting point since there would not be enough suction at the surface to maintain it down to depths of about 60 cm under Kabete conditions unless the water table influenced the moisture regime of the soil above it (Morh and van Baren, 1959 cited by Jackson, 1977). Moore (1939) suggested loss of water of the order of 0.5 mm a day from a water table 2 metres below the soil surface under strong drying conditions. Capillary conductivity would further be disrupted by cultivation. This assertion is supported by the work of Rose (1963) which revealed that upward capillarity movement of water is only possible in moderately dry soils while above 15 bar suctions, water mainly moves as vapour. Moreover evapotranspiration rates if high would further disrupt the capillary conductivity. Denmead and Shaw (1962) found that in silty clay loam soil, at transpiration rate of 6.4 mm/day, capillary conductivity was unable to maintain its rate at suctions exceeding 0.3 bar.

During the 3 seasons, the water table did not influence the moisture regime above it since it was well below 2 metres and there was no capillary fringe (Russell, 1973). Moreover temperature gradients strong enough to support capillarity could not have extended as deep as 60 cm except on exceptionally sunny days, although Russell (1973) reports seasonal variation in soil temperature at depths of about 1 metre at Muguga, Kenya. However a short-lived upward movement of water was possible (with a physical discontinuity at a depth of about 15 cm due to cultivation) at the beginning of the dry season when the rate of evaporation was low enough to allow water conduction upward (Cassell, 1970). This was terminated as the dry surface layer got thicker as the dry season extended.

It took the 0 - 10 cm layer about 5 days to dry from field capacity to wilting point during a period during which about 2.5 mm of rain fell (refer to Figure 10) between 18th August and 25th August 1977). During the short rains 1977/78 it took the 20 - 30 cm layer about 4 days to dry from a moisture content of about 33% (oven dry weight basis) to wilting point when no rain fell (figure 11a). Rather contrasting results were found by Pereira and Wood (1958) who found that it took the 15 cm layer 1 month to dry to 15 bar suction after the rainy season in 2 successive years when the mean monthly temperature at 7.5 cm depth exceeded 33°C. At deeper layers, they found that it took even longer time. The apparent discrepancy might be in part due to differences in soil type and initial moisture content, the depth of water table and evapotranspiration rates.

E Water availability

Throughout the 3 growing seasons, moisture was always available to crops below 70 cm depth. Moisture was available in the whole profile on the 8th, 10th, 12th and 18th August 1977; 23rd February, 14th March and 22nd March 1978. During the long rains 1977, only crops whose roots went below 70 cm were able to extract water at times when the soil dried to 70 cm while during both the short rains 1977/78 and long rains 1978, only crops whose roots went below 50 cm were able to abstract water during the periods when the soil was at wilting point at 50 cm.

However, the soil was brought above the wilting point at certain periods when heavy rain fell. The gravitational water present when the soil was above field capacity on dates 3rd, 5th, 8th, 10th, 12th and 18th August 1977; 23rd February 1978 and 14th and 22nd March 1978 was available to crops in the upper or deeper layers (for the deep rooting crops) but was transient in nature. Deep rooting crops abstracted water below 70 cm depth so were able to make growth even during the periods when the soil was dried below wilting point. Observations of the crops in field also did not show any permanent wilting during the period of the investigations which suggests that periodic recharges of water and abstraction of water from deep layers maintained a good moisture supply. This is agreement with what other workers found.

Pereira (1957) found that during drought, the roots of arabica coffee growing in deep red loam soil in Kenya removed water from more than 3 metres depth but only dried the top 150 cm of the soil to 15 bar suction without permanently wilting. Russell (1973) reported that in Great Britain, in dry summers, roots of annual crops and grasses go as deep as 120 cm but only dry the soil to 15 bar suction to depths not exceeding 50 cm. Cole and Mathens (1939) working in North Nebraska, U.S.A., found that in an area planted to wheat each year, the soil was dried below permanent wilting percentage at 60 cm to 150 cm. Results of Singh and Russell (1978) support this finding.

G. Soil moisture in relation to the eight crops

(i) Fluctuations of soil moisture under the eight crops

During the long rains 1977, loss of water by runoff occurred after the rain on the 15th August 1977 when the top soil was far above field capacity. During that time, the rate of water addition might have been higher than the infiltration rate so run off occurred (Jackson, 1977). Slayter (1962) reports infiltration rates of many clay-loams to be 3.8 - 1.3 mm/hr while Fabrother and Manning found that 39 - 64% of the 576 mm rain that fell was lost by runoff in an area with 2% slope in Namulonge, Uganda. Runoff also occurred after rain that fell on 16th February 1978 (23rd February1978) and between 14th and 22nd March 1978. During both these periods, the top soil was brought to field capacity and runoff was possible (refer to Figures 11a and 12). Percolation below the 180 cm depth was possible between 3rd and 15th August 1977 (Figure 10) and between

2nd and 9th February 1978 (Figure 11a). Between these periods, the deepest layer (and others) were above field capacity and it was possible that the profile could lose water by deep percolation (Hardy, 1946a; Singh and Russell, 1978).

However during the periods when the soil was below field capacity and above wilting point at depths to which crop roots could penetrate the major moisture loss was evapotranpiration. The soil lost moisture mainly by evapotranspiration from 18th August 1977 possibly till the end of the long rain season 1977. A similar pattern of moisture loss occurred throughout the later periods of the long rains 1978.

Appendices 5a to 5i show levels of soil moisture below the 8 crops at the nine depths through 3 seasons while Fig. 11b. represents the soil moisture under the eight crops at a depth interval of 30 - 50 cm during the short rains 1977/78. They all suggest second order interactions due to crops, sampling date and depth with respect to soil moisture (Bailey, 1959; Snedchor and Cochran, 1971). Thus crops abstracted varying amounts of water at different depths at different periods. They also suggest that the variability in soil moisture is large. This variability might have been due to the presence of cracks (which may or may not facilitate water loss by evaporation and drainage) and the presence of clay pans (such as was noticed at 120 cm depth in some areas) among other factors. Differences between crops seemed to be more noticeable during the dry periods than during the wet ones. In general, the effect of harvesting (removal of crops from the ground) on soil moisture was not discerned, possibly because during later stages crops used very little moisture.

(ii) Statistical analysis and interpretation of results

Though it is not easy to generalise on overall crop effects on soil moisture on account of the fact that there were interactions due to sampling dates and depths, something could be said about the effect of crops at different depths through the three seasons.

Results of analysis of variance and F-test carried out at the 5% probability for some three dates - 15th, 18th and 25th August 1977 (Table 10) suggest significant results in one out of three sampling occasions for the 10 cm depth and 2 out of three occasions for the rest of the depths. On the 18th August 1977, analysis of variance revealed significant differences due to crops with respect to moisture only at one depth (10 - 20 cm) while at the remaining depths the results were not significant. On the 25th August 1977, all the nine depths showed significant differences due to crop with respect to soil moisture at the 5% probability. These results suggest real differences in soil moisture due to crops and further show that rain water obliterates differences due to crops (as evidenced by the non significant differences on the 18th August which was a wet date).

Table 9 suggests that the overall effect of crops on moisture at specific sampling horizons according to the average moisture percentage over the three seasons is as follows:

Depth	Lowest average moisture	Highest average moisture
0 - 10 cm	linseed	maize
	field beans (average moisture 26%)	sunflower (28%)
10-30 cm	linseed	Irish potatoes
	wheat (28%)	sweet potatoes
		maize (30%)

Depth	Least moisture	Most moisture
30-70 cm	linseed sweet potatoes (31%)	Irish potatoes soya beans field beans(34%)
70-120 cm	sunflower sweet potatoes (33%)	Irish potatoes wheat linseed (35%)
120-180 cm	sunflower maize (34%)	Irish potatoes linseed wheat (37%)

In general, total soil moisture in the profile to a depth of 180 cm seemed to be:

a) lowest under sunflower (average moisture 31%) and

b) highest under Irish potatoes (average moisture 34%)

(iii) Possible explanation for the differences in soil moisture between crops

The variation in soil moisture under different crops within a single season is mainly due to varying uptake and evapotrnaspiration of different

Table 9 The mean soil moisture content under the eight crops at 9 different depths over the three growing seasons 1977/78

Depth (cm)	SF	M	LS	SB	FB	SP	IP	W	Means
0 - 10	27.85	28.2	26.36	26.29	25.95	27.68	26.25	26.89	26.93
10 - 20	29.35	28.26	26.25	27.95	26.98	29.05	28.34	26.48	27.52
20 - 30	30.15	30.97	28.4	30.64	30.37	30.53	31.67	29.23	30.21
30 - 50	30.86	31.97	30.31	32.60	33.19	31.74	34.17	30.91	31.96
50 - 70	31.46	32.73	31.44	33.96	34.64	32.24	35.7	32.71	33.11
70 - 90	32.05	33.24	33.79	35.12	36.33	32.97	36.41	34.44	34.29
90 - 120	32.68	33.65	35.88	35.82	36.46	33.7	36.85	35.59	35.07
120 - 150	33.06	34.12	35.67	35.72	36.39	34.17	36.58	35.71	35.17
150 - 180	33.91	34.71	36.25	36.19	36.97	34.74	36.51	35.71	35.63
Means	31.25	32.09	32.09	32.69	33.03	31.86	33.61	31.96	32.24

Table 10. F-test results (soil moisture) for 9 depths on 3 sampling dates

Sampling date	F-value for the 9 depths								
	0–10	10–20	20–30	30–50	50–70	70–90	90–120	120–150	150–180
15.8.77	2.43^{NS}	1.4^{NS}	5.32*	3.78*	3.32*	2.49^{NS}	4.38*	3.96*	2.89*
18.8.77	1.17^{NS}	5.44*	1.03^{NS}	1.57^{NS}	0.94^{NS}	1.71^{NS}	1.98^{NS}	1.07^{NS}	2.04^{NS}
25.8.77	4.21*	6.41*	2.69*	3.41*	9.29*	3.44*	9.79*	16.05*	10.44*

^{NS} F-value not significant

* F-value significant at 5% level

crops although soil moisture use is a complicated and dynamic process involving several factors (Hillel, 1973). Bennison and Evans (1968), working in Katumani, Kenya, found that moisture use by crops was related to their rooting habits, vegetative bulks and duration on the ground. Uptake by crops vary because of varying rooting habits (root intensity and depth) and varying abilities to extract water from the soil (Russell, 1961). However, it is evapotranspiration which accounts for a greater part of soil water variability due to crops. Singh and Russell (1978) found that transpiration was 35% of the total seasonal available water down to 127 cm depth of a fine clay soil mixed with udic Rhodustalf of a semi arid tropical climate of India. Scholl (1975) on the other hand found that evapotranspiration accounted for 98% of the precipitation during the dry period and accounted for 80% of the precipitation during the wet season in gravelly loam sand (covered with Chaparral shrubs) of Arizona, U.S.A.

The extent to which the different crops influence soil moisture regimes by drying the soil and producing cracks is another possible cause. However, no differential cracking due to crops was observed during the period of the trials. Yet another cause is the influence of crops on the soil physical properties (structure, porosity and permeability), but variations due to crops within a growing season would be small.

Maize and sunflower being deep rooting crops were able to extract more water at a depth of 120 - 180 cm than other crops. Pillsbury (1968) reported maize to be extracting water to 150 cm while Dagg (1965a) and Russell (1973) at Muguga, Kenya, reported maize to be rooting down to 150 - 200 cm. Sunflower on the other hand has been reported to be rooting as deep as 300 cm (Arnon, 1972) Sweet potatoes (together with sunflower) extracted more water than other crops at a depth of 120 cm which is consistent with the depth of 120 cm down to which Pillsbury (1968) reported sweet potatoes to be taking water.

Linseed, field beans and wheat abstracted more water in the top 30 cm than other crops partly because they have a higher root intensity (the amount of root mass per volume of soil) in the top 30 cm of the soil. Arnon (1972) reported that most of roots of linseed were found in the top soil although linseed has been reported to be rooting as deep as 61 cm by Chapman and Carter (1976) and 150 cm by Pillsbury (1968). Field beans have been reported by Pillsbury (1968) to be drawing water from 60 cm depth, although most of its roots are concentrated in the top soil while Hurd and Spratt (1975) found wheat roots to be growing as deep as 120 cm under wet and dry conditions although the majority of wheat roots were in the top soil. Arnon (1972) reported that 60% of the root system of wheat is in the top soil. Russell (1961) asserted that small grains should extract more water than maize and potatoes.

From the point of view of moisture use by the crops from the whole profile throughout the growing season, evapotranspiration, and duration on the ground are important in addition to rooting habit. Wangati (1972) at Mwea irrigation scheme found that the moisture use of maize and beans was closely related to evapotranspiration though his data in table 2 suggest that differences between crop coefficient of the various crops are small. Williams and Joseph (1971) and Kowal and Kassam (1978) observed that evapotranspiration is dependent on evaporative demand of the air, leaf area, stomatal aperture, crop resistance to water movement, display of leaves, density and height of foliage, absorptive and reflective (albedo) properties of foliage. The fact that moisture was lowest in the profile to a depth of 180 cm below sunflower can be explained in terms of its great vegetative bulk (hence high leaf area index), long duration on the ground and its deep rooting habit. Sunflower plants are tall and have many broad leaves with low albedos. It may root as deep as 300 cm (Arnon, 1972) and was the second last to be harvested. It therefore had a high evapotranspiration rate and used moisture in the whole profile in the later periods of growth.

Irish potatoes which had the lowest moisture below it in the profile throughout the three growing seasons, had a small vegetative bulk (so low leaf area index), exploited moisture in the top layers only and had a relatively short duration on the ground (was second to field beans which was harvested first). Moreover its above ground parts withered early. Sweet potatoes which had the second lowest moisture in the whole profile below it throughout the 3 seasons was the last to be harvested, was found to abstract water to about 120 cm depth and had a relatively large vegetative bulk while field beans which had the second highest moisture in the profile throughout the growing season was the first to be harvested (after 3 months), had a relatively small vegetative bulk and was found to explore the soil moisture mainly in the top 30 cm of the soil.

In general, it seems that a crops duration on the ground together with rooting depths are more important than the evapotranspiration rates in determining crop water use from the whole profile through a growing season, since Wangati's (1972) results in table 2 show that differences in crop coefficients between crops of beans, maize, potatoes, soya beans, sunflower and wheat are not great. Also moisture removal showed the major effect of the rooting depth and intensity of the various crops although some roots go deep but have slight effect on soil moisture. Similar observations were made by Cole and Mathens (1939), Pereira (1957), Russell (1973) and Singh and Russell (1978). The fact that throughout the 3 growing seasons the soil was dried to wilting point to about 70 cm depth suggests that most roots of the crops were concentrated in the upper 70 cm of the soil.

4.7. Crop yields

Tables 11 and 12 give the overall effect of the 8 crops on the grain yield of a test crop of maize during the long rains 1977 and 1978 according to the crops planted in the first season and the season immediately preceding the season of the test crop for both the 18 month and the 3 year rotations. Appendices 6, 7, 8 and 9 also give the yield of maize as influenced by the various crops while appendices 10 and 11 show the effect of each of the 8 crops on the yield of each of the other crops during the long rains 1977 (3 year rotation) and during the short rains 1977 (18 month rotation) respectively.

For the 3 year rotations, there was a fallow during the short rains between the first planting and the test crop while for the 18 month rotation, planting was done during the short rain season as well.

A. Variations in yield of crops

Table 12 and appendices 7, 8, 9, 10 and 11 show that the average yields of maize were 4.2

Table 11. The overall effect of the eight crops on the grain yield (in metric tonnes per hectare) of a test crop of maize during the long rains 1977 and 1978

Crops grown in the 2nd season	Crops grown during the 1st season								Grand mean
	SF	SB	SP	IP	M	W	LS	FB	
SF	2.15	2.49	2.44	2.32	3.18	2.39	1.97	2.25	2.40
SB	2.39	2.94	2.76	1.89	2.02	2.85	2.25	1.53	2.34
SP	2.53	2.36	2.97	2.63	2.64	2.23	2.43	2.79	2.57
IP	2.24	2.45	2.35	2.62	2.46	2.54	2.43	2.79	2.49
M	2.80	2.69	2.38	2.24	1.89	3.05	2.56	2.38	2.50
W	2.35	2.32	2.49	2.60	2.95	2.64	2.34	2.33	2.50
LS	2.38	2.26	2.89	1.76	2.27	2.11	2.21	2.28	2.27
FB	2.29	1.47	2.38	2.74	2.13	2.20	2.07	2.46	2.22
Grand mean	2.39	2.37	2.58	2.35	2.44	2.50	2.28	2.35	

Table 12. The effect of the eight crops on the yield of maize test crop grown during the long rains 1977 and long rains 1978

Crop	Yield of maize in metric tonnes per hectare					
	long rains 1977 (18 month rotation)		long rains 1977 (3 year rotation)		long rains 1978 (18 month rotation)	
	Mean yield	(S)	Mean yield	(S)	Mean yield	(S)
Soya beans	3.53	1.54	3.49	1.09	1.77	0.62
Irish potatoes	4.64	1.35	4.26	0.84	1.52	0.63
Wheat	4.66	0.93	4.31	1.31	1.43	0.57
Sunflower	3.86	1.31	4.10	1.33	1.69	0.59
Field beans	4.10	1.38	3.44	1.33	1.37	0.35
Sweet potatoes	4.77	0.96	3.9	0.74	1.5	0.51
Linseed	3.92	1.30	4.09	1.58	1.38	0.49
Maize	4.39	0.92	3.46	1.21	2.06	0.61
Means	4.2		3.9		1.6	

tonnes/ha (18 month) and 4.0 tonnes/ha (3 year) for the long rains 1977 and 1.6 tonnes/ha (18 month) and 0.7 tonnes/ha (3 year) during the long rains 1978. Analysis of variance of the data in appendix 6 reveals significant differences between the yield of maize in the two seasons. The mean yield of maize during the long rains 1977 was 4.1 tonnes/ha while during the long rains 1978, the average yield of maize was 1.2 tonnes/ha. This means that the average yield of maize per hectare during the long rains 1977 was higher than during the long rains 1978 by about 2,900 kgs. Appendices 10 and 11 show that the average yields of other crops were also higher during the long rains than during the short rains 1977. The low yields during the long rains 1978 were due to the fact that too much rain effected the growth and yield of maize in a negative way. On the other hand, the lower yield of maize during the short rain 1977 than during the long rains 1977, was due to the fact that more rain fell during the long rains than during the short rains 1977.

During the long rains 1977, the average yield of maize for the 18 month rotation was about 200 kg. higher than the average yield for the 3 year rotations. During the long rains 1978, the average yield of maize for the 18 month rotation was about 900 kgs. higher than the average yield of maize for the 3 year rotations.

These suggest that the fallow in the 3 year rotations probably had some effect which reduced the yield of maize grown in the third season.

The inhibitory effect of fallow grasses on nitrification is one possible effect of the fallow. The depletion of soil moisture for the crop grown in the following season, particularly in deep layers by the fallow grasses is another possible cause of the fallow effect. Yet another cause is the lack of soil organic matter exposure for subsequent mineralisation, during the fallow as opposed to a more thorough exposure through cultivation during the cropping period.

A. Yield of crops in relation to preceding crops

The yield of crops is considered from the point of view of the effects of different crops grown in a preceding season on the yield of a test crop of maize, the effects of sequences of crops grown during preceding seasons on the yield of a test crop of maize and the effects of preceding different crops on each of the other crops.

Analysis of variance of the data in appendix 6 shows no significant differences in the yield of maize grown during the long rains 1977 and 1978 (both rotations) due to sequences of crops grown in 2 seasons preceding the season of the test crop, though it reveals significant differences in maize yield due to seasons. Tables 11 and 12 and Appendices 7,8 and 9 show no significant differences in the yield of maize during the long rains and short rains 1977 and long rains 1978 due to effects of crops grown in seasons preceding the seasons of the test crop. Likewise the data in appendices 10 and 11 do not show any trend which suggests effects of the various preceding crops on the yield of the same crops.

The lack of evidence to suggest that crops had effects on their successors might simply be due to:

a) the level of the factor(s) responsible for the effect in the soil,
b) the depth at which the factor(s) are most effective in determining the yield of the test crop,
c) the fact that the effects were not noticeable after short cropping periods,
d) the fact that the effects were not carried from one season to the next,

e) the fact that the yield component (grain and tuber yield) studied were not significantly affected by the soil factor(s) responsible,

and

f) the fact that crops did not respond to the soil factors during the seasons of the trials because of soil moisture effects.

The effect of the level of the factors responsible for the effect in the soil has been observed by many workers. In relation to soil N, work reveals that responses to changes in soil N are only possible when the levels of residual mineral N are below the levels that cause maximum yield. This depends on the levels of total N and climatic conditions. Birch and Friend (1956) found that in the Kenya Highlands significant responses to N were only found in shallow soils where cultivation and burning of crop residues had reduced the soil organic matter and total N to 2.3 - 4% and 0.1 - 0.2% respectively. They further observed that the soils in the more temperate parts of East Africa are not deficient in available N except when organic matter level for one reason or another is low. Olson, Frank, Deibert, Drier, Johnson and Sander (1976) also

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However, in Kabete soil, with organic matter of about 5.5% (uncorrected) and organic N of approximately 0.286%, responses to added N are common which rules out possibility of the lack of the effect on the test crop due to inorganic N levels.

The depth at which the factors responsible for determining the yield of the test crop is effective is also important. Olson *et al.* (1976), working in Nebraska, U.S.A., found that the depth at which mineral N remains might also determines whether a crop responds to soil N or not. Olson, working with wheat and maize, found that for both crops, residual N in the sub soil had a major effect on percentage grain protein irrespective of the fresh fertiliser N applied, possibly because root activity declined in the surface soil as it dried. The subsoil N taken late in the season therefore became important in grain development. However this is not a likely cause of the lack of response since the soil N must have been leached down to the subsoil where uptake was possible. Moreover it is unlikely that mineral N could have moved to the top soil by upward movement during the dry season (late in the season).

The lack of evidence to support the fact that crops had effects on their successors might therefore be due to the lack of the crop effects after short cropping periods, the lack of carry-over from one season to the next (Russell, 1973), the effect on the yield component studied (Campell and Viets, unpublished) and soil moisture effects (Wild, 1972; Colman and Lozenby, 1975; Walia, 1980).

CHAPTER 5

5. CONCLUSIONS

5.1. Inorganic nitrogen

Inorganic nitrogen (NO_3-N, NH_4-N and N_2O-N) slowly accumulated in the top 30 cm of the soil during the dry periods, but increased rather sharply at certain times. After the increases, amounts rapidly declined as the rainy period progressed.

During the long rains 1978 and the short rains 1978/79 when above average rain fell, it was found that average amounts of inorganic N in the top 30 cm of the soil increased from about 29 ppm in mid July 1978 to 64 ppm during October 1978, then decreased during October and November 1978 to about 20 ppm during the first half of January 1979. After that they increased again rather sharply to about 26 ppm late in January 1979, dropped again to about 18 ppm during early February 1979 and then rose again.

The sharp but short lived increases of inorganic N noticed during the period 11th January - 26th January 1979 and after 7th February 1979 are assumed to be due to the flush of decomposition of organic matter and mineralisation of organic N at the onset of the rains (Birch effect) following alternate wetting and drying of the soil. The slow build-up of inorganic N in the top soil noticed between 18th July and 3rd October 1978 was assumed due to accumulation mainly due to continued mineralisation of organic N (either microbial or photocatalytic).

The rapid decreases of inorganic N in the top 30 cm of the soil during the periods 16th - 22nd August 1978, 3rd October 1978 - 11th January 1979 and 26th January - 7th February 1979, appeared mainly due to leaching of inorganic N (mainly NO_3-N) out of the top soil by soil water. The extent of leaching depended on the amount of water initially present in the soil, the amount of water required to bring the soil to field capacity, crop removals and evaporation of water. Leaching of soil inorganic N was greatest under Irish potatoes and least under linseed.

While the eight crops did not change the soil with respect to soil reaction and organic carbon during the period of investigation, significant differences in amounts of soil inorganic N between crops were found. The crops can be ranked according to their effects on soil inorganic N as follows:

linseed $<$ wheat $<$ field beans $<$ sunflower $<$ soya beans $<$ sweet potatoes $<$ maize $<$ Irish potatoes.

Although the amounts of inorganic N below the various crops varied more or less according to the sampling date, it was found that amounts were highest under Irish potatoes and lowest under linseed. Significant differences with respect to soil inorganic N were found:

- i) between Irish potatoes and all other crops,
- ii) between maize and wheat, field beans, linseed and soya beans,
- iii) between sweet potatoes and both wheat and sunflower.

The high amounts of inorganic N below Irish potatoes and maize and the low amounts below linseed and wheat were attributed mainly to uptake although the influence of the crops on rates of mineralisation could have been a contributory factor. The low levels below linseed and wheat was possibly due to the fact that they extracted more N in the top soil than did other crops (soil moisture investigations revealed that they abstracted more moisture from the top than did most of the crops, possibly because their roots are concentrated in the top soil). Irish potatoes and maize on the other hand abstracted less inorganic N than the rest of the crops (they extracted soil moisture at depths greater than 0 - 30 cm). Although field beans and soya beans fixed N, levels of inorganic N below field beans were below average and those under soya beans were only average. This may be partly because most of the N that they fixed was removed in seed and stover at harvest and partly because they have relatively high requirements of N.

The effects of weeding, earthing up, ground coverage (spacing) and the "priming" effect of fresh organic matter on the rates of mineralisation of organic N are also likely causes of high soil inorganic N amounts below Irish potatoes. Irish potatoes which had the highest amounts of inorganic N in the soil below it only poorly covered the soil and were weeded twice then earthed up. Moreover their above ground portions withered early and were incorporated into the soil. Linseed and wheat on the other hand covered the ground relatively well and were weeded only once. While possible effects of root exudates on the rates of mineralisation of organic N are open to investigation, weeding, earthing up and spacing could influence mineralisation rates through their effects on the soil temperature, aeration and soil moisture.

5.2. Soil moisture

Throughout the 3 investigation seasons, the average soil moisture was highest at a depth of 150 - 180 cm (mean moisture 35.63%) and lowest at a depth of 0 - 10 cm (mean moisture 26.93%) while fluctuations of soil moisture were largest at 0 - 10 cm depth and least at 150 - 180 cm. The large fluctuations of moisture in the top soil were related to crop uptake and evapotranspiration, periodic recharges from rain and drainage of water to deeper layers.

During the 3 seasons, stonger drying conditions existed during the long rains 1977 than during both short rains 1977/78 and long rains 1978. During the long rains 1977 the soil was dried to wilting point (15 bar suction and 29.32% moisture) down to a depth of 70 cm while during the long rains 1978, the soil was dried to wilting point down to only 50 cm during the periods of strong drying conditions. During the 3 seasons, crop did not wilt permanently because moisture was available below 70 cm depth all the time.

The drying of the soil below wilting down to intermediate depths during the long rains 1977, the short rains 1977/78 and long rains 1978 was by upward movement of water, mainly in the vapour phase and evaporation of water from the soil. Plant removal also contributed to drying of the soil but was important in drying the soil to wilting point only. The fact that the soil was dried below wilting point down to depths of about 60 cm during long rains 1977, suggests that the water table (which was well below 2 metres depth) did not influence the moisture regime above and that water moved upwards from that depth.

The effects of the various crops on the soil according to the average moisture percentage over the three seasons were as follows:-

Depth	Lowest average moisture	Highest Average moisture
0 - 10 cm	linseed	maize
	field beans	sunflower
	(26%)	(28%)
10 - 30	linseed	Irish potatoes
	wheat	sweet potatoes
	(28%)	maize (30%)

Depth	Least moisture	Most moisture
30 - 70 cm	linseed sweet potatoes (31%)	Irish potatoes soya beans field beans (34%)
70 - 120 cm	sunflower sweet potatoes (33%)	Irish potatoes wheat linseed (35%)
120 - 180 cm	sunflower maize (34%)	Irish potatoes linseed wheat (37%)

In the whole profile down to 180 cm, moisture was lowest below sunflower and highest below Irish potatoes.

The differences in soil moisture under the various crops were ascribed to varying rooting habits (rooting intensity and depth), varying extracting abilities and varying crop coefficients (evapotranspiration) which in turn is a function of the vegetative bulks and duration on the ground. Whereas the moisture use of the various crops was related to their rooting habits, the moisture use in the whole profile throughout the growing season reflected the major effect of crops duration on the ground, rooting habit as well as evapotranspiration.

Maize and sunflower being deep rooting crops abstracted more moisture than other crops while linseed, wheat and field beans abstracted more moisture in the top 30 cm of the soil than other crops because their roots are concentrated in the top soil. The fact that moisture was lowest in the profile to a depth of 180 cm below sunflower is due to the fact that its vegetative bulk is great, it is deep rooting and its duration on the ground is relatively long. The high moisture in the profile throughout the season under Irish potatoes is due to the fact that it had a small vegetative bulk (so low evapotranspiration), was shallow rooting and was harvested early.

5.3. Crop yields

The yield of crops was not found to vary within a season because of the effects of preceding crops, though the yield of crops did vary between seasons because of seasonal variation in rainfall. Crop yields were highest in the long rains 1977 and lowest in the long rains 1978 (because of too much rain), while yields of the short rains between the two seasons were intermediate.

Possible explanations for the absence of the effects of preceding crops on the yield of their successor in short rotations are:

a) the absence of the effects after short cropping periods,

b) the fact that the effects were not carried over from one season to the next,

c) the fact that the yield component studied might not have been significantly affected,

d) the possibility of crops not responding to the soil factors during the seasons of the trials because of soil moisture effects.

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Appendix 1a. Initial organic carbon (uncorrected) and p^H results of the top 15 cm layer of the soil Field 6, block 1

Plot No.	Organic carbon (%)	p^H in water	p^H in 0.01M $CaCl_2$
1	3.11	6.88	6.2
2	2.32	5.4	5.1
4	2.55	6.5	5.6
6	2.42	5.1	4.5
7	2.36	5.88	4.9
9	2.54	6.2	5.1
10	2.34	5.2	4.85
12	2.19	5.0	4.6
13	2.11	6.3	4.7
14	2.43	6.2	4.45
15	2.29	5.95	4.7
17	2.24	6.2	5.0
18	2.10	5.1	4.9
19	2.28	6.0	5.0
20	2.37	5.1	4.45
21	2.27	6.0	5.3
22	2.29	6.1	4.6
23	2.18	5.25	4.7
27	2.25	6.25	4.55
28	2.08	6.2	5.4
29	2.13	6.4	5.54
30	2.18	6.3	4.85
31	2.80	6.6	5.85
34	2.18	6.23	5.1
36	2.14	5.1	4.88
39	2.56	6.21	5.7
52	2.27	6.62	5.87

Appendix 1 b. Field 6, block 2

Plot No.	Organic carbon (%)	p^H in water	p^H in 0.01M $CaCl_2$
1	2.28	6.5	5.5
2	2.59	6.3	5.62
3	2.82	6.5	5.35
4	2.36	5.6	5.5
5	2.26	5.5	5.0
6	2.64	5.2	4.55
8	2.3	6.5	5.8
9	2.6	5.7	5.0
12	2.4	5.6	4.7
14	2.92	6.45	5.5
15	2.57	5.7	5.5
16	2.56	6.4	5.05
17	2.22	6.4	6.19
19	2.71	6.0	5.2
22	2.39	6.69	5.82
23	2.55	6.0	4.9
24	2.21	6.3	4.85
25	2.09	5.5	5.4
26	2.35	5.45	4.7
27	2.71	5.6	5.33
31	2.73	5.15	4.65
33	2.5	6.39	5.6
34	2.70	5.8	5.6
35	2.92	7.0	6.10
36	2.73	5.9	5.2
38	2.56	6.7	6.2
39	2.65	6.3	5.7
40	2.74	6.01	5.5
42	2.86	5.62	5.0
43	2.75	5.3	5.05
44	2.21	6.45	4.97
45	2.31	6.8	6.0
49	2.51	5.65	5.4
50	2.95	6.1	5.6
52	1.69	6.2	5.68
53	2.41	6.88	5.88
55	2.47	6.6	5.72
56	2.61	6.1	5.8
57	2.92	5.9	4.8
58	2.62	6.5	5.7
59	2.08	6.5	5.83
60	2.14	5.6	5.0
63	5.51	5.6	5.1

Appendix 1 C. Field 14, block 1

Plot No.	Organic carbon (%)	p^H in water	p^H in 0.01M $CaCl_2$
2	2.66	6.1	4.8
3	1.75	6.2	5.38
4	2.30	5.9	5.1
5	2.50	6.4	6.0
7	2.49	5.3	5.6
8	2.25	6.55	6.25
10	2.79	5.3	4.7
11	2.29	6.3	5.8
12	2.78	6.09	4.86
13	2.23	5.15	4.5
14	2.88	6.2	5.1
15	2.85	6.0	5.4
16	2.8	5.9	5.2
18	2.17	5.5	5.1
20	2.39	5.1	4.9
21	2.62	5.18	5.2
22	2.16	5.0	4.8
25	1.89	5.6	4.5
26	2.52	5.3	4.6
28	2.77	5.3	4.97
30	2.52	6.18	5.2
32	2.84	6.7	5.9
36	2.41	4.93	4.68
35	2.77	5.93	5.3
37	2.83	5.0	4.4
38	2.36	5.2	4.3
40	3.04	5.6	5.2
41	2.77	6.0	5.5
42	2.15	4.7	4.6
43	3.18	5.99	5.3
45	2.75	6.1	5.1
46	2.71	6.1	5.15
47	2.85	6.1	5.8
48	2.85	5.98	4.9
49	2.92	5.5	5.15
50	2.81	4.95	4.84
51	2.8	5.8	5.3
52	2.65	6.1	5.0
53	3.36	5.9	5.4
54	2.96	6.0	5.33
55	3.24	5.0	4.9
56	2.89	6.0	5.0
58	2.81	5.0	5.57
59	2.30	6.0	5.32
60	2.42	5.09	4.74
61	2.62	6.05	5.71
63	3.07	5.10	4.9
64	2.77	5.10	4.9

Appendix 1d. Field 14, block 2

Plot No.	Organic carbon (%)	p^H in water	p^H in 0.01M C[illegible]
4	2.7	6.02	5.25
5	2.86	6.0	5.2
7	3.12	5.3	5.2
8	2.14	6.1	6.0
9	2.79	5.3	5.15
10	2.68	5.3	5.2
11	2.62	5.7	5.2
12	2.3	5.2	4.8
13	2.85	6.6	5.8
15	2.49	6.19	5.0
17	2.85	6.2	5.5
18	2.24	5.0	4.77
20	2.56	6.9	6.7
21	2.5	5.1	4.89
22	2.47	5.0	4.5
24	2.40	6.24	5.07
25	2.29	5.2	4.55
28	2.75	5.45	4.57
30	2.53	5.45	4.57
32	2.03	5.7	5.09
33	2.0	6.0	5.22
34	2.12	5.1	4.92
35	2.47	6.0	5.23

Appendix 2 a. Organic carbon (uncorrected) in the top 15 cm of the soil under the eight crops (17th July 1978)

Crop	% Organic carbon					Means ($\bar{x}$)	Standard deviation (S)	Standard error (S.E.) Variance ratio (F)
M	2.88	2.55	2.88	2.67	2.82	2.76	0.13	
SF	2.46	2.83	2.61	2.76	2.88	2.70	0.17	
SP	2.94	2.12	2.55	2.76	2.1	2.49	0.38	S.E. = 0.022
SB	2.91	2.31	2.67	2.64	2.37	2.58	0.24	
FB	2.10	2.91	2.94	3.75	2.7	2.88	0.59	
LS	2.10	3.15	2.7	2.76	2.52	2.64	0.38	
IP	3.15	3.6	3.72	3.0	3.32	0.32	0.32	F = 2.91^{NS}
W	2.55	2.4	2.64	2.7	3.04	2.66	0.24	
Means						2.76		

Appendix 2b. Organic carbon (uncorrected) in the top 15 cm of the soil under the eight crops (7th August 1978)

Crop	% organic carbon					Means ($\bar{X}$)	Standard deviation (S)	Standard error (S.E.) variance ratio (F)
M	2.64	2.88	2.94	3.12	2.22	2.76	0.35	
SF4	3.03	2.82	2.7	2.94	2.76	2.85	0.13	
SP	2.49	3.0	3.0	3.12	2.34	2.79	0.35	S.E. = 0.02
SB	2.52	2.94	2.46	2.61	3.03	2.71	0.26	
FB	2.52	2.52	2.76	3.06	2.28	2.62	0.30	
LS	3.36	2.4	2.4	2.82	3.03	2.80	0.41	
W	2.88	2.82	3.18	2.31	2.28	2.69	0.39	F = 0.35[NS]
IP	3.18	2.82	3.18	2.52	2.72	2.88	0.29	
Means						2.77		

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Appendix 2C   Organic carbon (uncorrected) in the top 15 cm of the soil under the eight crops (15th August 1978)

Crop	% Organic carbon					Means ($\bar{X}$)	Standard deviation (S)	Standard error (S.E.) Variance ratio (F)
M	2.73	3.03	3.66	3.03	2.58	3.0	0.41	
SF	3.18	3.15	3.12	3.06	2.94	3.09	0.09	
SP	3.30	2.46	2.67	2.91	2.76	2.82	0.31	S.E. = 0.024
SB	3.0	2.79	3.57	3.6	2.37	3.03	0.48	
FB	2.76	3.15	2.55	2.64	2.94	2.80	0.24	
LS	2.7	2.67	2.94	3.36	2.76	2.88	0.29	
IP	2.73	3.27	3.36	3.18	2.58	3.02	0.35	
W	3.18	2.85	3.51	2.94	2.40	2.97	0.41	
								F = 0.46^{NS}
Means						2.95		

Appendix 2d Organic carbon (uncorrected) in the top 15 cm of the soil under the eight crops (21st August 1978)

Crop	% Organic carbon					Means ($\bar{X}$)	Standard deviation (S)	Standard error (S.E.) Variance ratio (F)
M	3.15	3.09	2.76	2.01	2.64	2.73	0.46	
SF	2.86	3.09	2.79	2.37	2.55	2.73	0.28	
SP	2.82	3.57	3.0	2.0	2.01	2.68	0.68	S.E. = 0.028
SB	2.73	2.83	3.03	2.76	2.4	2.75	0.23	
FB	2.85	2.88	3.6	2.52	2.61	2.89	0.42	
LS	2.76	3.0	3.3	2.7	2.7	2.89	0.26	
W	2.55	2.95	3.03	2.7	2.82	2.81	0.19	F = 0.28^{NS}
IP	3.03	2.88	2.76	3.0	2.82	2.89	0.12	

Appendix 3: The effect of the eight crops on soil reaction after the first season planting 1977

Crop	p^H of the soil in 0.01M $CaCl_2$														Means ($\bar{X}$)	Standard deviation (S)	Standard error (S.E.) variance ratio (F)
SB	5.0	5.2	4.9	5.2	5.2	5.05	4.95	5.1	5.05	5.3	5.25	5.3	5.4	5.1	5.14	0.15	
M	5.0	5.1	5.0	5.15	5.0	5.05	5.1	5.35	5.4	5,1	5.25	5.35	3.35	5.5	5.19	0.17	S.E.=0.0028
SP	5.25	5.0	5.05	4.9	4.8	5.0	5.65	5.25	5.35	5.5	5.4	5.35	5.05	5.1	5.19	0.24	
IP	5.1	4.8	5.2	5.25	5.25	5.3	4.9	5.1	4.8	5.2	5.25	5.25	5.3	4.9	5.11	0.19	
SF	5.1	5.2	4.9	5.0	5.2	5.1	5.3	5.2	5.3	5.35	4.95	5.25	5.3	5.35	5.18	0.15	
LS	5.55	5.2	5.15	5.15	5.1	5.2	5.1	5.5	5.4	5.4	5.15	5.3	5.4	5.4	5.29	0.15	$F=1.37^{NS}$
W	5.2	5.15	5.05	5.0	5.1	5.1	5.15	5.6	5.35	5.2	5.4	5.35	5.35	5.3	5.24	0.16	
FB	5.15	5.1	5.1	5.1	5.3	5.9	5.2	5.2	5.0	5.5	5.3	5.6	4.95	5.3	5.26	0.26	

Appendix 4: Inorganic nitrogen in the top 30 cm of the soil under the eight crops through two growing seasons (1978 and 1979)

Sampling date	Replicate	M	SF	LS	IP	SP	FB	SB	W	Overall mean ($\bar{X}$) Standard error Variance (F)
	1	46.8	21.4	19.6	43.8	18.8	24.92	27.2	21.0	$\bar{X}$ = 28.63
18.7.78	2	49.0	25.9	19.6	33.6	32.2	23.1	25.9	22.4	S.E. = 5.76
	3	30.8	24.5	19.6	50.4	22.4	29.4	35.0	22.4	
	4	32.2	25.2	22.4	39.7	23.8	25.2	28.7	29.4	F = 9.24**
	Means	39.7	24.25	20.3	41.87	24.3	25.65	29.2	23.8	
	Variance	90.82	3.93	1.96	49.8	32.14	7.07	16.24	14.36	
	1	28.0	25.9	33.6	45.5	22.4	25.2	36.4	21.7	
25.7.78	2	42.0	31.5	28.0	42.7	32.9	28.0	33.6	30.8	$\bar{X}$ = 32.99
	3	33.6	26.6	23.8	42.0	29.4	32.2	37.8	28.0	S.E. = 7.76
	4	49.14	33.86	28.0	44.8	45.92	25.2	37.8	29.4	
	Means	38.18	29.47	28.35	43.75	32.65	27.65	36.4	27.47	F = 4.55**
	Variance	86.11	14.82	16.16	2.78	97.21	10.95	3.92	16.16	
	1	29.4	23.8	30.8	33.6	29.4	29.4	37.8	28.0	
2.8.78	2	40.2	34.02	40.6	36.4	40.2	36.54	32.2	29.82	$\bar{X}$ = 34.42
	3	42.0	34.44	26.6	44.8	45.92	27.02	36.54	33.6	
	4	36.4	2.77	35.0	39.4	37.3	37.8	29.4	35.0	S.E. = 6.78
	Means	37.0	29.99	33.25	38.55	38.33	32.69	33.98	31.6	
	Variance	31.13	26.52	35.76	22.94	47.05	27.98	15.13	10.56	F = 1.5 NS
	1	33.88	33.6	32.2	42.0	38.5	36.5	51.8	29.4	
7.8.78	2	33.6	30.8	28.0	46.2	43.4	32.2	33.6	30.8	$\bar{X}$ = 36.76
	3	36.8	40.6	40.6	47.6	45.1	32.56	45.5	36.4	
	4	35.7	29.54	33.6	42.0	40.6	34.3	37.1	42.0	S.E. = 4.53
	Means	34.99	33.63	33.6	44.45	41.9	23.89	37.0	34.65	
	Variance	2.31	24.4	30.69	8.35	8.58	3.88	36.96	33.17	F = 3.82**
	1	50.4	36.40	36.4	50.4	53.3	54.6	44.8	28.0	
9.8.78	2	37.66	26.6	36.4	71.4	42.0	36.3	42.0	33.6	$\bar{X}$ = 41.9
	3	46.2	39.2	32.2	68.6	40.6	28.0	36.4	32.2	
	4	60.9	42.0	28.7	56.0	49.0	32.2	37.8	30.8	S.E. = 13.94
	Means	48.79	36.05	33.42	61.6	46.22	37.20	40.25	31.15	
	Variance	93.31	44.89	13.83	100.6	35.76	137.3	14.89	5.71	F = 7.13**

Appendix 4: (cont.)

Sampling date	Replicate	ppm inorganic nitrogen in the top soil								Overall mean($\bar{X}$) Standard error (S.E.), Varianc ratio (F)
		M	SF	LS	IP	SP	FB	SB	W	
16.8.78	1	72.8	50.4	25.0	65.8	47.6	43.4	42.0	39.2	
	2	53.2	26.6	26.6	64.6	51.8	40.6	47.6	4	$\bar{X}$ = [illegible]
	3	54.2	29.4	35.7	64.3	61.6	35.0	39.0	35.4	
	4	38.5	45.5	28.0	64.5	56.7	29.4	39.9	32.2	S.E. = 14.28
	Means	54.67	37.97	28.82	64.8	54.42	37.10	42.12	35.8	
	Variance	197.4	138.06	22.46	0.46	36.72	38.56	14.69	8.35	F = 10.39**
22.8.78	1	42.0	29.26	35.14	72.8	56.0	37.66	43.4	35.0	
	2	43.4	43.4	23.8	57.26	60.34	30.8	42.0	30.8	$\bar{X}$ = 42.53
	3	44.8	36.4	35.0	43.54	42.0	36.4	43.4	29.4	
	4	52.2	61.6	44.8	39.2	53.2	36.4	37.8	42.0	S.E. = 19.58
	Means	45.6	42.66	34.69	53.2	52.88	35.32	41.65	34.30	
	Variance	20.70	192.65	73.61	230.12	61.30	9.42	7.02	32.03	F = 3.01*
4.9.78	1	89.6	42.0	44.8	84.0	71.4	39.2	64.6	46.2	
	2	60.2	42.0	39.2	117.6	53.2	40.6	47.6	40.6	$\bar{X}$ = 54.5
	3	68.6	57.4	37.8	71.4	63.0	49.0	53.2	53.2	
	4	49.0	45.6	39.2	51.8	39.2	44.8	49.0	49.0	S.E. = 44.38
	Means	66.85	47.13	40.25	81.2	56.7	43.4	53.6	47.25	
	Variance	294.4	53.29	9.61	764.5	191.54	19.62	59.44	27.87	F = 4.22**
11.9.78	1	57.4	49.0	36.4	65.8	65.8	50.4	64.6	44.8	
	2	46.2	56.0	42.0	50.4	50.4	42.0	44.8	53.2	$\bar{X}$ = 56.47
	3	84.0	68.6	42.0	70.0	77.0	37.9	54.6	43.4	
	4	53.2	75.6	78.4	98.0	62.0	42.7	50.4	49.0	S.E. = 44.22
	Means	60.2	62.30	49.70	71.05	63.8	43.75	53.6	47.6	
	Variance	263.4	144.4	372.87	393.62	120.34	21.06	69.80	19.62	F = 1.97**
3.10.78	1	75.6	53.2	49.0	123.2	79.8	56.0	85.4	40.6	
	2	82.6	60.2	38.5	106.4	84.0	74.2	59.5	49.0	$\bar{X}$ = 63.34
	3	56.0	52.5	35.0	67.2	86.8	51.8	56.7	46.2	
	4	49.0	77.7	44.8	63.0	44.1	51.8	78.4	49.0	S.E. = 63.36
	Means	65.8	60.90	41.62	89.95	73.67	58.45	70.0	46.2	
	Variance	252.17	137.59	39.32	873.3	387.2	116.52	198.2	15.68	F = 3.72**

Appendix 4: (cont.)

Sampling date	Replicate	ppm inorganic nitrogen in the top soil								Overall mean ($\bar{X}$) standard error (S.E.), Variance ratio (F)
		M	SF	LS	IP	SP	FB	SB	W	
19.10.78	1	43.4	53.2	46.2	55.3	44.8	33.6	53.2	43.4	
	2	49.0	64.4	35.0	78.4	42.0	49.0	47.6	50.4	$\bar{X}$ = 52.03
	3	44.8	39.2	51.8	56.0	72.8	67.2	28.0	33.6	
	4	64.4	43.4	39.2	78.4	68.6	56.0	42.0	50.4	S.E. = 31.24
	5	70.0	56.0	21.0	78.4	51.8	43.4	47.6	44.8	
	Means	54.32	55.24	38.64	69.3	56.0	49.84	43.68	44.52	
	Variance	146.41	313.29	138.76	155.25	194.04	161.29	92.54	47.47	F = 2.91*
26.10.78	1	47.6	46.2	40.6	51.8	42.0	49.0	58.8	25.2	
	2	81.2	56.0	36.8	42.0	51.8	78.4	47.6	60.2	$\bar{X}$ = 51.71
	3	32.2	44.8	36.4	69.3	42.0	44.8	78.4	57.4	
	4	64.4	49.0	49.0	73.5	64.4	57.4	50.4	36.4	S.E. = 48.63
	Means	56.35	49.0	40.7	59.15	50.05	57.4	58.8	44.8	
	Variance	447.32	24.80	34.22	219.04	112.78	223.5	193.48	283.5	F = 1.00^{NS}
30.11.78	1	37.8	36.4	36.4	36.4	30.8	50.4	40.6	36.4	
	2	68.6	37.8	39.2	63.0	40.6	42.0	53.2	37.8	$\bar{X}$ = 47.93
	3	75.6	46.2	36.4	46.2	58.8	39.2	79.8	32.2	
	4	82.6	36.4	37.3	100.8	44.8	49.0	43.4	37.8	S.E. = 53.37
	Means	66.15	39.20	37.3	61.6	43.75	45.15	54.25	36.05	
	Variance	389.88	22.18	1.74	803.6	35.5	29.26	319.33	7.022	F = 2.45*
6.12.78	1	35.0	22.4	28.0	33.6	23.8	28.0	25.0	37.8	
	2	42.0	26.6	26.6	28.0	23.8	28.0	35.0	32.3	$\bar{X}$ = 31.24
	3	49.0	23.8	28.0	32.2	26.6	36.4	23.8	23.8	
	4	49.0	39.2	25.6	28.0	40.6	32.2	42.0	23.8	S.E. = 9.875
	Means	43.75	28.0	27.05	30.45	28.70	31.15	31.45	29.4	
	Variance	44.89	58.82	1.36	8.35	64.64	16.16	74.64	47.05	F = 2.82*
21.12.78	1	36.4	30.8	23.8	32.2	32.2	23.8	29.4	21.0	
	2	33.6	23.8	25.2	33.6	21.0	21.0	21.0	26.6	$\bar{X}$ = 28.32
	3	33.6	29.4	26.6	32.2	32.2	28.0	29.4	22.4	
	4	33.6	26.6	24.5	37.8	36.4	22.4	33.6	22.4	S.E. = 3.33
	Means	34.30	27.65	25.02	33.95	30.45	23.80	28.35	23.1	
	Variance	1.96	9.61	1.44	7.02	43.56	9.12	27.87	5.65	F = 5.62**

Appendix 4: (cont.)

Sampling date	Replicate	ppm inorganic nitrogen in the top soil								Overall mean ($\bar{X}$) standard error (S.E.), Variance ratio (F)
		M	SF	LS	IP	SP	FB	SB	W	
4.1.79	1	21.0	16.8	15.6	28.0	21.0	18.2	23.8	15.6	$\bar{X}$ = 21.75
	2	33.6	19.6	16.8	22.4	25.2	16.8	18.2	28.0	
	3	22.4	21.0	19.6	25.2	22.4	19.6	21.0	21.0	
	4	29.4	21.0	19.6	22.4	28.0	22.4	19.6	21.0	S.E. = 3.04
	Means	26.60	19.60	17.90	24.50	24.15	19.25	20.65	21.40	F = 3.0*
	Variance	35.28	3.92	4.08	7.18	9.61	5.71	5.71	25.60	
11.1.79	1	29.4	15.62	19.6	22.4	23.8	23.8	21.0	16.8	
	2	22.4	16.8	19.6	22.4	28.0	18.2	16.8	18.2	$\bar{X}$ = 20.56
	3	19.6	19.6	16.8	26.6	21.0	18.2	19.6	16.8	
	4	16.8	19.6	18.2	28.0	25.2	22.4	18.2	16.8	S.E. = 2.0
	Means	22.05	17.90	18.55	24.85	24.5	20.65	18.9	17.15	
	Variance	29.26	4.08	1.79	8.35	8.46	8.35	3.27	0.49	F = 4.4**
19.1.79	1	19.6	21.0	25.2	26.6	28.0	21.0	15.62	21.0	
	2	25.2	18.2	14.0	29.4	19.6	22.4	19.6	21.0	$\bar{X}$ = 23.36
	3	25.2	25.2	23.8	35.0	22.4	25.2	22.4	26.6	
	4	32.2	21.0	21.0	30.8	21.0	19.6	22.4	26.6	S.E. = 3.52
	Means	25.55	21.35	21.0	30.45	22.75	22.05	20.0	23.8	
	Variance	26.62	9.12	24.80	12.25	13.54	5.71	10.30	10.43	F = 3.16*
26.1.79	1	36.4	25.2	14.0	28.0	25.2	22.4	22.4	26.6	
	2	29.6	28.0	22.4	36.4	25.2	22.4	25.2	22.4	$\bar{X}$ = 25.99
	3	28.0	25.2	25.2	36.4	22.4	19.6	22.4	22.4	
	4	39.2	25.2	22.4	39.2	25.2	25.2	19.6	22.4	S.E. = 2.95
	Means	33.3	25.9	21.0	35.0	24.50	22.40	22.41	23.45	
	Variance	28.72	1.96	23.52	23.52	1.96	5.24	5.24	4.41	F = 9.38**
2.2.79	1	22.4	25.2	22.4	22.4	22.4	16.8	22.4	22.4	
	2	16.8	16.8	22.4	25.2	19.6	22.4	19.6	25.2	$\bar{X}$ = 21.72
	3	16.8	22.4	19.6	25.2	25.2	19.6	19.6	22.4	
	4	17.8	16.8	25.2	33.6	21.2	20.6	19.6	25.2	S.E. = 2.16
	Means	18.45	20.3	22.4	26.6	22.1	19.85	20.31	23.8	
	Variance	7.18	17.64	5.24	23.52	5.56	5.47	1.96	2.62	F = 3.10*

Appendix 4: (cont.)

Sampling date	Replicate	ppm ino:ganic nitrogen in the top soil								Overall mean ($\bar{X}$) Standard error (S.E.), Variance ratio (F)
		M	SF	LS	IP	SP	FB	SD	W	
7.2.79	1	25.2	16.8	14.0	22.4	22.4	19.6	16.8	19.6	
	2	22.4	11.2	14.0	22.4	14.0	14.0	11.2	16.8	$\bar{X}$ = 17.85
	3	14.0	14.2	11.2	19.6	19.6	19.6	22.4	19.6	
	4	16.8	16.8	19.6	16.8	19.6	16.8	22.4	19.6	S.E. = 3.22
	Means	19.6	14.7	14.70	20.30	18.90	17.50	18.20	18.9	
	Variance	26.11	7.18	12.39	7.182	12.39	7.18	28.72	1.96	F = 1.39^{NS}
9.2.79	1	13.7	16.8	25.2	22.4	22.4	19.6	16.8	19.6	
	2	19.6	16.8	19.6	25.2	25.2	22.4	16.8	22.4	$\bar{X}$ = 21.19
	3	22.4	19.6	25.2	25.2	19.6	22.4	22.4	22.4	
	4	25.2	16.8	16.8	28.0	19.6	19.6	19.6	22.4	
	Means	21.72	17.5	21.71	25.2	21.85	21.0	18.9	21.7	
	Variance	7.07	1.96	17.64	5.24	7.18	2.62	7.18	1.96	F = 3.24*

NS - Calculated F value not significantly greater than the table F value.

* - Calculated F value significantly greater than the table F value at only 5% level.

** - Calculated F value significantly greater than the table F value at both the 5% and 1% levels.

Appendix 5a. Soil moisture at a depth of 0 - 10 cm under the eight crops through three growing seasons 1977/78

Sampling date	Percentage moisture content of the soil (oven dry weight basis)								Means
	M	SF	LS	W	FB	SB	SP	IP	
3.8.77	30.33	39.3	26.07	23.68	28.77	24.11	27.92	23.32	26.68
5.8.77	27.82	29.42	24.97	24.01	23.54	24.83	23.92	23.12	25.20
8.8.77	38.13	37.15	35.84	36.12	35.57	34.33	37.56	29.[illegible]	35.[illegible]
10.8.77	37.10	37.56	36.47	32.85	36.02	33.89	37.29	34.57	35.71
12.8.77	36.77	33.01	32.03	30.1	33.01	30.32	34.26	30.33	33.12
15.8.77	30.43	28.55	25.36	28.74	28.28	26.39	31.00	29.18	28.55
18.8.77	41.56	39.06	37.19	38.02	39.39	38.31	39.71	39.56	39.10
25.8.77	31.46	28.11	25.43	30.47	27.02	26.42	32.32	28.31	28.69
31.8.77	25.63	26.30	20.34	26.49	22.27	25.84	24.62	25.45	24.61
7.9.77	25.25	21.63	20.57	21.86	20.18	22.23	24.31	19.16	21.97
13.9.77	19.51	19.49	18.61	19.5	23.87	18.82	25.33	18.98	20.51
20.9.77	23.69	27.51	25.82	23.44	22.13	21.74	24,38	22.9	23.95
22.9.77	26.98	29.70	25.41	28.04	26.31	25.55	29.2	26.85	27.25
27.9.77	22.83	21.91	20.34	21.98	21.05	20.54	22.78	21.48	21.61
4.10.77	19.65	16.59	19.45	19.00	16.59	17.86	19.43	20.31	18.61
12.10.77	21.07	17.02	18.36	23.29	21.23	25.15	20.57	21.24	20.99
21.10.77	25.26	21.72	24.83	23.67	21.53	22.93	22.68	23.94	23.32
2.2.78	28.05	31.87	25.03	26.34	27.19	25.08	30.03	25.44	27.37
7.2.78	27.46	25.59	25.52	35.55	22.39	24.85	21.69	21.68	25.59
14.2.78	21.32	21.14	22.57	22.57	22.61	20.99	19.89	19.21	21.28
16.2.78	21.72	20.12	22.2	21.7	20.58	19.70	22.14	19.6	20.97
23.2.78	39.3	38.48	39.45	40.77	40.35	38.7	38.80	39.78	39.45
1.3.78	27.96	32.85	26.78	30.59	24.56	31.93	27.07	28.0	28.71
7.3.78	25.15	27.08	24.59	23.17	21.77	22.8	23.62	24.04	24.02
9.3.78	26.78	22.86	25.59	25.83	25.50	25.40	26.89	22.43	25.16
14.3.78	45.49	42.40	43.8	40.81	39.05	43.65	40.95	46.18	42.79
22.3.80	39.37	40.23	37.46	40.18	37.91	39.86	36.91	40.26	39.02
12.6.78	24.28	26.74	21.54	19.72	23.30	22.99	24.51	25.94	23.62
19.6.78	25.69	26.90	25.73	25.99	23.05	23.53	24.71	26.86	25.30
21.6.78	23.74	23.87	26.67	22.92	23.53	22.05	24.19	23.04	23.75
26.6.78	21.86	22.56	22.04	21.60	18.72	21.10	23.66	22.03	21.69
3.7.78	29.93	24.83	25.16	24.21	24.25	25.85	28.72	25.21	26.02
5.7.78	25.33	26.91	25.73	25.53	22.92	25.45	27.28	25.43	25.57
10.7.78	24.20	28.09	21.49	20.96	22.7	23.13	24.7	21.88	23.39
19.7.78	26.13	23.12	23.46	21.50	21.30	23.44	25.89	23.42	23.53
Means	28.20	27.85	26.36	26.89	25.95	26.29	27.68	26.25	26.93

Appendix 5b. Soil moisture at a depth of 10 - 20 cm under the eight crops through three growing seasons 1977/78

Sampling date	Percentage moisture content of the soil (oven dry weight basis)								Means
	M	SP	LS	W	FB	SB	SF	IP	
3.8.77	30.37	30.86	26.69	26.32	34.86	31.25	31.17	30.21	30.26
5.8.77	31.45	30.12	27.37	28.50	28.16	29.10	29.49	27.77	28.99
8.8.77	34.92	37.38	29.45	35.81	34.13	33.63	37.24	34.04	34.57
10.8.77	35.92	37.10	32.49	26.43	30.91	35.70	35.81	32.[illegible]	33.34
12.6.77	32.58	38.64	32.55	29.55	31.34	31.74	28.72	29.21	31.79
15.8.77	31.94	33.22	28.66	30.06	28.31	29.11	31.30	31.83	30.55
18.8.77	37.00	35.0	28.51	38.03	34.93	36.48	38.20	36.88	35.63
25.8.77	33.06	30.06	26.76	34.32	29.67	30.37	34.82	32.55	31.45
31.8.77	28.15	29.55	23.27	31.24	26.74	28.62	31.21	26.83	28.20
7.9.77	29.53	26.88	19.75	19.70	26.64	24.2	27.14	21.57	24.42
13.9.77	23.72	25.50	17.02	18.99	16.45	21.84	28.28	25.27	22.13
20.9.77	25.74	25.71	23.91	25.03	25.53	28.32	25.88	26.33	22.29
22.9.77	28.17	27.27	25.23	22.44	27.77	26.35	31.04	28.66	27.11
27.9.77	25.20	22.79	21.37	22.07	23.37	23.27	26.56	23.01	23.45
4.10.77	21.87	25.29	20.00	16.95	15.40	24.51	20.90	22.46	20.92
12.10.77	24.52	24.25	19.44	23.57	23.5	23.58	20.30	20.90	22.50
21.10.77	25.03	24.47	24.19	23.87	21.68	24.47	23.04	25.77	24.06
2.2.78	28.22	33.65	29.57	28.66	29.51	25.22	32.60	28.75	29.52
7.2.78	28.44	26.26	27.30	25.32	26.34	19.84	22.24	25.90	25.20
14.2.78	22.39	22.94	26.94	23.63	21.17	23.0	22.59	23.30	23.24
16.2.78	21.44	23.9	19.10	16.70	23.36	21.32	21.38	21.66	21.10
23.2.78	32.39	34.05	35.73	32.60	34.79	34.82	30.08	35.77	33.77
1.3.78	31.76	29.11	29.32	29.76	30.19	33.43	31.31	29.24	30.51
7.3.78	25.81	27.20	25.99	25.28	26.39	25.13	26.89	31.80	26.89
9.3.78	27.39	26.79	26.92	26.61	26.54	27.85	29.14	27.51	27.34
14.3.78	45.46	42.56	41.63	38.03	42.16	42.54	43.15	44.68	42.53
22.3.78	43.87	40.53	35.97	41.11	39.69	39.82	40.99	42.77	40.60
12.6.78	25.59	24.06	31.58	21.44	23.99	24.82	28.13	26.69	24.53
19.6.78	26.49	30.37	25.52	24.21	23.74	28.75	25.69	28.12	26.61
21.6.78	26.68	25.08	25.08	22.93	20.84	23.48	27.09	23.61	24.44
26.6.78	22.63	19.55	22.03	22.37	19.68	24.95	23.36	24.51	22.38
3.7.78	32.25	27.39	25.75	25.08	26.4	25.44	28.07	27.34	27.37
5.7.78	26.98	28.84	25.69	26.75	26.39	25.86	28.11	26.00	26.82
10.7.78	28.38	28.76	23.09	21.89	23.7	24.75	26.33	22.41	24.91
19.7.78	28.57	21.78	24.94	21.65	19.43	23.87	28.79	26.13	24.39
Means	29.26	29.35	26.25	26.38	26.78	27.95	29.05	28.34	27.82

Appendix 5c. Soil moisture at a depth of 20 - 30 cm under the eight crops through three growing seasons 1977/78

Sampling date	Percentage moisture content of the soil (oven dry weight basis)								Means
	M	BP	LS	W	FB	SB	SP	TP	
3.8.77	32.50	32.86	29.37	30.52	34.06	33.65	31.30	31.56	31.97
5.8.77	32.40	31.86	28.20	29.84	30.8	26.52	31.27	28.92	29.97
8.8.77	32.19	31.57	28.46	30.69	34.02	33.51	31.57	31.71	31.71
10.8.77	31.63	30.73	29.52	29.97	33.14	34.11	32.63	32.8	31.81
12.8.77	32.14	[illegible]	29.41	30.02	32.49	32.53	32.11	32.76	31.87
15.8.77	31.72	32.86	27.41	29.85	30.40	30.81	30.24	33.72	30.87
18.8.77	32.64	35.10	30.39	33.74	31.05	34.47	34.54	35.20	33.41
25.8.77	32.40	31.12	28.93	31.15	31.44	32.31	33.68	32.36	31.67
31.8.77	30.50	30.28	26.93	32.96	29.84	36.08	31.67	31.88	31.26
7.9.77	30.70	31.74	26.12	26.86	30.41	34.0	30.45	31.61	30.23
13.9.77	30.80	25.74	20.78	25.69	24.81	30.46	29.09	29.83	27.15
20.9.77	27.10	28.27	25.54	27.22	29.16	31.50	29.16	30.83	28.59
22.9.77	30.76	29.72	25.94	27.48	29.57	32.57	30.49	31.21	29.71
27.9.77	30.56	26.83	24.90	25.95	27.46	25.88	26.28	28.47	27.29
4.10.77	27.57	26.75	22.99	23.18	20.10	27.00	26.62	31.14	25.66
12.10.77	29.27	25.94	25.91	28.27	28.0	25.87	24.72	28.35	27.04
21.10.77	26.30	24.43	26.82	26.95	26.32	28.44	25.81	32.11	27.14
2.2.78	32.47	35.36	36.38	33.55	33.43	26.80	33.37	35.96	33.41
7.2.78	31.39	26.95	32.80	26.65	27.22	30.64	21.85	31.10	28.57
14.2.78	31.11	28.10	28.84	29.33	31.87	29.73	28.71	30.52	29.77
16.2.78	24.08	28.01	19.91	21.02	28.34	23.87	28.32	26.33	24.98
23.2.78	32.12	29.62	36.05	31.11	37.22	24.64	29.67	30.75	31.39
1.3.78	28.56	28.35	27.92	32.84	32.11	29.26	30.18	36.18	30.69
7.3.78	27.03	28.27	24.73	29.38	33.89	29.86	31.51	35.11	29.97
9.3.78	28.96	27.97	29.44	30.32	34.37	31.12	29.16	31.35	30.33
14.3.78	44.22	41.60	41.75	40.61	39.45	41.23	41.56	45.24	41.97
22.3.78	40.80	39.11	38.89	39.93	39.45	39.48	40.18	39.93	39.72
12.6.78	29.59	31.09	29.18	23.88	27.17	31.34	32.05	30.34	29.33
19.6.78	31.09	33.17	28.78	27.52	30.20	31.08	30.64	31.44	30.49
21.6.78	31.00	29.48	27.99	26.53	32.28	28.05	30.67	38.70	29.33
26.6.78	27.14	23.09	26.91	25.94	24.00	28.93	30.35	30.50	27.10
3.7.78	32.36	28.62	26.73	26.25	27.77	31.44	28.63	28.17	28.75
5.7.78	29.48	30.11	26.72	28.29	29.41	30.28	30.45	27.47	29.02
10.7.78	31.06	30.04	26.25	25.46	26.89	28.55	28.93	25.98	27.89
19.7.78	30.13	27.14	27.38	25.09	25.05	26.72	28.86	29.20	27.44
Means	30.97	30.15	28.40	29.23	30.37	30.64	30.53	31.67	30.21

Appendix 5d. Soil moisture at a depth of 30 - 50 cm under the eight crops through three growing seasons 1977/78

Sampling date	Percentage moisture content of the soil (oven dry weight basis)								Means
	M	SF	LS	W	FB	SB	SP	IF	
3.8.77	32.61	31.34	29.83	32.46	35.83	35.62	32.42	35.82	33.24
5.8.77	32.50	30.51	28.30	31.65	34.07	34.37	31.60	35.17	32.27
8.8.77	34.02	31.06	29.47	31.61	34.13	35.23	31.75	35.27	32.82
10.8.77	31.92	31.32	29.77	32.51	34.74	36.26	32.27	35.92	33.08
12.8.77	32.29	31.51	29.72	32.34	34.5	35.30	32.47	34.59	32.82
15.8.77	31.51	31.85	29.45	31.82	33.23	32.40	31.33	35.58	32.14
18.8.77	31.37	31.45	30.46	31.00	33.49	33.76	31.65	34.44	32.30
25.3.77	32.20	30.17	31.19	31.88	33.75	32.43	31.70	32.43	31.56
31.6.77	30.11	30.41	27.79	33.24	33.80	34.61	30.12	34.75	31.85
7.9.77	31.60	31.13	27.93	30.15	32.95	31.91	29.88	33.26	31.10
13.9.77	31.14	28.02	26.9	27.29	29.03	30.88	28.99	31.17	29.17
20.9.77	31.66	31.43	27.56	29.01	30.76	-	30.02	33.14	30.51
22.9.77	30.97	29.73	27.0	28.53	30.01	34.38	30.79	34.38	30.75
29.9.77	30.06	28.05	26.03	27.30	29.91	28.78	29.07	31.23	28.80
4.10.77	29.03	27.60	26.69	28.02	27.83	28.21	28.42	28.96	28.05
12.10.77	31.38	26.53	26.94	27.85	31.50	28.03	25.89	30.49	28.57
21.10.77	31.92	27.01	29.77	29.00	31.87	31.30	28.22	33.08	30.26
2.2.78	35.08	34.77	37.61	34.00	37.20	35.13	35.93	38.49	36.02
7.2.78	34.40	32.37	35.27	32.61	35.78	31.83	31.93	34.77	33.62
14.2.78	34.51	29.76	32.78	32.58	34.56	31.75	30.57	35.73	32.78
16.2.78	24.35	28.54	33.01	30.75	36.94	30.13	28.17	35.66	30.94
23.2.78	32.25	29.72	35.58	33.45	35.58	33.44	40.37	36.23	34.57
1.3.78	32.19	29.72	32.85	31.11	35.35	31.22	33.05	37.38	32.85
7.3.78	30.26	29.51	29.18	30.93	35.78	32.00	31.22	35.61	31.84
9.3.78	29.57	29.73	30.93	33.00	34.53	31.03	28.26	33.60	31.33
14.3.78	31.14	39.64	37.21	33.82	37.69	36.94	41.29	44.31	37.75
22.3.78	39.93	39.90	39.45	38.95	39.29	38.62	39.88	39.93	39.49
12.6.78	34.36	33.25	33.12	31.19	34.19	33.47	34.96	34.15	33.56
19.6.78	34.34	32.89	31.85	29.77	33.72	33.19	34.92	34.69	33.17
21.6.78	33.39	30.31	24.50	28.92	32.29	31.38	33.03	31.75	30.69
26.6.78	25.48	28.11	28.68	30.71	28.00	30.93	29.99	33.01	29.36
3.7.78	33.87	30.43	27.79	27.66	31.27	31.46	30.87	30.50	30.48
5.7.78	32.33	31.65	28.41	31.64	29.58	31.70	31.60	28.90	30.75
10.7.73	33.96	30.16	29.61	26.84	29.10	30.87	30.67	30.99	30.13
19.7.78	31.42	30.43	29.53	28.50	29.52	29.95	27.91	30.85	29.76
Means	31.97	30.86	30.31	30.91	33.19	32.60	31.74	34.17	31.96

Appendix 5e. Soil moisture at a depth of 50 - 70 cm under the eight crops through three growing seasons 1977/78

Sampling date	Percentage moisture content of the soil (oven dry weight basis)								Means
	M	SB	LS	W	FB	SF	SP	IP	
3.8.77	32.60	36.69	31.52	34.30	37.05	33.39	33.40	36.89	34.56
5.8.77	32.73	37.25	29.40	33.58	35.51	30.94	32.98	35.80	33.52
8.8.77	34.46	37.23	30.87	33.21	35.00	31.57	31.68	35.98	33.81
10.8.77	32.47	35.69	30.78	34.63	37.00	32.04	31.99	35.33	33.74
12.8.77	33.66	36.01	30.40	35.10	37.24	32.13	33.33	35.[illegible]	34.22
15.8.77	32.48	34.08	31.12	33.99	34.60	31.79	32.24	36.35	33.33
18.8.77	31.54	34.22	31.68	33.26	34.12	31.42	32.52	34.34	32.88
25.8.77	32.56	35.21	31.18	33.97	35.79	30.14	32.31	34.30	33.18
31.8.77	29.46	34.81	30.38	34.49	34.60	31.04	31.86	36.56	32.90
7.9.77	32.73	31.91	28.70	33.11	34.12	31.66	30.44	35.26	32.24
13.9.77	30.84	34.46	27.57	29.97	30.46	30.39	30.13	32.54	30.79
20.9.77	32.00	33.56	29.06	31.66	27.84	31.29	30.40	34.29	31.26
22.9.77	32.08	35.44	30.07	30.22	33.08	29.96	31.93	35.82	32.32
27.9.77	31.98	31.58	29.10	27.83	32.39	31.45	30.03	34.61	31.12
4.10.77	30.25	27.12	28.67	28.92	30.00	27.62	29.07	34.12	29.47
12.10.77	31.10	29.46	31.19	30.28	35.50	26.77	27.90	31.82	30.50
21.10.77	30.19	32.80	31.14	29.88	32.43	29.59	29.50	34.16	31.21
2.2.78	36.02	36.10	38.33	35.98	37.00	36.05	36.39	38.31	36.77
7.2.78	35.54	32.80	36.55	33.80	36.00	34.25	34.63	36.84	35.05
14.2.78	34.24	33.93	33.87	32.90	34.28	30.56	29.72	38.44	33.49
16.2.78	30.10	30.03	33.50	32.31	33.68	29.71	30.41	35.35	31.88
23.2.78	32.35	31.96	34.50	35.9	36.65	30.15	31.38	36.43	33.66
1.3.78	34.69	38.41	33.09	34.94	35.08	30.62	29.88	39.59	34.53
7.3.78	26.79	32.34	27.27	32.08	35.97	30.08	32.66	36.03	31.65
9.3.78	31.16	31.79	31.08	33.89	35.92	30.24	29.56	34.59	32.27
14.3.78	30.91	32.19	33.46	30.23	38.70	29.70	32.47	40.75	33.55
22.3.78	38.49	37.73	36.03	40.28	39.23	40.26	38.05	41.31	38.92
12.6.78	36.15	35.65	37.69	32.56	40.33	34.31	36.51	37.50	36.33
19.6.78	35.12	36.62	32.80	31.65	37.00	35.12	36.10	36.02	35.05
21.6.78	35.75	32.10	30.09	34.10	34.15	31.29	34.93	34.82	33.40
26.6.78	30.43	31.87	29.45	30.61	33.18	29.09	33.69	35.58	31.73
3.7.78	35.26	35.07	29.35	32.03	30.92	31.35	32.59	34.12	32.58
5.7.78	32.22	33.32	29.45	32.62	34.35	32,29	33.92	33.59	32.72
10.7.78	35.11	35.85	30.74	28.81	31.37	30.72	32.06	33.11	32.22
19.7.78	31.91	33.64	30.60	31.33	32.15	32.15	31.78	33.36	32.11
Means	32.73	33.96	31.44	32.71	34.64	31.46	32.24	35.70	33.11

Appendix 5f. Soil moisture at a depth of 70 - 90 cm under the eight crops through three growing seasons 1977/78

Sampling date	Percentage moisture content of the soil (oven dry weight basis)								Means
	M	SF	LS	W	FB	SB	SP	IP	
3.8.77	33.41	33.59	36.65	35.22	40.15	37.37	33.82	38.06	36.04
5.8.77	32.32	31.40	35.40	35.00	36.84	36.47	33.29	36.57	34.67
8.8.77	33.98	31.94	35.97	35.07	37.01	38.03	33.62	37.47	35.38
10.8.77	33.23	33.42	33.02	36.49	38.40	38.71	33.98	37.55	35.60
12.8.77	33.63	32.27	33.21	36.26	38.97	38.05	32.99	36.76	35.26
15.8.77	32.76	32.30	33.24	35.25	35.67	36,29	32.79	36.62	34.36
18.8.77	31.95	32.48	34.15	34.88	35.18	34.96	32.24	35.16	33.67
25.8.77	33.41	31.33	35.13	34.72	36.82	36.43	32.34	34.02	34.27
31.8.77	30.53	31.68	31.81	34.60	36.37	35.88	32.08	35.59	33.56
7.9.77	32.90	32.27	33.34	34.60	35.82	35.78	32.52	35.04	34.03
13.9.77	30.99	31.59	30.34	34.12	32.04	35.04	30.41	34.31	32.35
20.9.77	32.99	33.62	34.04	35.81	33.01	36.21	30.65	35.97	34.03
22.9.77	32.14	31.58	34.67	35.98	35.83	36.36	32.24	37.38	34.52
27.9.77	33.62	32.07	32.24	32.10	33.30	33.05	29.66	33.99	32.50
4.10.77	30.75	28.77	31.16	31.52	31.62	33.32	28.20	34.22	31.19
12.10.77	31.87	27.78	29.88	30.30	36.00	31.35	26.82	32.14	30.76
21.10.77	30.23	27.42	33.35	30.63	32.70	33.24	29.7	34.48	31.46
2.2.78	37.06	36.52	37.62	36.47	38.20	36.93	37.08	38.08	37.24
7.2.78	34.54	35.73	35.56	38.02	37.21	35.01	36.29	37.04	36.17
14.2.78	35.62	30.56	35.40	35.11	36.26	35.69	33.03	36.95	34.82
16.2.78	32.31	32.62	32.74	34.41	36.78	32.3	32.01	37.51	33.83
23.2.78	34.47	30.31	35.73	36.16	38.33	34.15	32.63	38.18	34.99
1.3.78	33.07	31.62	34.67	34.84	40.64	32.14	32.09	36.85	34.49
7.3.78	28.50	30.69	32.60	35.94	36.57	33.61	33.78	36.02	33.39
9.3.78	30.96	31.05	31.56	35.20	35.81	33.85	31.48	35.36	33.15
14.3.78	30.29	30.40	33.19	29.62	39.01	33.39	33.75	36.83	33.31
22.3.78	33.28	36.82	35.32	36.45	38.74	33.95	34.21	39.72	36.06
12.6.78	36.80	34.18	35.44	35.27	37.60	36.92	37.71	38.71	36.57
19.6.78	37.44	36.07	38.07	33.75	36.88	37.33	37.70	36.99	36.77
21.6.78	37.03	35.54	35.02	34.70	36.38	34.88	35.50	37.10	35.76
26.6.78	30.46	27.26	32.30	33.66	35.34	35.90	35.44	38.77	33.64
3.7.78	36.24	32.70	31.46	33.90	35.04	34.50	33.37	36.33	34.19
5.7.78	34.12	32.22	33.36	34.48	35.98	34.32	34.38	35.54	34.30
10.7.78	37.11	29.23	33.66	32.44	36.2	34.31	33.49	36.76	34.15
19.7.78	33.72	32.85	31.45	32.57	34.92	34.31	32.68	36.32	33.60
Means	33.24	32.05	33.79	34.44	36.33	35.12	32.97	36.41	34.29

Appendix 5g. Soil moisture at a depth of 90 - 120 cm under the eight crops through three growing seasons 1977/78

Sampling date	Percentage moisture content of the soil (oven dry weight basis)								Means
	M	SF	LS	W	FB	SB	SP	IP	
3.8.77	33.41	34.52	38.28	35.32	39.11	39.58	37.63	38.75	37.07
5.8.77	35.56	34.42	36.96	36.99	40.45	34.50	34.48	36.95	36.26
8.8.77	34.0	32.76	37.11	38.04	37.55	37.93	33.77	38.55	36.21
10.8.77	35.74	33.97	37.83	37.64	37.83	38.59	34.14	37.63	36.67
12.8.77	35.01	32.70	36.45	36.77	38.24	38.64	34.98	37.98	36.34
15.8.77	33.39	33.29	35.71	34.43	35.72	36.42	33.64	37.05	34.95
18.8.77	33.40	33.15	37.35	36.49	35.47	35.95	34.65	36.22	35.33
25.8.77	33.14	29.54	34.72	35.09	37.52	37.24	34.98	35.33	34.69
31.8.77	32.35	31.89	34.88	36.34	37.53	35.09	34.74	36.75	34.94
7.9.77	32.07	32.61	37.11	35.35	35.71	-	30.0	35.31	34.02
13.9.77	31.33	29.26	35.27	34.20	31.29	35.02	30.60	36.82	32.97
20.9.77	30.33	34.79	34.68	38.69	33.39	37.27	31.13	35.72	34.50
22.9.77	31/76	32.33	34.87	35.00	35.36	38.04	33.63	37.47	34.80
27.9.77	33.35	29.96	35.28	29.73	33.87	34.35	28.77	35.87	32.64
4.10.77	29.88	30.30	33.40	33.91	32.74	34.25	29.55	35.29	32.41
12.10.77	31.73	27.06	35.43	33.98	35.28	31.53	26.84	34.41	32.03
21.10.77	31.22	30.42	35.73	33.53	36.07	33.38	30.58	34.41	33.16
2.2.78	38.94	37.98	39.04	37.38	38.45	37.60	38.15	38.87	38.30
7.2.78	36.23	34.84	38.89	37.73	38.59	35.82	37.38	38.27	37.21
14.2.78	34.81	30.37	36.06	37.91	37.88	35.53	34.41	37.50	35.55
16.2.78	34.60	33.00	34.05	34.60	40.27	34.86	31.96	37.55	35.11
23.2.78	32.18	32.41	36.88	37.98	23.21	31.82	32.46	38.25	34.52
1.3.78	30.37	30.71	36.93	35.40	41.24	34.42	34.05	40.17	35.41
7.3.78	29.90	31.95	35.36	35.94	35.19	33.98	35.15	37.98	34.43
9.3.78	31.86	31.37	34.89	37.47	37.43	36.06	31.62	37.81	34.81
14.3.78	28.21	32.57	34.11	31.79	37.11	34.69	32.34	38.99	33.72
22.3.78	33.92	37.46	37.64	38.61	38.71	35.79	33.64	38.93	36.83
12.6.78	38.37	34.94	37.62	34.94	38.32	37.49	37.21	33.71	36.57
19.6.78	37.68	36.07	38.05	35.6	35.76	39.36	36.19	36.43	36.89
21.6.78	35.56	32.40	35.81	33.18	32.32	35.26	35.94	37.37	34.73
26.6.78	32.45	30.72	33.56	35.00	34.79	34.43	35.60	36.66	34.15
3.7.78	36.60	34.18	32.81	35.36	34.99	35.12	34.96	35.55	34.94
5.7.78	36.99	34.69	34.96	36.29	37.05	36.23	35.01	35.57	35.84
10.7.78	37.77	29.81	33.98	34.26	35.57	37.12	36.6	35.26	35.04
19.7.78	33.68	35.66	34.22	35.00	35.41	34.55	32.90	34.88	34.53
Means	33.65	32.68	35.88	35.59	36.46	35.82	33.70	36.86	35.07

Appendix 5h. Soil moisture at a depth of 120 - 150 cm under the eight crops through three growing seasons 1977/78

Sampling date	Percentage moisture content of the soil (oven dry weight basis)								Means
	M	SF	LS	W	FB	SB	SP	IP	
3.8.77	36.69	37.53	37.32	37.18	39.65	39.88	37.25	38.64	38.01
5.8.77	35.77	33.0	35.69	37.16	39.40	38.35	35.10	37.05	36.44
8.8.77	35.42	33.22	38.0	37.25	37.35	37.27	34.96	39.84	36.66
10.8.77	35.74	34.72	38.07	37.04	38.32	38.47	36.54	36.85	36.96
12.8.77	35.5	33.61	36.90	37.0	38.10	38.47	36.30	37.31	36.64
15.8.77	35.31	33.72	37.27	35.55	36.03	36.34	35.51	37.39	35.89
18.8.77	34.61	34.69	36.25	36.38	36.03	36.25	35.87	36.28	35.79
25.8.77	33.47	31.22	35.93	36.47	37.48	36.28	35.85	35.84	35.31
31.8.77	32.93	33.79	35.76	35.75	38.32	36.30	35.57	36.87	35.65
7.9.77	32.3	30.90	36.0	35.60	36.41	34.34	31.80	35.35	34.08
13.9.77	33.04	30.43	34.54	34.38	33.26	34.99	31.24	35.35	33.40
20.9.77	33.50	34.42	34.99	38.96	33.44	36.54	31.95	35.64	34.93
22.9.77	33.0	31.66	34.89	34.75	36.01	34.84	31.73	36.25	34.14
27.9.77	31.91	31.37	34.57	30.62	30.79	35.49	31.30	33.86	32.48
4.10.77	30.19	29.32	33.11	34.39	33.35	34.53	29.92	34.85	32.45
12.10.77	33.02	29.81	35.13	36.30	36.50	31.55	27.39	35.0	33.08
21.10.77	31.97	31.61	36.27	35.11	35.14	34.78	29.91	36.06	33.85
2.2.78	37.69	37.85	37.60	36.91	37.18	36.55	38.28	38.25	37.53
7.2.78	35.79	35.51	38.00	37.22	37.49	36.05	37.80	39.78	37.20
14.2.78	35.30	28.71	35.53	36.06	36.54	32.90	32.42	37.27	34.34
16.2.78	33.70	34.95	34.76	34.7	38.64	34.55	33.32	35.20	34.97
23.2.78	32.13	29.38	36.48	35.91	36.06	31.97	33.34	36.15	33.92
1.3.78	32.64	32.08	36.44	34.61	41.03	35.35	35.20	36.59	35.49
7.3.78	28.58	31.49	34.48	33.41	35.27	36.92	32.53	35.34	33.50
9.3.78	34.46	32.38	34.59	37.57	37.54	35.39	33.78	36.97	35.33
14.3.78	29.10	32.22	34.05	32.10	35.94	33.93	33.97	36.01	33.54
22.3.78	35.72	35.43	37.60	37.73	38.52	34.82	31.39	37.48	36.08
12.6.78	37.87	36.18	37.03	36.23	36.89	36.83	36.93	36.82	36.84
19.6.78	35.27	36.73	35.38	39.15	33.01	36.77	36.23	38.08	36.32
21.6.78	36.53	29.78	35.21	33.95	36.77	35.64	36.19	38.00	35.25
26.6.78	34.14	31.53	32.65	33.9	34.44	33.07	36.97	36.46	34.14
3.7.78	35.85	34.78	33.73	36.14	34.98	36.15	34.95	36.81	35.42
5.7.78	35.93	37.21	35.26	36.38	36.64	37.09	35.45	35.54	36.18
10.7.78	35.39	31.44	35.89	33.96	35.48	37.42	36.3	35.89	35.09
19.7.78	33.35	34.75	33.11	34.53	34.95	34.45	32.98	35.23	34.23
Means	34.12	33.06	35.67	35.71	36.39	35.72	34.17	36.58	35.17

Appendix 5i. Soil moisture at a depth of 150 - 180 cm under the eight crops through three growing seasons 1977/78

Sampling date	Percentage moisture content of the soil (oven dry weight basis)								Means
	W	SF	LS	M	FB	SB	SP	IP	
3.8.77	37.84	38.37	-	36.59	40.88	38.14	37.42	39.62	38.40
5.8.77	37.01	36.20	39.13	35.93	39.20	37.27	36.60	37.19	37.31
8.8.77	38.01	36.34	38.35	36.75	42.82	39.73	36.36	38.39	38.34
10.8.77	38.04	35.22	38.84	37.07	40.81	38.08	37.41	36.69	[illegible]
12.8.78	38.50	36.46	37.99	37.52	37.35	38.60	36.93	35.26	37.32
15.8.77	35.46	34.20	38.0	36.66	37.14	37.46	35.57	37.04	36.44
18.8.77	35.47	36.25	39.16	35.05	36.83	38.66	36.47	36.25	36.76
25.8.77	34.84	30.40	36.23	33.72	37.14	36.81	36.84	35.60	35.19
31.8.77	35.51	35.43	36.08	33.07	36.41	39.45	38.19	36.76	36.36
7.9.77	36.01	30.69	35.23	33.99	35.87	35.6	32.09	35.41	34.36
13.9.77	34.35	31.12	35.31	34.59	32.97	34.66	31.46	35.41	33.73
20.9.77	37.64	34.82	35.84	34.89	34.88	35.25	31.41	35.48	35.02
22.9.77	34.91	34.24	34.11	35.14	37.61	36.77	-	36.10	35.55
27.9.77	30.38	31.74	34.79	32.30	34.14	32.66	30.35	33.80	32.52
4.10.77	34.3	29.68	33.62	28.27	34.52	35.41	30.41	32.15	32.29
12.10.77	34.50	30.25	35.06	32.12	36.48	32.66	27.44	36.34	33.10
21.10.77	35.96	33.48	37.35	33.08	35.51	39.68	32.59	34.89	35.31
2.2.78	36.34	37.55	38.52	36.34	37.87	36.48	38.55	38.82	37.55
7.2.78	35.05	36.49	37.31	37.66	37.37	36.92	37.53	38.60	37.11
14.2.78	36.61	30.73	37.62	37.48	36.59	33.65	35.75	36.05	35.56
16.2.78	34.5	35.00	34.33	36.90	39.44	36.66	33.94	36.77	35.94
23.2.78	36.11	29.74	37.83	31.97	38.09	33.69	31.65	37.02	34.51
1.3.78	38.81	32.93	39.04	35.41	38.22	33.20	36.26	35.87	36.21
7.3.78	30.96	32.18	32.97	30.10	36.54	37.00	27.16	38.11	33.13
9.3.78	36.69	32.83	35.60	34.98	36.68	34.68	33.47	34.95	34.98
14.3.78	32.32	32.76	34.36	30.21	36.93	35.45	33.94	39.35	34.40
22.3.78	37.56	34.61	37.89	34.73	39.77	35.64	34.89	38.06	36.64
12.6.78	36.94	36.56	37.26	35.65	36.54	36.64	37.47	34.85	36.48
19.6.78	36.36	36.42	36.84	35.15	33.87	36.67	36.54	38.46	36.28
21.6.78	37.08	30.63	35.98	36.46	37.09	34.87	37.30	36.18	35.69
26.6.78	33.37	36.17	33.65	32.36	36.28	35.20	36.84	37.05	35.11
3.7.78	35.63	35.03	34.01	36.80	35.58	35.50	36.00	36.58	35.64
5.7.78	35.43	33.6	35.17	36.59	36.43	36.75	36.09	35.39	35.68
10.7.78	34.46	32.85	35.37	36.60	34.44	37.52	37.37	36.55	35.64
19.7.78	37.03	35.93	33.80	32.78	35.88	33.44	32.95	36.90	34.83
Means	35.71	33.91	36.25	34.71	36.97	36.19	34.74	36.51	35.63

Appendix 6c Yield of the test crop of maize (in metric tonnes per hectare) as influenced by cropping sequences during the long rains 1977 and long rains 1978

Cropping sequences	the 18-month rotations				The 3-year rotations			Means
	1978 long rains		1977 long rains		1978 long rains		1977 long rains	
	1	2	1	2	1	2	1	
SB-SB	1.66	2.48	3.86	3.28	2.1	1.68	5.53	2.94
SB-M	3.01	1.99	3.78	5.05	0.28	0.61	4.17	2.69
SB-SP	1.66	1.10	2.73	4.55	1.09	0.85	4.55	[illegible]
SG-SF	0.99	1.09	2.29	4.99	0.99	1.15	5.93	2.49
SB-LS	0.91	0.95	4.83	3.56	0.85	0.331	4.42	2.26
SB-W	0.83	2.24	3.01	4.0	1.95	0.22	4.05	2.32
SB-FB	0.58	0.65	1.55	4.55	0.138	0.36	2.48	1.47
SB-IP	1.05	1.58	6.68	4.11	0.41	0.303	3.04	2.45
Means								2.37
M-M	1.93	0.69	2.93	4.28	0.16	0.55	2.73	1.89
M-SB	2.35	1.02	2.04	3.86	0.19	0.63	4.11	2.02
M-SP	1.10	1.63	5.79	3.73	1.93	2,01	2.35	2.64
M-SF	2.29	2.48	3.83	6.62	0.51	0.41	6.18	3.18
M-LS	1.79	1.99	1.71	5.85	0.16	0.55	3.84	2.27
M-W	1.79	1.02	4.86	4.66	0.49	1.29	6.56	2.95
M-FB	2.10	1.52	2.76	4.94	0.08	0.19	3.37	2.13
M-IP	0.99	2.59	3.04	6.51	0.38	0.74	3.03	2.46
Means								2.44
SP-SP	1.35	1.46	6.35	5.11	0.33	1.46	4.77	2.97
SP-SB	2.35	0.88	6.12	4.03	0.69	1.38	3.92	2.76
SP-M	2.54	2.15	4.64	4.66	0.14	0.33	2.23	2.38
SP-LS	1.63	1.57	5.91	4.42	0.25	0.63	5.85	2.69
SP-W	1.19	1.66	5.29	3.92	0.92	0.91	3.56	2.49
SP-FB	0.86	1.63	2.25	3.64	0.91	0.74	6.68	2.30
SP-IP	[illegible]	1.71	2.48	5.52	0.08	1.10	3.95	2.35
SP-SF	1.71	1.02	5.29	3.04	0.61	0.938	4.53	2.44
Means								2.58

Appendix 6. (cont.)

Cropping sequences	the 18-month rotations				the 3-year rotations			Means
	1978 long rains		1977 long rains		1978 long rains		1977 long rains	
	1	2	1	2	1	2	1	
IP-IP	1.21	1.49	5.54	4.86	0.303	1.29	3.69	2.62
IP-SB	1.21	2.35	1.19	3.84	0.54	0.41	3.71	1.89
IP-M	2.18	2.4	3.09	3.65	1.01	0.58	2.73	2.24
IP-SP	1.13	2.57	5.29	4.42	0.6	0.6	3.83	2.63
IP-SF	1.66	1.38	3.12	3.84	1.31	0.38	4.61	2.32
IP-LS	1.49	1.79	3.17	2.33	0.47	0.33	2.73	1.76
IP-W	0.86	1.96	6.07	4.55	0.49	0.69	3.58	2.6
IP-FB	1.10	1.05	6.76	4.91	0.79	0.85	3.77	2.74
Means								2.35
SF-SF	1.93	1.77	3.59	3.86	0.36	0.85	2.70	2.15
SF-SB	1.08	1.71	5.19	4.11	0.43	0.38	3.88	2.39
SF-M	2.32	1.24	5.58	4.94	0.47	0.52	4.55	2.80
SF-SP	0.77	1.99	5.93	4.31	0.33	0.71	3.72	2.53
SF-IP	0.41	1.96	2.87	5.27	0.61	0.82	3.75	2.24
SF-FB	1.33	1.21	4.17	4.09	0.22	1.29	3.78	2.29
SF-W	1.38	1.99	4.38	4.66	0.23	0.35	3.56	2.35
SF-LS	2.01	1.13	3.99	3.26	0.49	0.52	5.27	2.32
Means								2.39
LS-LS	2.21	1.27	5.85	3.73	0.49	0.57	1.38	2.21
LS-SB	2.84	2.21	1.91	3.69	0.46	0.57	4.08	2.25
LS-M	1.93	1.24	3.86	4.86	0.78	0.96	4.33	2.56
LS-SP	1.02	1.9	4.64	5.19	0.08	0.61	3.64	2.43
LS-IP	1.6	0.9	4.49	3.84	0.22	0.47	4.99	2.43
LS-SF	0.88	2.45	1.16	3.73	0.23	0.35	5.05	1.97
LS-W	0/95	1.71	6.38	4.11	0.38	0.30	2.56	2.34
LS-FB	1.2	1.41	3.15	3.09	0.75	0.88	4.02	2.37
Means								2.28

Appendix 6.(cont.)

Cropping sequences	the 18-mongn rotations				the 3-year rotations			Means
	1978 long rains		1977 long rains		1978 long rains		1977 long rains	
	1	2	1	2	1	2	1	
W-W	2.13	0.86	5.49	3.45	0.86	0.75	4.99	2.64
W-SB	2.10	2.26	6.43	3.37	0.83	0.94	4.05	2.85
W-M	2.73	2.48	3.84	5.99	0.82	2.45	3.06	3.05
W-SP	1.52	0.99	4.86	4.14	0.60	0.44	3.09	2.23
W-IP	1.68	2.68	3.62	4.17	0.65	0.58	4.41	2.54
W-SF	1.93	1.52	5.69	4.09	0.20	1.21	2.15	2.39
W-LS	0.83	0.58	3.78	2.65	0.37	0.60	5.96	2.11
W-FB	1.73	1.3	2.62	5.27	0.58	0.57	3.35	2.20
Means								2.50
FB-FB	1.79	1.88	5.77	4.49	0.36	1.02	1.93	2.45
FB-SB	1.35	1.66	1.38	2.18	0.36	2.01	2.18	1.58
FB-M	2.15	1.93	3.45	4.99	0.27	0.86	3.04	2.38
FB-SP	2.12	2.32	3.59	5.29	0.10	2.31	3.86	2.79
FB-IP	0.55	1.05	6.51	3.89	0.08	4.54	2.92	2.79
FB-SF	2.29	0.97	3.73	3.04	0.25	0.66	4.86	2.25
FB-LS	2.04	2.0	2.89	4.75	0.4	0.99	2.89	2.28
FB-W	0.86	0.99	4.14	4.97	0.08	0.88	4.39	2.33
Means								2.35
Overall means	1.6		4.2		0.7		3.9	

Appendix 7. The effect of the eight crops on the yield of maize test crop grown in the following season - long rains 1977 (3 year rotation)

Crop	Yield of maize in metric tonnes per hectare	Means ($\bar{X}$)	Standard deviation (S)	Variance & F-value
W	2.56, 4.02, 6.92, 3.56, 3.58, 5.85, 6.56, 4.05, 3.84, 3.45, 2.68, 4.99, 4.44, 5.27, 3.86, 4.39	4.31	1.31	
SP	3,72, 3.26, 4.66, 3.83, 3.64, 3.56, 3.42, 5.13, 3.27, 4.45, 3.75, 4,77, 2.95, 2.35, 4.55, 4.55	3.9	0.74	
SF	2.15, 4.86, 3.28, 4.53, 6.18, 4.61, 5.05, 3.53, 2.92, 2.7, 4.17, 3.64, 1.82, 5.88, 4.42, 5.93	4.10	1.33	$F=1.33^{NS}$
SB	5.25, 4.08, 2.18, 4.11, 3.53, 4.22, 3.92, 4.05, 1.93, 1.82, 3.26	3.49	1.09	$S^2=1.45$
FB	3.78, 3.37, 1.93, 2.48, 6.68, 2.81, 3.62, 5.16, 2.26, 3.28, 2.46, 3.48	3.44	1.33	
IP	3.03, 4.41, 4.74, 2.92, 5.18, 3.06, 5.41, 4.99, 4.39, 3.69, 4.86, 4.49, 4.88, 4.94, 3.95, 3.15	4.26	0.84	
LS	3.89, 5.96, 2.32, 5.22, 4.42, 5.16, 5.85, 4.5, 5.3, 2.73, 1.38, 1.35, 5.63, 4.75, 2.89	4.09	1.58	
M	2.73, 2.43, 2.23, 4.33, 4.17, 4.99, 4.44, 4.55, 2.84, 3.45, 2.68, 4.99, 4.44, 5.27, 3.86, 4.39	3.46	1.21	
Mean		3.9		

Appendix 8. The effect of the eight crops on the yield of maize test crop grown in the following season - long rains 1977 (18-month rotation)

Crop	Yield of maize in metric tonnes per hectare	Means ($\bar{X}$)	Standard deviation (S)	S^2 & F-value
SB	3.86, 1.19, 2.04, 6.43, 5.19, 1.38, 6.12, 1.91, 3.37, 3.84, 3.28, 2.18, 4.11, 4.03, 3.69, 3.86	3.53	1.54	
IP	6.68, 5.54, 3.04, 3.62, 2.87, 6.51, 2.48, 4.49, 4.17, 4.86, 4.11, 3.89, 5.27, 5.52, 6.51	4.64	1.35	$F = 2.06^{NS}$
W	3.01, 6.07, 4.86, 5.49, 4.33, 4.14, 5.83, 6.38, 3.45, 4.69, 4.0, 4.97, 4.66, 3.92, 4.11, 4.66	4.66	0.93	$S^2 = 1.52$
SF	2.29, 3.12, 3.83, 5.69, 3.59, 3.73, 5.16, 1.16, 4.09, 3.84, 4.99, 3.04, 3.86, 3.04, 3.72, 6.02	3.86	1.31	
FB	1.55, 6.76, 2.76, 2.62, 4.17, 5.77, 2.95, 3.15, 5.27, 4.91, 4.55, 5.49, 4.09, 3.64, 3.09, 4.84	4.10	1.38	
SP	2.73, 5.29, 5.79, 4.86, 5.93, 3.59, 6.35, 4.64, 4.14, 4.55, 5.29, 4.31, 5.11, 5.19, 3.73	4.77	0.96	
LS	4.83, 3.17, 1.71, 3.78, 2.89, 5.81, 5.85, 2.65, 2.39, 3.56, 4.75, 3.36, 4.42, 3.73, 5.85	3.92	1.3	
M	3.78, 3.09, 2.93, 3.54, 5.88, 3.45, 4.64, 5.99, 4.55, 5.05, 4.99, 4.94, 4.66, 4.86, 4.28	4.39	0.92	
Mean		4.20		

Appendix 9. The effect of the eight crops on the yield of maize test crop grown in the following season - long rains 1978 (18-month rotation)

Crop	Yield of maize in metric tonnes per hectare	Means ($\bar{X}$)	Standard deviation (S)	S^2 & F-value
SB	1.10, 1.66, 2.35, 2.10, 2.35, 2.84, 1.21, 1.08, 1.16, 0.88, 2.35, 2.26, 2.21, 1.71, 1.23	1.77	0.62	
IP	1.68, 2.29, 1.21, 0.99, 1.60, 1.63, 0.55, 1.10, 1.49, 1.96, 2.68, 1.71, 2.59, 0.9, 1.05, 0.88	1.52	0.63	
SP	1.79, 1.93, 1.66, 1.93, 1.19, 0.91, 0.88, 1.93, 2.48, 0.91, 1.38, 2.76, 1.52, 2.54, 1.42	1.69	0.59	F =2.75*
W	2.13, 2.10, 0.58, 0.86, 1.66, 1.38, 0.86, 0.86, 1.66, 1.99, 1.02, 0.99, 2.24, 1.71	1.43	0.57	S^2 =0.31
FB	1.79, 1.05, 0.99, 1.71, 1.10, 1.06, 1.02, 1.3, 1.52, 1.13, 1.63, 1.41, 1.05, 1.88, 1.96	1.37	0.35	
SP	1.35, 1.52, 1.10, 1.66, 1.13, 1.15, 0.77, 1.46, 1.63, 2.32, 1.10, 1.99, 2.57, 0.99, 1.9	1.51	0.51	
LS	2.21, 1.79, 1.49, 0.83, 0.86, 0.83, 2.04, 1.10, 1.33, 1.57, 1.27, 1.99, 1.21, 0.58, 1.79, 1.16	1.38	0.49	
M	1.93, 2.73, 3.01, 2.54, 1.93, 2.15, 2.18, 2.32, 0.69, 1.93, 2.48, 2.4, 2.15, 1.24, 1.24	2.06	0.61	
Mean		1.6		

Appendix 10. The effect of each of the eight crops on the yield of seven remaining crops grown during the second season - long rains 1977 (3-year rotations)

Crop	Mean yield of crops (metric tonnes per hectare)							Overall effect. Means
	IP	FB	W	M	SF	SP	SB	
SF	5.33	0.4	0.395	3.1	0.204	8.0	0.79	2.60
W	4.57	0.49	1.05	4.35	0.188	10.3	0.695	3.09
IP	6.55	1.26	1.125	4.95	0.241	13.05	1.54	4.10
SP	5.3	0.775	0.49	4.05	0.225	11.1	0.82	3.25
LS	5.83	1.175	0.775	4.5	0.179	5.8	0.89	2.73
M	5.23	0.77	0.915	3.45	0.171	6.4	0.86	2.54
SB	4.61	0.47	0.72	3.25	0.211	10.5	0.715	2.92
FB	4.53	1.26	0.835	4.55	0.087	10.45	0.75	3.20
Means	5.24	0.825	0.788	4.02	0.188	9.45	1.00	2.67

Appendix 11. The effect of each of the eight crops on the yield of seven remaining crops grown during the second season - short rains 1977 (18-month rotation)

Crop	Mean yield of crops (metric tonnes per hectare)							Overall effect. Means
	SP	IP	FB	SB	SF	W	M	
SF	4.76	5.815	1.195	0.758	1.135	0.98	3.58	2.60
W	4.38	4.05	1.09	0.668	1.77	1.025	3.87	2.40
IP	5.75	4.86	1.075	0.704	1.351	1.18	2.88	2.54
SP	3.79	5.7	0.7	0.53	0.63	1.06	3.6	2.28
LS	5.165	5.71	0.98	0.74	1.55	1.31	4.66	2.87
M	4.731	5.79	1.3	0.722	1.42	1.46	2.82	2.60
SB	4.43	4.25	0.824	0.673	1.52	1.48	3.07	2.32
FB	5.31	4.45	0.441	0.433	1.87	0.68	2.74	2.27
Means	4.79	5.07	0.95	0.65	1.40	1.14	3.4[illegible]2	2.48

Appendix 12. Monthly rainfall totals, mean monthly rainfall and mean annual rainfall for the period 1972 to 1979 for Kabete Field Station (rainfall in millimeters)

Month	Year								Mean ($\bar{X}$)	Standard deviation (S)
	1972	1973	1974	1975	1976	1977	1978	1979		
January	20.4	123.7	2.5	92.0	9.9	40.1	107.9	61.25	57.21**	46.43**
February	77.6	61.5	5.1	2.6	46.0	81.7	39.3	203.7	64.68**	63.45**
March	58.4	7.9	129.1	24.6	32.8	72.0	256.0	-	82.97	85.9
April	26.0	211.0	285.2	226.8	138.6	255.1	286.8	-	204.18	93.62
May	172.6	55.2	NR	154.2	116.8	203.9	48.4	-	125.5*	63.43*
June	124.2	41.3	95.5	11.9	33.3	49.5	16.3	-	53.14	41.73
July	15.0	2.0	107.9	22.5	10.7	23.9	15.2	-	28.17	35.91
August	5.7	6.2	35.1	4.3	1.2	53.6	23.9	-	18.57	19.8
September	50.3	64.3	40.3	88.1	44.5	16.8	6.8	-	44.44	27.48
October	179.1	13.0	54.7	54.7	12.3	53.1	104.8	-	67.38	58.3
November	149.9	81.8	92.1	84.1	102.6	233.9	125.2	-	124.22	54.15
December	28.8	32.5	55.3	48.3	24.0	90.9	129.7	-	58.5	36.69
Totals	908.0	700.4	-	814.1	574.7	1174.5	1160.3	-	928.96 ±	243.07

* Computed over 6 years

** Computed over 8 years

Appendix 13a. Daily rainfall (R), soil temperature (ST) and radiation (RD) for the months of July, August, September and October 1978

Day	July 1978			August 1978			September 1978			October 1978		
	R	ST	RD	R	ST	RD	R	ST	RD	R	ST	RD
1	-	18.4	246	20.3	19.7	346	-	19.1	353	12	20.1	411
2	-	16.6	192	-	18.2	173	1.2	19.4	657	-	20.0	[illegible]
3	-	18.4	292	-	18.4	368	-	20.15	645	-	19.7	453
4	0.7	17.9	204	-	19.55	499	-	19.9	444	-	20.5	575
5	-	17.8	195	-	19.1	265	-	19.7	529	-	21.1	642
6	-	17.7	189	-	18.65	262	-	20.6	61.7	0.5	20.8	648
7	-	18.5	398	1.7	18.5	192	0.8	21.0	547	-	21.5	611
8	-	18.2	441	-	19.1	447	-	21.5	575	-	21.9	450
9	-	17.7	243	-	19.0	426	-	20.8	483	-	21.6	526
10	-	19.9	362	-	19.5	453	-	21.7	651	-	21.4	578
11	-	18.1	328	-	19.8	423	-	21.5	553	-	21.9	572
12	0.9	18.8	417	-	19.1	304	-	21.4	535	0.3	21.2	438
13	2.9	18.4	131	-	18.0	161	-	19.6	307	4.5	21.0	407
14	0.8	17.4	292	1.0	18.0	192	-	19.0	374	-	20.1	456
15	-	17.9	155	-	18.15	292	-	19.4	474	-	21.1	675
16	-	17.5	204	-	18.1	170	-	19.5	411	-	21.2	654
17	-	18.2	514	-	20.0	176	-	19.5	477	-	22.3	559
18	-	18.4	590	-	19.05	404	-	20.0	423	-	21.6	638
19	-	19.0	526	-	19.2	435	-	20.0	508	-	21.2	629
20	-	19.6	508	0.3	19.0	341	-	20.25	635	9.2	21.8	505
21	-	19.5	392	-	19.0	362	-	19.8	602	33.8	20.0	325
22	-	19.3	459	-	19.5	395	1.3	21.05	544	0.2	19.1	496
23	3.2	18.6	313	0.3	19.7	587	1.2	20.6	471	-	21.4	569
24	-	18.6	246	-	20.3	496	0.5	19.9	216	-	21.6	626
25	-	18.5	313	-	19.7	359	-	19.2	319	28.1	21.6	392
26	-	18.4	365	-	18.7	286	-	20.6	549	0.4	18.9	395
27	-	18.4	316	-	18.0	313	-	21.0	596	8.6	19.9	335
28	-	18.6	389	-	18.2	353	-	21.8	353	-	21.0	645
29	1.0	18.9	416	-	19.2	541	1.8	21.1	207	2.3	21.1	566
30	5.7	18.7	511	-	19.3	523	-	19.8	353	15.7	20.15	155
31	-	18.6	377	0.4	20.3	526	-	-	-	-	19.65	496

Appendix 13b. Daily rainfall (R), soil temperature (ST), and radiation (RD) for the months of November, December 1978, and January, and February 1979.

Day	November 1978			December 1978			January 1979			February 1979		
	R	ST	RD	R	ST	RD	R	ST	RD	R	ST	RD
1	1.0	20.8	411	3.7	19.15	347	-	22.25	602	20.6	20.15	228
2	4.5	20.7	590	26.9	19.0	432	-	21.6	550	55.4	20.05	256
3	1.0	20.4	340	21.8	18.9	256	-	21.1	593	3.6	19.3	435
4	9.9	20.3	338	2.0	18.85	383	-	21.0	648	8.8	20.0	310
5	0.9	19.35	435	11.1	19.2	246	-	20.8	575	NR	20.75	560
6	0.4	20.1	456	-	19.05	462	0.4	21.2	484	-	21.5	623
7	1.1	20.1	499	-	19.5	657	0.9	20.3	271	0.6	21.9	596
8	0.7	20.3	566	0.6	20.2	505	-	19.6	289	-	22.6	645
9	-	20.6	575	-	20.4	471	-	19.9	480	2.7	22.2	620
10	-	21.0	672	4.4	20.8	505	-	21.0	493	9.7	21.85	602
11	-	21.9	608	-	20.4	392	2.6	20.9	447	NR	21.9	636
12	-	22.5	681	5.8	20.7	462	-	20.9	581	0.9	22.1	493
13	-	22.4	523	5.8	21.0	462	0.4	21.0	563	-	21.9	511
14	8.8	22.8	572	23.7	21.1	456	0.1	21.0	553	NR	21.5	593
15	14.9	21.0	398	4.4	21.0	578	NR	21.1	563	-	21.6	617
16	-	20.2	620	0.4	21.3	626	-	21.7	456	-	21.75	563
17	5.4	21.6	572	-	21.75	538	-	21.1	438	-	21.85	666
18	-	20.8	335	5.8	22.0	544	3.2	19.4	380	0.7	22.5	575
19	2.5	20.75	395	6.6	22.0	335	0.5	19.6	432	1.0	21.5	252
20	4.7	20.6	374	4.7	20.8	246	0.9	20.6	480	-	21.5	544
21	6.3	19.9	316	-	20.4	429	0.2	20.2	353	-	21.7	605
22	-	20.4	520	-	20.6	605	0.3	20.15	502	82.6	21.5	365
23	-	20.7	541	-	22.1	602	2.1	21.0	517	0.2	19.3	593
24	4.4	20.8	508	-	21.4	599	0.05	20.75	556	-	21.8	490
25	11.0	19.7	268	-	21.7	505	3.0	20.3	496	-	22.5	645
26	-	20.1	368	-	21.8	474	1.7	21.0	535	18.1	22.9	639
27	-	20.7	629	-	21.5	438	0.5	21.3	547	-	21.6	599
28	-	20.75	645	-	21.3	547	9.0	21.4	417	-	21.7	482
29	-	21.1	514	-	22.2	474	9.5	21.0	316			
30	8.1	20.0	310	-	22.1	663	20.3	20.7	414			
31	-			-	21.85	605	4.6	20.7	328			

Appendix 14. Mean daily radiation, air temperature, soil temperature, potential evaporation (open pan) humidity, and windspeeds for the months of the period of the trial

Parameter	1976	1977											
	D	J	F	M	A	M	J	J	A	S	O	N	D
Air temperature (°C)	18.15	18.67	19.52	19.2	18.7	18.19	16.26	15.8	16.17	17.2	19.03	17.7	17.7
Soil temp. at 10 cm depth (°C)	19.64	21.11	21.76	22.0	21.04	21.25	20.04	18.64	18.93	19.37	20.21	20.26	20.12
Radiation (Langleys/ day)	490.4	544.5	589.6	515.7	407.0	422.0	354.4	305.0	392.3	449.7	560.6	417.3	474.2
Potential evaporation (mm)	4.25	4.71	6.01	4.95	3.49	4.0	2.95	1.89	3.08	4.06	4.48	3.56	3.62
Percentage relative humidity	73	68.5	51.5	68.5	77.7	76.5	76.0	78.0	70.0	67.0	60	80	73
Windspeeds (miles/day)	107.6	77.27	86.88	85.3	58.9	55.35	47.15	42.4	52.8	54.6	65.81	62.89	71.3

Appendix 14.(cont.)

Parameter	1978												1979		Means
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	
Air temperature (°C)	17.66	18.84	19.05	18.6	17.28	16.5	15.74	16.06	17.6	18.2	17.7	18.13	18.0	18.6	17.79
Soil temp. at 10 cm depth (°C)	20.08	20.44	21.2	21.3	20.73	19.99	18.4	19.03	20.2	20.8	20.7	20.7	20.7	21.4	20.37
Radiation (Langleys/day)	591.7	588.1	459.2	485.2	446.8	393.4	350.8	357.0	480.2	505.1	485.9	478.8	479.3	526	464
Potential evaporation (mm)	4.44	4.55	3.49	3.82	3.31	2.66	2.4	2.79	4.2	4.15	3.6	3.48	3.6	4.25	3.77
Percentage relative humidity	68	67	73.0	73.5	72.5	74	74	76	67.5	67.5	72.5	73.0	74.5	64	71.2
Windspeeds (miles/day)	66.88	59.74	67.0	48.17	42.5	35.4	29.74	33.48	27.5	50.5	72.6	63.34	82.3	54.9	59.34