THE EFFECTS OF HIGH PLANT DENSITIES ON WATER USE OF
AND ON ROOT DISTRIBUTION, WATER INFILTRATION RATES
TOPSOIL BULK DENSITY.

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DECLARATION BY THE CANDIDATE

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

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TABLE OF CONTENTS:

Page

CHAPTER I: LITERATURE REVIEW.

1.	Intrάduction	1
1:1:1.	Close-spacing in apples and its advantages	2
1:1:2.	Close-spacing in coffee and its advantages	7
1:2	Crop water use	16
1:3	Methods of measuring soil moisture	24
1:3:1	Gravimetric method	25
1:3:2	Electrical resistance blocks	26
1:3:3	The neutron scattering method	27
1:3:4	Tensiometers	28
1:3:5	Thermal methods	29
1:3:6	Lysimeters	29
1:4	COffee water requirements	31
1:5	Root distribution, water infiltration rates and topsoil bulk density	34
1:5:1	Root distribution	35
1:5:2	Factors affecting root growth	36
1:5:3	Root systems of woody tropical crops	38
1:6	Water infiltration rates	42
1:6:1	Factors influencing infiltration rates and permeability of soil	46
1:7	Topsoil bulk density	49
1:7:1	Importance of bulk density	50
1:7:2	Factors affecting bulk density	50

1:7:3 Methods of determining bulk density 51

CHAPTER II: MATERIAL AND METHODS INCLUDING DATA COLLECTION AND ANALYSIS 53

2:1 Materials 53

2:1:1 Intensive coffee: 1971 planting 53

2:1:2 Conventional coffee: 1956 planting 54

2:1:3 Intensive coffee: 1969 planting 54

2:1:4 Soils 55

2:1:5 Meteorological station 56

2:2 Methods, Data collection and analysis 56

2:2:1 Main experiments 57

2:2:2 Climatic data 64

2:2:3 Root distribution 66

2:2:4 Water infiltration rates 69

2:2:5 Topsoil bulk density 74

2:2:6 Yields 77

CHAPTER III: RESULTS 78

3:1 Crop water use 78

3:1:1 Gravimetric soil moisture 78

3:1:2 Soil moisture by gypsum resistance blocks 113

3:1:3 Weather data 135

3:2 Subsidiary studies 150

3:2:1 Root distribution 150

3:2:2 Water infiltration rates 155

3:2:3 Topsoil bulk density 161

3:3 Coffee yields 163

CHAPTER IV: DISCUSSION AND CONCLUSIONS 167

Crop water use 167

Root distribution 180

Water infiltration rates 182

Topsoil bulk density 184

Coffee yields 187

REFERENCES 189.

			page
	D & E:	Crop coefficients, kc estimated from changes in soil moisture and rainfall	143
	F & G:	Crop factors $kpan = \frac{ET(crop)}{Epan}$ estimated from water use and open-pan evaporation.	145
	H:	Estimates of annual potential crop water use	148
V	A:	Root distribution as affected by plant densities: Core sampler method	152
	B:	Root distribution as affected by plant densities: Trench Method	154
VI		Water infiltration rates (mm/min) in wet soils	160
VII		Topsoil bulk densities (gm/cm^3) under coffee blocks	162
VIII	A:	Cherry and clean coffee production in three high density blocks	165
	B:	Cherry yields in kg/tree	166
	C:	Percentage clean/parchment coffee picked early and late November, 1976	166.

LIST OF FIGURES:

Figure:			Page
I	a - i:	Percentage soil moisture at different soil depths	104-112
II	a:	Water infiltration rates in dry soils (mm/min)	157
	b:	Water infiltration rates in wet soils (mm/min)	158
	c:	Water infiltration rates in three coffee spacings: Mean of dry and wet soils	159

DIAGRAM:

Double-ring Infiltrometer 71

SUMMARY

The water use study in high density coffee became a priority after coffee intensification showed promise as a means of increasing the crop production with apparently no increase in costs other than that of extra seedlings at the time of establishment. This study was further prompted by the fact that the water resource may be a limiting factor in the attempt to intensify coffee production by close spacing in some environments. While water use was the main subject of this study, it was thought that close spacing might have an influence on the properties of the topsoil. This led to the incorporation of subsidiary investigations on root distribution, water infiltration rates and soil bulk density.

The literature cited in this thesis shows that many of the advantages realized in the intensification of apples in the temperate countries are being demonstrated in coffee, a crop of tropical environments. High yields have been recorded in high density coffee. Other advantages of close spacing in coffee, such as less need for weed control and pruning, have also been shown. The review also discusses crop water use and the methods used for measuring soil moisture. Similarily, previous work on the subsidiary investigations is reviewed.

The work reported in this thesis addressed itself to the study of water use as distinct from water requirements, as no water was applied to the coffee during the trial, except the natural rainfall.

Two methods were used in the study of the soil moisture changes, the gravimetric and gypsum resistance block methods. Comparisons were made with meteorological estimates of crop water use.

Gravimetric soil moisture determinations were made every 28 days, from mid-April, 1976 to mid March, 1977. Water use in the four coffee blocks was compared by statistical analysis of the percentage soil moisture of the oven-dry soil. The percentage soil moisture was also converted into the quantity of water in the rooting zone in millimetres. This facilitated the comparisons of moisture changes at different sampling dates.

The results of this study, led to the conclusion that, coffee density per se may have no significant effect on the soil moisture. There was no evidence to the effect that close spacing increased crop water use as previously speculated. An interesting insignificant trend was discovered where coffee at higher plant densities appeared to use <u>less</u> water than at lower densities.

Soil water measurements using the gypsum resistance blocks were made at weekly intervals. This procedure was designed to provide additional information to supplement that obtained by the four-weekly gravimetric soil samplings. The results followed the same pattern as those of the gravimetric method. This strengthened the conclusion that there is no reason to believe that high density coffee would impose a higher demand on soil moisture.

Two methods were employed in the study of coffee root distribution in the topsoil, the core sampler and the trench.

The core sampler method was used to take samples at 0-6, 20-26 and 40-46 cm. soil depths. The trench ,method, on the other hand was used to take samples at 0-20, 20-40- and 40-60 cm. soil depths.

The results of the root distribution studies showed that, there were more roots per unit volume of soil below 40 cm soil depth in the intensive coffee plantings, and the quantity of roots in this soil layer increased as the coffee density increased.

The water infiltration rates were studied by the double-ring method. The trials were carried out under two different soil conditions, dry and wet.

The results revealed great variations from place to place. There was no consistent trend in relation to plant density. However, the infiltration rates in the dry soils were generally higher than those recorded when the soil was wet.

The topsoil bulk density was studied by taking undisturbed soil samples, at four different depths, the bulk density being calculated as the ratio of dry weight (in grams) to the volume (in c.c.).

The topsoil bulk density (0-6 cm) was found to decrease as the plant density increased. This effect was more pronounced in the upper part (0-3 cm) of this layer.

The three blocks of intensive coffee had been cropped four times by the time this trial was carried out. The yield data collected over four years was used to calculate the coffee yield per unit area and per tree.

The results showed that close spacing very substantially increases yield per unit area. However, the yield per tree was found to decrease with the increased plant density. This is in accordance with earlier work.

In spite of the occurrence of water stress, coffee quality was not affected by closely spaced coffee to any greater extent than in conventional coffee.

It is concluded that the water resource is no more likely to limit the suitability of any climatic zone for high density coffee that conventional densities have proved satisfactory.

CHAPTER I

LITERATURE REVIEW:

1. INTRODUCTION:

Crop water use in conventionally spaced coffee 2.74 x 2.74m (9' x 9') has been a subject of many investigations. Water use for the control of irrigation in Kenya coffee was studied by Pereira (1957), water use by irrigated coffee by Wallis (1963) and water use in irrigated and unirrigated Arabica coffee by Blore (1965). The findings of these researchers are discussed in the section of water use later in the chapter.

The available information on water use in coffee is based on the work done on conventional spacing. The present trend in world production of tree crops is towards high density planting systems. In Kenya, the present coffee intensification programmes started in 1969, as a result of views put up in an intensification seminar held at Nairobi in December 1968. The work undertaken by the Coffee Research Foundation - Kenya, since 1968 is reviewed by Mitchell (1976), and will be mentioned elsewhere. High density planting (HDP) in temperate fruits like apples has been shown to have many advantages, some like higher yields have already been demonstrated in coffee.

It is desirable to increase the production of coffee per unit area by intensification. However, before this can be undertaken as a general rule, it is important to be sure of the possible limiting factors. Environmental resources like water, light, soil nutrients plus other factors like diseases and pests and field managements may limit production as the plants are grown close to each other. This study was undertaken to discover the extent to which water use is affected by plant densities. In this review, the advantages and disadvantages of high density planting in apples and coffee are discussed first. The subject of water use follows and at the end the three subsidiary subjects: root distribution, water infiltration rate and topsoil bulk density are reviewed.

1:1:1 CLOSEE-SPACING IN APPLES AND ITS ADVANTAGES:

Jackson (1974) defined high density planting as understood by crop physiologists, as planting at a density in excess of that which suffices to give maximum crop yields at maturity under conditions where individual plants are allowed to grow to their full natural size. The author further explains that, in most apple growing areas, the traditional orchards with 100-200 trees/ha have been, or are being replaced by orchards at higher densities. However, there are arguments as to the optimum density and recommendations range from over 3000 trees/ha in the Netherlands (Elema and Roosje 1967; Wertheim, 1972), to less than 2000 trees/ha in the USA (Norton, 1973) and only 500-625 trees/ha in New Zealand (McKenzie, 1971).

It is clear that there is no general agreement on planting distances in apple orchards and each country or region seems to have its own plant population. For this reason, Jackson (1974) stipulated three tasks of a tree-fruit agronomist as: (1) To compare the profitability of different systems and planting densities under his local conditions. (2) To define combinations of rootstock, variety, costs of planting materials and labour and price of fruit which are likely to favour different degrees of intensification. (3) To solve the difficulties confronting fruit industries of the world as they try to adopt the high density planting systems which will increase the effective use of land resources. The same tasks may apply to any tree-crop agronomist, but in coffee one would consider seedlings and rooted cuttings as planting material and yields in kilogrammes clean coffee per unit area other than fruits.

The technical problems of the high density planting (HDP) orchards in terms of weed control, picking and fruit removal depend largely on the vigour of the stock/scion combination used. However, the fundamental problem which affects all HDP orchards is that of maintaining productivity as the orchard ages and naturally tends to become too crowded for maximum production of reproductive parts (fruits) (Jackson, 1974). The author gives three points around which the advantages and disadvantages of HDP revolve: (1) Costs of establishment (2) Time to attain a high level of productivity and (3) Costs of maintenance of this high level of productivity. The establishment costs increase with the increasing number of trees per hectare (Werth, 1976). The increasing density of planting leads to extra expenditure on trees (Jackson, 1974).

A number of arguments have been advanced in favour of high density plantings. Intensification is viewed as: (1) A means of making better use of diminishing agricultural land resources. (2) A method of increasing productivity per unit area. (3) A means of making better use of available environmental resources: light,soil nutrients and water. (4) A way of increasing returns to labour inputs as discussed later in relation to picking and pruning efficiency.

The most important advantage of high density planting is the increase in yields which give increased economic returns. With many crops substantial yield increases have been obtained by planting at closer spacings than those previous recommended. In temperate fruit growing, a revolution has taken place and new intensive methods of production have been developed based on HDP (Luckwell, 1968; Rogers, 1968). Jackson (1974) cites four prerequisites for efficient HDP orchards as: (1) Being able to achieve good light interception throughout their life-span. He points out that close-spacing achieves this in the early years although there is a risk of reducing the overall benefit of this by accepting too short an orchard life (2) achieve early cropping (3) be capable of economic management at maturity and (4) have suitable machinery.

Considerable research has been directed into these aspects, and has popularized high density orchards in temperate countries. The objective of developing HDP orchards as a direct means of more efficient land use and so that the fruit industry can make much earlier use of new varieties and rootstocks has been termed worthwhile by Jackson (1974).

Fruit quality studies in 1972 apple crop by Palmer, et al (1973) showed a clear reduction in fruit size at closer plant spacings. But on classification based on fruit russeting, those from higher densities had better quality. There is evidence that plant population does not adversely affect fruit quality. Werth (1976) stated that in HDP orchards fruit quality is just as good or even better than in other planting systems for Golden Delicious apple grown in Italy.

The ability of the plants to make better use of available environmental resources has been listed above as one reason favouring close-spacing system of fruit production. An ideal orchard would intercept all the available light in such a way as to permit maximum number of fruits to develop under conditions of adequate illumination (Jackson, 1974). In North-Western Europe and USA, fruits of satisfactory quality do not develop under conditions where they receive less than 30 to 40 percent of full daylight (Jackson, 1970; Heinicke, 1966). Radiant energy reaching the floor of the orchard instead of being intercepted by the tree canopy is wasted and does not contribute to fruit production. In choosing a HDP system, one must strike a compromise to balance between good light penetration and minimize waste of radiant energy.

Investigations by Atkinson (1976) showed depletion of soil water by Golden Delicious/M.9 followed the pattern of root distribution. He found that root pattern at wider spacings consisted of a horizontal scaffold of roots parallel to the surface and a number of vertical sinkers. At higher plant densities, the root systems consisted mainly of sinkers. Water use from depth was greater by the higher tree densities. At the widest spacing, most water use was from the surface layers of soil.

Atkinson (1976) estimated removal of mineral nutrients from the soil, and found it to be greatest at the highest tree density. Removal at lower densities as a proportion of that at the highest was similar for nitrogen and phosphorus, and relatively greater for potassium and lower for calcium. From these findings he concluded, in the high density plantings efficient use was made of renewable soil resources, such as water and nitrogen and of mineral nutrients, probably as a result of a high and relatively uniform density of roots. At very high densities excessive early water use did lead to some water stress in the plants.

Gyuro (1976) discussed economic efficiency of management of HDP in terms of productivity of work. In his analysis he considers the following operations for large-scale apple orchards grown in Hungary.

*fertilizer, soil cultivation, irrigation,

*plant protection

*pruning, bending, chemical growth regulation, fruit thinning, ripening regulation.

*fruit harvesting, picking, grading, packaging, storage.

In the apple orchards fertilization and plant protection have been almost fully mechanized. However, pruning and picking require the highest labour inputs in apple production. The operations can be made easier by planting high density low orchards (Gyuro, 1976).

The author presented data which show labour input of pruning was higher in standard orchards than in HDP per hectare. Picking efficiency was also found to be superior in HDP in terms of kilogrammes of fruit picked by an individual per unit time. This was further supported by Werth (1976); who found the annual orchard maintenance costs for all other systems to be higher than those of HDP in Italy.

Pruning is the most labour demanding single operation in an orchard, next to harvesting (Werth, 1976). Comparing the round canopy and palmetto pruning systems with HDP, the author found the latter to have higher performance capacity. He rated an individual's capacity in a pruning season as high as 8 to 10 ha in HDP as against 2.5 to 5 ha in other systems.

Generally HDP has superior picking and pruning performance in apple orchards. This is desirable and will be very useful if it turns out to be true for HDP systems in coffee.

1:1:2 CLOSE-SPACING IN COFFEE AND ITS ADVANTAGES:

In the above section, a detailed account of close-spacing in apples a temperate tree crop has been presented. The present section deals with coffee a crop of tropical environment.

The present research into the problems of close-spacing in coffee was stimulated by the same problems as those facing apple production and the vast advantages achieved by this system in that crop. So far nothing is known about the economic aspects of close-spacing coffee, nor is there anything known about nutrients requirements or crop water use. However, quite a considerable amount is known on yield and quality and management problems.

Although intensive research into close-spacing of coffee only started in 1969 in Kenya (Mitchell, 1976), a historical account of achievements of this system can be found in the Annotated Bibbiography on 'spacing coffee' (1941-1968).

As far back as the 1940's Perkins (1948-49) quoted results under Kenya conditions which indicated that under certain circumstances closer-spacing may have substantial economic advantages. By close-spacing is meant moving from conventional spacing of 2.74 x 2.74 m (9' x 9'). By early 1950s, it was known that yield at 2 x 2 m was nearly twice that at 2.5 x 2.5 m, about thrice that at 3 x 3 m and over 5 times that at 3.5 x 3.5 m (Anon., 1951).

Thirion (1952) working on Robusta coffee showed that the average yields of dry beans per hectare increased with increased plant density. When the trees were planted at these distances apart in lines of 3.6 m (812 trees/ha), 3.0 m (957 trees/ha) and 2.0 m (1450 trees/ha), the yields were 940, 1016 and 1102 kg/ha respectively.

Working on coffee spacing, Snoeck (1959) found that one single stem at 2 x 2 m gave the best results. In a crop yield and number of coffee trees in the planting hole trial by Robinson (1961), coffee yields over 4 years in terms of clean coffee per acre per annum produced by coffee planted at 1, 2, and 4 tree per hole were 7.04, 8.96 and 11.59 cwt. respectively. These results were obtained in Tanzania, under almost similar climatic conditions to those in Kenya.

In field experiments in the Philippines by Ramos and Pangilan (1962) a spacing of 1 x 3 m resulted in higher yields during the first 5 years than wider spacings. In the same year coffee growth under optimal shade conditions was found to improve as the spacing increased.

Handog and Bartolome (1963) reporting the results of 1961 and 1962, total yields of fresh berries in a progress report on the effect of spacing on the yield of Arabica coffee, gave figures of 1 x 3, 1.5 x 3, 2 x 3 and 2.5 x 3 m spacings as corresponding to 8.4, 8.1 , 3.8, 2.9 and 2.8 tonnes/ha respectively. This and the data of Pangilan (1963) show that yield in tonnes/ha increased progressively with increasing plant density.

In effects of planting distances on shaded coffee yields in a Puerto Rican study by Rodriguez _et al_ (1966) with planting densities varying from 2149 to 302 trees/acre; 3' x 6' spacing was found to be the best. At lower densities there was decrease in yield which could not be attributed exclusively to a decrease in plant population, since the same number of plants per acre differed in their yield.

Having looked at the historical account of close-spacing in coffee, we shall now turn our attention to more recent research into this problem with particular reference to the work undertaken by the Coffee Research Foundation - Kenya, since 1968. In that year, it was considered that the time would come when the Kenya coffee industry would reach a position when costs per unit area of land would make the present conventional methods of production uneconomic and only those farmers with more intensive methods would survive. Taking into consideration the increased research into close-spacing systems being undertaken in many coffee growing countries, the then Director of Research convened a Seminar on intensification of coffee growing in Kenya (Mitchell, 1976). This was held at Nairobi in December 1968, where over forty papers were presented covering a wide range of both practical and theoretical aspects of many technical, economic and social issues (Huxley, 1968). This seminar was the starting of increased research on the management problems of close-spaced coffee (Mitchell, 1976).

Mitchell reviewed the advantages of close-spacing for intensive coffee production in Kenya in which he differentiates two systems; high density block and hedge-row plantings.

(1) In high density block planting, much higher yield per hectare can be obtained without increased field costs, which result in a lower cost of production per tonne of coffee. The higher input costs for fertilization are more than offset by reduced costs for pruning, weeding and mulching.

Where coffee is planted in high density blocks with a population of 5000 trees/ha an average yield of about 4000 kg/ha might be obtained in a cropping year with good management.

(2) Intensification of coffee production by producing the same quantity of coffee from reduced area would give additional land for growing food crops or alternative cash crops.

(3) The advantages of single-row hedges are that they can be sprayed effectively with tractor sprayers. However, they give lower yields than high-density blocks.

(4) Regarding coffee quality and bean size, spacing and pruning treatments were found to have no effect on coffee quality. Mitchell (1976) concluded that a major factor influencing both coffee quality and bean size is the cultivar planted. This was illustrated by SL 28 and SL 34 data which produced larger beans of top quality as opposed to K 7 which produced fairly large beans with inferior quality.

The above findings conflicted with that of Browning and Fisher (1976) on yield results for the first cycle from systematic plant spacing designs (fans). They found a significant linear relationship between bean weight and plant density at all sites with a tendency for weight to be reduced at higher density. They further discovered that the optimum plant density for coffee yields lies between 3.6 and 8.5 thousand trees/ha, with a mean for SL 28 fans of 5.6 thousand trees/ha.

(5) The ecological zones under which arabica coffee is grown in most areas of Kenya have been termed unsuitable due to prevailing day temperatures, light intensities and atmospheric humidity requirements (Kumar and Tieszen, 1976). They explained that, the question of improving growing conditions has a partial answer in a close-spacing for the system will provide self-shading canopies favourable for (i) Co_2 assimilation (ii) lower day temperatures by a few degrees centigrade (iii) higher humidity and (iv) the increased leaf area will trap more solar energy utilizing it more effectively.

These findings were based on studies carried out using potted 12-month old seedlings of <u>Coffea arabica</u> L. under green-house conditions. They should not be accepted uncritically as they may not apply under field conditions.

As we found in the advantages of close-spacing in apples, numbers 1, 2 and 3 above combine economic and management aspects, number 5 deals partially with better use of available environmental resources. It should be emphasised here that there is a striking similarity between the two crops as regards the little that is known about coffee.

Still on the subject of the advantages of close-spacing in coffee; pruning, mulching and weed control need further emphasising. According to Mitchell (1976), pruning methods must be adapted to the spacing system, the growth rate of the coffee trees and the prevailing conditions, as well as the requirements for ease of spraying and picking. The methods should be simple and have low labour input in view of the greatly increased number of trees per hectare. Under Ruiru conditions, Mitchell recommends free growth with minimum pruning. By minimum pruning is meant desuckering to remove secondary branches arising within 20 cm of the stem and removal of lower branches touching the ground, for hedge-row planting. The best method of pruning high-density blocks was found to be free growth followed by stumping by blocks or rows after about five years. The advantage in this system is that pruning costs are greatly reduced but it has a disadvantage that yields are sacrificed from the time of stumping until the new heads establish and start producing a crop.

In conventional coffee production, mulch is beneficial both at establishment and production stages. This does not apply with close-spaced coffee. Grass mulch should be applied in strips along the tree rows when seedlings are planted in the field, and should be maintained for the first two years only (Mitchell, 1976). In two years time the soil in the tree rows is covered by the coffee canopy and mulching is no longer necessary. However, mulching is required again when the trees are stumped or are being converted into a new pruning cycle, by which time the prunings and leaves should be left in the tree rows as mulch cover to protect the soil until new heads have established. At this stage no mulching material is brought in from outside the field, and this cuts down on one factor of production.

Observations under high density coffee show that leaf litter falling from the aging canopy forms a mulch cover by itself, and conditions develop similar to those found under forest.

There is no reliable evidence to show the degree of the reduction in cost of production attributable to less mulch requirements.

Weed control particularly in high rainfall areas requires high labour inputs under the conventional system of coffee production. Mitchell (1976) recommended eradication of perennial grasses like couch and star grasses before the coffee is planted in high-density blocks because this cannot be done later without causing considerable damage to the roots of the plants. Broad-leaved weeds and annual grasses should be controlled by weeding for the first two years after which time the coffee canopy covers most of the soil surface suppressing weed growth by shading.

At what appears to be manageable plant density in coffee, about 5000 trees/ha, there is still a requirement for weed control because the ground is not completely covered to the extent that weed growth is completely suppressed. At higher densities where the coffee canopy shades weed growth, the yields are limited by overcrowding.

The advantages of close-spacing coffee can be utilized in the small-holder sector in areas which have become marginal for coffee production because of low yields, high incidence of CBD, soil erosion and the high costs of weeding. These areas Mitchell (1976) categorizes as those West of the Rift Valley and the high-altitude, high-rainfall areas on Mt. Kenya and on the Aberdares. He considers these are the areas best suited for high-density block planting and for interplanting and where a change to close spacing would have the greatest impact. The validity of this statement has been challenged by the findings of Browning and Fisher (1976) in fan trials which revealed that the highest optimum densities are to be found at the lowest sites.

Every system has its own advantages and disadvantages. In the foregoing paragraphs, the advantages of HDP have been discussed at some length. The disdvantages of this system are high costs of establishment (Mitchell, 1976). But this may not be as serious as in case of apples (Jackson, 1974; Werth, 1976) for in coffee the planting material is mainly seedlings while for apples it is buddings.

In coffee the main disadvantage is to create conditions which increase CBD incidence due to difficulties of obtaining adequate fungicidal spray and increased canopy humidity. Control of leaf rust is also less effective in a high density planting system (Mitchell, 1976).

Before coffee intensification can be recommended to the growers, a number of problems must be solved through research. In his review Mitchell noted the following: Economic aspects of close-spacing system from establishment through production; crop water use; the nutrients and irrigation requirements plus disease and pests control. The present study is aimed at defining the effect of plant density on water use.

1:2 CROP WATER USE:

Climate is one of the most important factors determining the amount of water loss by evapotranspiration from a crop. In addition to climatic factors, evapotranspiration for a given crop is determined by the crop itself and its growth characteristic There are other factors which influence the crop growth rates and hence evapotranspiration. These include, local envirinment, soil and soil water conditions, fertilizers, insect and disease infestat: agricultural and irrigation practices (Doorenbos and Pruitt, 1975).

The use of climatic data to dtermine crop water use has been practised widely in the past. The approach now adopted by FAO is to estimate first the reference crop potential evapotranspira ETO for a given period, e.g. one month at a given location. From this the potential evapotranspiration of the crop ET(crop) can be derived, having reference to the nature of the crop and its stage of growth. This provides an estimate of crop water requirements for irrigation or water budgeting purposes (Doorenbos and Pruitt, 1975). ETO is defined as the evapotranspiration of an 8-15 cm tall crop of grass, green actively growing, completely shading the ground and not short of water.

In relation to practical approach to the determination of the potential evapotranspiration Serraf (1972) states that many assumptions and simplifications are necessary since complete energy budget studies often require extensive and precise measurement equipment. Simple formulae have been developed through the years using one or several easily measurable weather elements which substitute for the fundamental terms. For practical consideration in his combination of energy - balance and aerodynamic approach, Penman discarded the temperature of the evaporative surface or leaf temperature and took the air temperature at 2 m above the soil surface. The general assumption that water availability is not limiting, reduces the importance of the plant physiological factors; that the assumed passive role of the plant is reflected in a simple crop factor which appears in a number of evapotranspiration formulae. In many empirical formulae there is the danger that oversimplification may lead to large deviations from the real evapotranspiration value, and therefore limit their general application. Actual field measurements of potential evapotranspiration are needed in many locations in order to verify their applicability under the given conditions.

Serraf (1972) further points out that recent measurements of actual water use by various crops tend to show that the peak water use may exceed the potential evapotranspiration or the water use for a short green grass with ample water supply. This, he explains could be attributed to the role of the plant, i.e. its geometry, roughness and leaf characteristics.

The consumptive use of water by plants is sometimes termed as evapotranspiration, which includes the loss of water by evaporation from the soil surface and transpiration by plants. This is the measurement in depth of water over the cropped area and is reported in millimetres for a definite interval as per day, week, month, or for the season. The consumptive use varies with the climatic conditions and ground coverage of the crop. The size of the plant or the amount of ground coverage to a large extent determines consumptive use, as it depends to a large extent on solar radiation, or the amount of sunlight intercepted by the leaves (Doneen, 1971).

Doneen presents data for 30 different plant species completely shading the ground which show a consumptive use to be more or less the same. Thus, under the same climatic conditions and with complete ground coverage if the consumptive use of a crop is known, it can be estimated for other crops. Also if the ground is not completely shaded but the percent coverage is known a rough estimate can be made for these crops.

Water use of crops with respect to potential evapotranspiration-ETp and evporation-Eo, has shown that good use of lysimeter data could be made to derive seasonal, monthly or shorter term crop coefficients (Serraf, 1972). The ratios over ten-day periods of the lysimeter - crop water use ET(crop) versus grass ETp or evaporation from standard devices, e.g. Class A Colorado pans, is one good approach.

The percent soil cover and/or the leaf area index as well as the plant growth stage and vigour should be indicated alongside the ratios to reveal the effects of the plant development and plant factors.

The comparison of crop water use with calculated ETp is another approach, the success of which depends on the choice of the appropriate formula after a systematic evaluation (Seraf ,1972

The level of evapotranspiration is controlled mainly by three factors, plant characteristics, extent of ground cover and stage of growth; water availability in the soil; and meteorological parameters or the evaporative demand (Castano, 1974). Maximum or potential evapotranspiration (ETp) occurs when the soil water is non-limiting and the crop is in an active stage of growth with full ground cover; the level of ETp for a given plant species is then mainly governed by the meteorological conditions.

The actual evapotranspiration (Eta), sometimes called consumptive water use, is the actual quantity of water lost during crop growth by evaporation from land surface and by transpiration (Castano, 1974).

The Eta may reach ETp level if conditions permit. However, it is more difficult to estimate ETa than ETp since several factors play interacting roles. The ETa can be determined directly by periodic soil sampling and oven-drying; in this way changes in soil water by a growing crop are followed and layerwise depletions are studies in the effective root zone of the crop.

However, this does not work well for all field conditions. Under arid and semi-arid plant communities, the location of sampling points require careful planning to ensure representative samples for the entire field under investigation (Slatyer, 1962).

The ETp can be computed from meteorological parameters such as temperature, radiation, wind velocity and humidity.

Several different formulae are used for this computation, and below are some of these formulae from Dastane (1974). They are used to predict evapotranspiration and alongside are the variables considered.

FORMULA	VARIABLES CONSIDERED	ENTITY MEASURED
1. Thornwaite, 1931	1) Temperature	Et crop
	2) Sunshine hours/ Cloud cover	
	3) Correction factor	
2. Penman, 1948 U.K.	1) Temperature	Eo or Et crop
	2) Air humidity	
	3) Daylight hours	
	4) Sunshine hours/Cloud cover	
	5) Radiation	
	6) Wind velocity	
	7) Crop factor	
3. Blaney-Criddle, 1950, U.S.A.	1) Temperature	Cu crop
	2) Daylight hours	
	3) Crop factor	
4. Thornwaite-Mather 1955, U.S.A.	1) Temperature	Et crop and soil water balance
	2) Sunshine hours/cloud cover	
	3) Soil factor	
	4) Precipitation	
	5) Corrective factor	

FORMULA	VARIABLES CONSIDERED	ENTITY MEASURED
5. McIlroy, 1961 Australia	1) Temperature	ET crop
	2) Air humidity	
	3) Dry-wet bulb temperature	
	4) Daylight hours	
	5) Sunshine hours/cloud cover	
	6) Radiation	
	7) Wind velocity	
	8) Crop factor	
6. Linarco, 1967 Australia	1) Temperature	ET crop
	2) Air humidity	
	3) Daylight hours	
	4) Sunshine hours/cloud cover	
	5) Radiation	
	6) Wind velocity	
	7) Crop data	

NB: ET = Evapotranspiration

CU = Consumptive use of water

Eo = Evaporation from USA Class A evaporimeter placed in a grass field.

None of the formulae listed suits all situations perfectly. It can also be said that they were developed under the climatic conditions of those countries listed along with them. However, recently the modified Penman method as presented by Doorenbos and Pruitt (1975) has gained wider application and has been adopted by FAO.

The basic relationship in themodified Penman method is:

$$ETo = W.Rn + (1-W) f(u) (eo-ea)$$

Where W is the weighting factor

Rn the net radiation

f(u) a function of windspeed

eo the saturated vapour pressure at mean air temperature and

ea the actual vapour pressure.

In this method reference crop evapotranspiration, ETo is estimated first. ETo and crop coefficient, Kc are used to estimate crop evapotranspiration in the following relationship:-

$$ET(crop) = ETo.kc$$

where ET(crop) is the crop evapotranspiration

kc is the crop coefficient

This is one of the best methods of estimating reference crop evapotranspiration where a complete set of meteorological data is available (Doorenbos and Pruitt, 1975).

This method of crop water use ET(crop) prediction take into account the climatic conditions and crop characteristics and assume that soil water is in ample supply. In the absence of appreciable drainage losses, after irrigation or rain, the soil water content will ne reduced primarily by evapotranspiration. As the soil dries out, the rate of water transmitted through the soil and supplied to the roots will reduce and consequently the rate of water uptake by the plant will be affected.

Blaney-Criddle (1950) derived a formula estimating the crop consumptive use of water. This method use temperature, daylight hours and crop factor. It is not applicable at high altitudes (greater than 500 m) or dose to a large body of water. The Blaney-Criddle factor (f) is calculated from the relationship:-

$$f = p(0.46t + 8.13) \text{ mm day}^{-1}$$

where t is the mean air temperature (°C)

p is the mean daily percentage of annual day time hours,

which under Kenya conditions is taken as a constant 0.27 (Doorenbos and Pruitt, 1975).

In East Africa an evaporimeter of the raised Class A pan type is in common use. However, it is not regarded as a reliable estimate of ETo as is the case with Penman due to the problems of exposure and edge effects (Dagg, 1969).

Of the other factors which affect crop water use mentioned in the opening paragraph, local environment, rooting system and soil need further stressing.

The altitude and temperature greatly influence the crop environment. The crop water use ET(crop) changes significantly with altitude in a given climatic zone (Serraf, 1973; Doorenbos and Pruitt, 1975). The differences are not caused by variations in altitude as such but mainly by changes in temperature, humidity, and in the day-night distribution of wind from areas near the coast to higher mountain valleys. Also radiation at high altitudes may be rather different than in low-lying areas (Doorenbos and Pruitt, 1975). High temperatures increase transpiration and this is enhanced by low air humidity.

The kind, and extent of various plant roots affect crop water use by largely determining the amount of water required at each irrigation and to a considerable degree govern the frequency of irrigation (Doneen, 1971). However, root system become more important as a determinant of crop water use in areas where water is in short supply. Deep rooting is only important when there is water to be exploited from great depths.

Soil is an important medium between water and plants, acting like a reservoir from the moisture supply to the crop (Dastane, 1974). The soil properties of absorption, retention, release and movement of water influences the degree of effective rainfall. The amount of water available to plants varies considerably in different soils depending on their texture (Dastane, 1974).

Pereira (1957) using electrical resistance gauges showed that brief periods of heavy rainfall can set up zones of active drainage which pass slowly down through deep uniform soil, taking over 15 days to reach the 6th foot (180 cm) and upto 3 months to reach the 10th foot (3 m). For coffee whose roots reach this depth, water is held long enough to be utilized by the plants.

1:3 METHODS OF MEASURING SOIL MOISTURE:

Over the past years investigators have employed many methods in soil moisture studies. Kellsy *et al.* (1946) gives three reasons for soil moisture study. Soil moisture content is followed to determine:-

(a) the amount of available moisture remaining in the soil or the amount of water required to raise the soil moisture to the field capacity.

(b) the availability of the moisture and its relation to plant growth or to the other factors affecting plant growth, or

(c) in irrigated regions to determine when a particular soil should be irrigated.

The author points out two factors involved in following soil moisture changes as: (1) the amount of water per unit mass or volume of soil, or percentage moisture, and (2) the availability of the soil water.

The availability of the water present in a given soil is often estimated by relating the amount to quantities present at the field capacity, and the permanent wilting point percentage. The difference between these is considered to represent the amount of water available to the plants. Some of the methods employed in soil moisture studies are briefly discussed below:-

1:3:1 GRAVIMETRIC METHOD:

Soil samples secured from various depths and locations in the field is the simplest and most widely used and probably the best method, for measuring soil moisture (Doneen, 1971). The soil samples are placed in an air tight container which may be made of aluminium, metal or glass and sealed immediately to prevent the loss of moisture en route to the laboratory.

In the laboratory, the moisture samples are weighed, dried to constant weight in an oven at 105° - 110°C and reweighed. The difference in weight is due to loss in water and is divided by the dry weight of the soil to give the percent of moisture on a dry weight basis. The method is laborious and time consuming unless only the surface soil is sampled.

Gravimetric method of soil moisture determination is to date the most accurate. However, it suffers the disadvantage of being applicable where labour is cheap. In addition, it inconveniently riddles the small plots with sampling holes.

1:3:2 ELECTRICAL RESISTANCE BLOCKS:

Moisture measurements depend upon determination of the electrical resistance between two electrodes imbedded in a block of gypsum which is in equilibrium with the soil (Kelley, et al., 1946).

Porous absorbant blocks usually made of plaster of paris (gypsum) with the two electrode embedded are buried in the soil. Insulated wire leads connect the electrodes to a specially designed meter which may be calibrated to read directly the percent of available moisture. These blocks are made in several sizes and shapes and are most sensitive in the lower ranges of available soil moisture (Doneen, 1971). They should not be used in a very wet or poorly drained soil. Their sensitive range being in the lower 25 percent of available range usually provides ample warning that the moisture supply is low before the soil reaches the permanent wilting percentage.

Pereira (1955) calibrating gypsum blocks with sunflower seedlings in coffee soil found a resistance of 4.8 log-ohms to be equivalent to permanent wilting percentage of Kikuyu Red Loam Soil. Gypsum blocks are not sensitive to moderate concentrations of salt in the soil solution, but high concentrations will affect their readings and cause a deterioration of the blocks.

Other resistance blocks using nylon or fibreglass have been developed, but are sensitive to changes of salt concentrations in the soil solution and could not be recommended for soils with moderate to high salt content (Doneen, 1971).

Calibration for most blocks may not remain constant after they have been in the soil for sometime. The blocks are placed in holes where the soil has been disturbed and roots must penetrate the region of disturbed soil before a meaningful reading can be taken. To measure the amount of soil moisture quantitatively all these devices must be calibrated by testing them in soil of known moisture content (Doneen, 1971). This requires the test made for different soils occurring in the field. Nevertheless, the instruments will show that changes in soils moisture are taking place, and may be used as guide for irrigation.

1:3:3 <u>THE NEUTRON SCATTERING METHOD:</u>

The neutron scattering is a recently developed method for measuring water content on a volume basis. According to Doneen (1971), it is satisfactory for measuring the water in a profile but inaccurate near the soil surface or in indicating water content in any specific narrow depth interval. These are distinct disadvantages of the method. However, measuring the soil moisture during the season at one location without disturbing the soil is an advantage in eliminating soil variation and in addition the moisture content is known immediately.

The equipment is costly and the user risks radiation hazards. At the present time, the neutron probe is still a research tool and not applicable to routine field moisture determination. It could not be used in this study because it was not available.

1:3:4 TENSIOMETERS:

Tensiometers give accurate and reproducible measurements provided they are always at the same temperature and are in both thermal and moisture equilibrium with the soil. They are calibrated to give the soil moisture tension or negative pressure, in terms of the equivalent height of water column in centimetres (Kelley, *et al.*, 1946).

Tensiometers are limited to the higher moisture content as the instrument is restricted to less than 1 atmosphere which for fine-texture soils is less than half the available range and about three fourths the range for sandy soil (Doneen, 1971). The tensiometer is not recommended in estimating the soil water content unless crude estimates are adequate, then each soil should be calibrated separately. Tensiometers consist of a porous cup which is embedded in the soil in the zone of major root activity, with a tube connected to a vacuum gauge or mercury manometer. The cup and the tube are filled with boiled water to exclude air. In the field considerable skill is required to maintain these instruments in a reliable operating condition

(Hagan, et al., 1967).

1:3:5 THERMAL METHODS:

Kelley et al (1946) used thermal units to study soil moisture. Moisture measurements with these units depend upon changes in eletrical resistance due to heat losses to the gypsum jacket and the soil after a definite quantity of electrical energy has been supplied to the resistance wire. A special meter is used to obtain the readings. The installation of the units is like that of gypsum blocks. This method is not used for practical purposes.

1:3:6 LYSIMETERS:

Lysimetry is a method which provides complete information on all the components of water balance (Dastane, 1974). Lysimeters can be used not only for measuring evapotranspiration but also for checking emperical formulae for computing ET. The method gives high accuracy in estimating evapotranspiration.

A lysimeter is a large container with soil in which crops are grown and water losses and gains can be measured. The container is filled with suitable inlet for irrigation and outlet for drainage. The lysimeters are buried in the field and are surrounded by the same crop as is grown in them. The size of lysimeters varies from small oil drums (Gilbert and van Bavel 1954) to large and deep ones (Harrold and Drielbelbis, 1958, 1967; Pruitt and Angus, 1960; McIlroy, 1963). Lysimeters can be of two types, weighing and non-weighing types.

In non-weighing lysimeters, changes in water balance are measured volumetrically weekly or bi-weekly. No accurate daily estimates can be obtained. A layer of pebbles is placed at the bottom to facilitate easy drainage. Excess water is collected from below at a suitable distance.

Weighing lysimeters can provide precise information on soil moisture changes for daily or even hourly periods. The lysimeter is placed inside another tank which is in contact with the surrounding soil. The inside container is free for weighing. Also the lysimeter tank can be floated in water, a suitable heavy liquid like $ZnCl_2$ is used whereby the change in liquid displacement is a measure for water gain or loss to or from the lysimeter tank (Doneen, 1971).

In East Africa, hydraulic lysimeters (Glover and Forsgate, 1962) are commonly used. This type of lysimeter enables direct measurement of changes inweight of an extensive block of soil, complete with its vegetative cover, by difference of two simple readings of a water filled manometer. The apparatus comprises a large water-tight tank, of a depth adequate to contain the major part of the root range of the crop under study, supported on a series of water-filled bolsters and placed in a suitably reverted pit with a sump so that the surface of the soil in the tank is level with that of the surroundings (Forsgate, Hosegood and McCulloch, 1964). Changes in weight of the tank, due to water application or to transpiration, result in changes in pressure in the water-filled bolsters and hence in changes in the height of water in an open-ended manometer which provides a hydrostatic balance for the system. The system experiences atmospheric pressure both on the soil filled tank and on the measuring column and so is not affected by atmospheric pressure (Forsgate, et al., 1964). Dagg (1969) tested the performance of this type of lysimeter in estimating the evapotranspiration in tea. He found it operating satisfactorily and capable of producing valid evapotranspiration data over periods of a few days.

Apart from the high costs, the major problems with lysimeters are the restricted root growth, the disturbed soil structure in the lysimeter causing changes in the water movement and possibly the tank temperature regime resulting in condensation of water on the walls of the container. Harrold and Drielbelbis (1967) estimated the errors due to dew formation in the order of 250 mm per annum. Other limitations include the suggested "bouquet effect" when the canopy of plants grown in the lysimeter is above and extends over the surrounding crop, resulting in high evapotranspiration rate. Inspite of these limitations, it is the best technique for precise studies on evapotranspiration.

Lysimeter method differs from the others discussed above. While here moisture changes are measured in the whole soil volume, the other methods can be used to measure moisture horizon by horizon down the soil profile.

1:4 COFFEE WATER REQUIREMENTS:

The amount of water required for maintaining optimum transpiration rates for coffee at conventional spacing is known from the work of Pereira (1957), Wallis (1963) and Blore (1965) and is easily predicted from rainfall and evaporation data for climatic conditions East of the Rift Valley. The available water storage capacity of the Kikuyu Red friable (loam) soil on which most of Kenyan coffee is grown was found to be about 300 mm (12 inches) Pereira (1957), in the top 3 metres (10 ft) soil profile. He came to this important conclusion after estimating the permanent wilting point and field capacity to approximately 900 mm (36 ins.) and 1200 mm (48 ins.) respectively. Wallis (1963) stated that irrigation treatments recommended for coffee ensures that there is always available water in the top 120 centimetres (or 4ft) of the soil where the main feeder roots are found.

In conventional coffee spacing, ground cover is far from being complete, and only accounts for 50 - 60 %. However, the crop has a high rate of water use in the rains, at 0.8 Eo, which has an evaporation component due to direct evaporation from the soil surface (or through weeds) (Dagg, 1968). The effective ground cover is defined by Doorenbos and Pruitt (1975) as the percentage of ground cover by the crop when ET(crop) is approaching maximum, and is generally 70 to 80 per cent. From observations in the experimental plots at Ruiru, 80% ground cover is more than achieved in intensively planted coffee at 5 thousand trees/ha in the second year of establishment.

In the dry season, the rate of water use for conventionally spaced coffee is known to fall to 0.5 Eo, which is equivalent to the rate of 0.83 Eo from a 60% ground cover. According to

Dagg (1968), this is a suggestion that transpiration rate is not appreciably reduced despite the development of large soil moisture deficits and the physiological stress in the plants noticed at smaller soil moisture deficits.

Wallis (1963) found an overall low water use at Ruiru of 863.6 mm at 0.57 Eo for unirrigated, and 1066.8 mm at 0.69 Eo for irrigated coffee. This was considered a reflection of wide spacings in conventional coffee growing system in which the roots exploit a volume of soil greater than that directly under the canopy that intercepts solar radiation. Since wide spacing is seen as a moisture conserving technique; close spacing with a complete ground cover can be expected to raise the potential annual water use to about 0.8 Eo, or 1219.2 mm for Ruiru (Dagg, 1968).

The use of crop coefficient, Kc based on ETo in estimation of crop water use by the modified Penman method has been suggested. For mature coffee grown without shade where clean cultivation and mulching are practised coefficients of about 0.9 are recommended throughout the year. Where significant weed growth is allowed, coefficients close to 1.05 to 1.1 are said to be more appropriate (Doorenbos and Pruitt, 1975). This may apply to close spaced coffee where ground cover is normally complete. It must be noted that ETo is not equal to Eo and the computation of crop water use slightly vary depending on which method is used.

Coffee yields in relation to plant density werestudied by Browning and Fisher (1976). They discovered the biological optimum plant density for coffee yields lies between 3.6 and 8.5 thousand trees/ha, with a mean for SL 28 fans of 5.6 thousand trees/ha. A density of 5 thousand plants/ha was found to be within 13% of the maximum yield at all sites. They suggested the practical plant density optimum may be about 5 thousand trees/ha for management reasons. In regard to leaf water potential as a measure of plant water status, (Kumar, CRF Progress Rep. 1976/77) found a gradual diminishing water potential as the density increased. His results revealed a lowering of water potential i,e. more water stress, where the area represented densities more than 4000 trees/ha. Similarly, stomatal resistance followed the water potential pattern.

This is in contrast to the findings of Fisher (unpublished data) who found high water potentials in plant densities greater than 5000 trees/ha. For all periods studied, there was a general upward trend in water potential with increasing density to 8 thousand plants/ha. Of more importance was the significantly higher potential at 6.7 and 8 thousand trees/ha during the dry period between December 27, 1974 and March 25, 1975. It should be pointed out here that while this work was done in small blocks of coffee, the former was done in fan spacing design. As coffee is normally grown in blocks, the latter findings may be more applicable but further field trials are required on large blocks before this can be established conclusively.

1:5 ROOT DISTRIBUTION. WATER INFILTRATION RATE AND TOPSOIL BULK DENSITY

Root distribution, infiltration rate and topsoil bulk density are plant and soil aspects which bear a direct relationship with crop water use. The amount of water entering the soil is affected by the degree of soil compaction and only water in the rooting zone can be used by the plant roots.

1:5:1 ROOT DISTRIBUTION

A review of literature (De Roo, 1969, Russell, 1971; Newman, 1966; and Weddington, 1971) show there are many methods used in root study. Below is a list of some of these methods:

i) Trench Method:

It is the simplest method of root study techniques. Root distribution can be studied on a wire grid or glass face of the trench.

ii) Washing Back of Soil Profile:

As in (i) a trench is dug and the soil is washed with a jet of water. It is a useful method in wide spaced tree crops like citrus or coffee. Sometimes wires are used to support the roots.

iii) Root Laboratory:

An underground trench with glass windows for observation is called a root laboratory. Plants are grown near the glass windows and their growth is observed through the windows.

iv) Use of Soil Cores:

A volumetric core sampler is used whose volume is known. The soil is washed away after sampling and the weight or length of the roots from the soil core is determined.

Alternatively, roots in defined layers of the soil are separated and weighed.

v) Use of Radioactive Material:

^{86}Rb abd ^{32}p have been used widely. The plant is fed with radioactive material and later soil cores are taken at different depths to determine the extent of radioactivity.

ivi) Laboratory technique:

Plants are grown in polythene bags from which root behavoiurs can be followed.

vii) Use of Water Culture:

Growing of plants in water culture enables the comparison of rooting systems in different plant species.

1:5:2 FACTORS AFFECTING ROOT GROWTH

The root growth of apple in relation to rootstock, soil, seasonal and climatic factors is well documented by Rogers (1939). He found that low soil temperatures checked root growth. Under warm soil conditions a check in root growth was found to coincide with soil drying. It was clear, therefore, that root growth occurs only when soil temperature and moisture are optimal. The importance of temperature in root growth has been shown by many investigators on different tree crops. Nightingale (1935) had come to the same conclusion for apples and peaches. Mouseli (1947) showed that soil temperature limits root growth of citrus trees during the cool season in Israel. The pattern of new root production in raspberry at East Malling was found to correlate with soil temperature. Denisov (1971) in a study of the growth of Almond roots under irrigated conditions concluded that the moisture and temperature of the rhizosphere determine root activity.

In Malawi, Willat (1970) showed that irrigation at all levels significantly increased rooting depth of tea. Under Kenyan conditions, Trench (1933-4) recorded immediate commencement of surface root activity after a heavy rainfall. He further found root growth in coffee continued during the rains and gradually eased off as the dry weather set in. Marloth (1950) citing the studies of Waynick (1930), Cossman (1940) and Mouselise (1947) stated that there was evidence in citrus trees that root growth is limited during periods of soil drying. He further showed that root growth was active in subtropical climates throughout the winter months and as a result concluded that adequate soil moisture was important to prevent a check on root growth.

Soil temperature and moisture are not the only factors affecting root growth. Accumulation of carbon doixide (Cannon and Free, 1925) and depletion of inorganic nutrient materials (Rogers, 1939) are powerful factors in limiting root growth. Variation in food supply from leaves during defoliation have a large influence as well (Heinecke, 1933). Head (1939) recorded small quantities of white root in spring on nitrogen deficient apple trees growing in grass, while NK fertilizer application greatly increased the amount of white root within a few weeks.

In a study of the effects of fruiting and defoliation

(Head, 1969) found that interference with proper functioning of leaves, or with the transport of material from the leaves reduces root development of many crop plants. This was further confirmed by Atkinson (1972) in his study of the influence of simulated mechanical harvesting on seasonal periodicity of black currant root growth.

Plant root growth is affected by many factors. Ashby (1969) groups the variations in soil environment which affect root growth under five headings as follows: the soil atmosphere and drainage, soil temperature, soil water, the soil solution and its reaction, and soil organisms and humus. The first two factors influence growth and activity of the roots as discussed above, while the other three concern the supply of materials available for absorption, and use by the whole plant.

1:5:3 ROOT SYSTEMS OF WOODY TROPICAL CROPS:

Thomas, (1944) investigated the root systems of woody tropical crops grown in Uganda with particular interest in Robusta coffee (*Coffea canephora*). The range of crops studied include Arabica and Excelsa coffees, tea, cocoa and cinchona. An attempt was made to discover whether there was any correlation between the amount of roots present, their depth in the soil, and the distance from the tree. Although no correlation was found, it seemed that when coffee had reached maturity, the distribution of roots was influenced by minor local variations in soil composition more than by distance from the trees.

In compact soil little root of *Coffea canephora* can be expected below 48 cm in Uganda, and the few that had penetrated deeper had followed the traces of dead roots of other plants (Thomas, 1944). The 48 cm depth was believed to comprise at least 95 per cent of the total length of roots. However, most of the roots of Robusta coffee were found in the top 16 cm of the soil and the author considered that at least half of the roots were in this 16 cm layer.

A comparison of Arabica and Excelsa coffees in Uganda by Thomas (1944), with Robusta showed remarkable differences between the length of the roots of Robusta and Arabica coffees. The Arabica coffee roots were not so much concentrated near the surface of the soil but had a distribution resembling that of Arabica coffee roots in acid soils recorded by Nutman (1933). On the other hand, investigations in Puerto Rico have shown a shallow root system of Arabica coffee, with 95 per cent of the roots in the top 12 inches (30 cm) of the soil (Guiscafre-Arrillaga and Gomez, 1940). In Uganda, the root system of Excelsa coffee resembled that of Robusta coffee. The roots seemed to concentrate in the upper layers of the soil, as expected for both coffees are found in association in moist hollows of some forests.

In case of Tea (Thea sinensis), root distribution varied with soil conditions and management. Where soil was heavy and with little disturbance as a result of cultivation, rooting was shallow.

Cocoa (Theobroma cacao) had most of its roots near the surface of the soil, and so did the Para rubber tree (Hevea brasiliensis). Surprisingly the latter species with well-developed tap-root was found to have very few feeding roots at depths below 16 cm.

Cinchona josephiana a broad-leaved vigorous form of C. ledgeriana, does not normally possess a well-developed tap-root even when it is a seedling. The tree was found to have more roots at the lower depths than did Para rubber.

In a study of Arabica coffee rootsystem, Nutman (1933) concluded that although coffee roots exploit 10 ft (3m) of soil, most of the absorbing roots grow horizontally forming "surface plate" of roots inhabiting the upper layers. The surface plate is most developed in cool moist soils. Wallis (1963) found the bulk of the root system of C. arabica to be generally concentrated within the top 3 and 4 feet of soil. This was in contrast to reports by Thomas (1944) for C. canephora and C. excelsa grown in Uganda, and Suarez de Castro et al (1961) for Arabica coffee grown in several places and different soils of Central America, that coffee roots only reached a depth of about 1 foot. Root development differences in Kenya were attributed to alternating conditions of severe drought and seasonal rains in contrast to conditions of more adequate rainfall in coffee growing areas of Central America (Wallis, 1963). Some cases of shallow rooting in coffee are due to poorly drained subsoils (Haarer, 1962).

The study of the distribution of functional roots of Coffea arabica L. in Kenya using ^{32}P, by Huxley et al (1973) revealed the root activity decrease down the rooting zone with higher activity at the topsoil becoming negligible at 180 cm deep.

Considering the distance, the authors recorded higher root activity near the trunk than further from it. The latter finding led Huxley and Cannell (1970) to suggest that close spacing of coffee would in no way be detrimental from the nutritional point of view.

On seasonal changes in root activity of C. arabica, Huxley et al (1973) distinguishes three general patterns of activity in relation to climatic changes:

*After prolonged drought, there is concentration of root activity at mid-depth and near the trunk.

*When the soil is re-wetted, the most uptake is near the surface and especially concentrated at the quarter-row distance (65 cm).

*When roots have been in a fully wetted profile for a short time there is a more general distribution of functional roots.

The implication from these patterns is that, in order to maintain root activity soil must be maintained moist enough.

On plant spacing and root growth, Thomas (1944) wrote on coffee and tea grown in Uganda. In drier areas, tea and coffee are planted at wide spacings to allow maximum area for exploitation of moisture and minimize competition. The wide spacings advised for these crops under Uganda conditions would not give optimum yields in wetter countries, where the supply of water is not a limiting factor to plant growth. He sites an example of Ceylon (presently Sri Lanka) where the present tendency is to adopt closer and closer spacings for tea and to maintain the supply of nitrogen in the soil.

Cultural methods are known to affect the extent of root system of _Coffea arabica_ L. Irrigation of young trees for instance can cause shallow rooting and mulching increases the density of fine roots.(Bull, 1963). Root concentration near the surface is affected by cultivation, where less or minimum cultivation was practised, Thomas (1944) found more roots in the topsoil than where continuous cultivation was practised.

While cultural method are known to modify the coffee root system, Huxley and Cannell (1970) state, "It seems very unlikely that a modification in plant spacing would not, itself, change the extent of rooting". However, they point out that this aspect needs considerable attention as it may be a vital factor in the argument concerning water use. They also commented on water use by coffee in the 10 ft (3m) soil profile. Thus, although water can be used from upto 10 ft, only occasionally is the soil dried out beyond 6 ft (180 cm).

1:6 WATER INFILTRATION RATE

By definition the infiltration rate of a soil is the maximum rate at which a soil, in a given condition at a given time, can absorb rain (Richards, 1952). It may be also be defined as the maximum rate at which a soil will absorb water impounded on the surface at a shallow depth when adequate precautions are taken regarding border or fringe effects (Parr and Bertrand, 1960). Quantitatively, infiltration is the volume of water passing into the soil per unit area per unit time and has the dimensions of velocity. Russell (1973) terms the rate of entry of water into soil its infiltration rate. And this rate, he adds, is initially high for all soils if they are dry. But once they are wet, the rate is dependent on the distribution, continuity and stability of the coarse pores.

To distinguish infiltration rate from permeability, Parr and Bertrand (1960), qualitatively define the latter as the quality or state of a porous medium relating to the readiness with which such a medium conducts or transmits fluids. Percolation is a quantitative term applying to the downward movement of water through soil especially, the downward flow of water in saturated or nearly saturated soil.

The rate of water entry into the soil fluctuates widely between soil types, and also wide differences can be found within a single soil type, depending upon the soil moisture levels and management practices (Parr and Bertrand, 1960). Very permeable soils will have infiltration rates as high as 35 cm/hr, while soils of low permeability will have rates of 0.03 cm/hr or less (Russell, 1973).

When water is flooded on the surface of a dry soil core, the initial percolation rate falls sharply and may take many hours to become steady (Pereira, 1955). Reeve (1953) give times from 50 to 100 hours to reach such equilibrium. The reduction of percolation rate is an important measure of soil stability. In his assessment of structure in tropical soils Pereira (1955) found soil in the poorest structural condition, in each soil type, transmitted water at rates exceeding 9 inches per hour.

Water run-off before the soil reaches its maximum transmission capacity is due to the failure of the heavy rain to infiltrate into surfaces which have slumped and sealed under rainfall impact. Pereira recorded high infiltration rates of 5.8 inches per hour from soil newly broken from napier grass. And low rates of 3 inches per hour, from over-tilled continuous arable land.

Provided maximum soil water conservation can be achieved, high infiltration rate ensures an effective use of water supplies on farms and to plants. In this review, it is not intended to go into the theory of infiltration as detailed by Philip (1958 a & b). The main concern here are the factors that cause the great variations in infiltration rates which normally occur. However, it is appropriate to say something here about the methods of infiltration rate determination.

Many methods have been tried in determination of the soil infiltration rate. Double-ring infiltrometer give comparable results provided large rings are used. Swartzendruber and Tamlin (1961) found that large ring systems with an inner ring of 40-inch diameter were adequate for all conditions they considered in their study. The outer ring performs the useful function of cutting down the effect of lateral movement of water in the soil (Marshall and Stirk, 1950).

Cylinder infiltrometers are metal rings or compartments used in the study of infiltration rates and permeability of soils. The metal rings are usually driven into the soil to depths ranging from a few inches to more than a foot, to hold back the lateral or divergent flow of water from the rings to a minimum

(Parr and Bertrand, 1960). The methods of adding water to these cylinders include such principles as constant head, falling head, and sprinkling applications. In the earlier studies only single rings were employed and many of the data indicated a high degree of variability, probably due in part to uncontrolled lateral movement of water from the rings. Later double-ring or multi-ring devices were used to minimize divergent by means of a buffer area surrounding the central compartment. Measurements of infiltration rates in the centre compartment are supposed to be indicative of the vertical component of flow (Parr and Bertrand).

The method has a serious limitation in the way the ring devices are placed. Most of the methods of placement cause a certain degree of disturbance of natural conditions, and the resulting disturbances manifested as shattering or compaction may cause a large variation in infiltration rates between replicated runs. The interface between the soil and the side of the metal ring may cause unnatural seepage planes which result in abnormally high infiltration rates. Variability of data caused by ring placement could be overcome by leaving the rings in place over an extended period, before, or during a series of measurements.

A further limitation to the use of rings is the problem of entrapped air inside the soilcolumn, caused when a constant head of water is applied upon the surface. The inability of air to escape from the soil under conditions of saturated flow was found by Powers (1934) to create an internal air cushion which results in an impeded downward flow movement.

1:6:1 FACTORS INFLUENCING INFILTRATION RATES AND PERMEABILITY OF SOILS:

It has been mentioned in the opening paragraphs that variations in infiltration rates occur in the same soil type as well as different soil types. Horton (1940) suggested the following factors affecting infiltration rate: (1) soil type and soil profile; (2) biological factors and macrostructure within the soil; (3) vegetal cover. Horton was of the opinion that infiltration rate is governed mainly by conditions at or near the soil surface.

Lewis and Powers (1938) listed a large number of factors affecting infiltration rates and they divided them into two major groups (1) those factors influencing the infiltration rate at a given time and point, such as texture, structure, and organic matter; (2) those factors influencing the average infiltration rate over considerable area and period of time such as slope, vegetation and surface roughness.

The rapid reduction in the rate of intake by cultivated soils, as rain falls on the surface, is accompanied by the formation of a thin, compact layer at the surface, and water is able to pass through this layer slowly (Duley, 1939). The influence of vegetative factors studied by Duley and Russell (1939) by leaving crop residues at the soil surface revealed: (1) infiltration rate was greatly increased, (2) evaporation from the surface soil was reduced, (3) water erosion was reduced, and (4) wind erosion was reduced. The overall effect was that greater soil water conservation was effected.

Christiansen (1944) studied the effect of entrapped air upon the permeability of soil. He found some air entrapped in the soil regardless of whether the water was applied from top, from the bottom by capillarity, or under a head. Entrapped air caused a large reduction in permeability compared with completely saturated soils.

A study of orchard plots under different systems of soil management and of annual and perennial cover crops to determine the effects of treatments upon physical characteristics of the soil and its moisture relationships was undertaken by Li and associates (1942). The findings were: different soil covers produced marked changes in soil organic matter level and in physical properties, which in turn altered the infiltration rate and moisture status of the soil. Cultivation, with annual crops reduced permeability and a more compact surface layer resulted, further resulting in poor infiltration characteristics.

Musgrave (1955) summarized the major factors that affect intake of water by soil as follows: (1) surface conditions and the amount of protection against the impact of rain; (2) internal characteristics of the soil mass, including pores, depth and thickness of the permeable portion, degree of swelling of clay and colloids, content of organic matter, and degree of aggregation, (3) soil moisture content and degree of saturation; (4) duration of rainfall or application of water; (5) season of the year and temperature of soil and water.

The influence of the products of microbial activity on soil structure and infiltration rate was investigated by McCalla (1942). Addition of microbial decomposition products of plant residues resulted in a marked increase in the water stability of the soil structure which increased the infiltration rate significantly.

The importance of soil genesis and morphology in infiltration was emphasised in a study of pedological relations of infiltration phenomena (Smith, 1949). He observed that the initial moisture content of soil had a great influence on infiltration; that the type of soil structure, especially at the B-horizon, was of great importance; and cultivation of the soil that caused fragmentation at the B-horizon was responsible for a reduction in infiltration rate. The conclusion was that apart from infiltration being a function of porosity and texture, soil structure and moisture content are also important. The infiltration rate was found to vary inversely with soil moisture content.

Tisdall (1951) used a ring infiltrometer to investigate antecedent soil moisture and its relation to infiltration rate. An observation was made that the lower the initial soil moisture, the higher the infiltration rate. It was found that the longer the time of water application, the less effect antecedent soil moisture would have. In the first few hours of an infiltration run, antecedent moisture was thought a probable major factor determining initial infiltration rates.

An important observation by Bertoni *et al* (1958) in the U.S.A. was that final infiltration rates varied with the season of the year. Their data showed final infiltration rates increasing gradually from March to mid-June and then increase sharply until late July, followed by a decrease until mid-October. They suggested that the higher infiltration rates during July as compared to the Spring and fall seasons was due to increased vegetal cover protecting the soil surface against sealing. The same phenomen could be influenced by factors such as lower surface moisture and consequent greater deep soil cracking, and high soil and water temperatures (Parr and Bertrand, 1960).

The importance of high infiltration rates have been cited firstly by Parr and Bertrand (1960) as means of achieving maximum soil water conservation, thus making effective use of water supply. And secondly by Nelson and Muckenhirn (1941) as one of the primary factors affecting the amount of surface run-off in the field. The infiltration rate is ordinarily at its maximum when water is first applied to the soil, and then as pore spaces become filled and swelling occurs, it decreases until a more or less stable minimum is reached (Nelson and Muckenhirn, 1941).

1:7 TOPSOIL BULK DENSITY

The bulk density is the mass of dry soil per unit volume including the air space. It is also the ratio of the weight of soil to that of the weight of equal volume of water. It is expressed in grammes per cubic centimetre. It differs from soil particle density in that, the latter refers to mass per unit volume of the soil particles (Buckman and Brady, 1969). McIntyre and Loveday (1974) define Bulk Density as the ratio of the mass of a given sample to its bulk volume. The mass is obtained by drying the sample to a constant weight at 105°C, and the bulk volume is that of soil particles plus pore space at the time of sampling. For expansive soils, bulk density is dependent on the moisture content.

Bulk density is a method of expressing soil weight and takes into consideration the total soil space, i.e. space occupied by solids and pore spaces.

1:7:1 IMPORTANCE OF BULK DENSITY

The importance of bulk density was explained by McIntyre and Loveday (1974). Bulk density is required firstly for determining the degree of compactness as a measure of soil structure, secondly as an indicator of earation status (for which the moisture content is also required), and thirdly to convert soil moisture and nutrients values from gravimetric to the volumetric basis.

Excessive compaction is believed to cause or, at least, to be related to decreases in the productivity of many soils (Rosenberg, 1964). This as Fontaine (1958) pointed out is affected by increased mechanical impedence, reduced aeration, altered moisture availability and heat flux which follows from increased soil density and reduced pore space.

1:7:2 FACTORS AFFECTING BULK DENSITY

Many factors are known to affect soil bulk density. Buckman and Brady (1969), Brady (1974) give an account of some of these factors.

Bulk density is determined by the quantity of the pore spaces and soil solids, thus loose and porous soils have low weights per unit volume and compact soil have high values.

Particles of sandy soils tend to lie in close contact so that such soils have high bulk densities. Sandy soils may also have very low organic matter.

Particles of finer surface soils such as silt, clay loams and clays do not rest close together. This is because they are well granulated a condition encouraged by their relatively high organic matter contents. These soils are fluffy, and porous which result in low bulk density values.

There is always a tendency for bulk density to rise with profile depth. This results from a lower content of organic matter, less aggregation and root penetration, and a compaction caused by the weight of the overlying layers.

The system of crop and soil management employed on a given soil is likely to influence its bulk density, especially of the surface layers.

Addition of farm manure in large amounts tend to lower the weight figures of surface soils and hence the bulk density.

Intensive cultivation increases the bulk density by destroying the soil structure and accelerating or diminishing organic matter in the soil by faster decomposition. This happens after the soil has settled as cultivation lower surface bulk density immediately after cultivation (N.M. Fisher personal communication).

1:7:3 METHODS OF DETERMINING BULK DENSITY

Soil bulk density is determined in the laboratory. The most common laboratory methods use a core or clod. Generally the bulk density of a small clod will be significantly greater than that determined on a core (Tisdall, 1951; McIntyre and Loveday, 1968). This is said to be due to poor representation of inter-clod space. The opposite effect can occur if the sample is taken from a wet soil depth, in that a core confined laterally by the sampling tube can have a higher bulk density than a clod from the same depth, for the latter can expand in three dimensions when the confining forces due to surrounding soil are removed. The bulk density of a clod approximates that of the core, when a large clod is isolated (McIntyre and Loveday, 1974).

The core method is preferred to clod in bulk density determination. The bulk volume of a core obtained by an integral sampler is determined from the dimensions of the cylinder. For a composite sampler with internal relief, the relevant diameter is that of the cutting edge. For the comparison of bulk densities of expansive soils, the soil cores should all be brought to a standard matric suction. This is not necessary for non-expanding soils.

CHAPTER II

MATERIALS AND METHODS

INCLUDING DATA COLLECTION AND ANALYSIS

2:1 MATERIALS

2:1:1 INTENSIVE COFFEE: 1971 PLANTING

In 1971, three blocks of coffee (*Coffea arabica* L, CV. SL 28) were planted at the Coffee Research Station, Ruiru, with spacings: 1 x 1, 1 x 1.5 and 1 x 2 metres at plant populations of 10,000, 6,666 and 5,000 trees/ha respectively. The actual number of trees planted in these blocks were 1462, 680 and 510 corresponding with the spacings given above. The experimental blocks occupied areas of 289 m^2, 424 m^2 and 578 m^2 respectively within which only 289 coffee trees of each planted blocks were included in the marked experimental areas.

The coffee was intended to be managed by stumping rather than conventional pruning and had not been pruned upto the time when this experiment started. It had been irrigated twice in each dry season, weeded and given 260 kg/ha/year of nitrogen fertilizer applied three times a year in form of calcium ammonium nitrate (CAN). The fertilizer programme for these intensive blocks allows 25 gm of N/tree for 1 x 1m, 37.5 gm of N/tree for 1 x 1.5 m and 50 gm of N/tree for 1 x 2 m spacings. These blocks were selected in April 1976 as the material for the crop water use study which lasted a period of 12 months upto March 1977.

2:1:2 CONVENTIONAL COFFEE: 1956 PLANTING

This conventionally spaced coffee i.e. 2.74 x 2.74 m (9ft x 9ft) was planted at the Coffee Research Station, Ruiru in 1956. The experimental block occupied an area of 1074 m^2 enclosing 143 trees. The whole plot was planted with two cultivars SL 28 and SL 34 of Coffea arabica L. on alternate rows. The coffee has been pruned on the capped multiple stem system and is adjacent to the intensive blocks discussed in 2:1:1. In the absence of suitable material, comparable in age and management but at conventional spacing, a block was marked in this plot for comparison purposes.

This block represents the standard management for conventionally spaced coffee. In making any deductions for comparative purposes, the age and pruning management differences are to be borne in mind.

2:1:3 INTENSIVE COFFEE: 1969 PLANTING

Three blocks of close spaced coffee were planted in 1969. One block was planted at 1.07 x 0.92 m (3.6 x 3ft) staggered (10,255 trees/ha), another at 1 x 1.5 m and the third one at 1 x 2 m spacing. 72 trees per block were used for soil sampling for moisture determination. These blocks were selected in February 1977 to confirm the findings of intensive blocks discussed in 2:1:1.

The coffee was intended to be managed by stumping like the 1971 planting above. The trees had been clean stumped in April 1975 after completing the first cycle, and were carrying their first crop after stumping at the time data for this study were collected. This coffee is irrigated regularly to prevent occurrence of water stress.

2:1:4 SOILS:

The main experimental site on plots 7 and 14 which are adjacent to each other is on slightly sloping area of Kikuyu dark red friable (loam) soil (Keter, 1974). The Kikuyu red loam soil was described by Pereira (1957) and Keter (1974) as being deep, porous and well drained. Pereira pointed out that this type of soil is capable of holding 300 mm (12 inches) of available water at field capacity. This amount of water was considered held in the top three metres (10 feet) of the soil profile. The top soils on plots 7 and 14 appear dark in colour, which can be attributed to the humus staining at the surface.

On plot 12, where blocks 17, 24 and 27 were situated, the soil has a different history and appearance. The slope on this land is far greater than was found in plots 7 and 14. The land was under napier grass (Pennisetum purpureum L.) before it was planted with coffee. The soils here are reddish from the surface unlike plots 7 and 14, this may be due to the slope and use which has not allowed humus accumulation on the surface. However, the soils have a field texture of a friable loam like that of the soils of plots 7 and 14. Keter (1974) differentiated between the Kikuyu red and dark red friable clay (loam) soils by the greater depth of dark top soil in the latter.

The soil depth in plot 12 was found to be less than that of plots 7 and 14. On four occasions during sampling, the soil augers reached a layer, locally referred to as "murram" consisting of hard ferruginous nodules, which probably overlies a fairly hard parent rock (trachyte) at 285 cm depth. It is a common feature in the area to find relatively shallow soils on the steeper slopes of the catena in contrast to the generally deep soils of the flattish summits and upper slope areas.

2:1:5 METEOROLOGICAL STATION:

The weather conditions are recorded at a Meteorological Station at the Coffee Research Station, Ruiru. The meteorological site is approximately one kilometre from the experimental site.

The altitude of this station is 1609 metres (5300 feet) above sea level. The meteorological site is equipped to record temperature, radiation, evaporation, windrun, humidity, rainfall, sunshine duration and dew point among other elements of climatic interest.

Rainfall recording has been going on for the last 32 years. The recording of other elements although more recent is of high standard. The climatic factors so recorded are used for estimation of crop water use by a modified Penman method as given by Doorenbos and Pruitt (1975).

2:2 METHODS, DATA COLLECTION AND ANALYSIS

Gravimetric Moisture determination and weekly monitoring of soil moisture by gypsum resistance blocks began in April 1976. Subsidiary investigations were included and carried out during the 12 month experimental period. These studies are coffee root distribution, water infiltration rates and topsoil bulk density. Climatic data has been compiled for the whole of experimental period to be used as explained in 2:1:5 above.

2:2:1 MAIN EXPERIMENTS

Throughout the experiment two methods were employed to determine water consumption rate in four blocks of coffee spaced at 1 x 1, 1 x 1.5, 1 x 2 and 2.74 x 2.74 metres. These methods were:-

(a) Gravimetric method

(b) Gypsum resistance block method

The experimental plots were in the middle of the blocks to avoid possible edge effects. The blocks were divided into 8 replications each of 28 coffee trees. These replications provided one sampling site at each sampling date.

Gravimetric soil sampling was later extended to three other blocks on a completely different site. These new blocks were spaced at 1.07 x 0.92 m (3.6 ft x 3 ft) staggered, 1 x 1.5m and 1 x 2 m. They were included in this exercise as mentioned elsewhere to confirm the findings of the first three intensive blocks. For that reason and due to the limited area available, only 6 replications were marked out per coffee spacing.

At the beginning of the experiment, two replicates of gypsum resistance blocks were installed approximately in the middle of the four experimental blocks. Each replicate had 12 resistance block units, giving a total of 96 units for the four coffee blocks. The gypsum resistance blocks were installed in the soil profiles on 15th April, 1976, and remained in the soil for the whole of the experimental period to March 1977. This was desirable for the gypsum blocks to stabilize in the soil, and since after sometime the plant roots were expected to grow around the once disturbed soil, the resistance readings were expected to reflect moisture changes in the undisturbed soil.

(a) GRAVIMETRIC METHOD

This method of soil moisture determination involves soil sampling, weighing, drying and reweighing. For this experiment, soil samples were taken at different depths down the soil profile to three metres. The sampling operation was carried out at four week intervals for a period of 12 months.

At each sampling date, eight soil profiles were randomly chosen per coffee spacing, which constituted 32 profiles in total. This work required 2 days to complete. Two teams of 3 labourers and 1 Field Assistant worked in the field, while a third Field Assistant was stationed in the Soil Laboratory to weigh the samples as they came in. During the 12 month experimental period, 13 soil samples were completed. An extra sampling was done on 22nd February, 1977 in three other coffee blocks where 6 replications per block were sampled.

EQUIPMENT:

Five pieces of equipment were used for sampling, transporting, weighing and drying of the soil samples. Sample trays, balance and an oven were used along with two described here.

(i) Jarret Soil Augers, diameter 10 cm (4") of Australian type of which 3 were required for the operation. The stems of these augers were marked in centimetres according to the depths of the soil to be sampled.

(ii) Samples Tins: The tins are airtight and were numbered at the bottom and the lids. The weights of these tins and their lids were known and recorded to two places of decimal.

PROCEDURE

After putting the sample in the tin the lid was replaced immediately to prevent soil moisture loss to the atmosphere. The samples were put under shade or cover while sampling was going on. The samples were transferred to the laboratory soon after one profile was finished and the wet weights taken immediately.

The soil samples were then placed in the oven with lids removed. The temperature was set at 105°C and left for 24 hours or more until constant weights were reached.

After drying, the samples were removed from the oven, the tin lids replaced and their weights taken immediately to avoid moisture gain from the atmosphere. At times it was found necessary to cool the samples in a dessicator. Occasionally, the weights of the empty receptacles were taken on the balance to check any possible changes with time and repeated use. All the weights were taken to the nearest 0.01 gm.

In relation to gravimetric soil moisture determination, investigations into soil field capacity, wilting point and bulk density down the three metres profile were necessary. The field capacity and wilting point estimations were carried out at $\frac{1}{3}$ and 15 atmospheres respectively using the soil moisture equipment at the Department of Soil Science, University of Nairobi. Field capacity was determined on "undisturbed" soil cores while wilting point was done on disturbed soil. The data used in this study is mainly a mean of three samples which were completely soaked before being put under pressure in the moisture equipment. The samples were weighed after being subjected to the defined pressure and dried in an oven at 105°C., before taking their dry weights. The bulk density determination was carried out using facilities at the Coffee Research Station,Ruiru. For this determination, a volumetric sampler was required to give samples of known volume.

DATA ANALYSIS:

The coffee layout was such that strict statistical comparison of the density effects was not possible, the replicates being sites within the same block. For this reason, data is first presented with a mean of eight and standard error for each density and soil layer independently.

The calculation of moisture percentage in each soil sample was worked from the difference in fresh weight and dry samples. Percent moisture was obtained by dividing the weight of water driven out by drying by the weight of oven-dry soil and multiplying the quotient by hundred. The formula used is as follows:

$$\% \text{ moisture} = \frac{\text{weight of water}}{\text{weight of oven-dry soil}} \times 100$$

The same formula applies for moisture held at both the field capacity and wilting points. The moisture available to the plant is that held between these two points.

Moisture contents expressed as the percentages of oven-dry soil are of limited use in quantitative investigations of crop water use, when changes in the total moisture content of the soil profile are measured at different times of the season. Expressing moisture content in inches or millimetres of water is more convenient because rainfall and irrigation are measured in inches or millimetres of water over a field or plot.

In order to convert percentage moisture into volumetric water content, the bulk density of the soil must be known. This requires measurements on undisturbed soil cores.

Soil cores of known volume were taken with a volumetric sampler at intervals (similar to those for moisture determination) down the profile over the root depth (three metres). Each core was dried at 105°C for 24 hours and weighed after oven drying. From the weights and volume so obtained, the bulk density was calculated for all samples. By multiplying the bulk density with a corresponding soil layer thickness, conversion factors were obtained, thus:-

$$\text{Conversion factor} = \text{Bulk density} \times H$$

where: $$\text{Bulk density} = \frac{\text{weight of the soil sample}}{\text{weight of the same volume of water}}$$

H is the soil layer thickness in millimetres.

By multiplying the conversion factor by the percent soil moisture, the amount of water in millimetres was obtained for a particular layer, thus:-

Water in millimetres = % soil moisture x conversion factor

The working agrees with that of Peters (1965) in which he gave the conversion formula as:-

$$Pv = Pw\ (B)(1/w)$$

where: Pv = water percent per unit volume,

Pw = water percent per oven dry weight,

B = bulk density

w = density of water

The author further gave a formula to work the amount of water in a given depth as:-

Millimetres (inches) of water = (Pv)(depth)

where: pv = water percent per unit volume obtained from the first formula.

The water quantity in the whole coffee rooting depth of three metres was then calculated by adding individual quantities in different soil layers of the whole profile. This was done for all soil samplings completed between April, 1976 and March 1977.

(b) GYPSUM RESISTANCE BLOCK METHOD

Gypsum blocks are electrical resistance blocks which measure changes in soil moisture by means of changes in electrical resistance. The water content of the block changes with that of the soil producing measurable changes in the electrical conductivity between the electrodes. The electrical resistance blocks are recommended for measuring metric potential in the field.

In this project, gypsum blocks were used to monitor weekly soil moisture changes. The resistance recording was done every Monday morning. It took about three minutes to connect the terminals, generate the current and take a reading in "Log-ohms" using a Sciex Moisture Meter for each resistant unit.

Before the gypsum blocks were installed in the field, they were placed in water for 24 hours, after which their initial minimum resistance was recorded. The minimum resistance was re-checked first before the block units were put in the holes.

Any increase or decrease in resistance of a particular block was compared with the initial minimum resistance records. It was intended to follow the drying and wetting of the soil in this manner over the experimental period.

The Sciex moisture meter has a recording range of 2.0 - 6.0 log - ohms. In wet soils, the readings tend to be on the lower end while in drying soil, the reverse happens. During the dry periods, the soils were found to develop resistances greater than the recordable maximum of the meter scale. When this happened, the reading was put down as greater than six (>6.0), as the exact resistance could not be ascertained.

The plants were observed closely as the resistance approached 4.8 log - ohms which Pereira (1955) found to correspond to the wilting point. This occurred as the prolonged dry period of August-October 1976 started.

DATA ANALYSIS:

This data analysis was mainly done by following resistance in log-ohms building up and decline as the soil dries or becomes wet. This was possible as the meter recording scale range and initial minimum resistance were known.

The increase or decrease in resistance can also be followed throughout the experimental period by finding the difference between resistance recorded and the initial minimum resistance. In the same way, the drying of the soil in the region of wilting point as determined by Pereira (1955) can be followed.

After thorough critical examination of the data, most of analytical work was based on the gypsum blocks in the upper portion of the soil profile 0-165 cm, instead of the whole coffee rooting zone of three metres. This is supported by gravimetric data analysis which showed little changes over time in water content at depths greater than 165 cm.

2:2:2 CLIMATIC DATA

For the purpose of this experiment, mean air temperatures, relative himidity, sunshine hours per day, wind velocity, radiation and rainfall were carefully collected for 12 months from April 1976 to March 1977. These records were grouped as ten-day means before they were used for computation. This was necessary to take care of what Pereira (1957) called great weather variability over longer periods around the equator.

The data so collected was used in computation of crop water use estimates by modified Penman method as outlined by Doorenbos and Pruitt (1975). In this method the reference crop evapotranspiration, ETo in mm/day is first estimated from the formula:

$$ETo = W.Rn + (1-W)\ f(u)\ (eo-ea)$$

where W: is a weighting factor

Rn: the net radiation or estimate thereof,

f(u): function of wind speed

eo: saturated vapour pressure at the mean air temperature.

ea: actual vapour pressure

The terms in this formula are derived from the tables of Doorenbos and Pruitt. The net radiation can be calculated in two ways, firstly by using sunshine hours per day or secondly the daily distillation from Gunn-Bellani Radiation Integrator. When the second method is used, distillation is first converted into radiation using the formula supplied by the East African Meteorological Department, for the particular instrument used. For radiometer No. 1058:-

$$R = 29.76\,d + 51$$

where R = radiation in cals/day

d = distillation in ml/day

This was the method preferred for ETo computation.

The next step after estimation of reference crop potential evapotranspiration, is to estimate crop evapotranspiration ET(crop) from the formula:-

$$ET(crop) = ETo.kc$$

where kc is a crop coefficient.

The crop coefficient recommended for conventionally spaced coffee is 0.9. In coffee where weed growth is allowed, coefficients of 1.05 and 1.1 have been suggested (Doorenbos & Pruitt, 1975). In this study all these coefficients have been used plus 1.08, which is a mean of 1.05 and 1.1. The idea being to try which one of them fits the close-spaced coffee.

ETo estimates are first computed for 10-day mean and then for 28 day intervals. This was found necessary as the soil sampling intervals were also 4 weeks.

2:2:3 ROOT DISTRIBUTION

Root distribution is a subsidiary investigation included in this study in an attempt to discover the effects of close spacing on the root growth pattern particularly in the upper 50 cm of the soil. Two methods were used in the four main experimental blocks and one of them, the trench method, was extended in two other blocks of close-spacing coffee in a completely different site to try and confirm the findings of the first blocks.

Root distribution was first studied using a volumetric soil core sampler. The root samples were collected, using the core sampler, at the midpoints of the diagonals of four coffee trees in the intensive planting, and at the dripline of the tree canopy approximately 1 metre from the tree trunk in the conventional spacing. The samples were obtained at three soil depths 0-6 , 20-26 and 40-46. Although it was intended to get samples from 0-20, 20-40 and 40-60 cm. this was not possible because of the small size of the sampler.

The determination required the use of a soil auger and a core sampler. The auger has a wider diameter of 15 cm (6") while the core sampler was 10 cm (4"). This was necessary because the auger was used to open the way for the core sampler. The use of the core sampler facilitated comparison of roots from equal soil volumes.

PROCEDURE:

*A core sample is taken by pressing the sampler into the soil at the required depth of 0-6, 20-26 and 40-46 cm. This was done carefully to press the sampler far enough to fill it but not so far as to compress the soil in the confined space of the sampler.

*The sampler and its contents was removed carefully to preserve the packing of the soil.

*The two cylinders of the sampler were separated retaining the undisturbed soil in the inner cylinder.

*The soil extending beyond each end of the sample holder was trimmed using a straight-edged knife.

*The sample was spread on polythene sheet where the roots were carefully sorted from the soil. Care was exercised to separate the coffee roots from those of other plants.

*The soil was discarded and the roots were placed in sample tins labelled like those used for gravimetric soil samples, and the numbers were recorded against their depths.

*The root samples were transferred to the laboratory in these tins. They were carefully washed in a jet of water while placed on a 0.5 mm mesh sieve to avoid losing small roots.

*The roots were then dried in paper towels and their fresh weights recorded.

*To get oven-dry weights, the samples were dried in the oven at a temperature range of 60–80°C for 24 hours.

Trench Method:

This method was employed in root study of all 1969 and 1971 coffee plantings. Four trenches of 1 metre long by 0.3 metre width and 0.7 metre deep were dug in each block at right angles to the direction of the coffee rows. The trenches were dug in sets of two separated by one coffee plant. Each set of trenches facilitated root sampling of three coffee trees, giving a total of six trees sampled per spacing.

The root samples were obtained by careful sampling on the vertical face of the trench. This was done by cutting a rectangular block of soil 20 x 15 x 5 at different trench depths. What could not be achieved by core sampler method was achieved here as samples were taken between 0-20, 20-40 and 40-60 cm. deep.

After the rectangular blocks containing roots were cut the procedure of root sorting, washing, drying and weighing was the same as for core sampling outlined above.

DATA ANALYSIS:

It was not possible to compare the root data obtained by core and trench methods because of the disparity in volumes used. As a result the two sets of data were analysed independently of each other. The analysis involved the calculation of the mean root weights. From the total weights, the mean root weights were calculated.

The separate analysis is aimed at comparing root distribution at different root densities based on two sample depths of 0-6, 20-26 and 40-46 cm for core sampler method and 0-20, 20-40 and 40-60 cm depth for trench method.

2:2:4 WATER INFILTRATION RATES:

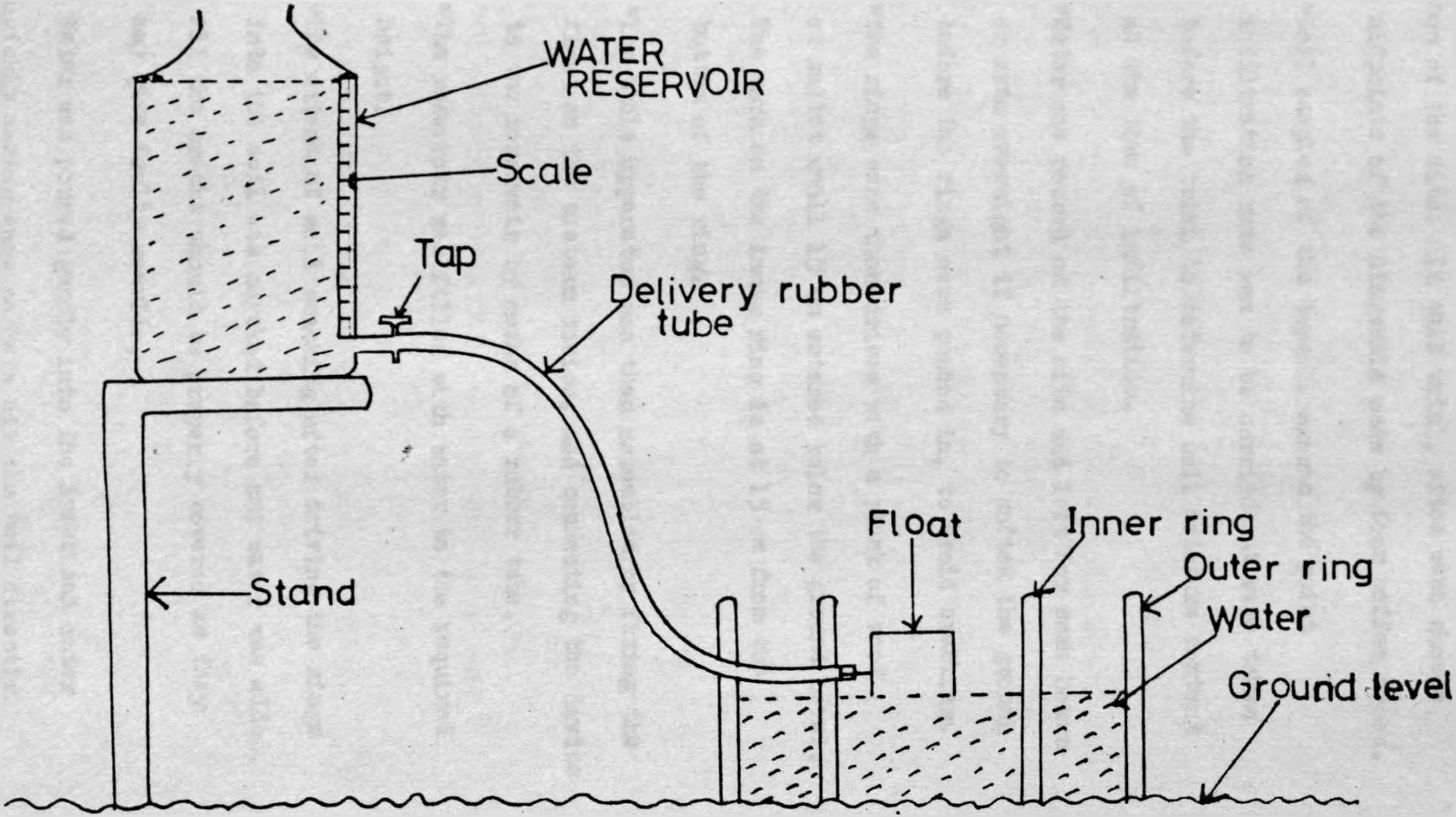
The aim was to find whether close spacing in coffee has any effect on the rate at which water enters the soil. For this reason, infiltration rate determinations were carried out in the intensive coffee of 1971 planting. The "Double-Ring" method was used.

The apparatus consisted of two rings of different diameters (see diagram 1). The inner ring had a mark which shows the depth to which it should be driven in the soil during the infiltration trial. Both rings had a hole about a third of the way down the side. Through this hole a rubber tube from the water reservoir passed in the outer ring and is connected to a cistern device fixed at the hole, at the side of the inner ring, which has a float which falls or rises with the level of the water in the cylinder. As the float falls, it opens the valve for the water from the reservoir to enter the ring and replace that which has entered the ground by infiltration.

The water reservoir was supported on a metallic or wooden stand, at a higher level than the infiltration rings. It had a tap at its side near the bottom. During the trial, this tap is connected to the inner ring by a rubber tube, which acts as a delivery tube, when the tap is opened. In order to be able to record the amount of water that infiltrates, a marked piece of paper is attached along one side of the reservoir. This paper is graduated in millimetres or inches and should be protected from water.

The use of double-ring apparatus was preferred as the inner cylinder measure the infiltration rates while the outer one maintain vertical water movement from the inner cylinder by reducing lateral water flow.

DIAGRAM : DOUBLE RING INFILTROMETER



PROCEDURE:

Infiltration rate determination start off with the selection of the site. In this trial, sites were chosen at the midpoints of the diagonals made by four coffee trees.

*Soil samples of the topsoil around the point infiltration rate was to be carried out were taken before the trial to determine soil moisture content at the time of infiltration.

*Water was poured on the site and left for some hours or even overnight if necessary to soften the ground before the rings were pushed in, to avoid cracking.

*The rings were then driven with a plank of wood or mallet until 15 cm entered below the ground level. The mark on the inner ring is at 15 cm from the bottom of the ring.

*The whole apparatus was then assembled by fixing the float on the cistern device, and connecting the device to the reservoir by means of a rubber tube.

*The reservoir was filled with water to the required height.

*The extent of soil cracking after driving the rings into the soil was checked before any water was added. All the cracks should be properly covered as they may give faulty results.

Water was poured gently into the inner and outer rings quickly making sure no jets hit the soil directly.

The water impact can be broken by putting one hand in the ring so that water lands on it before hitting the ground. The water level was quickly brought to the level at which the cistern device was closed by the bouyancy of the float. At this point the tap in the reservoir was opened and any fall in its water level was recorded as infiltration after multiplying by afactor derived from the diameters of the reservoir and the infiltration ring which were different. The amount of water entering the soil can be recorded easily using a stopwatch.

The water in the outer ring also infiltrates the ground. Its head should be maintained by adding water from an external source from time to time. As before, care should be taken to avoid water hitting the ground surface directly.

DATA ANALYSIS:

Infiltration rate trials were carried out for a duration of two hours at one point. The recording was done every minute for the first 5 minutes and afterwards at 10, 20, 30, 45, 60, 90, 120 minutes.

Five sets of data per coffee spacing were collected while the topsoil moisture content was approximately 28.3% and three sets at 38.1 % moisture. These moisture levels are referred to as dry and wet, as the first trials were done before the onset of the rains while the second trials were done after some rains had fallen. The data collected as above gives cumulative infiltration rate for the two hours at each point.

The data analysis mainly involved the calculation of mean infiltration rates per coffee density, the infiltration rate per unit time for different trials individually and the mean infiltration rates for all the sites per coffee spacing.

The plot of infiltration rate per unit time was expected to show the point at which the infiltration steady state was reached. The calculation of mean infiltration rates was done to facilitate comparison of different coffee spacings.

2:2:5 TOP SOIL BULK DENSITY

Soil bulk density is the ratio of the mass to the bulk volume of soil particles plus pore spaces in a sample. The mass is determined after drying the soil sample to constant weight at 105°C, and the volume is that of the sample as taken in the field.

Bulk density is a widely used value and is needed for:-

(a) Converting water percentage by weight to content by volume.

(b) Calculating porosity when the particle density is known.

(c) Estimating the weight of a volume of soil, such as the weight of a furrow slice.

Bulk density varies with structural conditions of the soil, particularly as they affect packing. Consequently, it is often used as an indirect measure of soil structure. Bulk density is expressed in weight per cubic volume e.g. grams per cubic centimetre (g/cm^3).

Soil samples for bulk density determination are taken carefully using a volumetric sampler to avoid compaction, and to maintain the natural soil structure. Extensive soil sampling was carried out under coffee blocks taking samples at 0-3, 3-6, 15-18 and 18-21 cm depths.

PROCEDURE:

The procedure outlined here covers all the operations from the field, through the laboratory upto the time data was available for bulk density calculation.

*The sampler was driven into the soil surface far enough to fill the sampler, but not so far as to compress the soil in the confined space of the sampler.

*The sampler and its contents was removed carefully to preserve the natural structure and packing of the soil.

*The two cylinders were separated retaining the undisturbed soil in the inner cylinder.

*The soil extending beyond each end of the sample holder was trimmed with a straight-edged knife. (The soil sample volume was taken as the same as volume of the sample holder).

*The soil was transferred into a container, and placed in an oven set at 105°C. until constant weight was reached. The dry weight of each sample was recorded.

Using this method, samples as many as 21 per plot per coffee spacing were collected at each sampling depth. After going through the above process the data was used for the calculation of topsoil bulk density.

DATA ANALYSIS:

The bulk density has been defined above as the ratio of mass to the bulk cvolume. When only one sampler is used as was the case in this trial, a constant volume is used as the mass varied from point to point and possibly depth to depth. The volume of the cylinder was determined from its diameter and depth. The soil mass was determined by weighing oven-dry samples.

The calculation of bulk density was worked out using the formula:-

$$\text{Bulk density} = \frac{\text{weight of oven-dry soil}}{\text{volume of the same soil}} \ g/cm^3$$

The denominator in this formula is sometimes replaced by 'Equal volume of water' which in actual sense is the volume of the sampler. After calculating bulk density for each sample, the means per depth and coffee spacings were computed for comparison purposes.

2:2:6 YIELDS

The intensive coffee blocks planted in 1971 on which the study was based had reached its maximum yield peak by the time the project was started. However, there were yield records for the first four years this coffee had cropped. In addition, quality samples were taken during the experimental period. This exercise was extended in the conventional spacing in an attempt to discover the effect of water stress on bean quality.

DATA ANALYSIS:

The yield data for the coffee crop years 1973/74, 1974/75, 1975/76 and 1976/77 has been analysed to give:-

(a) Total cherry weight per hectare

(b) Total clean coffee per hectare

The data was also used to calculate mean yield for the four years and the cherry yield per tree per coffee spacing.

The quality sample data was used to calculate the clean/parchment coffee percentages.

CHAPTER III

RESULTS

3:1 CROP WATER USE:

3:1:1 GRAVIMETRIC SOIL MOISTURE

In this section soil moisture expressed as a percent by weight of oven-dry soil is presented in tables and graphs. In this way the figures are intended to depict the soil moisture fluctuations over wet and dry seasons.

Tables 1(A-M) show soil moisture expressed as a percentage by weight of oven-dry soil. Columns two to four of these tables are mean percentage moisture of eight replicates per coffee spacing, while the fifth column present the pooled standard errors of the means. Columns seven to nine present the variance ratios for orthogonal comparisons between conventional and close coffee spacings; linear and quadratic comparisons within the close spacings. In assessing these comparisons it should be remembered that the "replicates" were profiles within unreplicated blocks of coffee.

Table I N presents both the percent and the amount of water in millimetres held by different soil horizons down the three metre soil profile, at 15 and $\frac{1}{3}$ atmosphere respectively. In this table the percentage soil moisture values are means of three samples, obtained as explained in chapter II above.

The soil sampling on 14th and 15th April, 1976 was done during the long rains, hence the high percentage figures particularly in the top soil layers shown in table 1 A. A comparison of the amount of water in the soil between the conventional and close spaced coffee shows that there was no statistically significant difference in most of the soil layers. However, significant differences were recorded at 30-45, 75, 195 and from 255 cm down to 300 cm depths. Where significant differences occurred, conventional coffee had wetter soil at 30-75 cm and drier soil at 255-300 cm.

In April, 1976 the soil moisture content increased as the coffee spacing increased for the soil layers down to 105 cm. Since the quadratic term was significant at these depths, the moisture relationship was curvilinear, for water use at 0-15 cm. The moisture percent by weight was 39.0%, 37.9% and 41.4% for 1x1, 1x1.5 and 1 x 2 m spacing respectively. This was due to the time of sampling as there was heavy rainfall between 14th and 15th April, sampling dates.

During the wet months, more soil moisture differences were recorded in the topsoil especially within the close spacings. This was shown to be true for the soil sampling on 23rd and 24th November, 1976 during the short rains (Table II) and January 1977 (Table IK). The differences in these months were not as pronounced as those recorded for April, 1976 probably due to the poor short rains in that year.

At certain times of the year the conventional coffee spacing was found to have less soil moisture in the lower horizons, than the close spacings. This was true for April (Table IA), June (Table IC), July (Table ID), between August and September (Table IF), October (Table IH) and December (Table IJ).

This could be explained by the fact that the 2.74 x 2.74 m coffee was much older than the intensive blocks, and as such had better established root system toexploit soil moisture from greater depths. Further to this, 1976 was a dry year and there being no ample moisture near the soil surface for the plants to extract, water from lower soil layers was extracted by the deeper roots.

TABLE I A: PERCENTAGE SOIL MOISTURE ON 14TH AND 15TH APRIL, 1976 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	Coffee spacing in metres				S.E.	Variance ration (F)		
	1X1	1x1.5	1x2	2.74x2.74		Convent. v's close	Linear	Quadratic
0-15	39.0	37.9	41.4	38.9	.70	.43 NS	5.82**	7.12**
15-30	37.8	36.6	44.5	41.4	.78	3.81 NS	36.50**	22.44**
30-45	32.0	29.1	41.9	42.4	1.63	14.05**	31.22**	21.87**
75	28.5	29.0	41.4	44.0	.91	110.67**	100.86**	28.87**
105	29.8	29.6	37.5	34.8	1.70	1.63 NS	10.30**	3.80 NS
135	33.5	32.6	35.5	34.7	1.12	.42 NS	1.60 NS	1.93 NS
165	33.9	33.5	35.6	33.2	.73	1.80 NS	2.70 NS	1.95 NS
195	34.7	33.6	35.5	33.3	.49	5.39**	1.36 NS	6.38**
225	35.1	34.1	34.8	33.4	.56	3.85 NS	.14 NS	1.54 NS
255	34.2	34.5	34.4	33.4	.38	4.92**	.14 NS	.19 NS
285	33.9	34.5	34.6	32.9	.34	13.70**	2.18 NS	.37 NS
300	33.8	34.3	34.4	32.8	.39	9.34**	1.20 NS	.18 NS

TABLE IB: PERCENTAGE SOIL MOISTURE ON 11TH AND 12TH MAY, 1976 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	Coffee spacing in metres					Variance ratio (F)		
	1x1	1x1.5	1 x 2	2.74x2.74	S.E.	Convent. v's close	Linear	Quadratic
0-15	33.8	29.4	29.0	28.6	.76	6.07**	20.48**	4.74**
15-30	34.1	33.0	32.7	32.5	.52	1.66^{NS}	3.70^{NS}	.40^{NS}
30-45	35.0	36.0	34.8	34.8	.43	.90^{NS}	.11^{NS}	.46^{NS}
75	35.6	36.3	36.4	35.2	.53	2.21^{NS}	1.16^{NS}	.22^{NS}
105	37.5	37.4	37.6	37.6	.35	.07^{NS}	.04^{NS}	.13^{NS}
135	37.7	37.6	37.4	38.5	.36	5.03**	.35^{NS}	.01^{NS}
165	35.9	36.4	37.4	36.7	.68	.03^{NS}	2.49^{NS}	.09^{NS}
195	34.7	35.9	35.7	36.7	.64	3.05^{NS}	1.27^{NS}	.83^{NS}
225	34.7	35.9	35.3	36.4	.56	2.93^{NS}	.58^{NS}	1.74^{NS}
255	34.0	35.3	35.0	35.0	.49	.17^{NS}	2.11^{NS}	1.79^{NS}
285	33.7	34.8	34.8	34.7	.44	.28^{NS}	3.23^{NS}	1.08^{NS}
300	33.9	34.4	34.2	34.8	.65	.73^{NS}	.11^{NS}	.20^{NS}

TABLE I C: PERCENTAGE SOIL MOISTURE ON 8TH AND 9TH JUNE, 1976 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	Coffee spacing in metres				S.E.	Variance ratio (F)		
	1 x 1	1 x 1.5	1 x 2	2.74x2.74		Convent. v's close	Linear	Quadratic
0-15	29.6	28.7	27.1	27.6	1.20	.40^{NS}	2.21^{NS}	.06^{NS}
15-30	31.0	30.8	30.9	30.8	.83	.01^{NS}	.01^{NS}	.02^{NS}
30-45	31.3	32.3	31.4	31.6	.88	.0^{NS}	.01^{NS}	.80^{NS}
75	33.9	34.3	33.7	32.0	.57	9.21**	.06^{NS}	.53^{NS}
105	35.4	35.9	34.9	34.2	.65	2.59^{NS}	.30^{NS}	.90^{NS}
135	35.8	36.8	36.0	34.9	.40	7.92**	.13^{NS}	3.38^{NS}
165	35.2	35.6	35.2	34.6	.61	1.10^{NS}	.0^{NS}	.29^{NS}
195	35.3	35.7	35.2	34.8	.43	1.54^{NS}	.03^{NS}	.77^{NS}
225	35.0	35.5	35.2	34.3	.45	3.31^{NS}	.10^{NS}	.54^{NS}
255	34.3	35.7	34.5	33.5	.47	6.20**	.09^{NS}	5.24**
285	34.0	34.9	35.7	33.2	.51	8.25**	5.72**	.01^{NS}
300	34.3	34.8	34.4	33.0	.52	6.25**	.02^{NS}	.50^{NS}

TABLE I D: PERCENTAGE SOIL MOISTURE ON 6TH AND 7TH JULY, 1976 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	coffee spacing in metres				S.E.	Variance ratio (F)		
	1 x 1	1 x 1.5	1 x 2	2.74x2.74		Convent. v's close	Linear	Quadratic
0-15	32.1	31.9	32.6	29.7	.60	13.69**	.37^{NS}	.39^{NS}
15-30	32.7	33.4	34.7	32.8	.46	2.29^{NS}	9.52**	.29^{NS}
30-45	32.3	34.2	35.3	33.0	.44	3.48^{NS}	24.00**	.57^{NS}
75	32.0	33.6	34.2	31.3	.58	8.93**	7.45**	.51^{NS}
105	34.7	35.9	34.7	33.7	.61	4.03^{NS}	.0^{NS}	2.63^{NS}
135	35.4	35.3	35.0	35.3	.58	.01^{NS}	.25^{NS}	.02^{NS}
165	34.5	35.1	34.7	34.7	.45	.02^{NS}	.10^{NS}	.84^{NS}
195	34.8	34.7	35.0	34.1	.40	2.64^{NS}	.13^{NS}	.18^{NS}
225	35.1	34.8	34.5	34.8	.36	.0^{NS}	1.38^{NS}	.0^{NS}
255	34.4	34.6	34.1	34.2	.32	.22^{NS}	.47^{NS}	.86^{NS}
285	34.2	35.3	34.0	33.4	.35	7.73**	.17^{NS}	8.17**
300	34.2	34.6	34.5	33.3	.36	7.41**	.35^{NS}	.32^{NS}

TABLE I E: PERCENTAGE SOIL MOISTURE ON 3RD AND 4TH AUGUST, 1976 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	coffee spacing in metres				S.E.	Variance ratio (F)		
	1 x 1	1 x 1.5	1 x 2	2.74x2.74		Covent. v's close	Linear	Quadratic
0-15	27.1	27.3	28.2	29.3	.53	8.44**	2.18^{NS}	.29^{NS}
15-30	29.0	29.9	29.9	31.0	.39	10.02**	1.80^{NS}	.90^{NS}
30-45	29.1	29.9	30.6	31.3	.55	5.27**	3.85^{NS}	.01^{NS}
75	30.7	31.7	32.5	31.4	.65	.10^{NS}	3.93^{NS}	.02^{NS}
105	33.0	35.0	34.7	33.7	.44	1.14^{NS}	7.71**	4.70**
135	34.3	35.7	35.6	35.2	.35	.0^{NS}	7.71**	3.33^{NS}
165	33.4	35.1	35.7	34.1	.32	3.17^{NS}	27.84**	2.12^{NS}
195	34.4	34.8	35.3	33.9	.25	12.44**	7.71**	.03^{NS}
225	34.3	34.6	35.3	34.1	.32	3.17^{NS}	5.26**	.28^{NS}
255	34.0	34.3	34.8	33.6	.35	3.75^{NS}	2.72^{NS}	.06^{NS}
285	34.0	34.4	34.6	33.6	.27	5.76**	2.57^{NS}	.10^{NS}
300	33.9	34.4	34.7	33.8	.30	2.59^{NS}	3.88^{NS}	.08^{NS}

TABLE I F: PERCENTAGE SOIL MOISTURE ON 31ST AUGUST AND 1ST SEPTEMBER 1976 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	coffee spacing in metres				S.E.	Variance ratio (F)		
	1 x 1	1 x 1.5	1 x 2	2.74x2.74		Convent. v's close	Linear	Quadratic
0-15	22.6	23.2	20.6	22.0	.30	.04^{NS}	6.72**	5.74**
15-30	26.0	26.2	26.5	24.9	.73	2.54^{NS}	.24^{NS}	.0^{NS}
30-45	26.7	27.5	27.6	26.9	.43	.58^{NS}	2.35^{NS}	.47^{NS}
75	28.9	30.1	29.4	28.6	.66	1.33^{NS}	.30^{NS}	1.42^{NS}
105	31.5	32.4	32.8	32.0	.95	.05^{NS}	.95^{NS}	.05^{NS}
135	34.4	35.0	34.1	31.7	1.40	3.00^{NS}	.02^{NS}	.19^{NS}
165	34.1	34.6	33.7	30.7	1.39	4.63**	.04^{NS}	.17^{NS}
195	34.0	34.2	34.3	33.7	.39	1.11^{NS}	.31^{NS}	.01^{NS}
225	34.2	34.6	34.3	33.4	.32	7.01**	.05^{NS}	.82^{NS}
255	33.8	34.3	34.2	32.7	.48	9.97**	.54^{NS}	.41^{NS}
285	34.0	33.7	34.1	32.9	.43	4.51**	.03^{NS}	.46^{NS}
300	34.0	33.9	33.9	32.8	.27	14.82**	.08^{NS}	.03^{NS}

TABLE I G: PERCENTAGE SOIL MOISTURE ON 28TH AND 29TH SEPTEMBER 1976 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	coffee spacing in metres				S.E.	Variance ratio (F)		
	1 x 1	1 x 1.5	1 x 2	2.74x2.74		Convent. v's close	Linear	Quadratic
0-15	24.4	23.3	21.6	23.7	.64	.66^{NS}	9.62**	.15^{NS}
15-30	26.2	25.8	25.6	25.6	.60	.15^{NS}	.51^{NS}	.02^{NS}
30-45	26.7	27.1	26.6	26.9	.45	.04^{NS}	.03^{NS}	.68^{NS}
75	27.9	30.5	28.9	29.2	.94	.01^{NS}	.57^{NS}	3.38^{NS}
105	31.7	34.0	32.0	30.0	.94	5.63**	.05^{NS}	3.51^{NS}
135	33.2	34.5	33.9	32.4	.94	1.87^{NS}	.28^{NS}	.70^{NS}
165	33.4	34.4	33.6	33.3	.57	.60^{NS}	.06^{NS}	1.71^{NS}
195	33.9	34.4	34.1	33.4	.39	2.73^{NS}	.14^{NS}	.72^{NS}
225	33.8	34.3	34.1	34.1	.27	.01^{NS}	.64^{NS}	1.17^{NS}
255	33.8	34.1	33.9	33.3	.43	1.72^{NS}	.03^{NS}	.24^{NS}
285	33.4	34.6	33.9	33.6	.32	1.06^{NS}	1.32^{NS}	6.33**
300	33.3	34.8	33.7	33.2	.35	3.43^{NS}	.68^{NS}	9.59**

TABLE I H: PERCENTAGE SOIL MOISTURE ON 26TH AND 27TH OCTOBER 1976 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	coffee spacing in metres				S.E.	Variance ratio (F)		
	1 x 1	1 x 1.5	1 x 2	2.74x2.74		Convent. v's close	Linear	Quadratic
0-15	23.0	21.2	19.2	21.1	.46	.00^{NS}	35.22**	.03^{NS}
15-30	24.5	24.6	24.1	24.8	.50	.49^{NS}	.33^{NS}	.25^{NS}
30-45	25.8	25.7	25.6	26.2	.32	1.97^{NS}	.21^{NS}	.00^{NS}
75	26.8	27.7	27.9	26.7	.35	3.83^{NS}	5.26**	.71^{NS}
105	29.5	31.9	30.5	28.1	.66	11.39**	1.18^{NS}	5.70**
135	32.6	33.5	33.5	30.1	.66	16.86**	.95^{NS}	.32^{NS}
165	33.3	33.9	34.0	31.6	.42	21.00**	1.51^{NS}	.26^{NS}
195	34.0	34.5	33.8	33.0	.27	13.96**	.31^{NS}	3.69^{NS}
225	34.0	34.1	34.0	33.3	.25	7.68**	.00^{NS}	.13^{NS}
255	33.9	33.7	33.9	32.8	.27	12.32**	.00^{NS}	.41^{NS}
285	33.8	34.1	33.9	33.6	.35	.71^{NS}	.04^{NS}	.35^{NS}
300	33.5	34.0	33.9	33.2	.29	3.48^{NS}	1.03^{NS}	.77^{NS}

TABLE I I: PERCENTAGE SOIL MOISTURE ON 23RD AND 24TH NOVEMBER 1976 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	6666 coffee spacing in metres					Variance ratio (F)		
	1 x 1	1 x 1.5	1 x 2	2.74x2.74	S.E.	Convent. v's close	Linear	Quadratic
0-15	37.2	34.3	34.5	29.5	.80	40.83**	5.83**	2.56^{NS}
15-30	37.6	29.6	31.9	31.1	1.04	2.63^{NS}	15.25**	16.60**
30-45	31.4	27.0	27.3	27.8	.86	.60^{NS}	11.44**	5.01**
75	28.1	28.0	27.8	26.9	.40	5.42**	.29^{NS}	.01^{NS}
105	29.6	30.4	30.3	28.2	.72	5.39**	.49^{NS}	.27^{NS}
135	31.0	32.3	33.2	30.5	.74	3.88^{NS}	4.50**	.05^{NS}
165	31.9	33.2	33.5	31.4	.64	4.06^{NS}	3.22^{NS}	.42^{NS}
195	32.5	33.4	33.8	32.7	.51	.82^{NS}	3.25^{NS}	.16^{NS}
225	33.6	34.1	34.1	33.3	.32	3.17^{NS}	1.32^{NS}	.44^{NS}
255	33.3	33.2	33.7	33.1	.35	.60^{NS}	.71^{NS}	.53^{NS}
285	32.2	33.7	34.1	33.4	.45	.02^{NS}	9.26**	1.03^{NS}
300	33.6	33.8	33.9	33.5	.27	.76^{NS}	.64^{NS}	.02^{NS}

TABLE I K: PERCENTAGE SOIL MOISTURE ON 18TH AND 19TH JANUARY, 1977 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	Coffee spacing in metres				S.E.	Variance ratio (F)		
	1x1	1x1.5	1x2	2.74x2.74		Convent. v's close	Linear	Quadratic
0-15	29.3	25.3	25.7	26.3	.56	.54^{NS}	21.25**	10.58**
15-30	32.5	30.2	31.0	30.8	.40	.89^{NS}	7.14**	10.17**
30-45	32.6	31.9	32.2	32.1	.53	.05^{NS}	.29^{NS}	.61^{NS}
75	33.6	33.3	31.0	32.6	.55	.00^{NS}	11.36**	2.24^{NS}
105	32.6	34.3	31.9	33.5	.79	.40^{NS}	.41^{NS}	4.63**
135	32.2	33.0	30.7	32.7	.80	.63^{NS}	1.76^{NS}	2.51^{NS}
165	32.9	33.3	32.5	32.1	.73	.93^{NS}	.56^{NS}	.47^{NS}
195	33.3	33.0	33.0	33.4	.51	.26^{NS}	.18^{NS}	.06^{NS}
225	33.1	33.3	33.3	33.3	.32	.04^{NS}	.22^{NS}	.07^{NS}
255	33.5	33.3	32.9	33.1	.32	.13^{NS}	1.80^{NS}	.07^{NS}
285	33.3	33.7	33.3	33.1	.23	1.85^{NS}	.00^{NS}	2.37^{NS}
300	33.4	33.5	33.3	33.1	.20	1.80^{NS}	.13^{NS}	.40^{NS}

TABLE I J: PERCENTAGE SOIL MOISTURE ON 21ST AND 22nd DECEMBER 1976 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	coffee spacing in metres				S.E.	Variance ratio (F)		
	1 x 1	1 x 1.5	1 x 2	2.74x2.74		Convent. v's close	Linear	Quadratic
0-15	38.2	37.8	36.7	36.0	.38	13.64**	8.33**	.61^{NS}
15-30	38.9	39.5	39.3	37.0	.39	25.36**	.54^{NS}	.72^{NS}
30-45	39.0	38.6	38.9	38.5	.42	.51^{NS}	.03^{NS}	.49^{NS}
75	37.2	35.6	36.9	37.6	.52	2.97^{NS}	.17^{NS}	5.19**
105	36.1	33.4	35.4	34.9	.93	.00^{NS}	.29^{NS}	4.32**
135	33.6	32.8	34.5	33.0	.94	.35^{NS}	.47^{NS}	1.20^{NS}
165	34.0	33.4	34.7	32.3	.54	7.57**	.82^{NS}	2.02^{NS}
195	34.4	34.0	34.6	33.1	.47	5.25**	.09^{NS}	.77^{NS}
225	34.8	34.0	34.7	33.4	.42	5.50**	.03^{NS}	2.27^{NS}
255	33.9	34.1	34.6	33.2	.40	4.76**	1.56^{NS}	.10^{NS}
285	34.0	34.2	34.6	33.8	.32	1.72^{NS}	1.89^{NS}	.07^{NS}
300	33.8	34.3	34.6	33.5	.35	3.43^{NS}	2.72^{NS}	.06^{NS}

TABLE I L: PERCENTAGE SOIL MOISTURE ON 18TH AND 19TH FEBRUARY, 1977 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	Coffee spacing in metres				S.E	Variance ratio (F)		
	1x1	1x1.5	1x2	2.74x2.74		Convent. v's close	Linear	Quadratic
0-15	28.6	23.5	23.0	25.8	.84	$.63^{NS}$	22.56**	5.07**
15-30	29.4	27.8	27.5	29.9	.64	5.08**	4.40**	$.69^{NS}$
30-45	29.7	29.0	29.1	31.3	.73	5.91**	$.34^{NS}$	$.20^{NS}$
75	32.1	30.9	31.5	30.4	.70	1.88^{NS}	$.37^{NS}$	1.12^{NS}
105	32.2	33.7	32.5	32.2	.77	$.46^{NS}$	$.08^{NS}$	2.07^{NS}
135	33.2	34.0	33.1	32.5	.86	$.90^{NS}$	$.01^{NS}$	$.66^{NS}$
165	32.8	34.0	33.4	32.8	.71	$.55^{NS}$	$.36^{NS}$	1.09^{NS}
195	33.5	34.0	33.2	33.0	.55	$.82^{NS}$	$.15^{NS}$	$.95^{NS}$
225	34.3	34.2	33.8	33.6	.39	1.29^{NS}	$.86^{NS}$	$.10^{NS}$
255	33.6	33.9	33.6	33.1	.29	3.60^{NS}	$.00^{NS}$	$.80^{NS}$
285	33.6	33.9	33.6	33.1	.27	4.15^{NS}	$.00^{NS}$	$.92^{NS}$
300	33.2	34.2	33.2	33.1	.23	5.13**	$.00^{NS}$	14.82**

TABLE I M: PERCENTAGE SOIL MOISTURE ON 15TH AND 16TH MARCH, 1977 UNDER FOUR BLOCKS OF COFFEE

SOIL DEPTH (CM)	coffee spacing in metres				S.E.	Variance ratio (F)		
	1x1	1x1.5	1 x2	2.74x2.74		Convent. v's close	Linear	Quadratic
0-15	27.8	25.3	25.0	26.2	.72	.04^{NS}	7.76**	1.60^{NS}
15-30	28.8	28.0	27.6	25.8	.66	9.50**	1.67^{NS}	.06^{NS}
30-45	30.2	28.2	28.1	30.9	.59	9.49**	6.53**	1.78^{NS}
75	32.4	28.4	29.2	29.9	.59	.02^{NS}	15.28**	11.46**
105	34.0	30.9	31.9	30.4	.77	4.56**	3.85^{NS}	4.89**
135	35.2	32.6	32.9	31.6	.70	6.11**	5.57**	2.95**
165	34.4	33.1	33.1	32.5	.54	2.83^{NS}	2.99^{NS}	1.00^{NS}
195	34.1	33.3	33.4	32.9	.45	1.88^{NS}	1.26^{NS}	.69^{NS}
225	33.7	33.2	33.4	33.3	.38	.10^{NS}	.33^{NS}	.61^{NS}
255	33.6	33.3	33.5	32.8	.35	2.67^{NS}	.04^{NS}	.37^{NS}
285	33.5	33.4	33.6	32.7	.32	5.05^{NS}	.05^{NS}	.16^{NS}
300	33.5	33.3	33.5	32.7	.48	1.79^{NS}	.00^{NS}	.12^{NS}

With the exception of the above, it can be generally tstated that very little differences in percentage soil moisture between different spacings could be detected statistically. The main differences appear to occur within the same coffee spacing depending on the time of the year. The highest percentages by weight of oven-dry soil were recorded during the rains while the lowest were recorded during the dry season. This soil moisture fluctuation was found to be caused mainly by the seasonal rainfall and the intervening dry periods.

Table IN shows soil moisture status at 15 and $\frac{1}{3}$ atmospheres, corresponding to field capacity and wilting point respectively. The quantity of water held by the three metre soil profile at 15 atmospheres agree with the findings of Pereira (1957) of 914.4 mm (36") at wilting point but that at $\frac{1}{3}$ atmospheres is very much below his figure of 1219.2 mm (48"). In the same table, the soil bulk density used in the conversion of gravimetric soil moisture into volumetric values, down the profile is also shown in the second column.

In the course of the experiment a trend was noticed whereby the peecentage soil moisture in the subsoils tended to be higher in the intermediate spacing of the three high density coffee plantings. Although this increase was not outstanding in the final statistical analysis as presented in table I(A-M) above, the trend was further investigated on 22nd February, 1977, on an independent layout on the station. The findings of this investigation are presented in the two tables I O and I P.

TABLE I N: SOIL MOISTURE STATUS AT ⅓ AND 15 ATMOSPHERES

SOIL DEPTH (CM)	BULK DENSITY (g/cm^3)	PERCENTAGE MOISTURE		AMOUNT OF WATER (MM)	
		15 ATMOS	⅓ ATMOS	15 ATMOS.	⅓ ATMOS.
0-15	.93	26.1	36.5	36.5	51.1
15-30	.95	27.7	35.4	39.6	50.6
30-45	.97	28.9	35.2	42.2	51.4
75	.97	29.5	35.1	85.9	102.1
105	.98	30.0	35.6	88.2	104.7
135	1.00	30.0	35.2	90.0	105.6
165	1.03	29.8	35.5	92.1	109.7
195	1.04	30.8	35.9	96.1	112.0
225	1.04	30.8	35.3	96.1	120.1
255	1.07	30.8	35.2	98.9	113.0
285	1.07	31.0	34.5	99.5	110.7
300	1.10	30.6	34.7	50.5	57.3
TOTAL				915.6	1026.9

TABLE I O: PERCENTAGE SOIL MOISTURE ON 22ND FEBRUARY, 1977 IN COFFEE REGULARLY IRRIGATED

SOIL DEPTH (CM)	Coffee spacing in metres				Variance ratio (F)	
	.92 x 1.07	1 x 1.5	1 x 2	S.E.	Linear	Quadratic
0-15	27.9	25.6	25.9	1.05	1.84^{NS}	1.04^{NS}
15-30	29.7	28.8	28.5	1.01	$.72^{NS}$	$.06^{NS}$
30-45	29.1	30.7	31.4	.46	13.04**	$.67^{NS}$
75	30.6	33.8	30.4	.55	$.07^{NS}$	24.48**
105	32.4	35.7	31.1	.51	3.32^{NS}	40.53**
135	34.4	37.1	32.8	.68	2.83^{NS}	18.02**
165	35.6	38.2	34.6	.54	1.75^{NS}	22.35**
195	36.1	38.1	34.3	.39	10.80**	37.38**
225	36.6	38.9	35.4	.36	5.69**	44.27**
255	37.3	38.9	36.1	.56	2.38^{NS}	10.64**
285	37.1	38.7	36.3	.35	2.67^{NS}	22.23**
300	36.7	38.4	36.3	.42	$.48^{NS}$	14.44**

TABLE I P: AMOUNT OF WATER (MM) IN THREE METRE SOIL PROFILE ON 22ND FEBRUARY, 1977, IN COFFEE REGULARLY IRRIGATED

SOIL DEPTH (CM)	Area per coffeeplant (m^2)			Variance ratio (F)		
	0.98	1.5	2.0	S.E.	Linear	Quadratic
0-15	39.06	35.84	36.31	1.46	1.718 NS	1.050 NS
15-30	42.47	41.18	40.69	1.43	.805 NS	.075 NS
30-45	42.49	44.82	41.57	2.50	.061 NS	.351 NS
75	89.05	98.36	88.48	1.57	.086 NS	25.369**
105	95.26	104.96	91.51	1.55	2.967 NS	40.003**
135	103.20	111.30	98.24	1.91	14.004**	20.255**
165	110.00	118.04	107.00	1.60	1.672 NS	23.995**
195	112.63	118.87	102.39	1.80	16.131**	26.761**
225	114.19	121.37	110.38	1.23	5.009**	35.059**
255	119.73	124.87	115.66	1.43	4.148 NS	17.113**
285	119.09	124.23	116.50	1.20	2.296 NS	19.553**
300	60.56	63.36	57.88	2.00	0.00 NS	2.927 NS
TOTAL	1047.73	1107.20	1006.61		7.936**	21.360**

Table I 0, clearly shows that pecentage soil moisture by weight of oven-dry soil increases quadratically from 75 cm. down to 300 cm. soil depth as the coffee spacing increases from 1 x 1m. through 1 x 1.5 to 1 x 2m. The same trend is repeated when the amount of water in millimetres is considered for different soil layers (Table IP). This finding provides independent evidence that the plant density of 1 x 1.5m appear to retain more water in the soil irrespective of the irrigation treatment. This coffee had been irrigated on 31st January, about three weeks before the soil sampling.

Table IP, further shows that there was an increase in the total amount of water in the soil at the higher plant density, although the curvilinear relationship remained significant.

It is important to note that the total quantities of water in the soil profiles in this regularly irrigated coffee sampled on 22nd February, 1977 was 1047.73 mm, 1107.20 mm and 1006.61 mm for 1.07 x .92, 1 x 1.5 and 1 x 2 m coffee spacings respectively. These figures had a mean of 1047.73 mm of water which compare very well with 1026.90 mm at ⅓ atmospheres presented in table IN. The fact that these irrigated blocks had greater quantities of water than the estimated FC shows that these soils can hold more water than that estimated by laboratory determination at ⅓ bar. This could as well be due to different soils used for the soil moisture determinations.

The total amount of water in the three metre soil profile was calculated in an attempt to discover the existence of differences between coffee densities at each sampling date. The figures are presented in table 10 which shows:-

*For all coffee spacings between mid-April and early August 1976, soil moisture content was between 1000 and 1,100 mm.

*From late August to late November, 1976, the soil moisture was permanently below 1000 mm, for all spacings.

*In December 1976 and January 1977, immediately following the short rains, the soil moisture increased to over 1000 mm, except in the two wider spacings where soil water was slightly less than 1000 mm in January.

*In February and March, 1977, the soil moisture fell again for all the spacings except 1 x 1 m which had 1010.50 mm in March.

TABLE I Q: TOTAL AMOUNT OF WATER (MM) IN THREE METRE SOIL PROFILE AT EACH SAMPLING DATE.

DATES 1976/77		coffee spacing in metres					Variance ratio (F)		
		1x1	1x1.5	1x2	2.74x2.74	S.E.	Convent. V's close	Linear	Quadratic
APRIL	14 & 15	1023.40	1009.80	1132.16	1097.60	5.94	6.40**	83.90**	43.70**
MAY	11 & 12	1074.90	1087.65	1084.40	1088.50	7.19	$.09^{NS}$	$.44^{NS}$	$.41^{NS}$
JUNE	8 & 9	1036.50	1060.10	1040.70	1018.10	7.18	1.86^{NS}	$.09^{NS}$	2.99^{NS}
JULY	6 & 7	1041.50	1058.51	1052.70	1026.90	6.67	29.17**	$.71^{NS}$	$.98^{NS}$
AUG.	3 & 4	1002.70	1027.80	1041.00	1016.11	7.06	$.15^{NS}$	7.37**	$.24^{NS}$
AUG. 31 & SEPT. 1		979.58	993.90	984.60	946.98	7.35	3.53^{NS}	$.12^{NS}$	$.12^{NS}$
SEPT.	28 & 29	964.70	999.96	975.30	962.60	7.35	$.70^{NS}$	$.52^{NS}$	5.54**
OCT.	26 & 27	955.00	969.90	960.40	926.40	7.37	2.88^{NS}	$.13^{NS}$	$.91^{NS}$
NOV.	23 & 24	984.00	981.30	992.40	950.80	6.06	4.20**	$.48^{NS}$	$.43^{NS}$
DEC.	21 & 22	1075.90	1057.25	1082.20	1048.20	5.95	1.98^{NS}	$.28^{NS}$	4.51**
JAN.	18 & 19	1003.70	1002.10	979.08	993.70	6.56	$.01^{NS}$	3.52^{NS}	$.89^{NS}$
FEB.	15 & 16	996.60	997.90	983.50	981.70	6.93	$.31^{NS}$	$.89^{NS}$	$.43^{NS}$
MAR.	15 & 16	1010.50	966.60	974.37	962.10	7.08	1.18^{NS}	$.72^{NS}$	4.44**

The table shows that, in a relatively wet season like April to August, all the soils under coffee tend to have reasonably high moisture contents irrespective of plant density. In like manner, during the dry season, from August to November, 1976, a general decline in soil moisture took place. Here again, the plant density does not seem to have played a significant role. This statement is strongly supported by the evidence in table IQ where a comparative analysis between the conventional and close, close versus close spacings are presented.

*Apart from the month of April, where all the comparisons turned out to be significant, it was only in two other dates in July and November, 1976 that conventionally spaced coffee had significantly less soil moisture than the intensive plantings.

*On 3rd and 4th August, 1976 the amount of water in the soil profiles increased linearly as the coffee spacing increased.

*Within the close spaced coffee the relationship between the three spacings turned out to be curvilinear in the months of September, December, 1976 and March, 1977. For all statistical comparisons in this table, significant differences are very rare isolated cases. Otherwise nonsignificant differences were most common.

The changes with time are illustrated by plotting percentage soil moisture by weight of oven-dry soil against time in Figures 1(A-I), from May, 1976 to March, 1977. The graphs are drawn on layer by layer basis down to 165 cm. depth thereafter two other layers at 225 and 300 cm are presented.

At 0-15 cm. soil depth (Fig. 1a) in May which was during the long rains, soil moisture percentages were about 29% for all coffee spacings except 1 x 1m which had about 34%. There was a general decrease in soil moisture under all coffee spacings in June followed by a maximum rise in July before occurrence of dry season in August. From July to October, the trend was such that soil moisture declined sharply and had fallen below the determined 15 atmospheres moisture percentage for that particular layer by mid-August. Due to the fact that the short rains in 1976 started very late in November, October turned out to be the driest month in that year and hence the lowest percent moisture reached especially in 1 x 2 and 2.74 x 2.74 coffee spacings.

The highest point reached in 0-15 cm was about 38% moisture content in December in the two closest spacings of 1 x 1 and 1 x 1.5 m. This high peak was immediately followed by a sharp drop through January and February 1977, and seemed to stabilize between 25 and 28% moisture content in March 1977.

At 15-30 cm soil depth (Fig. 1b) the soil moisture pattern was similar to that in 0-15 cm discussed above. An important point to note here is that, the lowest percentage soil moisture reached in October in this layer was higher - 24.1%, while the highest moisture content reached in December was still higher than that reached in the former layer. This can be attributed to the effects of evaporation and feeder roots near the soil surface.

This general trend was also seen at 30-45 cm, 75 cm, and 105 cm soil depths. In all these figures, the deeper the sampling layer, the high the soil moisture particularly during the dry seasons. During the driest months of 1976 i.e. August to October, the percent moisture content was lower than determined at 15 atmospheres down to 135 cm. The nearer the surface, the greater was this disparity.

At 105 cm depth soil moisture content was below the 15 atmespheres percentage in two intensive plantings (1 x 1½ and 1 x 2m), in October, and November. From 135 cm downwards the moisture contents tended to fall with time at all depths down to 300 cm. and showed no rewetting after the short rains.

Another trend starting at 165 cm and continued in 225 cm and 300 cm soil layers, is that of percentage soil moisture was progressively higher than the 15 atmospheres percentages as one moves down the soil profile particularly during the dry months.

The above discovery is very important because it shows that coffee plants make use of the water in the upper soil layers. and that in the greater depths remain relatively at the same level irrespective of the season. Between May 1976 and March 1977, there was a decrease of about 35 mm of soil water in 165-300 cm soil depth with the highest decrease of 9.9mm and lowest of 3.0 mm at 165 cm and 300 cm respectively.

Fig 1a: PERCENTAGE SOIL MOISTURE AT 0-15Cm. DEPTH, 4-WEEK INTERVALS

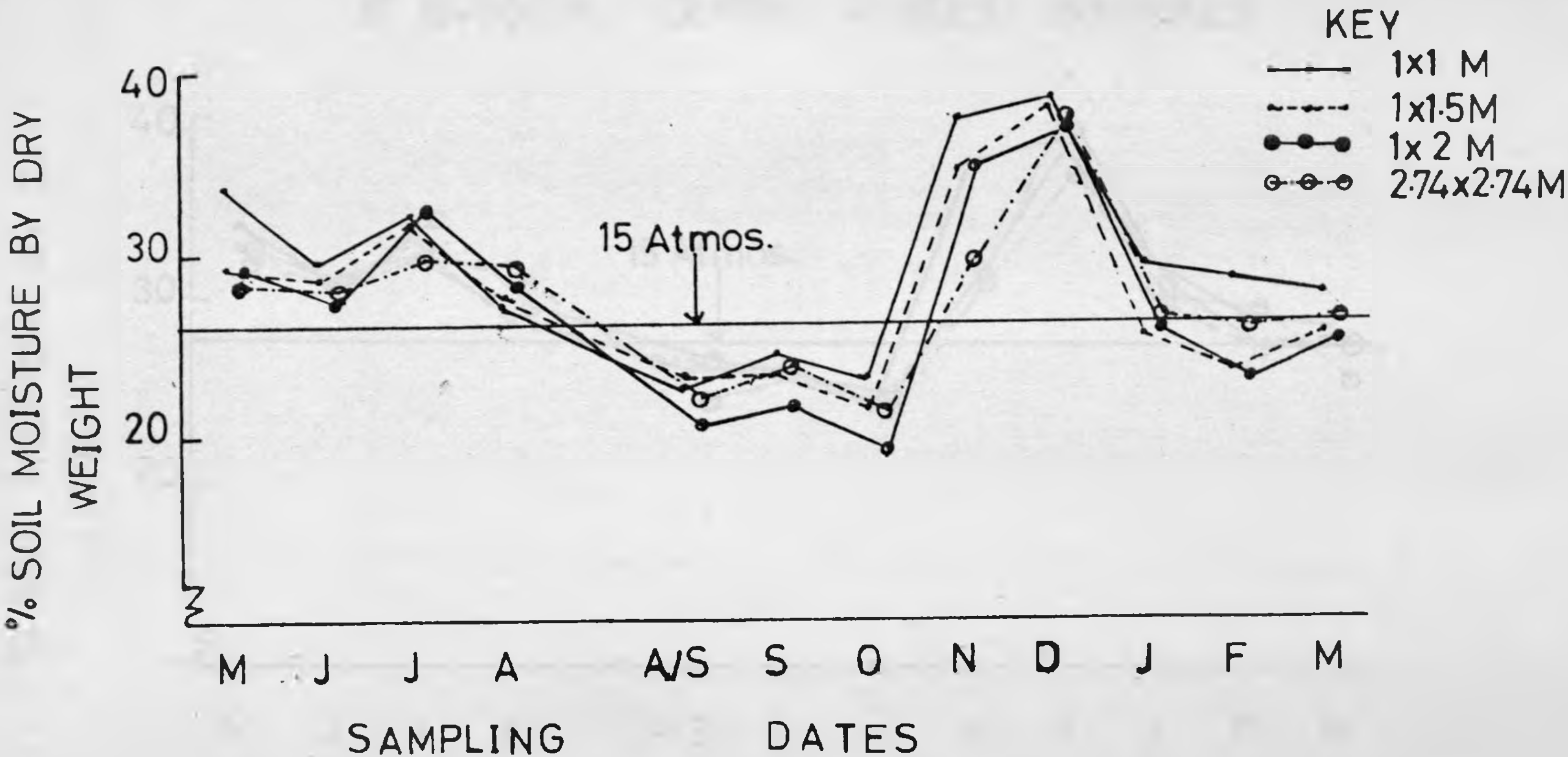


Fig 1b: PERCENTAGE SOIL MOISTURE AT 15-30 Cm. DEPTH, 4-WEEK INTERVALS

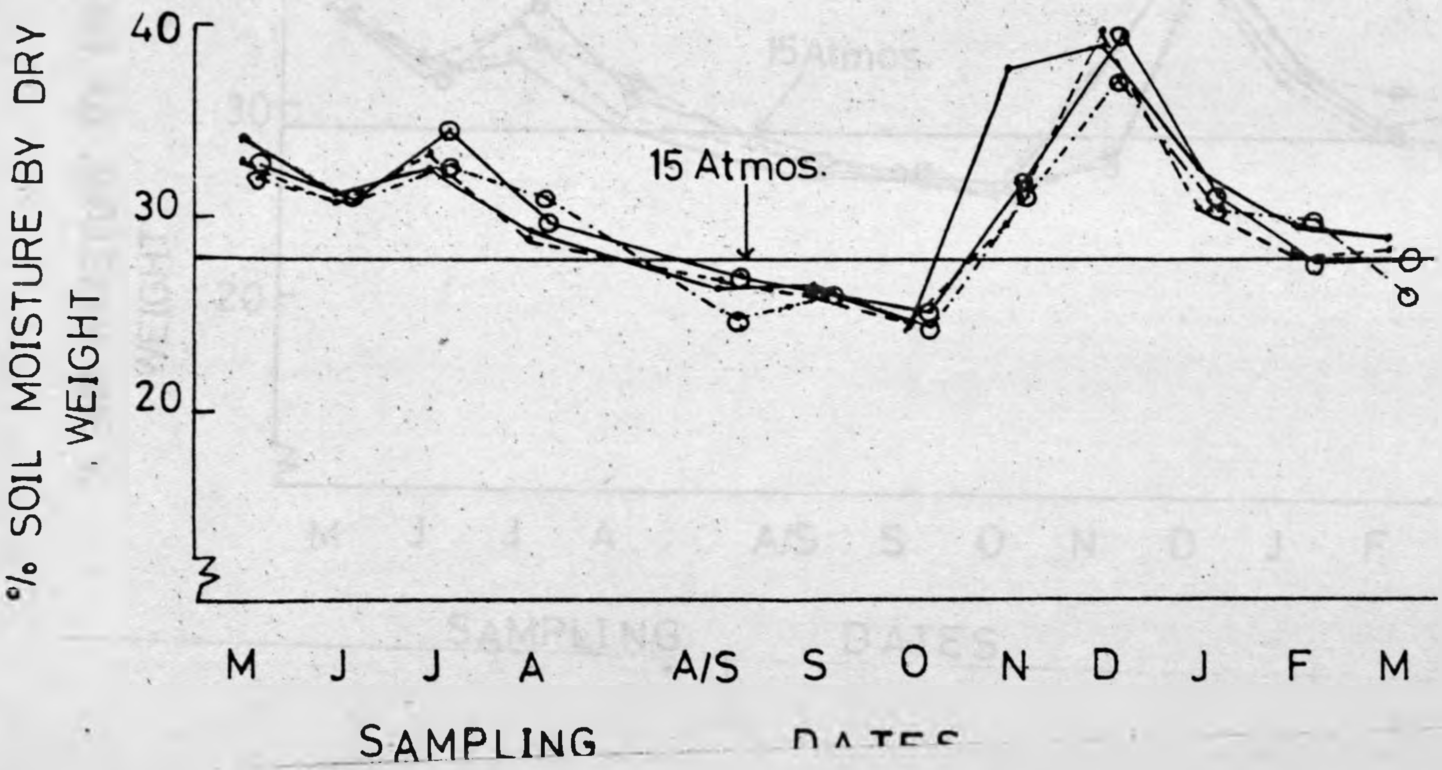


Fig 1c: PERCENTAGE SOIL MOISTURE AT 30-45Cm. DEPTH, 4-WEEK INTERVALS

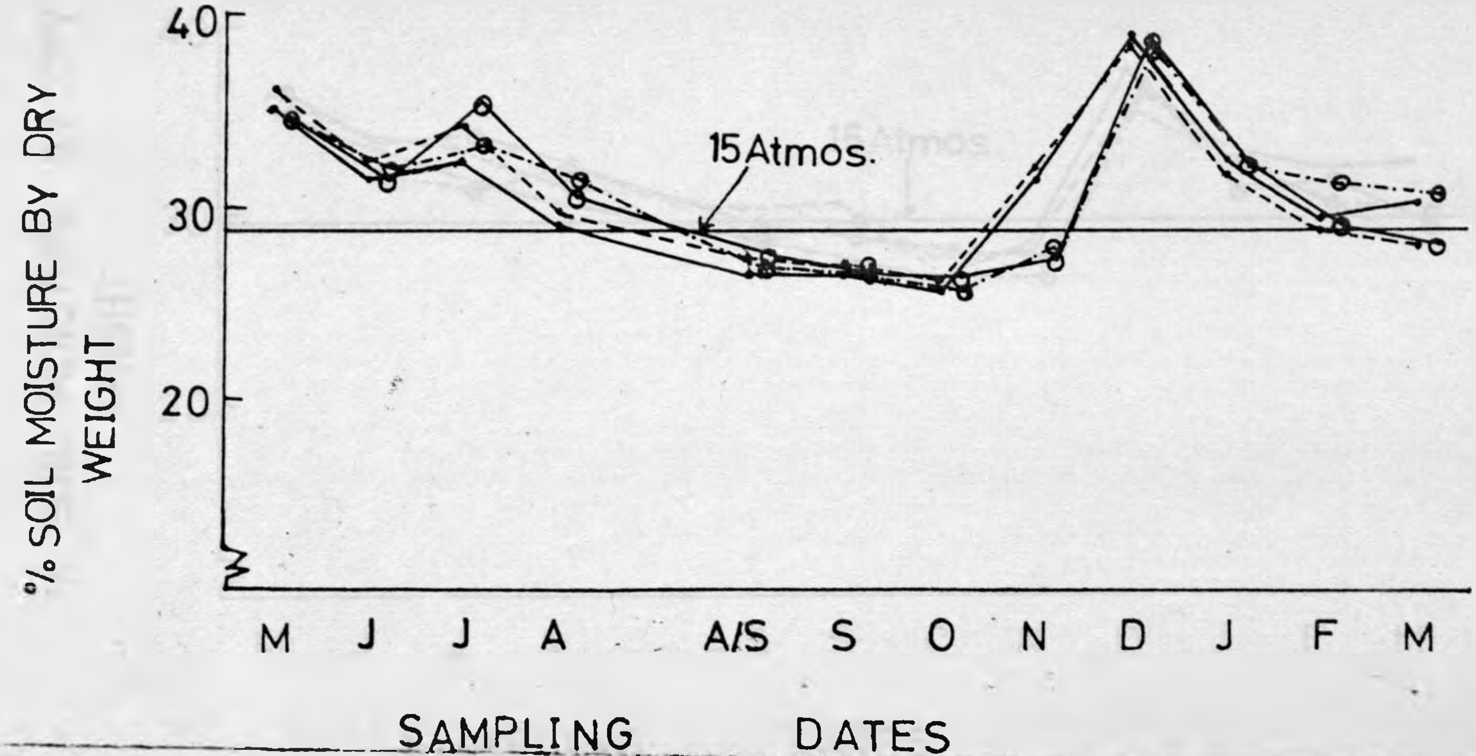


Fig 1d: PERCENTAGE SOIL MOISTURE AT 75 Cm. DEPTH, 4-WEEK INTERVALS

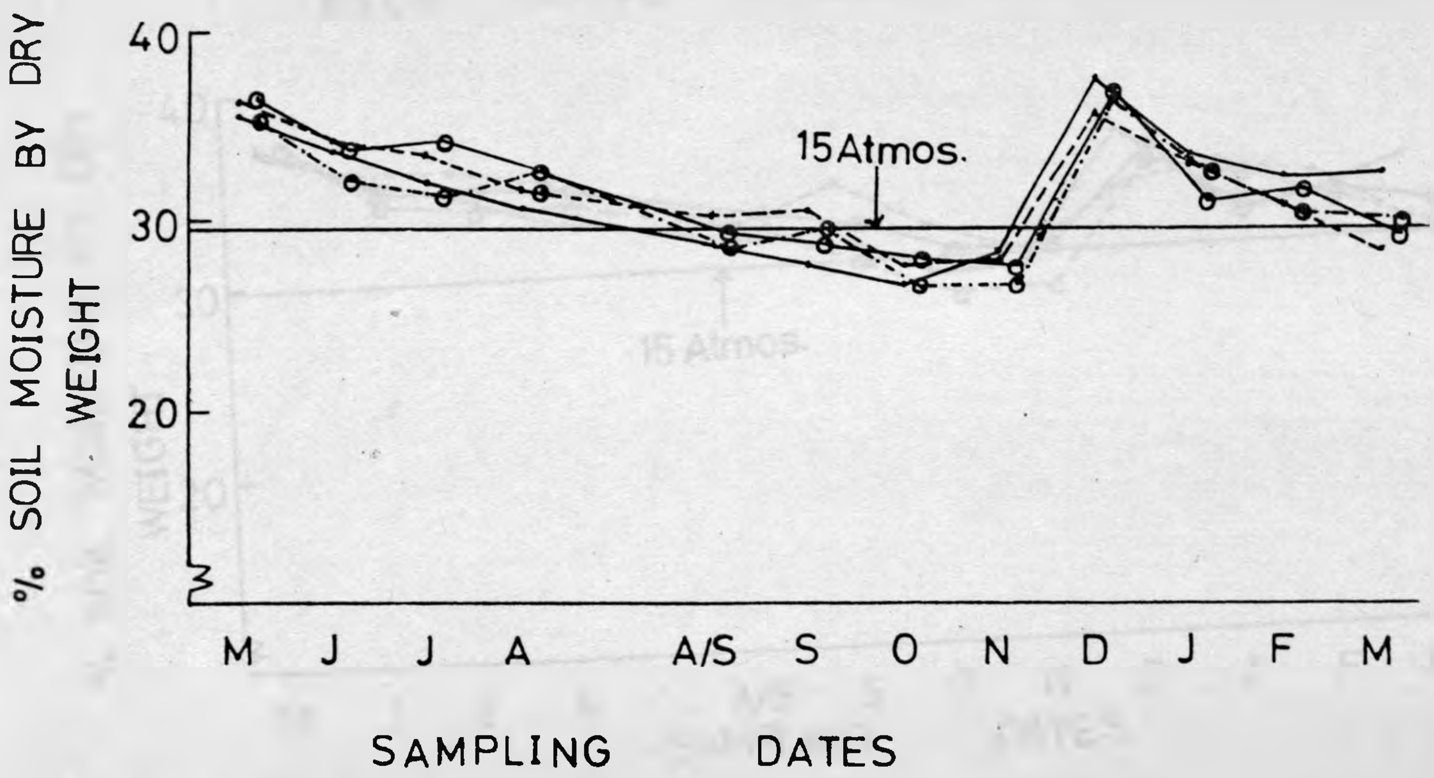


Fig 1e: PERCENTAGE SOIL MOISTURE AT 105 Cm. DEPTH, 4-WEEK INTERVALS

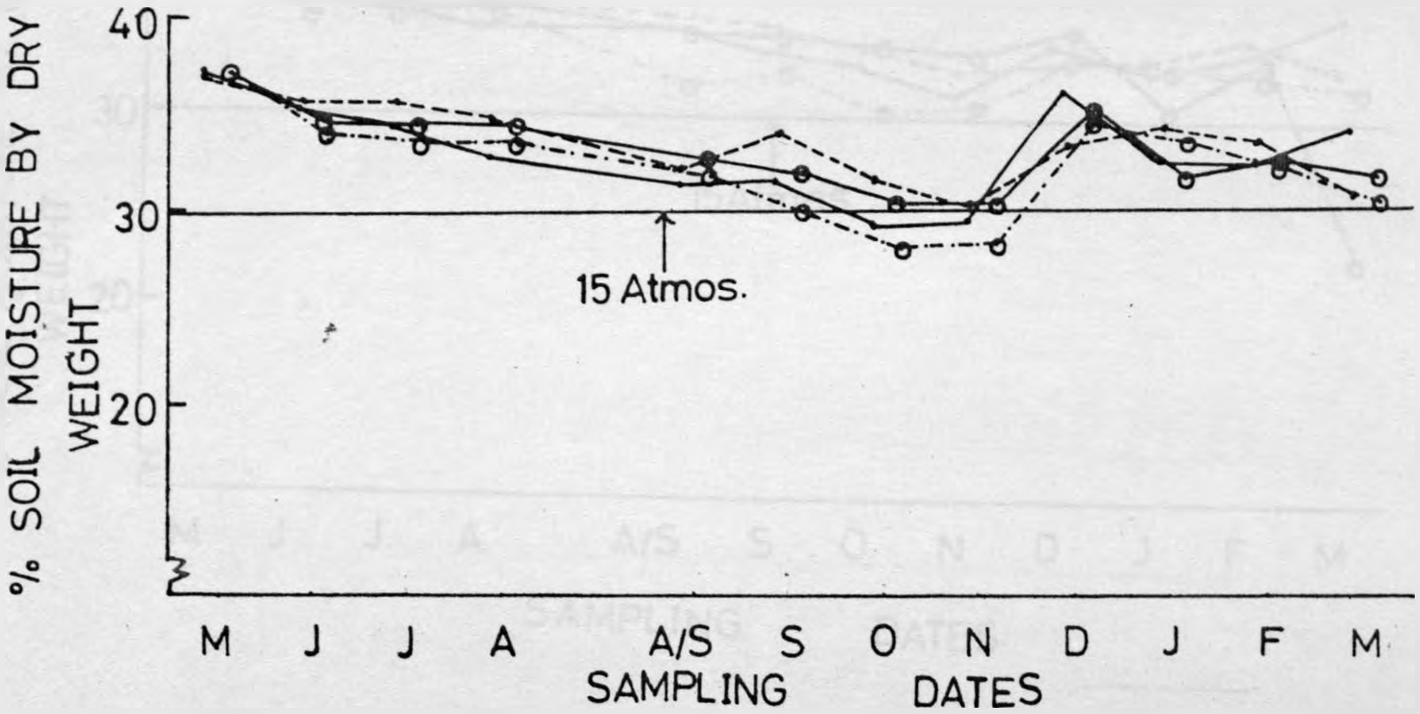


Fig 1f: PERCENTAGE SOIL MOISTURE AT 135 Cm. DEPTH, 4-WEEK INTERVALS

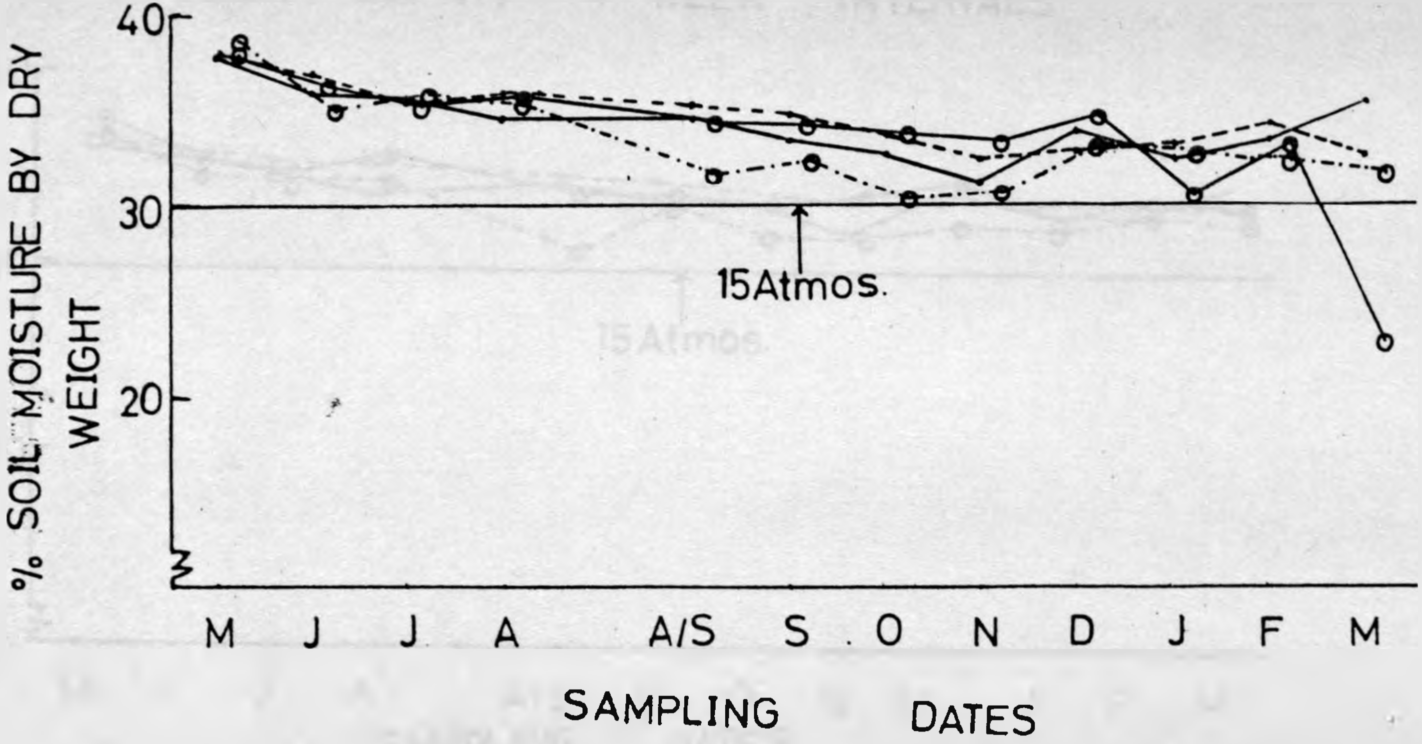


Fig 19: PERCENTAGE SOIL MOISTURE AT 165Cm. DEPTH, 4-WEEK INTERVALS

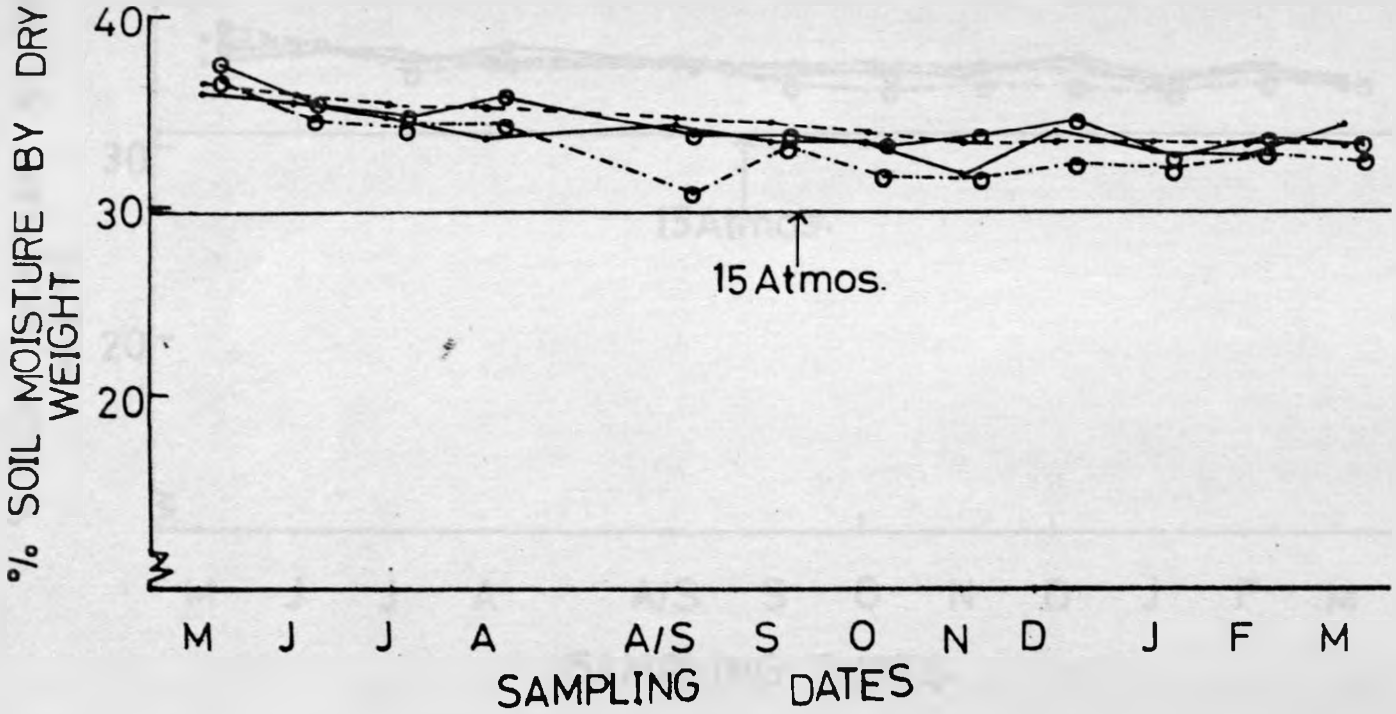


Fig. 1h: PERCENTAGE SOIL MOISTURE AT 225 Cm. DEPTH, 4-WEEK INTERVALS

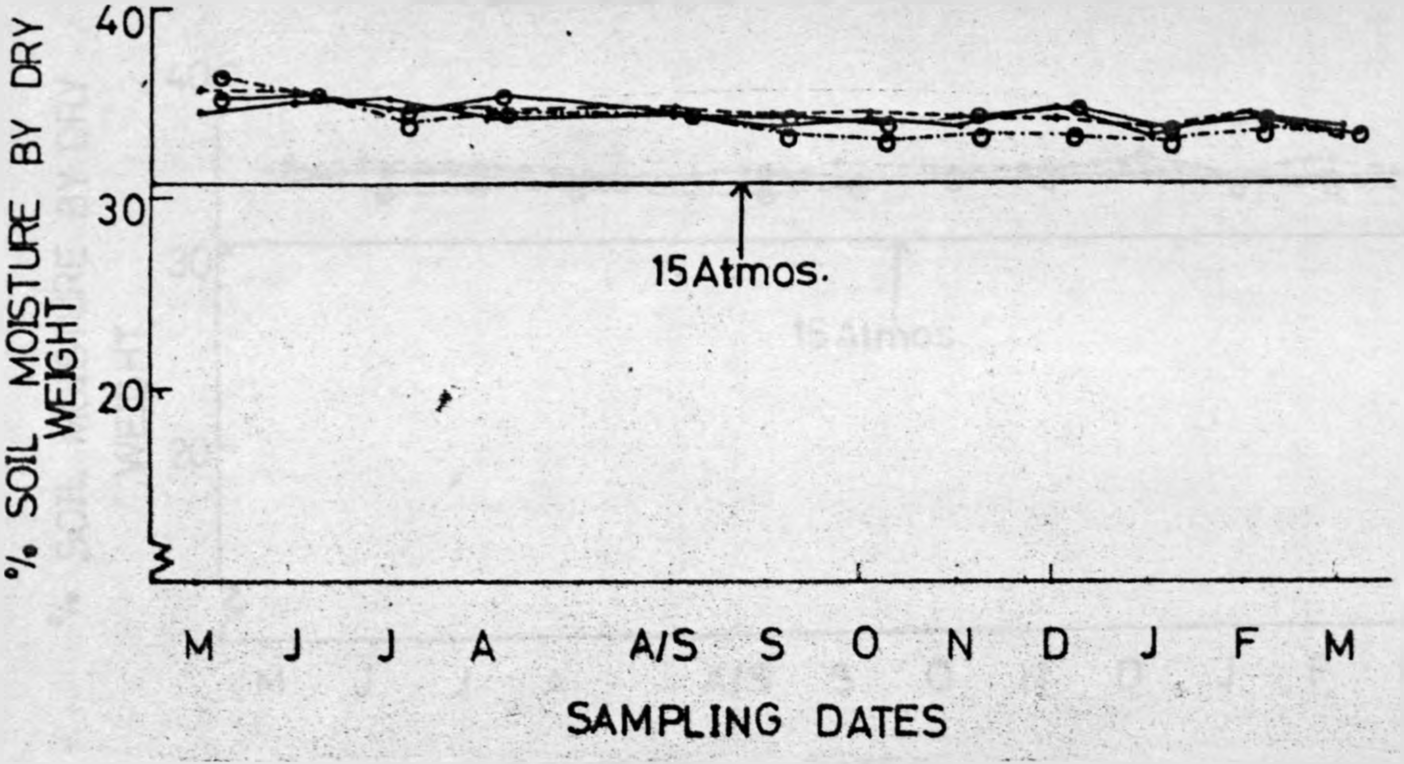
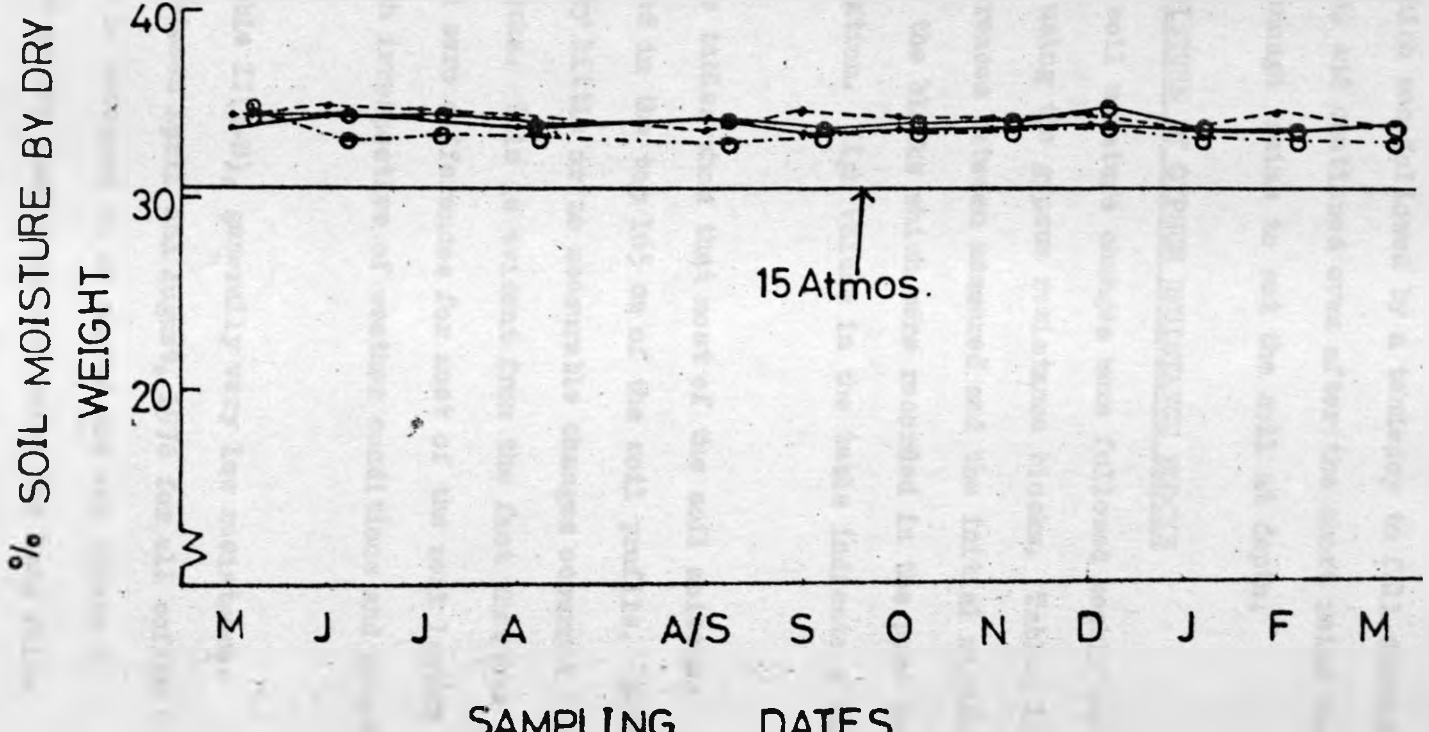


Fig1i: PERCENTAGE SOIL MOISTURE AT 300 Cm. DEPTH, 4-WEEK INTERVALS



The above graphs show a general drop in soil moisture content for all soil layers down to 165 cm depth from May to October. In November, 1976 moisture content began to rise and reached a peak in December in the upper soil layers. In the lower soil layers, moisture contents reached a peak during the long rains, which was followed by a tendency to fall during the dry period, and continued even after the short rains as there wasn't enough rains to wet the soil at depth.

3:1:2 SOIL MOISTURE BY GYPSUM RESISTANCE BLOCKS

The soil moisture changes were followed weekly over the 12 months using the gypsum resistance blocks. Tables II(A-L) show the differences between measured and the initial minimum resistances of the blocks which were recorded in the pure water before installation. High values in the table indicate a dry soil.

These tables show that most of the soil moisture changes occurred in the top 165 cm of the soil profile. Below this depth, very little or no measurable changes occurred for most of the blocks. This is evident from the fact that the blocks recorded zero differences for most of the soil layers below this depth irrespective of weather conditions and plant density.

In table II(A-D), generally very low resistances were recorded between April and August, 1976 for all coffee spacings. This is referred to as period one and covers a relatively moist months during and following the long rains which were inadequate compared with what is expected for a normal year.

In 1 x 1 m coffee spacing (Table IIA) quite high moisture resistance differences were recorded on 14th June at 15 and 30 cm and on 28th June at 30 cm soil depths. The first two figures referred to are marked 2.7^{++} and 2.4^{++} which means the soils were dry and close to wilting point.

At 1 x $1\frac{1}{2}$ m (Table IIB) very high dry soil conditions were only recorded on 14th June, in the top two soil layers of 15 and 30 cm depths. The same pattern was repeated in 1 x 2 m (Table IIC) and 2.74 x 2.74 m (Table IID) but 15 cm and 30 cm soil depths were affected for the former and latter spacings respectively. The soil moisture conditions for the four coffee spacings for the three periods are summarised down to 165 cm depth in tables III(A-C) and will be considered later.

<u>KEY</u>: Tables II(A-L)

* Maximum recordable resistance difference.

+ Decline from maximum resistance.

++ Approximate Pereira's (1957) wilting point.

TABLE IIA : WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 1 x 1 m

DEPTH (CM) & REPLICATES		MINIMUM RESIST.	APRIL '76			MAY '76					JUNE '76				JULY '76		
			19	21	26	3	10	17	24	31	7	14	21	28	12	19	26
15	A	2.7	.1	0	.1	.1	.1	.1	0	.1	.2	1.0	.2	.1	.1	0	.1
	B	2.6	.2	.1	.1	.2	.3	.1	.1	.1	.7	2.7++	.1	.1	.1	.1	.3
30	A	2.5	.3	.2	.2	.2	.2	.2	.1	.2	.3	.4	.3	.4	.3	.2	.2
	B	2.5	.2	.3	.1	.2	.2	.1	.2	.2	.8	2.4++	.2	3.5*	.3	.4	1.1
45	A	2.5	.4	.3	.2	.3	.2	.2	.2	.2	.2	.2	.3	.3	.2	.3	.3
	B	2.7	0	0	0	.1	0	0	0	.1	.2	.2	0	.2	.1	.1	.3
75	A	2.7	.1	0	0	0	0	0	9	0	0	0	0	0	0	0	.1
	B	2.5	.3	.1	0	.3	.2	.2	.1	.2	.3	.5	.9	.3	.3	.5	.6
105	A	2.5	.2	.1	.2	.2	.1	.1	.2	.1	.2	.1	.2	.2	.3	.2	.2
	B	2.7	0	0	0	0	0	0	0	0	.1	.1	.4	0	.1	.1	.3
135	A	2.7	.1	.1	.1	.1	0	0	0	0	.1	.0	.0	.1	0	0	0
	B	2.6	.2	.2	0	.1	.1	0	0	0	.2	0	.1	.2	.1	.2	.2
165	A	2.9	.1	0	0	.1	0	0	.1	0	0	0	0	0	0	0	0
	B	2.6	.2	.1	.1	.1	.1	0	0	.1	.1	0	.1	.1	.1	.1	.1
195	A	2.8	.2	.1	.2	.2	.2	.2	.1	.1	.2	.2	.2	.1	.2	.2	.2
	B	2.7	.7	.2	.1	-	-	-	-	-	-	-	-	-	-	-	-
225	A	3.0	.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	3.0	.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
255	A	2.9	.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.8	.1	.2	.1	0	0	0	0	0	0	0	0	0	0	0	0
285	A	3.0	.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	.2	.1	0	.1	0	0	0	0	0	0	0	0	0	0	0
300	A	3.0	0	0	0	0	0	0	0	0	00	0	0	0	0	0	0
	B	2.9	.1	.1	.1	0	0	0	0	0	0	0	0	0	0	0	0

TABLE II B: WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 1 x 1½ m

DEPTH (CM) & REPLICATES		RESIST.	APRIL '76			MAY '76					JUNE '76				JULY '76		
			19	21	26	3	10	17	24	31	7	14	21	28	12	19	26
15	A	2.6	.2	0	0	.1	.4	.2	.1	.2	.4	3.4*	.2	.3	.1	.3	.4
	B	2.7	.1	.1	0	0	1.0	.2	0	.2	.7	3.2+	.2	.2	.1	0	.4
30	A	2.5	.3	0	0	.1	.2	.2	.1	.2	.1	.3	.1	.2	.1	.2	.1
	B	2.6	.2	.2	0	0	.2	.2	0	.1	.2	.2	.1	0	.1	0	.1
45	A	2.8	.1	0	0	0	0	0	0	0	0	.3	.8	0	.1	.1	.1
	B	2.7	.1	.1	0	0	0	0	0	0	.1	.1	.2	.1	0	.1	0
75	A	2.6	.3	.1	0	.1	.1	.1	.1	.1	.1	.1	.1	.3	.1	.2	.1
	B	2.7	.1	0	0	.1	0	0	0	0	0	0	0	.2	0	0	0
105	A	2.6	0	.3	0	0	0	0	.1	.1	.1	0	0	.1	0	.1	0
	B	2.5	.2	.2	.2	.4	.2	.2	.1	.2	.2	.2	.2	0	.1	.2	.1
135	A	2.7	.2	0	0	0	0	0	0	0	.1	0	0	0	0	0	0
	B	2.9	0	0	0	0	0	0	0	0	0	0	0	0	.2	0	0
165	A	2.6	0	.1	.1	.1	.1	.1	0	.1	.1	0	0	0	0	.1	0
	B	2.9	0	0	0	0	0	0	0	0	0	0	0	0	.2	0	0
195	A	3.0	0	0	0	2.2	2.5	0	0	0	0	0	0	0	0	0	0
	B	2.7	.4	.2	.2	.2	.2	.2	.2	.2	.2	.1	.1	.1	.1	.1	.1
225	A	3.0	.1	.0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	.1	.1	1.3	0	0	0	0	0	0	0	0	0	0	0	0
255	A	3.0	.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	3.0	.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
285	A	2.9	0	.1	.1	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.6	.5	.3	.3	.2	.3	.3	.2	.2	0	.2	.2	.3	.2	.3	.2
300	A	3.0	.1	.1	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.8	.3	.8	.1	.2	.1	.1	0	.1	0	0	0	.1	.1	.1	0

TABLE II C: WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 1 x 2 m

DEPTH (CM) & REPLICATES		RESIST.	APRIL '76			MAY '76					JUNE '76				JULY '76		
			19	21	26	3	10	17	24	31	7	14	21	28	12	19	26
15	A	2.6	.2	.3	.4	.2	1.2	.2	.1	.2	1.2	3.4*	.2+	.3	.2	.2	.5
	B	2.7	.1	0	0	0	.2	0	0	0	.1	.5	.1	.1	0	.1	0
30	A	2.5	.2	0	.2	.2	.2	.2	.2	.2	.3	.8	1.2	.3	.1	.2	.5
	B	2.6	.1	.1	0	0	.2	.1	.1	.1	.2	.1	.2	.2	.1	.1	.2
45	A	2.7	0	.2	0	0	0	0	0	0	0	.1	.3	.1	0	.1	.2
	B	2.6	.1	.1	0	.1	.1	.1	0	.1	.1	.2	.3	.1	.1	.1	.1
75	A	2.6	.1	.4	0	.1	.2	.1	.1	.1	0	.2	.2	.3	.2	.3	.3
	B	2.6	.1	.1	0	.1	0	.1	.1	.1	.1	.3	.3	.2	.2	.3	.5
105	A	2.6	.1	.6	0	.1	0	0	0	0	0	0	0	.1	0	.1	0
	B	2.6	.1	.1	0	.1	0	.1	0	0	.2	.1	.2	.2	.5	.7	.8
135	A	2.7	0	.4	0	0	0	0	0	0	0	0	.1	.1	0	0	0
	B	2.7	.1	0	0	0	0	0	0	0	0	.1	0	.1	.1	.2	.3
165	A	2.7	0	.5	0	.1	0	0	0	0	0	0	0	0	0	.1	0
	B	2.7	.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
195	A	2.6	.4	.3	.2	.3	.1	.3	.2	.3	.2	-	.2	.3	.2	.3	.2
	B	3.0	0	0	0	0	0	0	0	0	0	-	0	0	0	0	.2
225	A	3.0	0	0	0	0	0	0	.3	0	0	.2	0	0	0	0	0
	B	2.9	.1	0	0	0	0	0	.1	.1	0	.1	.1	.1	.1	.1	0
255	A	2.9	.1	.1	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.7	.2	0	0	.1	.2	.2	.1	.2	.2	0	.1	.1	0	.1	0
285	A	3.0	0	.1	0	.1	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	.2	0	0	0	0	0	0	0	0	.2	0	0	0	0	0
300	A	2.9	0	.1	.1	.1	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	.2	.1	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE II D: WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 2.74 x 2.74 m

DEPTH (CM) & REPLICATES		RESIST.	APRIL '76			MAY '76					JUNE '76				JULY '76		
			19	21	26	3	10	17	24	31	7	14	21	28	12	19	26
15	A	2.7	.1	.1	.2	0	.1	.1	0	0	.2	1.0	0	.1	0	0	.1
	B	2.6	.2	.3	.3	.1	.4	.1	.1	.1	.4	3.4*	.2	.1	.1	.2	.3
30	A	2.6	.2	.2	.1	.1	0	.1	0	0	.1	.1	.1	.1	.1	0	.1
	B	2.6	.1	.3	0	.2	.1	.1	0	0	0	0	0	0	.1	.1	0
45	A	2.7	0	0	.1	0	0	0	0	0	0	.1	0	.1	0	0	0
	B	2.6	.1	.3	0	.1	.1	0	0	0	0	0	0	0	.1	0	0
75	A	2.7	0	.2	0	0	0	0	0	0	0	.1	.4	.1	0	0	0
	B	2.6	.1	.1	.1	0	0	0	0	0	0	0	0	0	.2	.3	.5
105	A	2.7	0	.2	0	0	0	0	0	0	0	.1	0	.1	0	0	0
	B	2.6	.1	0	0	0	0	0	0	0	0	0	0	0	0	.1	.1
135	A	2.6	.2	0	0	.1	.2	.1	.1	0	0	0	0	.1	0	.1	.1
	B	2.6	.1	0	0	.1	.1	0	0	0	0	0	0	.1	.1	.1	0
165	A	2.6	.2	.4	0	.1	.1	0	0	0	0	0	0	0	0	0	0
	B	2.7	0	0	.3	.1	0	0	0	0	0	0	0	0	0	0	0
195	A	3.0	.1	.1	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.7	.2	.1	.1	.1	0	.1	0	0	0	0	0	0	0	0	.1
225	A	3.0	.2	.1	.1	.1	0	0	0	0	0	0	0	0	0	0	0
	B	3.0	0	0	.2	.1	0	0	0	0	0	0	0	0	0	0	0
255	A	3.0	.1	0	.1	0	0	0	0	0	0	0	0	0	0	0	0
	B	3.0	0	0	.1	0	0	0	0	0	0	0	0	0	0	0	0
285	A	2.8	.2	.2	.2	.2	.1	0	.1	0	0	0	0	.1	0	.1	0
	B	2.9	.1	.1	.3	0	0	0	0	0	0	0	0	0	0	0	0
300	A	2.9	0	0	.1	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.7	.2	.2	.6	0	0	0	0	0	0	0	0	0	0	0	0

Period two 2nd August, to 29th November 1976 is presented by tables II (E-H). These were very dry months apart from late November when finally the short rains started. For all the four coffee densities, extremely dry soil conditions became evident in early August as the dry period set in, and continued through September, October and started easing in November. The two wider spacings 1 x 2m (Table G) and 2.74 x 2.74 m (Table IIH) show a decline in resistances early in November while in the two closest coffee spacings 1 x 1 m (Table IIE) and 1 x 1½ m (Table IIF) moisture resistances did not drop until later in the month. The drop in resistances was particularly marked in the top soils and was attributed to the soil wetting caused by the onset of 1976 short rains. The differences noted when the wider and close spacings had their resistances drop from their measured maximum can be attributed to the tree canopy effects. Prior heavy showers to which started on 18th November, there were light showers which were intercepted by the closed canopy of the closer spaced coffee in 1 x 1 m and 1 x 1½ but reached the soil surface in wider spacings due to the less ground cover. These earlier showers caused the soil wetting and hence the drop in resistances on 8th November as seen in tables IIF, IIG and IIH. After the heavy showers, the canopy effect was overcome and resistances dropped dramatically from 22nd November onwards.

Although the pattern of soil drying in this period two was similar in all coffee spacings the extent in depth varied slightly. In 1 x 1m (Table IIE) soil drying started in the top soil early in August and by the end of the month had reached 105 cm depth. Drying did not extend below this depth for the next two months until November when soils were found to be close to wilting point from 8th to 29th at 135 cm depth.

In 1 x 1½ m (Table IIF) dry soil conditions started from the top layers in August and never reached 75 cm depth until 20th September. Drying did not go below this depth until November when the short rains set in. It was only on 29th November during the short rains that soils at 105 cm depth were found to be close to wilting point, and nothing greater than that.

In 1 x 2 m (Table IIG) soil conditions were comparable to those found in 1 x 1m coffee spacing and stabilized at 135 cm depth from 20th September through November. In 2.74 x 2.74 m (Table IIH) soil drying reached a maximum depth of 165 cm. This was the greatest depth reached in all these spacings and could possibly be explained by the well established roots of this older conventionally spaced coffee.

TABLE IV E: WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 1 x 1m

DEPTH (CM) & REPLICATES		RESIST.	AUG. 1976					SEPT. 1976				OCT. 1976				NOV. 1976			
			2	9	16	23	30	6	13	20	27	4	12	18	25	1	8	15	22	29
15	A	2.7	.4	1.3	3.3*	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	.4	3.3	0+	0
	B	2.6	.6	2.9++	3.4*	3.4	3.4	3.4	3.4	3.4	3.4	-	2.2	3.4	3.4	3.4	3.5	3.4	.1+	.1
30	A	2.5	.4	.6	1.0	3.3	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	.3+	.2
	B	2.5	2.5++	3.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	-	3.5	3.5	3.5	3.5	2.2	3.5	.3+	.2+
45	A	2.5	.3	.3	.4	.3	.4	.5	.7	1.0	1.6	3.5*	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	B	2.7	.4	.6	1.4	3.3	3.3	3.3	3.3	3.3	3.3	-	.4+	1.3+	3.3	3.3	3.3	3.3	.1+	.1
75	A	2.7	0	0	.1	0	.1	0	0	.1	0	.2	.3	.4	.7	.3	1.6	3.3	3.3	3.3
	B	2.5	.9	1.5	2.9++	3.5*	3.5	3.5	3.5	3,5	3.5	-	.6	1.2	3.5	3.5	3.5	3.5	3.5	3.5
105	A	2.5	.3	.4	.4	.4	.4	.5	.5	.6	0	.9	1.1	1.3	.6	1.8	2.2++	2.8++	.5	1.0
	B	2.7	.4	.7	1.4	3.1++	3.3*	.3	3.3*	3.3*	3.3*	-	3.3*	3.3*	3.3*	3.3*	3.3*	3.3*	3.3*	3.3*
135	A	2.7	.1	.1	.1	0	.1	.1	0	.2	.2	.2	.3	.2	.2	.3	.4	.4	.5	.6
	B	2.6	.3	.3	.3	.3	.4	.1	.4	.6	.7	-	111	1.3	1.6	1.9	2.3++	2.5++	2.7++	2.5++
165	A	2.9	0	0	0	0	0	0	0	0	0	0	0	0	.1	0	0	0	0	0
	B	2.6	0	.1	.1	.1	.1	0	.1	.1	.1	-	.1	.1	.2	.1	.2	.2	.2	.2
195	A	2.8	.2	.2	.2	.2	.2	.1	.1	.2	.1	.2	.3	.2	.2	.2	.2	.2	.2	.2
	B	2.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
225	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.1	0	0	0
	B	3.0	0	0	0	.2	0	.2	0	0	.1	-	0	0	0	.1	0	0	0	.2
255	A	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.8	0	0	0	0	0	0	0	0	0	-	0	0	0	0	0	0	0	0
285	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	0	0	0	0	0	0	0	0	0	-	0	0	0	0	0	0	0	0
300	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	0	0	0	0	0	0	0	0	0	-	0	0	0	0	0	0	0	0

TABLE II F: WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 1 x 1½ m

DEPTH (CM) & REPLICATES		RESIST.	AUG. 1976					SEPT. 1976				OCT. 1976				NOV. 1976				
			2	9	16	23	30	6	13	20	27	4	12	18	25	1	8	15	22	29
15	A	2.6	.8	3.4*	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	.5+	3.4*	.2	.2
	B	2.7	.6	3.3*	3.3*	3.3*	-	2.6	3.3	3.3	1.8	3.3	1.6	3.3	3.3	3.3	.3+	3.3*	.1	.1
30	A	2.5	.2	.2	.5	.8	3.5*	3.5*	3.5	3.5	.8	3.5	3.5	3.5	3.5	3.5	2.8+	3.5*	.3+	.2
	B	2.6	.3	.3	.3	.6	-	2.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	.6+	.3+
45	A	2.8	.2	.7	1.8	3.2*	.6	3.2*	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	2.4	3.2
	B	2.7	.1	.2	.4	.8	-	3.3*	3.3*	3.3*	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
75	A	2.6	.3	.3	.3	.3	.1	.9	1.5	3.4*	3.4*	3.4*	3.4*	3.4*	3.4	.7	3.4	3.4	3.4	3.4
	B	2.7	0	.1	.1	.1	-	.3	.3	.5	.9	1.4	3.0	3.3*	3.3*	3.3*	3.3*	3.3*	3.3*	3.3*
105	A	2.6	0	0	.1	0	0	0	0	.1	0	.1	.1	.1	.1	.2	.4	.5	.7	1.0
	B	2.5	.1	.2	.6	0	-	.2	.2	.3	.2	.4	.4	.5	.6	.4	.9	1.3	1.8	2.2++
135	A	2.7	0	0	0	0	.1	0	0	0	0	0	0	0	0	.1	.1	.1	.2	.2
	B	2.9	0	0	0	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0
165	A	2.6	.1	0	.1	0	0	.1	0	.1	0	0	0	0	0	.2	0	.1	.1	.1
	B	2.9	0	0	0	0	-	.1	0	0	0	0	0	0	0	0	0	0	0	0
195	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.7	.2	.2	.2	.1	-	.1	0	.1	0	0	.1	0	.1	.2	0	0	.2	.1
225	A	3.0	.0	0	0	0	-0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	.1	0	0	0	-	.1	0	0	0	0	0	0	0	0	0	0	0	0
255	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	3.0	0	0	0	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0
285	A	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.6	.2	.3	.3	.2	-	.3	.2	.1	.2	.2	.2	0	.2	.2	.2	.2	.3	.2
300	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.8	0	.1	0	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE II G: WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 1 x 2 m

DEPTH (CM) & REPLICATES		RESIST.	AUG. 1976					SEPT. 1976				OCT. 1976				NOV. 1976				
			2	9	16	23	30	6	13	20	27	4	12	18	25	1	88	15	22	29
15	A	226	1.8	3.2++	3.4*	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	1.3+	3.4*	.2+	.3
	B	2.7	.1	.5	3.3*	3.3	3.3	3.3	3.3	3.3	3.3	3.3	1.9	3.3	3.3	3.3	3.2+	3.3	.1+	0
30	A	2.5	1.1	3.3++	3.5*	3.5*	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	.3+	.4
	B	2.6	.3	.4	1.0	3.4*	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3,4	3.4	3.4	3.4	3.4	.4+	.1
45	A	2.7	.3	.6	.9	2.2++	3.3*	3.3++	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	2.4+	3.3*
	B	2.6	.2	.3	.4	.6	1.0++	2.2	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	.3+	.4
75	A	2.6	.4	.6	.9	1.8++	2.2	3.4*	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	2.0+	3.4*
	B	2.6	.7	1.0	1.7	2.9	3.2	3.4*	3.4	3.4	1.7	3.4	3.4	3.4	3.4	3.4	3.4++	3.4	3.4	.2+
105	A	2.6	1.1	.1	.1	.1	.3	.2	.2	.3	.1	.5	.1	.8	1.0	1.4	2.0	3.4*	3.4*	.2
	B	2.6	.9	1.1	.3	1.8	3.4*	3.4*	3.4*	3.4*	3.4*	3.4	3.4	3.4	3.4	3.4	1.4	3.4	.3	.7
135	A	2.7	.2	0	.1	.1	.2	0	0	.1++	.1	0	.1	0	0	0+	0	0	0	0
	B	2.7	.3	.3	1.4	.5	.7	1.0	1.7	2.9	3.3*	3.3*	3.3*	3.3*	3.3*	3.2	3.3*	3.3*	3.3*	3.3*
165	A	2.7	0	.2	.2	0	.1	.1	.1	.2	.2	.1	.2	.1	.2	.2	.1	.2	.3	.2
	B	2.7	.1	.1	1.1	0	.1	.2	.2	.1	.2	.2	.2	.3	.4	.5	.6	.8	.5	1.3
195	A	2.6	.2	.3	.2	.2	.3	.3	.3	.3	,2	,3	.2	.3	.3	.3	.3	.3	.3	.3
	B	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.1	.1	.2
225	A	3.0	.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
255	A	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.7	0	.1	.1	0	.1	0	0	0	0	.1	0	.1	.1	0	0	0	.1	.1
285	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	A	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE II H: WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 2.74 x 2.74 m

DEPTH & (CM) & REPLICATES		RESIST.	AUG. 1976					SEPT. 1976				OCT. 1976				NOV. 1976				
			2	9	16	23	30	6	13	20	27	4	12	18	25	1	8	15	22	29
15	A	2.7	.1	.2	.3	2.3++	3.3*	3.0	3.3	3.3	.1+	.1	.3	3.3*	3.3	3.3	.1+	3.0	.1	0
	B	2.6	.4	1.2	3.4*	3.4*	3.4*	3.4	3.4	3.4	.4+	1.7	.7	3.4*	3.4	3.4	.2*	3.4*	.2+	.2
30	A	2.6	.2	.3	.3	.6	1.4	2.9	2.0	3.4*	.3+	.4+	.3+	1.7+	3.4*	3.4	.2+	1.3	.1	.1
	B	2.6	.3	1.0	1.3	2.9++	3.4*	3.4	3.4	3.4	.3+	1.7	.3	.9	3.4*	3.4*	.1+	.7	.1	.1
45	A	2.7	0	0	0	.2	.5	.8	2.8	2.8	0+	.6	.1+	.6	3.3*	3.3*	.1+	.6+	0+	0
	B	2.6	.3	1.1	1.2	.2	1.9++	3.4*	3.4	3.4	2.3	3.4	.2	3.4*	3.4	3.4	.2++	1.8	.1+	.1+
75	A	2.7	0	0	0++	.2++	.4	1.1	1.3	2.9	3.3*	3.3	3.3	3.3	3.3	3.3	3.3	3.3	1.4	1.3+
	B	2.6	.8	1.2	2.1	2.8	3.4*	3.4*	3.4*	3.4*++	3.4*	3.4	3.4	3.4	3.4	3.4	3.4	3.4	.2	.3
105	A	2.7	.1	0	.2	.2	.3	.6	.3	2.4	3.3*	3.3*	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	B	2.6	.2	.2	.1	0	.2	.3	.4	.6	.7++	1.1++	1.5	2.4	3.4	3.4	3.4	3.4	3.4	3.4
135	A	2.6	.1	.1	.2	.1	.2	.4	.3	1.4	2.5	2.9	3.4*	3.4*	3.4*	3.4*	3.4*	3.4*	3.4	3.4
	B	2.6	.1	.1	.1	0	.3	.3	.4	.5	.6	.8	.9	1.0++	1.2++	1.5++	1.5++	.6	1.7+	1.6++
165	A	2.6	.1	.1	0	0	.1	.1	.3	.5	.8	1.2	1.6	2.3	2.9	3.2	3.2	3.4*	3.1	3.2
	B	2.7	0	.1	0	.1	0	0	0	0	0	0	0	.1	0	0	.1	0	.1	.1
195	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.7	.1	.1	.1	.1	.1	.1	0	0	.1	.1	.1	.1	0	.1	.1	.1	.1	.1
225	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	3.0	00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
255	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	3.0	0	0	0	0	.3	0	0	0	0	0	0	0	0	0	0	0	0	0
285	A	2.8	.1	0	0	0	.1	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	0	0	0	0	.1	0	0	0	0	0	0	0	0	0	0	0	0	0
300	A	2.9	0	0	0	0	0	.1	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.4

Tables II(I-L) shows soil moisture resistances changes between December 1976 and March 1977 termed as period three of the experiment. The data represents a relatively moist soil conditions as compared to period two discussed above.

In 1 x 1m (Table II I) very little changes were recorded during this period. The only significant high resistances of this spacing occurred on 21st February on the top soil layers at 15 and 30 cm depths. In 1 x 1½ m (Table II J) very dry soil conditions were recorded on 24th January only in 15 cm depth and on 14th and 21st February in the same layer. From 14th March through to 21st and 28th March significant dry conditions were recorded in this spacing at 45 cm depth.

At wider spacings 1 x 2 (Table II K), 2.74 x 2.74 m (Table II L) soil drying occurred on the soil surface and in the greater depths. By 14th February, soil drying in 1 x 2m coffee spacing was close to wilting point and three weeks later maximum recordable resistance differences were reached at this depth. This continued to the end of March 1977.

The conditions were even more critical in 2.74 x 2.74 m (Table II L). Although high soil moisture resistances were temporarily removed by the short rains, late in November and early December, by 13th of the latter soils were close to wilting point in this spacing at 165 cm depth. From this date to the end of the period III, soils at this depth remained fairly d

TABLE II I: WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 1 x 1 m

DEPTH (CM) & REPLICATES		MINIM. RESIST.	DECEMBER 1976				JANUARY, 1977					FEBRUARY'77				MARCH 1977			
			6	13	20	27	3	10	17	24	31	7	14	21	28	7	14	21	28
15	A	2.7	0	0	0	0	0	0	.3	.8	.1	.2	0	3.3*	.2	.2	.3	0	0
	B	2.6	.3	.2	.2	.2	.1	.1	.2	.4	.2	.3	0	2.6++	.2	.3	.4	.2	.3
30	A	2.5	.3	.2	.1	.2	.2	.2	.3	.4	.2	.3	.4	.7	.3	.3	.5	.2	.2
	B	2.5	.2	.2	.1	.2	.1	.2	.2	.3	.3	.4	1.0	3.5*	.2	.2	.5	.1	.3
45	A	2.5	.3	.3	.2	.2	.2	.2	.2	.2	.1	.2	.2	.3	.2	.3	.3	.1	.1
	B	2.7	.2	0	0	.1	0	0	0	0	0	0	0	.1	.1	.1	.1	.1	0
75	A	2.7	.1	0	0	.1	0	0	.1	.1	0	0	0	.1	0	0	0	0	0
	B	2.5	.2	.2	.2	.3	.2	.2	.2	.2	.2	.2	.3	.3	.1	.3	.4	.3	.3
105	A	2.5	.5	.6	.3	.3	.2	.2	.3	.3	.3	.4	.4	.5	.3	.4	.5	.2	.4
	B	2.7	.1	0	0	.1	0	0	0	.1	0	0	0	0	.2	.1	0	.1	.1
135	A	2.7	.5	.6	.6	.5	.5	.4	.4	.3	.3	.3	.3	.4	.2	.2	.1	.2	.3
	B	2.6	.3	.1	.2	.3	.2	.3	.3	.2	.1	.1	.1	.2	.1	.2	.2	.1	.2
165	A	2.9	0	.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.1
	B	2.6	.1	.1	.1	.2	.2	.2	.1	.1	.1	.1	.1	.1	0	.1	0	.1	.2
195	A	2.8	.3	.2	.2	.2	.2	.2	.3	.1	.1	.2	.2	.2	.2	.3	.2	.2	.2
	B	2.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
225	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	3.0	0	0	0	0	0	.1	0	0	0	0	0	0	.1	0	0	0	0
255	A	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
285	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	0	0	00	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE II J: WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 1 x 1½ m

DEPTH (CM) & REPLICATES		MINIM. RESIST.	DECEMBER '76				JANUARY '&77					FEBRUARY '77				MARCH '77			
			6	13	20	27	3	10	17	24	31	7	14	21	28	7	14	21	28
15	A	2.6	.2	.2	.1	.2	.1	.2	.8	3.4*	.3+	.7	3.4*	3.4*	.3+	.3+	.9	.3	.2
	B	2.7	.1	.2	0	.1	0	.1	.8	3.3*	.2+	.5	3.3*	3.3*	.2+	.3+	1.3	.2	.1
30	A	2.5	.2	.1	.1	.2	.1	.2	.2	.5	.2	.2	.5	.9	.3	.3+	.4	.4	.4
	B	2.6	.2	.2	0	.10	.1	.1	.1	.3	.2	.2	.1	.4	.2	.3+	.4	.1	.1+
45	A	2.8	0	0	0	0	0	0	0	.2	0	.1	.5	1.8	.6	.9+	3.2*	3.2*	2.8+
	B	2.7	0	.1	0	0	0	0	0	.2	0	.1	.3	.4	.5	.7	.9	1.3	1.3
75	A	2.6	.3	.2	.2	.3	.1	.3	.2	.3	.2	.2	.4	.4	.1	.2	.3	.1	.2
	B	2.7	1.2	.2	1.1	1.0	0	1.0	1.0	1.0	.9	.9	1.4	1.1	0	.9	1.0	1.1	1.2
105	A	2.6	1.2	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.7	2.0++	2.2++	1.7	1.9
	B	2.5	.5	.5	.5	.5	.5	.5	.5	.5	.4	.5	.5	.1	.7	.6	.5	.6	.6
135	A	2.7	.3	.3	.3	.4	.4	.5	.4	.5	.5	.4	.5	.5	.5	.6	.6	.6	.6
	B	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
165	A	2.6	.1	.1	0	.2	.1	.1	.1	0	.1	.2	0	.1	.2	.2	.2	.1	.1
	B	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
195	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	-	-	-	-	-
	B	2.7	.2	.1	.1	.1	0	.1	.2	.1	.1	.1	.1	0	.1	.2	.1	.3	.1
225	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
255	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.7	0	0
285	A	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.6	.2	.2	.2	.3	.3	.3	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
300	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.8	0	0	0	0	.1	.1	.1	.1	.1	0	.1	.1	.1	.2	.1	.1	.1

TABLE II K: WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 1 x 2 m

DEPTH (CM) &	REPLICATES	MINIM. RESIST.	DECEMBER '76				JANUARY '77					FEBRUARY '77				MARCH '77			
			6	13	20	27	3	10	17	24	31	7	14	21	28	7	14	21	28
15	A	2.6	.2	.2	.1	.1	.1	.2	.8	3.4*	.2	.8	3.4	3.4	.3	.5	3.4*	.2+	.2
	B	2.7	0	.1	0	0	0	.2	1.0	3.3*	.1	2.0++	3.3*	3.3*	.2	.3	3.3*	.1+	.1
30	A	2.5	.2	.3	.2	.2	.1	.2	.5	1.0	.2	.5	1.8++	3.5*	.4	.5	1.2	.8	.6
	B	2.6	.2	.1	0	.2	.1	.1	.4	.8	.2	.4	2.0	3.3*	.3	.4	.8	1.2	.6
45	A	2.7	.1	.1	0	0	0	.1	.1	.3	.1	.1	.6	.6	.1	.1	.3	.6	.7
	B	2.6	.1	.1	.1	0	.1	.1	.4	.3	.1	.2	.3	.5	.1	.2	.3	.5	.6
75	A	2.6	.1	.1	.1	.1	.1	.1	.2	.2	.3	.4	.6	.8	.2	.2	.4	.6	.8
	B	2.6	.1	.1	.1	.1	.2	.3	.3	.4	.2	.3	.5	.6	.2	.4	.5	.8	1.2
105	A	2.6	.1	.1	.2	.1	.2	.2	.2	.2	.3	.3	.3	.2	.3	.6	.6++	.7	.3
	B	2.6	.2	.2	.2	.3	.3	.3	.3	.5	.2	.3	.6	.9	1.0	1.4	2.4	3.4*	3.4*
135	A	2.6	.1	0	.1	.2	.2	.1	.2	.1	.1	.2	.2++	.1++	.4	.2++	.2	.1	.1
	B	2.7	.2	.1	.5	.6	.7	.8	1.0	1.2	1.4	1.6	2.0	2.8	3.3*	2.7	3.3*	3.3*	3.3*
165	A	2.7	.3	.3	.3	.3	.3	.3	.3	.3	.3	.4	.4	.3	.1	.4	.3	.3	.4
	B	2.7	.1	.1	.1	.2	.2	.2	.3	.3	.3	.3	.4	.4	.5	.6	.6	.7	.8
195	A	2.6	.3	.3	.3	.4	.3	.3	.4	.3	.3	.4	.4	.2	.2	.4	.3	.3	.3
	B	3.0	.3	.3	.4	.5	.5	.5	.5	.6	.6	.6	.6	.6	.6	.7	.7	.7	.8
225	A	3.0	0	0	0	0	0	0	0	0	0	0	0	.3	.3	0	0	.1	0
	B	2.9	.1	.1	.1	.2	.1	.2	.2	.1	.1	.2	.1	.1	.3	.1	.2	.1	.1
255	A	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.7	.2	.1	.1	.1	.1	.1	.1	.1	.1	.2	.2	.2	.3	.2	.2	.3	.2
285	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	A	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE II L: WEEKLY SOIL MOISTURE AS DIFFERENCE BETWEEN MINIMUM AND MEASURED RESISTANCES IN LOG-OHMS

COFFEE SPACING 2.74 x 2.74 m

DEPTH (CM) & REPLICATES		MINIM. RESIST.	DECEMBER '76				JANUARY '77					FEBRUARY '77				MARCH 1977			
			6	13	20	27	3	10	17	24	31	7	14	21	28	7	14	21	28
15	A	2.7	.2	0	0	0	0	0	.2	.7	.1	.1	.5	3.3*	.2	.2	.4	0	.2
	B	2.6	0	.1	.2	.1	0	.1	.5	2.9	.2	.4	1.9	3.4*	.2	.3	.7	.2	.3
30	A	2.6	.2	.1	0	.1	0	0	.1	.2	.1	.1	.2	.5	.1	.2	.3	0	.2
	B	2.6	.2	0	.1	.1	0	0	0	.1	.1	0	.1	.3	.2	.2	.2	.1	.1
45	A	2.7	.1	0	0	0	0	0	0	0	0	.1	.1	.5	0	0	.2	0	0
	B	2.6	.1	0	.1	.2	0	0	0	.1	.1	.1	.2	.4	.1	.1	.3	0	.1
75	A	2.7	.1	.1	0	0	0	.1	.3	.6	.7	.9	1.4	2.4	1.8	1.5	2.2++	2.9	2.7
	B	2.6	.1	.1	.1	.3	0	.1	.3	.4	.1	.3	.4	.7	.1	.3	.4	.6	.9
105	A	2.7	.1	2.4++	1.9	1.7	1.5	1.4	1.5	1.6	1.7	1.8	2.1	3.1	3.1	2.5	2.8	3.3	3.3
	B	2.6	.2	.1	.1	.1	0	0	.1	.1	.1	.1	.2	.2	.1	.2	.3	.3	.4
135	A	2.6	.1	3.4*	2.9++	2.5	2.5	2.3	2.2	2.2	2.1	2.2	2.3	3.2	2.8	2.8	3.4*	3.4*	3.0+
	B	2.6	.2	1.1	.9	.7	.6	.5	.5	.5	.4	.4	.5	.5	.2	.3	.2	.4	.6
165	A	2.6	.3	2.6++	2.3++	2.2++	2.2++	2.1++	2.1++	2.2++	2.1++	2.1++	2.2++	2.4++	2.4++	2.2++	2.6++	2.5++	2.4++
	B	2.7	.1	.1	.2	.1	0	0	0	01	0	0	0	.1	.1	0	.1	0	0
195	A	3.0	.3	0	0	.1	0	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
	B	2.7	.3	.1	.1	.2	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.2	.1	.1
225	A	3.0	0	0	0	.1	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	3.0	.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
255	A	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	3.0	.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
285	A	2.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	A	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	2.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The soil moisture conditions during the three experimental periods are summarized in Tables III(A-C), which show the mean resistance increases above the initial minimum down to 165 cm depth for all the coffee spacings.

Table III A which shows the data for period I, April to August 1976 reveal that the topsoil layers developed higher resistances than the lower layers of the profile over the period. While there was variability within all soil layers, the plant densities did not appear to influence the soil resistances to any appreciable extent.

In period III(Table IIIB) generally high resistances were recorded as this coincided with the driest months of the year. Down to about a metre of the profile, resistances greater than 12 log-ohms were recorded in all coffee spacings. There was a general tendency of the close spacing blocks to have slightly higher resistances than the conventional spacing particularly in the top three layers (down to 45 cm). It would appear that the coffee at close spacings of 1 x 1, 1 x 1½ and 1 x 2 m used more water from the top soil (0-45) cm. But subsoil (105-165) cm of wide spaced coffee used more.

The data for period 3 is presented in table IIIC, which covers December 1976 to March 1977. Overall, very low resistances were recorded during that period. This was the period between the 1976 short rains and 1977 long rains. The soils had been moistened by rains falling in November and December 1976.

Soil resistance variability at all depths was again predominant in this period. Density effects could not be picked out here possibly because real differences never existed. The higher mean resistances in 105, 135, and 165 cm soil depths in 2.74 x 2.74 m spacing need further qualification. It has been pointed out that a higher resistance value meant drier soil conditions. The same effect was noted in connection with table IIL above, and the explanation advanced could as well apply to this table.

TABLE III A: EFFECTS OF PLANT DENSITIES ON SOIL MOISTURE, MEAN RESISTANCE 19TH APRIL TO 2ND AUGUST, 1976

SOIL DEPTH (CM)	Area per coffee plant (m^2)			
	1	1.5	2	7.5
15	.35	.40	.35	.35
30	.55	.15	.35	.10
45	.20	.10	.10	.05
75	.20	.05	.15	.10
105	.20	.15	.20	.0
135	.05	.0	.10	.05
165	.05	.05	.05	.05

TABLE III B: EFFECTS OF PLANT DENSITIES ON SOIL MOISTURE: MEAN RESISTANCE 9TH AUGUST TO 29TH NOVEMBER, 1976

SOIL DEPTH (CM)	Area per coffee plant (m^2)			
	1	1.5	2	7.5
15	2.65	2.70	2.80	2.10
30	2.90	2.40	2.90	1.55
45	2.25	2.85	2.55	1.60
75	1.75	2.10	2.85	2.45
105	1.85	.40	1.65	1.90
1.35	.70	.0	1.25	1.45
165	.05	.0	.25	.75

TABLE III C: EFFECTS OF PLANT DENSITIES ON SOIL MOISTURE: MEAN RESISTANCE 6TH DECEMBER, 1976 TO 28TH MARCH 1977

SOIL DEPTH (CM)	Area per coffee plant (m^2)			
	1	1.5	2	7.5
15	.35	.85	1.00	.60
30	.40	.25	.75	.10
45	.10	.60	.20	.10
75	.10	.50	.35	.65
105	.25	1.05	.60	1.15
135	.30	.25	.95	1.50
165	.05	.05	.35	1.15

WEATHER DATA:

Table IVA presents the weather elements collected and used to compute the crop water use during the experimental time. As can be seen in this table, the figures are grouped as means of ten days from April 1976 to March 1977. The mean distillation values were converted into radiation in calories per day as per formula in the materials and methods, chapter II above, before they could be used in the computation.

The rainfall and evaporation conditions at the Coffee Research Station, Ruiru are presented in Table IVB. The table is split into two parts. The left side of the table has two data columns which show monthly rainfall in millimetres. The first column shows the mean rainfall for all the months from April 1976 to March 1977, as calculated for the last 32 years. The second column presents the actual monthly rainfall recorded during the trial. An important point to note here is, in most months during the trial, the rainfall was much less than the mean for that month. This resulted in total rainfall recorded being about 200 mm less than the mean for the same period, compare 818.8 mm and 1027.6 mm over 32 years.

The second part of the table on the right side shows the total rainfall, open-pan evaporation and potential evapotranspiration, ETo in intervals of 28 days. These 28 day intervals correspond with the soil sampling for the gravimetric moisture determination presented in 3:1:1 above. The total rainfall recorded during the actual experimental time was 707.2 mm, about 100 mm less than the monthly records. This is because the experimental work started on 14th April, 1976 and the last sampling was on 15th and 16th March, 1977 covering a period of 11 months. The open-pan evaporation during this time was about twice the amount of rainfall received,as can be seen from the figures of 1350.3 mm. The estimation of ETo during the same time was 1564.1 mm. ETo was greater than Epan by a difference of about 214 mm. These figures demonstrate that there was certainly more water particularly lost to the atmosphere from the soil than was received from the rains. Evidently, the class A pan was found unusually to underestimate the crop evapotranspiration. Unlikely, as they may appear, these results were carefully computed and could be in line with what was found for the Faculty of Agriculture, University of Nairobi, Kabete pan; which underestimates the Penman evapotranspiration. (N.M. Fisher, personal communication).

TABLE IV A: WEATHER CONDITIONS PREVAILING AT COFFEE RESEARCH STATION, RUIRU BETWEEN APRIL 1976 AND MARCH 1977

Period Groups of 10 days		Mean air tempera-ture °C	Mean Relative humidity %	Sunshine hours per day	Mean distil-lation ml/day	Wind velocity km/day
April 1976	1st	20.7	68	6.9	15.5	99
	2nd	19.3	81	4.5	10.9	88
	3rd	19.8	77	5.4	10.0	82
May	1st	20.3	67	8.5	13.9	69
	2nd	19.7	74	4.0	10.4	68
	3rd	20.2	74	5.4	12.5	64
June	1st	19.5	66	6.3	14.7	61
	2nd	18.7	68	2.6	12.2	75
	3rd	17.2	74	2.2	13.5	57
July	1st	17.5	70	3.9	13.2	54
	2nd	17.9	73	4.1	11.2	50
	3rd	17.1	72	5.5	11.3	70
August	1st	16.7	80	2.2	9.0	60
	2nd	18.4	69	6.2	15.8	82
	3rd	17.3	71	5.2	12.9	84
September	1st	18.5	71	6.1	15.8	86
	2nd	19.4	65	8.2	16.5	90
	3rd	19.2	72	5.9	14.3	101
October	1st	19.0	67	6.9	14.8	102
	2nd	20.9	60	8.9	18.2	103
	3rd	20.4	60	9.1	18.3	106

continued

Period Groups of 10 days		Mean air temperature °C	Mean Relative humidity %	Sunshine hours per day	Mean distillation ml/day	Wind Velocity km/day
November	1st	20.6	66	7.3	14.5	113
	2nd	21.1	62	8.3	17.5	114
	3rd	19.9	76	5.2	12.5	85
December	1st	19.0	68	9.0	16.9	104
	2nd	19.0	76	8.0	15.2	114
	3rd	18.6	70	7.7	15.2	98
January 1977	1st	19.7	72	8.3	19.2	94
	2nd	19.7	71	7.8	17.7	104
	3rd	20.1	62	9.2	20.1	100
February	1st	19.7	57	9.3	20.9	108
	2nd	21.0	56	10.7	22.5	123
	3rd	21.0	72	7.6	17.4	105
March	1st	20.6	68	8.9	20.4	109
	2nd	20.7	69	7.8	18.7	122
	3rd	21.1	72	7.6	15.5	100

TABLE IV B: RAINFALL AND EVAPORATION CONDITIONS AT THE COFFEE RESEARCH STATION, RUIRU

MONTH OF THE YEAR	MONTHLY RAINFALL (mm)		PERIOD	28 DAY INTERVALS		
	MEAN OF 32 YEARS	1976/77 ACTUAL RECORDS		RAINFALL (mm)	Epan (mm)	Eto (mm)
APRIL	238.5	230.5	APRIL 14 - MAY 11 '76	183.3	94.1	108.1
MAY	181.0	52.3	MAY 12 - JUNE 8 "	49.4	95.2	112.1
JUNE	47.6	60.3	JUNE 9 - JULY 6 "	62.6	89.4	116.0
JULY	29.6	29.5	JULY 7 - AUG. 3 "	27.2	76.7	101.6
AUGUST	28.7	1.5	AUG. 3 - AUG. 31 "	1.1	97.4	108.4
SEPTEMBER	33.3	22.7	SEPT. 1 - SEPT. 28 "	21.7	116.0	129.1
OCTOBER	68.7	22.9	SEPT. 29 - OCT. 26 "	22.9	135.5	144.9
NOVEMBER	145.8	147.5	OCT. 27 - NOV. 23 "	61.9	133.2	134.7
DECEMBER	75.0	80.9	NOV. 24 - DEC. 21 "	145.3	104.4	130.1
JANUARY	48.1	53.1	DEC. 22 - JAN. 18 '77	22.3	114.6	148.8
FEBRUARY	41.0	52.9	JAN. 19 - FEB. 15 "	52.3	157.3	165.0
MARCH	90.3	64.7	FEB.16 - MAR. 15 "	57.2	136.5	165.3
TOTAL	1027.6	818.8		707.2	1350.3	1564.10

The crop water use, ET(crop) estimates for each coffee spacing are presented in table IVC. The data is grouped in four week intervals with totals for the twelve periods at the bottom of the table. The ET(crop) values were derived from the changes in soil moisture and rainfall between the gravimetric sampling dates.

From table IVC, it appears that the crop water use for the whole experimental time decreases with increased plant density. That is at a coffee spacing of 1 x 1 m where plants occupied an area of one square metre, less water was used than in the widest spacing of 2.74 x 2.74 m where the area per plant was 7.5 square metres. The water use in the three closely spaced coffee blocks increased as the area per plant increased as from 1 to 2 square metres as seen from the totals. A striking similarity was found in 1 x 2 and 2.74 x 2.74 m coffee spacings where each of them used about 864 mm of water over 48 weeks and 936 mm over 52 weeks.

TABLE IV C: CROP WATER USE FOR DIFFERENT COFFEE SPACINGS

PERIOD (28 DAYS)	coffee spacing in metres				Variance ratio (F)			
	1 x 1	1 x 1.5	1 x 2	2.74x2.74	S.E.	Convents. v's close	Linear	Quadratic
APRIL 14 - MAY 11	131.77	105.72	229.82	182.58	27.54	.36 NS	9.50**	7.43**
MAY 12 - JUNE 8	78.69	76.79	93.04	119.61	9.88	5.19**	1.58 NS	.84 NS
JUNE 9 - JULY 6	66.58	64.38	50.46	52.90	4.04	1.32 NS	11.94**	2.10 NS
JULY 7 - AUG 3	65.84	57.81	39.22	38.00	[illegible]	1.68 NS	8.95**	.47 NS
AUG 4 - AUG 31	24.39	35.12	57.34	70.24	10.41	3.39 NS	7.52**	.31 NS
SEPT 1 - SEPT 28	31.63	12.62	30.98	37.18	4.63	2.16 NS	.02 NS	11.50**
SEPT 28 - OCT 26	37.53	53.03	38.11	59.12	5.42	3.37 NS	.01 NS	7.89**
OCT 27 - NOV 23	33.00	50.51	29.90	37.45	4.54	.002 NS	.35 NS	17.64**
NOV 24 - DEC 21	53.34	69.34	55.68	47.88	4.56	2.41 NS	.200 NS	10.56**
DEC 22 - JAN 18	49.39	77.53	126.18	76.93	15.87	.09 NS	17.30**	.44 NS
JAN 19 - FEB 15	59.57	56.43	47.19	64.52	3.65	2.89 NS	8.64**	.70 NS
FEB 16 - MAR 15	41.16	88.44	66.12	77.69	10.15	.57 NS	4.54 NS	11.77 NS
TOTAL	673.49	747.72	864.04	864.10				

Table IVD shows the crop coefficients, ko estimates calculated for 28 day periods for the four coffee blocks. In these calculations the changes in soil moisture and rainfall between sampling dates were taken into account. Table IV E presents the mean values of ko for May 12th - August 3rd, August 4th - November 23rd 1976 and November 24th 1976 - March 15th 1977, and the overall ko mean values plus water use (ETo.ko) estimates using these coefficients.

A notable feature of these crop coefficients is the great variability which seems to have been greatly affected by the quantity of moisture in the soil in each particular period. During the wet months relatively high coefficients were the rule while the reverse was true during the dry months. This is clearly shown in table IVE. The mean ko from May 1976 to March 1977 was found to have an increasing trend as the area per coffee plant in the blocks increased. The water use estimates from total ETo and these coefficients also followed a similar trend as the ko values.

TABLE IV D: CROP COEFFICIENTS, ko ESTIMATED FROM CHANGES IN SOIL MOISTURE AND RAINFALL

28 DAY PERIODS 1976/77	AREA PER COFFEE PLANT (m^2)			
	1	1.5	2	7.5
APRIL 14 - MAY 11	1.219	.978	2.126	1.689
MAY 12 - JUNE 8	.702	.685	.830	1.067
JUNE 9 - JULY 6	.574	.555	.435	.456
JULY 7 - AUG. 3	.648	.569	.386	.374
AUG 4 - AUG. 31	.225	.324	.529	.648
SEPT. 1 - SEPT.28	.245	.121	.240	.288
SEPT.29 - OCT.76	.259	.366	.263	.408
OCT.27 - NOV 23	.245	.375	.22	.278
NOV.24 - DEC. 21	.410	.533	.428	.368
DEC. 22 - JAN 18	.336	.521	.848	.517
JAN 19 - FEB 15	.361	.342	.286	.391
FEB. 16 - MAR 15	.249	.535	.400	.470
MEAN	.456	.492	.583	.580

TABLE IV E: PERIODIC CROP COEFFICIENTS AND WATER USE ESTIMATES, 11TH MAY 1976 TO 15TH MARCH, 1977

WET & DRY PERIODS 1976/77	AREA PER COFFEE PLANT (m^2)				
	1	1.5	2	7.5	MEAN
MAY 11 - AUG 3	.641	.603	.550	.632	.607
AUG 4 - NOV 23	.244	.297	.314	.406	.315
NOV 24 - MAR 15	.339	.483	.491	.437	.438
MEAN ko	.39	.45	.44	.48	.44
Eto. ko	567.8	655.2	640.6	698.9	640.6

The crop factors - kpan were calculated from crop water use and open-pan evaporation values and presented in Table IVF, for the 28th day periods between April, 1976 and March 1977. Like table IVE, table IVG presents kpan-mean values for the three experimental periods between May 1976 and March 1977 plus estimates of water use, k.Epan.

The kpan factor seemed to be affected by weather and soil moisture conditions in a similar manner like ko. The period between August 4th and November 23rd 1976 had the lowest kpan values. This period coincided with the driest months of the trial. The mean kpan-values show an increasing trend as the coffee spacing increased though the trend showed a sag at 1 x 2 m coffee spacing which was an intermediate density between 1 x 1½ and 2.74 x 2.74 m. However, the drop in mean kpan-value at this spacing may not be considered significant. The water use - kpan.Epan estimates followed the same trend as ko-values. The kpan-Epan values were slightly higher than ETo.ko values presented in table IVE.

TABLE IV F: CROP FACTORS (k pan = $\frac{ET(crop)}{E\ pan}$) ESTIMATED FROM WATER USED AND OPEN-PAN EVAPORATION

28 DAY PERIODS 1976/77	AREA PER COFFEE PLANT (m^2)			
	1	1.5	2	7.5
APRIL 14 - MAY 11	1.40	1.12	2.44	1.94
MAY 12 - JUNE 8	.83	.81	.98	1.26
JUNE 9 - JULY 6	.75	.72	.56	.59
JULY 7 - AUG 3	.86	.75	.51	.50
AUG 4 - AUG 31	.25	.36	.59	.72
SEPT. 1 - SEPT. 28	.27	.13	.27	.32
SEPT. 29 - OCT 26	.28	.39	.28	.44
OCT 27 - NOV 23	.25	.38	.23	.28
NOV.24 - DEC 21	.51	.66	.53	.46
DEC. 22 - JAN 18	.44	.68	1.10	.67
JAN 19 - FEB. 15	.38	.36	.30	.41
FEB 16 - MARC15	.30	.65	.48	.57
MEAN	.543	.584	.689	.680

TABLE IV G: PERIODIC CROP FACTORS AND WATER USE ESTIMATES: 11TH MAY, 1976 TO 15TH MARCH 1977

WET & DRY PERIODS 1976/77	AREA PER COFFEE PLANT (m^2)				
	1	1.5	2	7.5	MEAN
MAY 11 - AUG 3	.81	.76	.68	.78	.76
AUG 4 - NOV 23	.26	.32	.34	.44	.34
NOV 24 - MAR 15	.41	.59	.60	.53	.53
MEAN	.47	.54	.53	.57	.52
kpan.Epan	590.4	678.4	665.8	716.0	662.7

It was assumed that crop water use was not limited by the soil moisture during the wet seasons. Four months, May to early August, 1976 were considered reasonably wet months during the trial, when crop evapotranspiration was not limited by the soil moisture deficit. Both the crop coefficients, ko and the crop factors, kpan were calaculated for all the coffee spacings and were then used in the estimations of the potential crop water use (Table IVH a&b).

Using ko, the total crop evapotranspiration estimates by the modified Penman method for 44 weeks from 12th May 1976 to 15th March, 1977 was multiplied by the relevant crop coefficient for the different coffee spacings. The values so obtained were then converted to annual crop water use. The figures presented in table IVH(a) show that there was not much difference in the potential water use in the range of the four coffee densities considered.

In an attempt to estimate potential crop water use by kpan method, the long term open pan evaporation mean for 23 years for Ruiru was used. The mean pan evaporation of 1549.4 mm was multiplied by the relevant kpan values in the same way as ko values above. The values so obtained were slightly higher than those obtained by ko method, except for 1 x 2 m coffee spacing where ETo.ko was greater than Epan.kpan (Tables IVH a& b). Generally, the potential water use estimates were found to be comparable with Dagg's (1968) predicted annual potential water use value of 1219 mm for close spaced coffee. However, these values were obtained by assuming the crop coefficients and factors for wet months throughout the year, a condition which is unlikely to happen in nature. Ample irrigation may be required during the dry months to maintain such conditions.

TABLE IV H (a): ANNUAL POTENTIAL CROP WATER USE (mm) ESTIMATED BY CROP COEFFICIENTS.

Coffee spacing in metres	Crop Coefficient Ko	Water use 44 wks	ET(crop) 52 wks
1 x 1	.64	932	1101
1 x 1.5	.60	874	1032
1 x 2	.55	946	1119*
2.74 x 2.74	.63	917	1084
MEAN	.61	917	1084

TABLE IV H (b): ANNUAL POTENTIAL CROP WATER USE ESTIMATED BY CROP FACTOR AND LONG-TERM PAN EVAPORATION MEAN OF 1549.4 mm.

Coffee spacing in metres	Crop factor k pan	water use ET(crop) (mm), 52 weeks
1 x 1	.81	1255
1 x 1.5	.71	1100
1 x 2	.68	1054*
2.74 x 2.74	.78	1209
MEAN	.75	1155

$*ET_o.k_o > E_{pan}.k\ pan$

The statement of water used as influenced by plant density was further investigated by statistical analysis (Table IVC). A comparison between the conventional and close spaced coffee shows that there was no significant difference in the amount of water used for all the periods except between May 12th and June 8th, during which 2.74 x 2.74 m spacing had used more water than the other three. This was during the long rains and all coffee densities appear to have used high amounts of water.

A linear comparison between the close spacings revealed that: 1x2 m used significantly higher amount of water between April and May 1976; less water between June and July; and still less between July and August, 1976. In August, however, the trend was reversed and the linear increase was such that the wider spacing the higher was the water use. Statistically significant differences were also recorded in the periods between December/January and January/February.

Further water use relationships within the three close spacings was compared quadratically. Of the twelve periods, five of them came out statistically significant. This revealed a degree of curvilinear relationship existed within the water use values in close spaced coffee. However, the curvilinearity was not in all cases positive. Looking at the table again, no straight statement can be made about the water use. Sometimes the middle density appeared to have higher figures, while in other times the same density had lower values. Considering the three comparisons, then one can say that the present data does not show any evidence of difference in crop water use as affected by the coffee plant densities.

3:2 SUBSIDIARY STUDIES:

3:2:1 ROOT DISTRIBUTION

Tables VA & B show the coffee root distribution down to 60 cm of the soil depth. In table VA the results presented are those obtained by volumetric core sampler method, while VB are the results of the trench method.

On the left side of table VA data of the mean dry root weights is presented for four coffee densities. The figures were obtained after the root samples were dried in the oven. For each coffee density and soil depth the mean root weight is shown, accompanied by its standard error. The data shows that:-

*For all the coffee densities root distribution, that is mean root weights in gm/sample decreased from 20-26 to 40-46 cm.

*In 1 x 1.5 and 1 x 2 m spacings, the 20-26 cm soil depth had more roots than the 0-6 cm depth.

*The closest 1 x 1 m and the widest 2.74 x 2.74 coffee spacings had more roots in the top soil, though the latter had about .10 gm more than the former.

*There was great variability in root weights in soil samples at all depths.

*Except in 1 x 2 m, the close spacings had more roots than the conventional spacing in 40-46 cm soil layer.

The data presented on the right portion of the table VA, was from coffee regularly irrigated to avoid occurrence of water stress. Here only the three high density blocks were sampled. The fresh root weights rather than dry weights were considered in this case.

Of importance to note here is that the mean root weights increased in the top soils as the plant population increased. The same trend was repeated in the 20-26 and 40-46 cm soil layers. As was noted in dry root samples, the root distribution was such that in all coffee spacings, there were more roots in the topsoil than lower layers and of greater significance is that the closest spacing had more roots at this layer than the other two.

TABLE V A: ROOT DISTRIBUTION AS AFFECTED BY PLANT DENSITIES: CORE SAMPLER METHOD

SOIL DEPTH (CM)	MEAN ROOT DRY WEIGHT (gm/sample) IN UNIRRIGATED COFFEE 1/12/1976 coffee spacing in metres				MEAN ROOT FRESH WEIGHT (gm/sample) IN IRRIGATED COFFEE 2/12/1976 coffee spacing in metres		
	1 x 1	1 x 1.5	1 x 2	2.74x2.74	1 x 1	1 x 1.5	1 x 2
0-6	.74±.22	.60±.29	.21±.09	.84±.10	1.09±.21	.85±.48	.12±.04
20-26	.30±.12	.63±.19	.41±.22	.60±.32	1.28±.58	.71±.26	.48±.10
40-46	.24±.08	.49±.15	.04±0	.15±.11	.67±.37	.61±.31	.53±.04

Table VB presents the mean root weights and their standard errors obtained by the trench method. The larger soil samples obtained by this method accounts for the higher values shown per sample. All values stand for fresh weights.

The data presented on the left side of the table was obtained from the same coffee as that shown in table VA above. With bigger root samples the pattern of root distribution was very much the same as that demonstrated by smaller samples. The validity of the top soil having more roots than the lower layers, and that closely spaced coffee had more roots at greater depths than the wider spacings seems to be confirmed. At this stage it was thought that site in addition to plant density might have an influence on the coffee root distribution. Root sampling was then extended to two coffee blocks on a different site. The results so obtained are presented in table VB, right side portion. These conformed very much with the root distribution pattern shown by the earlier sampling. 1 x 1.5 had more mean root weights at all soil depths than was the case with 1 x 2 m.

TABLE V B: ROOT DISTRIBUTION AS AFFECTED BY PLANT DENSITIES: TRENCH METHOD

SOIL DEPTH (CM)	MEAN ROOT FRESH WEIGHTS (gm/sample) on 19/4/1977			MEAN ROOT FRESH WEIGHTS (gm/sample) on 20/4/1977	
	coffee spacing in metres			coffee spacing in metres	
	1 x 1	1 x 1.5	1 x 2	1 x 1.5	1 x 2
0-20	11.95±2.81	5.03±.87	5.88±1.07	4.14±1.52	4.03±1.99
20-40	5.52±1.82	4.69±1.52	4.17±1.74	2.64±.85	1.34±.26
40-60	3.53±1.08	3.29±.45	1.67±1.07	1.86±.54	1.20±.22

3:2:2 WATER INFILTRATION RATES

Figures II(a-c) shows the water infiltration rate graphs. The values used in this plot are means for five sample sites carried out for a duration of two hours.

From figure II(a), the infiltration rate in 1 x 2 m coffee spacing was found to be generally higher than in 1 x 1 and 1 x 1.5 m spacings. The amount of water entering the soil in 1 x 1 and 1 x 2 m spacings was found to be above the average of the three spacings. The data was obtained on dry sample site at approximately 28.3% soil moisture down to 75 cm depth.

In the first five minutes the water infiltration rates under the three coffee spacings were found to be very high. However, the rates slakened from the 10th minute and finally reached a steady state after the 30th minute of infiltrating. In this figure, the infiltration rate curves for 1 x 1 and 1 x 2 m coffee spacings stabilized at a higher point than the mean of the three curves.

Figure II b shows the water infiltration rates in wet soils, which was found to be approximately 38.1% moisture content in the top 75 cm. As in the dry soils 1 x 1.5 (fig. II a) coffee spacing had higher infiltration rates in the first two minutes after which the trend in the dry soil was followed. The mean infiltration rate for the three coffee spacings was lower than that found for dry soils. It was 4.4 mm/min. as compared to 5.0 mm/min at the 120th minute of infiltrating. There was less divergence in infiltration curves in wet soils than was in dry soils.

The mean infiltration rates in dry and wet soils for different coffee spacings were taken and presented in figure II c. In this figure the pattern of infiltration rate curves shown in dry and wet soils is maintained. The overall infiltration rates in 1 x 1 and 1 x 2 m spacings followed almost a similar curve while the 1 x 1.5 m spacing showed the lowest rates of steady state.

The results of water infiltration rates were characterised by tremendous variations from site to site within and between coffee spacings. This is evident from the figures II c below. This variability was common in both the dry and wet soils. To demonstrate this, data from one sampling when the soils were relatively moist was used to calculate the means and standard errors from the 10th to thel 120th minute. The latter was considered a steady state whereby the infiltration curves seems to flatten to approximate horizontal straight line. To indicate the degree of varaibility, the means of five sampling sites were presented in a table.

From the 10th to the 120th minute, there was a decline of about 2 mm/min in 1 x 1 m coffee spacing, about 3 mm/min in 1 x 1.5 and 1 x 2 m coffee spacings respectively. The variation between sites was high as can be seen from the standard errors at all infiltrating intervals. But most probably this varaability had no significant difference.

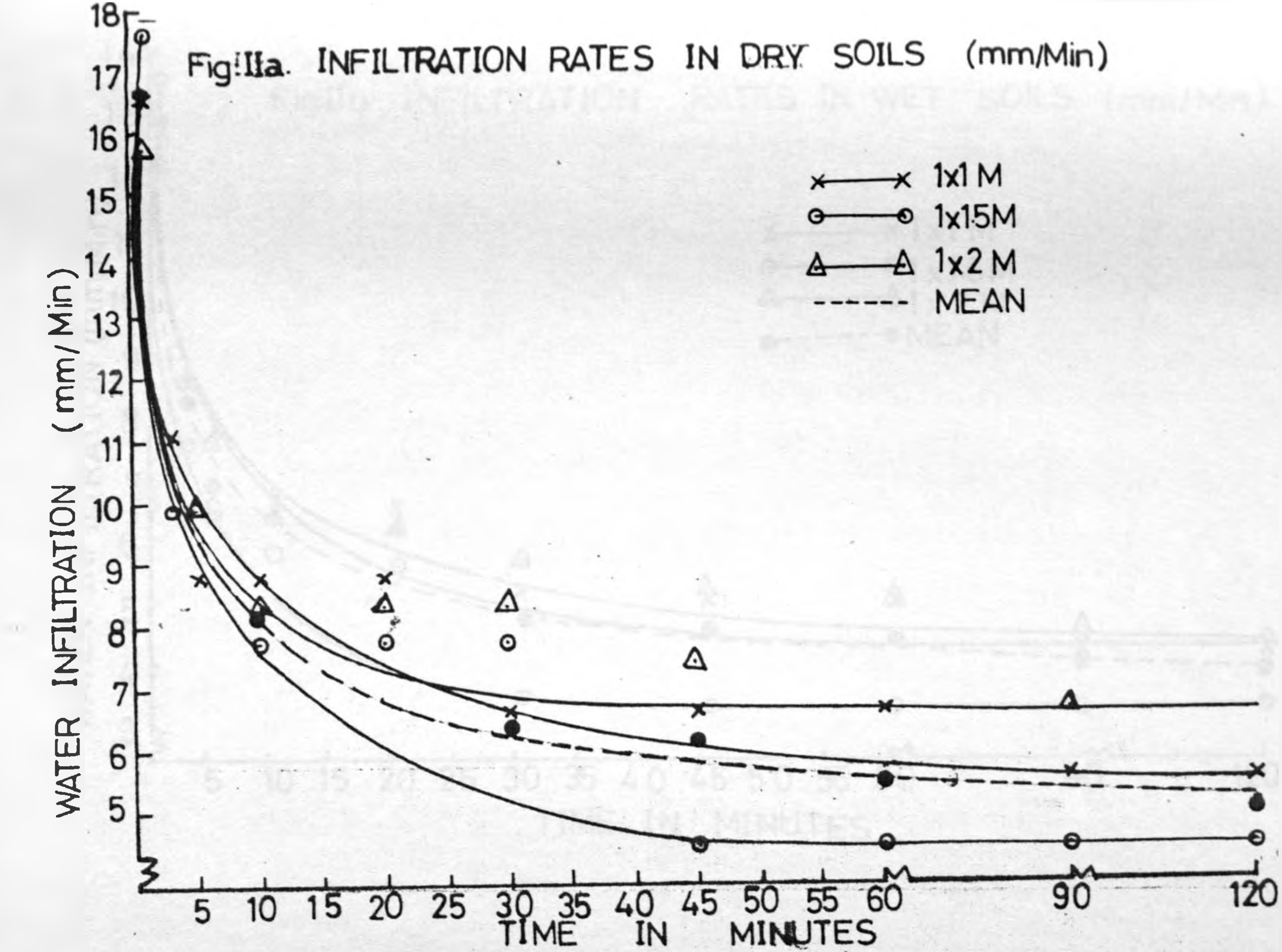


Fig. IIa. INFILTRATION RATES IN DRY SOILS (mm/Min)

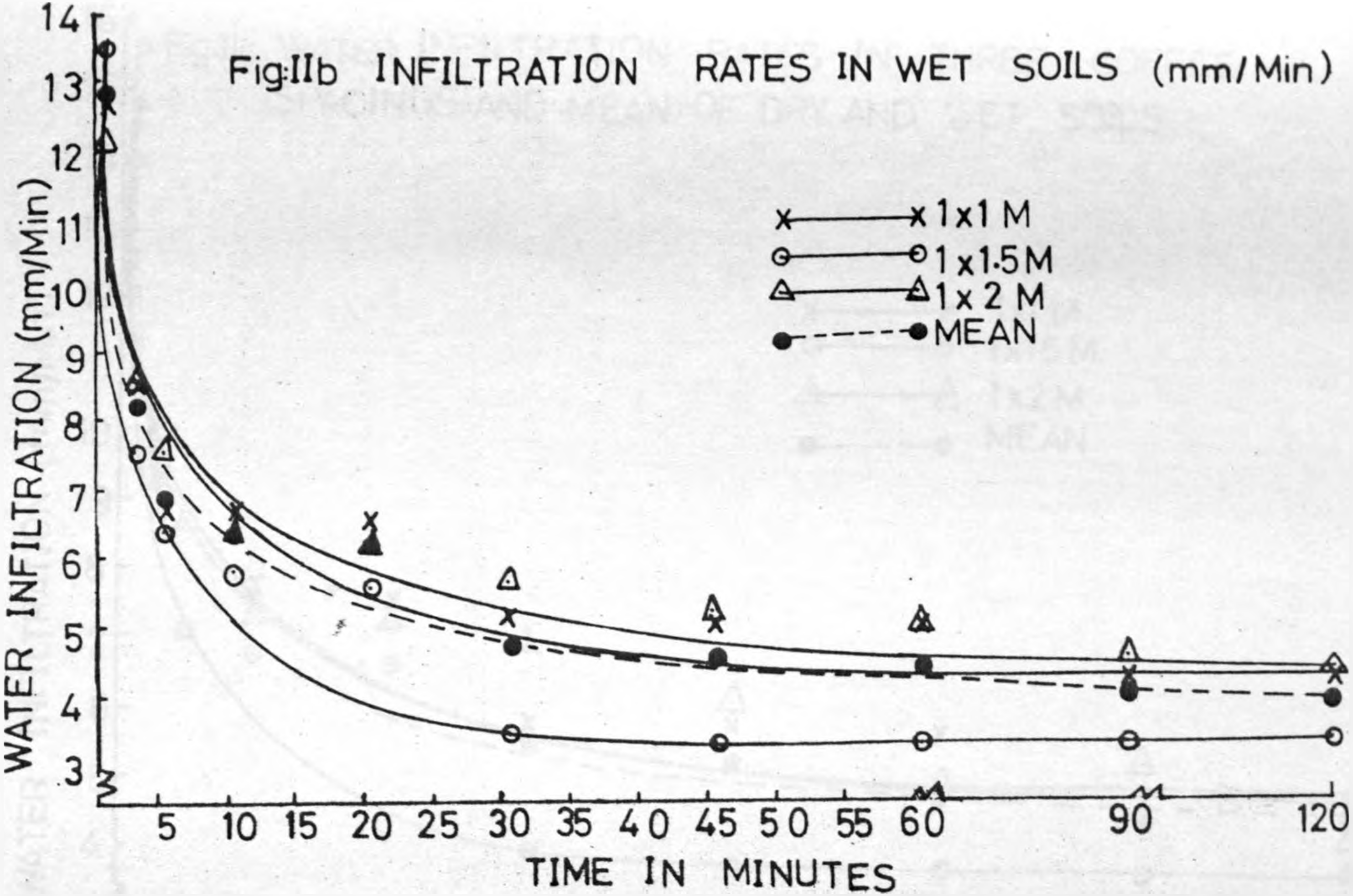


Fig:IIb INFILTRATION RATES IN WET SOILS (mm/Min)

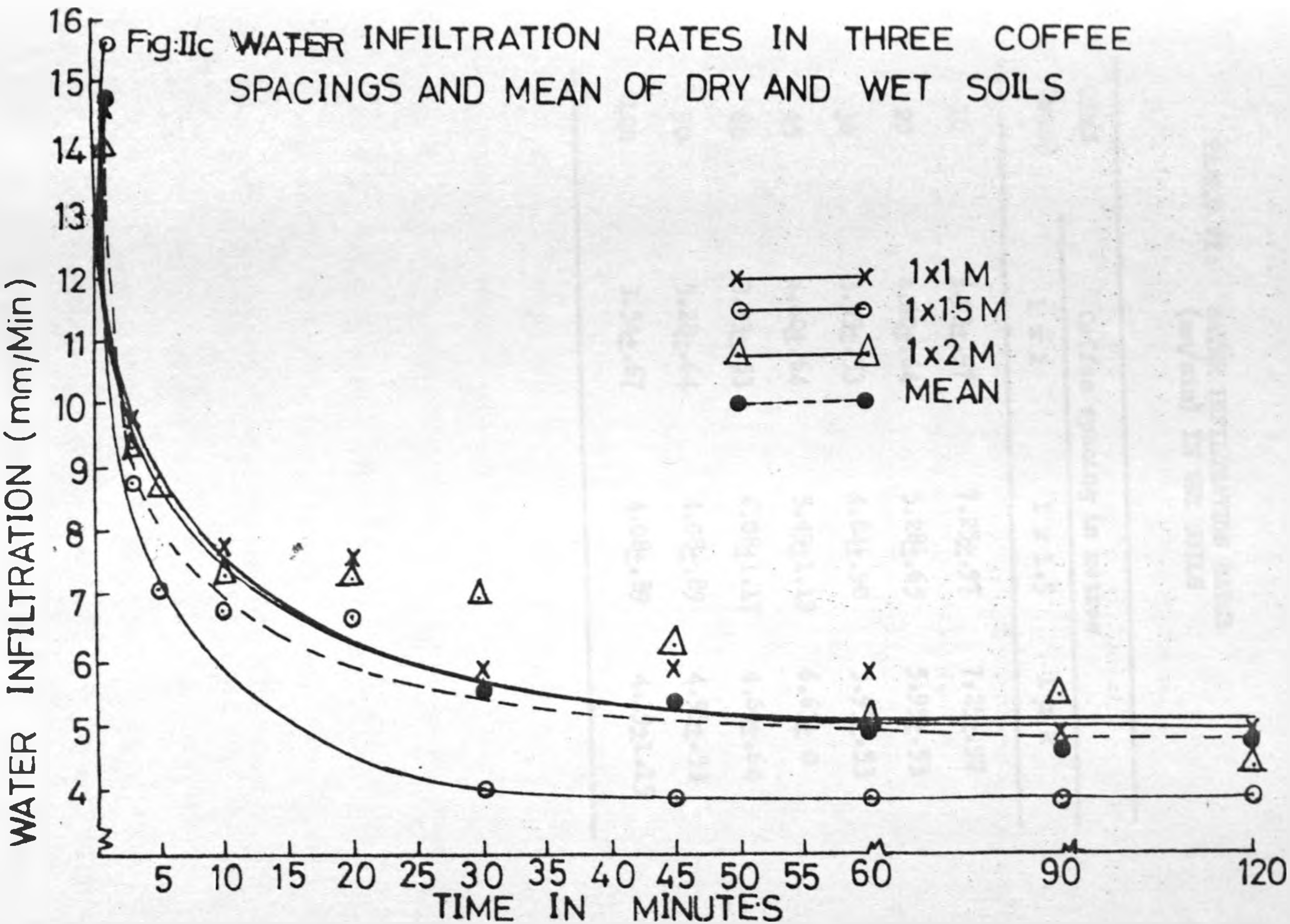


Fig:IIc WATER INFILTRATION RATES IN THREE COFFEE SPACINGS AND MEAN OF DRY AND WET SOILS

TABLE VI: WATER INFILTRATION RATES (mm/min) IN WET SOILS

TIME (Min)	Coffee spacing in metres		
	1 x 1	1 x 1.5	1 x 2
10	5.93±.97	7.25±.97	7.25±.97
20	4.60±.64	5.28±.65	5.95±.53
30	3.93±.53	4.84±.90	5.95±.53
45	4.60±.64	5.49±1.19	6.63± 0
60	3.93±.53	6.08±1.17	4.60±.64
90	5.28±.64	4.08±.89	4.93±.53
120	3.54±.67	4.08±.89	4.19±1.15

3:2:3 TOPSOIL BULK DENSITY

Table VII presents all the data on topsoil bulk density determinations. At the same time, the depth and the number of samples considered are shown.

In 0-3 cm soil layer, the bulk density showed a progressive increasing tendency from the closest spacing of 1 x 1 m to the widest spacing. That is, the most densely populated coffee had the lowest bulk density. In 3-6 cm soil layer, the trend of events in the upper layer is almost maintained in that the closest spaced had the lowest bulk density while 2.74 x 2.74 m still showed the highest value of .91 gm/cm^3. Nevertheless the sequence was interrupted at 1 x 2 m spacing which had lower value than the preceeding density of 1 x 1.5 m, however, the drop was not significant being only .01 gm/cm^3.

In 15-18 cm soil layer, bulk density under all spacings seemed to be equal except that in 1 x 1.5 m which was non-significantly lower than the other three. Here the coffee plant density did not seem to play a role in the soil bulk density.

In 18-21 cm soil depth, the tendency was that the bulk density decreased with the increased coffee spacing. The highest values were recorded in the closest spacing and vise versa.

One striking finding was that except for 1 x 1 m coffee spacing, the bulk density values decreased with increased depth. In 2.74 x 2.74 m the bulk density in 18-21 cm layer was about .10 gm/cm^3 less than the values generally quoted for these soils.

TABLE VII: TOPSOIL BULK DENSITIES (gm/cm^3) UNDER COFFEE BLOCKS

SOIL DEPTH (CM)	coffee spacing in metres								MEAN
	1 x 1		1 x 1.5		1 x 2		2.74 x 2.74		
	No. of samples	Mean & S.E.	no. of samples	Mean & S.E.	No. of samples	Mean & S.E.	No. of samples	Mean & S.E.	
0 - 3	19	.85±.018	21	.90±.014	20	.91±017	11	.92±.020	.89
3 - 6	20	.87±.019	19	.90±.013	19	.89±.015	11	.91±.026	.89
15 - 18	18	.85±.013	19	.83±.015	19	.86±.020	10	.85±.023	.85
18 - 21	20	.86±.015	21	.84±.010	20	.84±.016	11	.80±.020	.84
MEAN		.85		.87		.88		.87	.87

3:3 COFFEE YIELDS

The yields presented here are those covering 1973/74 to 1976/77 crop years. A total of four crops were picked before the high density blocks of coffee were clean stumped in April 1977 after the first production cycle, to start a new one. In November, 1976 quality samples were taken from the four experimental blocks. They were intended to show as whether drought after withdrawing irrigation had any effect on bean quality.

Table VIII A shows both total cherry and clean coffee yields in kg/ha. The yield per year for each spacing and the mean for the four years are presented in the table.

Considering the cherry yields, it can be said that coffee at closer spacing produced more berries per unit area over the four years. The same can be said for the clean coffee yields.

The cherry weights were used to calculate the yields per tree. The results so obtained are presented in table VIII B. While the yield increased per unit area as the plant population increased, the cherry yield per tree decreased. This means that the widest spacing of 1 x 2 m had higher yield (kg/tree) than the 1 x 1 m. The means for four crop years are given at the bottom of the table.

From the quality samples collected in early and late November 1976 percentages of clean coffee to parchment coffee are shown in table VIII C.

The overall percentages did not seem to be affected by the drought in any appreciable way in any of the coffee densities. The two closest spacings and the two widest spacings had equal figures. However, the data used here was very much limited and one must be careful in interpreting the results.

TABLE VIII A; CHERRY AND CLEAN COFFEE PRODUCTION IN THREE HIGH DENSITY BLOCKS

cherry kg/ha

CROP YEAR	coffee spacing in metres		
	1 x 1	1 x 1.5	1 x 2
1973/74	12,985	13,342	8,519
74/75	17,045	12,012	7,931
75/76	9,576	16,926	11,949
76/77	12,978	8,827	16,002
MEAN	13,146.00	12,776.75	11,100.25

Clean coffee kg/ha

CROP YEAR	coffee spacing in metres		
	1 x 1	1 x 1.5	1 x 2
1973/74	1855	1906	1217
74/75	2435	1716	1133
75/76	1368	2418	1707
76/77	1854	1261	2286
MEAN	1878	1825	1586

TABLE VIII B: CHERRY YIELDS IN Kg/TREE

CROP YEAR	coffee spacing in metres		
	1 x 1	1 x 1.5	1 x 2
1973/74	1.113	1.715	1.461
74/75	1.461	1.544	1.359
75/76	.821	2.174	2.047
76/77	1.112	1.135	2.742
MEAN	1.127	1.642	1.903

TABLE VIII C: PERCENTAGE CLEAN/PARCHMENT COFFEE PICKED EARLY AND LATE NOVEMBER 1976

Time of the Month	coffee spacing in metres			
	1 x 1	1 x 1.5	1 x 2	2.74x2.74
EARLY	80	79	81	82
LATE	78	79	81	80
MEAN	79	79	81	81

CHAPTER IV

DISCUSSION AND CONCLUSIONS

CROP WATER USE:

Intensification of coffee growing was taken seriously in Kenya towards the end of the 1960s. Since the inception of research into close spacing of coffee, there has been much speculation about water use. In the absence of scientific evidence, two opposing theories were proposed:

1. Close spacing of coffee would result in higher water use.

2. Water use in high density coffee may decrease or remain the same as in the conventionally spaced coffee.

The first theory was based on the assumption that planting coffee close together would increase the leaf cover which would result in higher evapotranspiration. Dagg (1968), commenting on the high rates of evaporation in Kenya, and water conservation as an important aspect of land management pointed out that, without irrigation, the close spacing of coffee should be adopted with caution and only after considering the likely water balance, which would result from the increased transpirational demand. It was possibly for the same reason that Mitchell (1976) cautioned recommending of high density coffee systems in areas of low rainfall where irrigation facilities are not available. The supposed high water use in closely spaced coffee was most probably inferred from the already known high rate of water use at 0.8 Eo in the conventionally spaced coffee during the rains. In this spacing only 50-60% of the ground is covered by the coffee leaves, which allows direct evaporation from the soil surface or transpiration through the weeds (Dagg, 1968). The author predicted an increase in potential water use for close spaced coffee with complete ground cover at 0.8Eo throughout the year per annum, or 1219 mm in Ruiru. It was assumed that the lower water use in the dry season was due to reduced direct soil evaporation and that this would no longer operate with little bare soil at high density.

The second theory was based on canopy considerations. In the close spacing of coffee bushes, depending on spacing between the plants, the canopy was expected to close together forming a more continuous smooth canopy surface. This means that the possible wind eddying prevalent in present conventional spacing systems would be reduced to a minimum. Huxley and Cannell (1970) argued that close spacing of coffee would result in a canopy with possibly reduced "roughness" which would affect the aerodynamics of water vapour transfer sufficiently to offset the increase in water use occasioned by the greater crop cover.

In the context of crop water use, more emphasis should be placed on radiation interception than the percentage ground cover, particularly with tall tree crops. Radiation interception is considered a better criterion because the limiting factor for evaporation is not the area from which water evaporates but the energy required to evaporate it. Because much radiation is incident at an angle to the vertical, the difference in radiation interception between conventional and close spacing may not be as great as the difference in ground cover.

The work reported here covered April, 1976 to March 1977 and was carried out at the Coffee Research Station, Ruiru and was aimed at discovering the effect of plant density on water use in unirrigated coffee. The data obtained show that there were high soil moisture fluctuations depending on the season of the year. During the wet seasons, (long and short rains, 1976) relatively high moisture values were recorded while as expected soils were found to have less moisture during the dry seasons. Blore (1965) noted this phenomenon when he discovered by soil sampling that during the dry seasons (January - March and June - October) due to high soil moisture deficits, evapotranspiration was much less than sunken pan evaporation, Penman evaporation or solar radiation. This led him to use a modification of seasonal factors used by Pereira (1957) in estimation of crop water use. The moisture fluctuations occurred mainly in the top 165 cm of the three metre soil profile sampled. At lower depths, very little change occurred. These changes were caused by the increase in soil moisture during the rains and loss of the same water through evapotranspiration.

Soil moisture fluctuations with seasons were expected. The plant density effect on water use was investigated by comparing the moisture expressed as a percentage by weight of the oven-dry soil. The comparisons were between the conventional and close spaced coffee, and within a range of high densities. The statistical analysis presented in table 1(A-M) generally failed to show differences in water use between conventional and close spaced coffee, except that high densities used more water in the topsoil than in the subsoils. A statistical comparison among the closely spaced coffee plantings similarly failed to show significant differences in water use.

The fact that high density coffee plantings appeared to use more water in the topsoil than the conventional spacing can possibly be explained by the fact that these high density blocks had a higher concentration of roots near the surface than the conventional spacing. In a further attempt to find differences in water use, three densities of closely spaced coffee at another site on the station also yielded similar results as above. However, for all blocks considered in this study, there were isolated cases of higher or lower water use in different soil layers of the three metre soil profile, but they were not consistent with the plant densities.

The total amount of water summed for the whole soil profile at each sampling date showed no differences between close spaced and the conventional densities, nor were differences among close spacings demonstrated.

The effects of plant density on soil moisture changes were also investigated using gypsum resistance blocks at weekly intervals. The resistance responses to soil moisture followed a similar pattern to the percent soil moisture. During the wet seasons, very low resistances were experienced under all coffee blocks, indicating that the soils were moist. The reverse happened during the dry seasons when very high resistances as evidence of soil drying were recorded under all coffee densities.

From the results in tables II(A-L), it is clear that, the times when resistances started to build up or decline corresponde ∠ the drying and wetting of the soil as dictated ∠with by the weather conditions. This necessitated the breaking of the experimental duration into three periods.

Period I, was between April and August, 1976. During this period, the soils were relatively moist as a result of the long rains. The resistances recorded in these months were low while the soil moisture percentages were high. There were zero resistance differences for most of the soil layers, but towards the end of the period, higher values were recorded as the soil moisture started to decline in the topsoil layers.

Period II covered August to November, 1976. This included some of the driest months of the trial. Soil moisture continued to decline. Maximum resistances were recorded in the months of September, October and the first half of November. The high soil moisture resistances recorded during this dry period agreed with the considerable moisture tensions recorded by Wallis (1962) under unirrigated coffee during the dry seasons.

As in the moisture percentages, these high resistances were only found in the top 165 cm of the soil profile. Below this depth, soil moisture was fairly constant. Towards the end of the period, the short rains fell and there was a recovery in soil moisture. The high resistances which had built up during the dry period declined drastically shortly after the onset of the rains.

The weather changes from wet to dry and dry to wet periods which occurred between April and November 1976 affected the plant behaviour in relation to the soil and atmospheric conditions. Field observations revealed that plants started to wilt early in August but recovered during the night until early in September. From about this time until the onset of the short short rains in November (late that year), the plants remained in a wilted condition. The wilting was comparable in all coffee blocks irrespective of density. The examination of soil moisture resistances when the plants started to wilt showed that, the topsoils had resistances of about 4.8 log-ohms which was given by Pereira (1955) as corresponding to the wilting soil moisture percentage for Kikuyu Red loam soils.

December, 1976 to March 1977 was termed period III. These were relatively dry months but there was enough soil moisture following the short rains of 1976 to maintain low soil resistances in most of the soil layers. However, since the short rains had failed to wet the soil profile adequately, some blocks developed high resistances during the period. This happened in the 1 x 2 and 2.74 x 2.74 m coffee spacings.

While the soil resistances changes closely followed the soil moisture changes as discussed in the three periods, there was no evidence to show that plant density influenced the soil moisture levels even in the driest period. However, more water was used by the high densities from the topsoils as already mentioned. In the subsoil, on the other hand, conventional density was found to use more water than high densities, as shown in tables III (A-C). It should be remembered that higher resistance values meant drier soil conditions. The main feature of the soil moisture was the increase and decrease in soil resistances in all densities at about the same time following the soil drying and wetting.

In this study, crop water use was estimated from changes in soil moisture (Table IVC), for all sampling dates the total water use increased as the coffee density decreased. The closest spacing had the least total water use. A striking similarity was found in 1 x 2 and 2.74 x 2.74 m spacings. The total water use in these spacings was 864 millimetres in 48 weeks and annual water use of 936 millimetres in both cases. This was similar to the low annual water use of 863.6 mm at 0.5Eo for conventional unirrigated coffee (Wallis, 1963). Thus, the water use by 5,000 tree/ha was the same as by 1329 trees/ha. This means that the increase in plant population per unit area by a factor of about five, does not appear to have any effect on the soil water use. In closer spacings, than 1 x 2 m, the water use decreased as the population increased.

The statistical analysis of the water use values presented in table IV C revealed no significant differences between close and conventional spacings. During the long rains, the widers spacings seemed to use more water than the close spacings. As in the moisture percentage analysis, the water use relationship in the subsoil among the closely spaced blocks was curvilinear for the four 28 day periods between September 1 and December 21, 1976. The period September 1-28, water use at 1 x 1.5 m coffee spacing was much less than in 1 x 1 and 1 x 2 m spacings. In the other three periods, this medium density of 1 x 1.5 m much more water than the other two, which had comparable figures for all these four periods. The four periods discussed here coincided with the driest months of the trial and with a poor short rain season.

An important finding is that the amount of water used by each coffee density at each particular period did not appear to be affected by density, particularly when conventional was compared with close spacings (Table IV C). However, the total water use for the whole period showed a density effect. Water use was greater at wider spacings. 1 x 2 and 2.74 x 2.74 mm used about 864 mm, while 1 x 1.5 m and 1 x 1 m used 748 mm and 674 mm respectively. In addition to the fact that these results were obtained in unirrigated coffee during a relatively dry year when both the long and short rains were below average, there are two other main limitations to their interpretation. (1) The study was concerned with actual water use and not potential water use. In this way, the results cannot be compared with the predicted potential water use. (2) The sampling sites were such that in intensive coffee plantings, the midpoints of the diagonals of four coffee plants were taken while in the conventional spacing a radius of one metre from the tree trunk was sampled.

It has been shown (Table IVC) that total water use for the 11 month experimental period was 674, 748 and 864 mm for 1 x 1, 1 x 1.5 and 1 x 2 and 2.74 x 2.74 m spacings respectively. It appears from these figures that, reduction of the area per plant from 7.5 square metres in 2.74 x 2.74 m to 2 square metres in 1 x 2 m spacing, does not seem to affect the water use. A further reduction in the area per plant through 1.5 m^2 to 1 m^2 resulted in a progressive reduction in total water use. If anything, close spacing of coffee seems to improve the soil moisture status. This seems to contrast with Dagg's (1968) opinion that wide spacing is a moisture conservation practice but does not entirely disprove it since no samples were taken under bare soil in conventional density where water extraction may have been less.

The assumption that evapotranspiration was not limited by soil moisture during the wet months of May, June, and July 1976 gave a method of estimating the potential crop water use by means of crop factors. The estimates are tabulated in table IV H(a) & (b) and show that the highest spacing being on the higher side. This was irrespective of the estimation method used. The kpan method gave values which compared favourably with Dagg's (1968) prediction of potential annual water use of 1219 mm in close spaced coffee. However, the ETo values were generally lower than the above mentioned potential water use. This is an indication that the assumption made above possibly still underestimated the potential evapotranspiration rates.

It appears that for optimum coffee growth, adequate moisture in the topsoil is most important. The soil water measurements showed conclusively that the depth of most water content changes was down to 165 cm. This was the case in the whole range of densities 10,000, 6,666, 5,000 and 1,329 trees/ha blocks. The 1956 conventional coffee spacing (1329 trees/ha) compared with the 1971 high density plantings showed that this was the greatest depth from which roots of mature trees effectively extract water even during the dry periods. The quantity of soil water in 165 cm of the soil profile seemed to depend very much on the season of the year, while below that depth, the seasons appeared to have little effect. By calculation, it was found that about 35 mm. of water was used below 165 cm from May 1976 to March 1977. This was a very small quantity of water for that period and bearing in mind the layer considered was 165-300 cm thick. The amount of water used during the same period was about 540, 645, 634 and 680 mm for 1 x 1, 1 x 1.5, 1 x 2 and 2.74 x 2.74 m coffee spacings respectively.

It is generally agreed that coffee roots can grow to 3 metre soil depth. However, in this study, coffee bushes were found to draw most of their water requirements from down to 165 cm only. This was also found by previous workers. Wallis (1963) said that irrigation treatment recommendations for coffee are to ensure that there is always available water in the top 120 centimetres (4ft) of the soil, where the main feeder roots are found. Huxley and Cannell (1976) stated that only occasionally is the soil dried out beyond 180 cm (6ft).

Increasing coffee plant density from 1.3 to 10 thousand trees/ha does not appear to increase the crop water use. There is no evidence to show that high density adversely affect the soil moisture status. In addition to gravimetric soil moisture determination, gypsum resistance block measurements suggest that closer spacing might even improve the soil moisture status, as shown in tables II(A-L). As the 1976 short rains were poor, the soil moisture status during the January/March, 1977 dry period was such that in the wider coffee spacings of 1 x 2 and 2.74 x 2.74 m, dry conditions developed between 105 and 165 cm. The soils in close coffee spacings remained fairly moist throughout this period.

The measurements of leaf water potential and stomatal apertures by Fisher and Browning (in preparation) in irrigated coffee showed that high density coffee has very little effect on water stress. They found small improvements in water status as the plant density increased from 5 to 10 thousand plants/ha, which was attributed to increased mutual shelter of one tree by its neighbours. The 6,666 trees/ha coffee density which was found to have higher soil moisture contents, and the 10,000 trees/ha, found to use less soil water in this study were all within the 5 to 10 thousand trees/ha range studied by Fisher and Browning.

If close spacing really improves or at least does not have adverse effects on the soil and plant water status, and considering that high density gives higher yields, it appears, then that the coffee industry in Kenya can benefit greatly from this system, and that high density coffee can be grown anywhere that conventional densities have proved satisfactory. Arguments of ground cover and reduction in canopy roughness have been advanced as the possible determinants of crop water use in coffee. The ground cover and smooth tree canopy are interrelated. Planting of coffee bushes close together would definitely increase the leaf area which would result in greater percentage ground cover. The increased number of trees per unit area would also form a more continuous canopy with reduced roughness.

In crop water use, evapotranspiration is made up of two components: transpiration through the plant system and direct evaporation from the soil surface. In order to evaporate water, an energy input is required. Water loss to the atmosphere through transpiration is a common feature in all plant communities, and this applies to coffee whether conventionally or close spaced. But direct evaporation would vary with the amount of solar radiation reaching the ground surface. It is conventionally considered that bare soil with a dry surface layer loses little water by direct evaporation once that dry layer is sufficiently thick to protect the underlying soil. However, if close spacing reduces total water use, while presumably reducing the relative importance of direct evaporation, it may be that in dry times, coffee with closed stomata (Fisher and Browning in preparation) may lose less water than the same area of unshaded bare soil. Two considerations suggest that the direct evaporation component may have been understimated. Firstly, the very large pore-space of these soils (bulk density <1.0) may facilitate evaporation of water from much deeper layers under a dry surface, with much more water transported to the surface as vapour, than would occur in soils with a more typical pore space. Secondly, bare soil can dry out at the surface to well below the wilting point, whereas shaded soil does not usually do so. Figures 1(a-d) show that during the dry period (August to November 1976) the soils in all coffee spacings dried below 15 atmospheres percentage moisture down to 75 cm depth. It should not be difficult to test these possibilities but for this thesis, it must remain as a possible interpretation of the result that the extra canopy achieved by higher densities transpires less under dry soil conditions than is lost by evaporation from the bare ground which it replaces. Fisher (unpublished data) measured interception of photosynthetically active radiation (P.A.R.) in August 1975 as 96%, 81%, 75% and 65% for 1 x 1m, 1 x 1.5 m, 1 x 2 m, and 2.74 x 2.74 m coffee spacings respectively. This means that, at conventional spacing, about 30% more energy reached the ground surface than at 1 x 1 m coffee spacing.

From these arguments, one can come to the conclusions that one or both of the following could account for the results:

(1) The reduced roughness at closely spaced coffee accounts for relatively less water use.

(2) The sealing or protective effect of the bare soil between wide spaced plants against evaporation may have been over-estimated for these particular soils.

The gypsum resistance blocks were found to be very useful in measuring soil moisture changes. They have an advantage over the gravimetric method in that, the moisture conditions are known immediately in the field. They could be very useful in irrigation control and timing. In this study most of the resistance blocks were found to have initial resistances of 2.5 to 3.0 log-ohms. One would need to irrigate when the blocks in the upper 1.4 or so metres indicate a resistance rather less than that of the wilting point (4.8 log-ohms) is reached.

For meteorological estimates of irrigation timing, it seems that the crop coefficients which have been used in the past for conventional densities could be applied without modification to high density coffee.

ROOT DISTRIBUTION:

The results of root distribution clearly demonstrate that the topsoil had more roots than any other soil layers irrespective of the coffee spacing. The results also show that the quantity of roots decreased as the soil depth increased and that there were more roots in the closer spacings at greater depths than in wider spacings.

Close spacing in apples has been found to modify the plant root systems. Atkinson (1976) showed that at high plant densities, the root systems consist mainly of sinkers in contrast to wider spacings where the root pattern consist of horizontal roots parallel to the surface with a number of vertical sinkers. He further showed that at higher plant densities, more water was used from greater depths. The data for coffee root distribution presented here covers a depth of 60 cm and is considered inadequate to prove that intensification modifies the root system. The extent of coffee rooting has been reviewed in chapter one above. It is possible that Huxley and Cannell (1970) were right when they predicted that close spacing of coffee may not modify the root system of the individual tree. Coffee roots would normally grow in the surface soil where organic matter levels are higher and where fertilizers are applied, and which is wetted by rain from light showers. As in apples, root competition for water and nutrients near the soil surface may account for the tendency of the roots to explore greater depths in closely spaced coffee. The fact that more roots were found at greater depths in the closely spaced coffee and tended to increase with increased density needs further explanation. At closer spacings there were more plants per unit area. This higher plant density possibly contributed a high root population per unit volume of the soil, at all depths considered. The increase in root distribution at greater depths could as well be due to a possible modification of the coffee root system. However, no emphasis can be laid on this and the effect of coffee intensification on root system can be suggested for further studies.

In discussing coffee root distribution in the topsoil the influence of leaf litter should also be considered. It was found that at closer coffee spacings, more roots were concentrated in the surface soils. The continuous leaf fall from the aging canopy formed a self mulching layer on the soil surface. The closer the spacing the thicker was this decaying organic matter. This encouraged root growth near the surface.

Whether the spacing modifies the coffee rooting system or not, one thing is clear from this study. The whole soil volume under intensive coffee planting was effectively ramified by root growth, The effectiveness of this ramification was found to correspond to increasing coffee density. This was strongly supported by the results of the volumetric soil sampler. The samples were taken from the diagonals of four coffee plants which was actually the furthest distance from any of the four plants.

The exploitation of the whole soil volume by the coffee roots for available water and nutrients is an advantage of close spacing. Dagg (1968) stressed the importance of maintaining the topsoil moist enough to facilitate nutrient uptake by the roots, as many plant nutrients are concentrated in the topsoil in association with the organic fraction. In considering fertilizers and irrigation applications, close spacing of coffee appears to have more advantages as the results of root distribution have shown that more roots are found at greater depths than is the case with conventional spacing. Roots at greater depth will possibly take the nutrients like nitrogen which may be leached down from the upper part of the profile and which would otherwise not have been taken up by the plant. The greater volume of the soil exploited by these roots would enable the plants to make fuller use of available water for a longer time.

WATER INFILTRATION RATES:

The water infiltration rates were characterized by high variability between the sampling sites. There was no trend consistent with plant density. Initially, there were three reasons which lead to this exercise being undertaken: (1) the different root distribution caused by varying plant populations was expected to affect water intake rates. (2) the humus from the leaf litter which decomposes and adds to the store of organic matter in the soil. (3) the degree of ground cover by the coffee canopy. These factors, along with others were also considered in relation to bulk density determinations, as discussed further below.

The water infiltration rates during the dry seasons were generally higher than the wet seasons. It has been established that infiltration rates are inversely proportional to the amount of water in the soil (Tisdall, 1951). The soil cracking during the dry seasons caused a faster water entry than during the wet season when most of the cracks were closed. The quantity of soil moisture during these different times no doubt had an influence on infiltration rates. It has been shown that the moisture content in the direst and wettest months differed by as much as 20% of the oven-dry soil weight.

The infiltration rates in dry soils were higher than in wet soils and took a longer time to reach the steady state. The fact that differences in filtration rates as affected by plant densities did not show a systematic trend can be explained by considering the factors which were expected to account for infiltration differences.

The coffee in the three intensive blocks was only five years of age. Possibly at this age the root system had not established itself well enough to have significant effects on soil conditions. Faster rates would be expected where the older roots had died and decayed, leaving channels in the soil. It is possible that this stage had not been reached in these coffee blocks.

The fallen leaf litter found on the soil surface had possibly not decayed enough to be incorporated into the soil. As a result of this, 1 x 1 metre coffee spacing which had the thickest layer of leaf litter failed to show higher infiltration rates.

It is likely that the soil cracking due to the sun's radiation drying of the topsoil, particularly in 1 x 2 m coffee spacing which did not have a complete ground cover, had same influence on the higher values obtained for that spacing. The degree of surface soil cracking was greater in this wider spacing, possibly because it also had the least leaf litter which protected the soil from direct radiation effects in the higher coffee densities.

In conclusion, it is worth pointing out that accurate infiltration rate values for these soils may be achieved by taking many points. By having many replications, the variability encountered here may be reduced to a minimum. It is possible, this may also reveal differences between different coffee spacings.

TOPSOIL BULK DENSITY:

In the surface soil represented by 0-3 cm, the bulk density showed an increasing trend as the coffee spacing widened. The lowest bulk densities (gm/cm^3) were found in 1 x 1 m.which was the highly populated coffee block, while the highest bulk densities were found in conventionally spaced coffee (2.74 x 2.74 m). This trend was partly maintained in the underlying layer of 3-6 cm except for 1 x 2 m which failed to show densities consistent with the rising trend. The overall picture in the 0-6 cm soil layer was that the closer the coffee spacing, the lower was the bulk density. This shows that close spacing of coffee may have an effect on the degree of soil compaction, at least in the topsoil. Less soil compaction is an advantage in providing suitable conditions for root growth and water entry into the soil.

It appeared that the factors that affect the topsoil bulk density were localized in the top 0-3 centimetres, and to a lesser extent in 3-6 centimetres soil layers. Taking 0-6 cm as the topsoil, a pronounced trend in which the bulk density tended to decrease with increasing coffee densities was clearly evident. In the subsoil, that is below 15 cm the factors which decreased the bulk density of the topsoil did not appear to be operative. This conclusion was reached from the insignificant trend obtained for this depth. In fact, the coffee density effects seemed to be a reverse of what happened in the topsoil.

There are three possible reasons which may help in the explanation of the lower bulk density in closely spaced coffee as opposed to the conventional one. Two of these have already been mentioned in relation to water infiltration rates.

It has been established in the section on root distribution that at closer spacings there were more roots per unit soil volume than in wider spacings. Plant materials are generally lighter than soil particles. From the root distribution point of view, a soil sample taken in close spaced coffee would, definitely have more roots than the one taken at any other wider spacing. The roots taken together with the soils, would therefore affect, the weight of the samples and hence the bulk density. The more the roots, the greater would be the effects and possibly this is what happened in the topsoil. But since the trend did not hold in the subsoils other factors may as well have played an important role.

The quantity of leaf litter under the coffee blocks was relatively high in the closer spacings. In the closest spacing of 1 x 1 m, the conditions on the soil surface were similar to those found under local forest vegetation. There was about 2.5 cm of leaf litter decaying on the soil surface. The quentity decreased as the coffee spacing increased and only traces of occasional leaves could be found in the conventional spacing. For all purposes, the leaf litter acted as a mulch and was so effective in the highest coffee density that small roots could be seen growing into it. As a result of organic matter decay and the activities of soil fauna, some of the litter could have been incorporated into the topsoil and so affect the bulk density. This may also explain why the decreasing bulk density trend was very pronounced in the top 0-3 cm soil layer, and the fact that such a trend was not maintained in the lower soil layers. The presence of leaf litter per se should not be over emphasized. Self mulching and the presence of organic matter help maintain moist conditions in the topsoil which encourage prolonged micro-organism activities which as Dagg (1968) pointed out improve the soil structure and nutrient supply to the roots.

Soil compaction due to trampling effects is another factor worth considering in this context. In close spacings, there has been no room to move farm machinery during the five years the coffee has been in existence. This has not been the case in conventional spacing where most of the general farm operations like herbicide and fungicide spraying plus fertilizer applications are routinely carried out using tractor-trailed implements. At the same time, in conventional and 1 x 2 m coffee spacing there are avenues wide enough for people to move between the coffee bushes and rows, either working or passing to the neighbouring plots. In the closer spacings, the lateral branching overlap so much that hardly any people pass through the blocks unless it is really necessary. The fact that no farm machinery is used and no unnecessary human trafficking through the high density blocks might partly account for the less soil compaction in closely spaced coffee.

COFFEE YEILDS:

The cherry and clean coffee yields per unit area have been shown to increase with increased tree population. This was shown in the four year yields considered in the results. In a spacing-variety trial, van der Vossen (1977) discovered highly significant spacing and variety effects. For all the eight varieties compared, SL 28 was found to have the highest yield with a mean of 5.46 t/ha clean coffee over the first two years of production. The highest yield of 6.54 t/ha was realized in 1975 at 6,666 trees/ha. In this trial, the overall yields for all varieties increased over the two years as the plant population increased. The data presented in the results for the first cycle before the high density blocks were stumped in April, 1977 show that, by close spacing of coffee, land is utilized more fully. This is because high yields per unit area are obtained which mean higher economic returns. Other advantages of high density coffee plantings have been cited as less need for weed control and lower pruning requirements (Mitchell, 1976).

The effects of drought on the coffee bean quality was investigated for the 1976/77 crop in unirrigated coffee. The quality was investigated by calculating the percent clean coffee to parchment. The spacing did not appear to affect the quality in the coffee which was allowed to suffer water stress. Browning and Fisher (1976) found a linear relationship between bean weight and plant density with a tendency for weight to be reduced at higher density. Significant spacing effect on bean size and liquor quality were discovered by van der Vossen (1976). The best bean size was at the medium coffee density of 4,000 trees/ha while the best liquor was produced at the highest density of 6,666 trees/ha. It appears as if liquor quality may compensate for bean size at higher coffee density.

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