

WATER USE EFFICIENCY OF MAIZE (*Zea mays* L.) IN  
A DRYLAND AREA OF KENYA.//

BY

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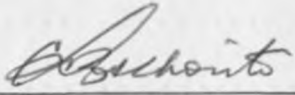
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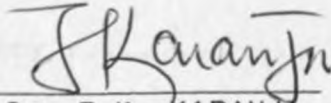
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DECLARATION.

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

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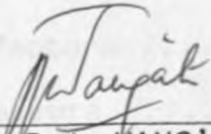
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## LIST OF SYMBOLS.

Symbol	Meaning
Z	depth (cm)
$U_z$	net downward flux of water at depth Z (mm)
$Z_0$	depth to the lowest point of measurement ( $z=0$ ) (cm)
D	runoff
$E_t$	evapotranspiration (mm)
$\Delta SW$	change in water content of the soil (mm)
$\theta$	volumetric soil water content ( $\text{cm}^3/\text{cm}^3$ )
t	time (weeks)
WUE	water use efficiency (g/mm)
Y	yield dry matter (Kg)
$R_s$	solar radiation (mm/day)
$R_a$	extra-terrestrial radiation (mm/day)
n	measured bright sunshine hours
N	maximum possible sunshine hours
R	rainfall (mm)
E	open water evaporation (mm)
$R_{ns}$	net short wave radiation (mm/day)
$\alpha$	crop surface albedo (0.25)
$\delta$	Stefan Boltzman constant ( $1.98 \times 10^{-9} \text{ mm/day/k}^4$ )
$e_a$	actual vapour pressure (mb)
$R_{nl}$	net long wave radiation (mm/day)
W	individual plant dry weight (gm)
$\bar{R}$	mean relative dry matter accumulation rate

$\sum$	sum of
$\int$	integral
lsd	least significant difference
HI	harvest index (%)
	absolute value
$N_c$	number of full evaporation pan cups
$C_4$	plants utilising the 4-carbon dicarboxylic acid pathway for carbon fixation
$C_3$	plants utilising the Calvin-Benson pathway for photosynthesis
CAM	Crassulacean Acid Metabolism
PMA	phenylmercuric acetate
PAR	photosynthetically active radiation
ASAL	arid-semi-arid lands



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ABSTRACT

This study was undertaken to investigate the variations of water use efficiency of two varieties of maize (*Zea mays* L.), viz. makueni and katumani composite B with planting density and meteorological parameters under rainfed conditions. The study was conducted during the short rains season of 1990 at Kibwezi Dryland Research Station of the University of Nairobi in Machakos district, Kenya.

The experimental design comprised two blocks, one for each maize variety, and three treatments characterised by Low (24,000 plants/ha), Medium (36,000 plants/ha) and High (83,000 plants/ha). Planting was done manually on 10<sup>th</sup> of November 1990. Neither manure nor fertilisers were used. Weeding was also done manually on 1<sup>st</sup> of December 1990.

Dry matter in kg/ha was obtained on weekly basis by harvesting two plants chosen at random from the centre of each plot. From grain filling stage, the grain dry matter was separated from the total above-ground dry matter. Harvest index was computed as a percentage of grain yield dry matter to total above-ground dry matter. Evapotranspiration was determined weekly by the water balance approach. Water use efficiency in g/mm was computed as a ratio of dry matter to evapotranspiration.

Makueni composite gave higher harvest indices than katumani composite for all the plots. Medium planting

densities gave the highest harvest indices.

Relative dry matter accumulation rates between makueni and katumani varieties and also planting densities were not significantly different. Makueni composite was superior to katumani composite B in absolute dry matter accumulation rate during grain filling stage.

Makueni composite outyielded katumani composite B in grain yield by approximately 23.5% and by 14.1% in total above-ground dry matter.

Katumani composite plots showed higher crop water use than the corresponding makueni composite plots under the prevailing meteorological and soil water conditions. Crop water requirement was maximum during silking period for both varieties of maize.

Makueni composite exhibited higher water use efficiency than katumani composite B in both grain and total above-ground dry matter production. For both yield components, water use efficiency decreased with increasing plant population.

Although long term studies in the literature recommend a planting density of 37,000 plants/ha for maize in dryland areas, this study shows that it is possible to get higher yields with a planting density of 83,000 plants/ha.



## CHAPTER ONE

### 1.0 INTRODUCTION

#### 1.1 Background Information

Agriculture plays the greatest role in Kenya's economy and provides food for her rapidly growing population. Besides providing food security and export earnings, the agricultural sector provides a range of other benefits such as creation of employment opportunities, generation of family farm incomes and growth of productive off-farm activities in the rural areas.

Kenya's population growth rate of about 3.4% per annum (Kenya Economic Survey, 1991) is high and therefore efforts aimed at increasing food production are required in order to meet the ever increasing food demand. Kenya's staple food is maize. Studies aimed at increasing maize production, on both, per unit area of high potential land and in terms of greater utilisation of marginal lands are therefore essential. Increased production would permit accumulation of reserves for anticipated years of poor production and for possible exportation.

Researchers should strive to maximise the output of maize through development and application of appropriate agricultural technology. Knowledge derived from research may help alleviate the problem of importation of maize. Increased maize production will therefore provide food self-sufficiency

through permissible on-farm storage of produce and national food reserves.

Due to the land pressure in the high potential arable areas of Kenya, the required expansion of food supply must come from the semi-arid and arid lands. The effect of this pressure has been rapid expansion of smallholder farming into drier regions. Apparently, this is the only hope since further improvement in agricultural technology, ie, use of improved seed varieties, high rates of fertiliser application, disease and pest control in the high potential areas of Kenya may not assure expected increases in food production. The causes of this phenomenon include expansion of human settlement due to rapid population growth and rapid urbanisation.

Further, the food and energy problems have of late emerged as some of the most critical contemporary issues. Their increasing demand calls for efficient use of the available natural resources such as land and water. In dryland farming systems, water availability is the prime limiting factor (Sinclair and Tanner, 1984). Wittwer (1975) presented similar views and noted that water is the second most important factor in food production, after land area. Stewart and Hash (1981) noted that the most vexing problem in semi-arid areas is the tremendous variability in rainfall from year to year and season to season but not water shortage per se. As such the distribution of rainfall in these areas is crucial.

Even though the problems of food and water shortage experienced in the drylands are environmental, they are nonetheless not impossible to solve. Thorough and proper

utilisation of the available resources, and application of appropriate research techniques in maize crop production may help transform the marginal land areas into more productive lands for maize. Solutions of this nature will alleviate the problem of dependence of dryland areas on inter-district food transfers and famine relief.

### 1.2 Statement of the problem.

Water availability for agriculture through rainfall is limited in the Kibwezi area in Machakos district and therefore crop water use efficiency must be increased in order to attain increased yields. To achieve this requirement, a thorough understanding of this subject in this area is needed. To this end, no investigations of this nature have been reported in the literature, especially for maize crop.

Lack of information described in the preceding section hampers application of appropriate agricultural technology in the area of study. Farming systems involving use of supplemental (or full) irrigation methods are not possible or may be uneconomical if undertaken. Findings on water use efficiency will reveal to a fair approximation the quantity of both biological and economic yields of maize per unit of water consumed. This then can serve as a base for scheduling irrigation inputs, where possible.

In the study area, maize forms the staple food despite its marked scarcity. The scarcity of maize in this area arises due to a variety of factors: low rainfall amounts, late onset and early cessation of rainfall, high rainfall variability and

poor rainfall distribution in a growing season and results in poor production. Therefore, for most part of the year, people in this area survive through buying of maize grain from local traders at exorbitant prices. Another problem leading to poor production in this region is the inefficiency by the communities in selecting maize varieties and farming practices most suitable for stabilisation and maximisation of food production in their diminished rainfall circumstances.

Farmers in the study area have adopted a planting system in which the maize harvested in one season is used for sowing in the subsequent cropping seasons. This recycling activity of the maize seed in the same field is likely to be a cause of yield reduction in the study area. This practice encourages dominance of undesirable genetic traits in the maize seeds. In addition to this factor, their life cycle may be relatively long such that silking, the growth stage most sensitive to water stress, sets in after cessation of the short-lived 'long' and 'short' rainfall seasons.

Knowledge on increasing water use efficiency through cultural and genetic modifications that shorten the growing season or allow the growing season to be shifted to a cooler or lower potential evapotranspiration part of the year as suggested by Namken et al. (1974) need to be obtained. An optimum value for stabilisation and maximisation of the water use efficiency is therefore an essential tool. This may act as our frame of reference in designing and operating agricultural systems with the aim of improving food self-sufficiency.

Mechanisms that influence water use efficiency need to be

well understood. This will clarify the important variables and the opportunities available for further improvements in water use efficiency. The question remains whether increase in food production can be achieved through improved or higher water use efficiency. It is therefore in view of this problem that this study seeks to contribute to the existing information gap concerning water use efficiency of maize in the dryland areas of Kenya. Kibwezi was chosen as a characteristic dryland area of Kenya.

A variety of definitions for water use efficiency both hydrological and physiological have been presented in literature. According to Sinclair and Tanner (1984), the physiological aspect of water use efficiency may be given as a ratio of biomass accumulation expressed as carbon dioxide assimilation, total crop biomass, or total grain yield ; to water consumed expressed as transpiration, evapotranspiration, or total water input into the system. The time range of the definition varies from instantaneous, through daily to seasonal.

Stanhill (1986) in a purely hydrological context, defined water use efficiency as the ratio of the volume of the water used productively through transpiration and evaporation to the volume of water potentially available (both from irrigation and rainfall). In the case of irrigation projects, Bos and Nugteren (1974) defined water use efficiency as the increase in the water content of the root zone following irrigation expressed as a fraction of the total quantity of water supplied to the irrigated area.

In this study, the physiological definition of water use efficiency relating the total above-ground dry matter of maize harvested and the amount of water consumed expressed in terms of evapotranspiration will be adopted. This definition is superior to the other alternatives because of its dual constituency of methods of water loss. Water losses through both evaporation from the surface of the soil and transpiration of the crops are incorporated. Only the above soil plant dry matter is considered because it is the utilisable part of the maize plant for food (the grain component) and fodder (leaves and stalks).

### 1.3 The objectives of the study.

The general objective of this study was to employ the water balance approach to investigate evapotranspiration and yield performance, and hence the water use efficiency of maize in the dryland areas of Kenya.

The specific objectives in this study were to :

1. compute weekly water use efficiency of maize in terms of total above-ground and economic yield dry matter throughout the growing season.
2. Investigate the effect of planting density between and within two maize varieties on water use efficiency.
3. Investigate the variation of water use efficiency of maize with meteorological parameters.

The entire work therefore strives to find how much dry matter a maize crop accumulates for every unit depth of water

depleted through evapotranspiration.

#### 1.4 Significance of the study

This study on water use efficiency will enable us understand how maize in the dryland farming environments of Kenya can translate the available utilisable soil water into accumulation of dry matter and effective grain yield. Such an understanding may help in manipulating crops through increasing dry matter or lowering quantities of water used. This also may serve as a pointer to the economic levels of supplemental irrigation under conditions of water stress. For these management practices to be appropriately effected there should be some bases related to optimal crop yield and water consumption by the crop, ie, the concept of water use efficiency.

Water use efficiency studies also offer opportunities to aid in the development of sound agronomic systems for water limited regions such as the study area. This may be achieved through choosing of crop varieties and seasons which will minimise evapotranspiration rates. The study will also aid in selecting a planting density most suitable to the study area. Information based on planting density appears to be deficient in the area of study. This is evidenced by the type of farming practices carried out. Very narrow rows and in some cases no rows at all and high seed-rate mode of planting was noted amongst the smallholder farmers who form the largest proportion.

In full-irrigation projects, knowledge on water use

efficiency can help determine appropriate amounts of irrigation water and therefore flow rates, and right time of irrigation. These operations would help increase crop yields through adequate supply of water, and avoiding devastating effects of drought and excess irrigation water. Drainage and salinity problems which could result would also be avoided.

The following chapter presents a review of past research work in crop water use efficiency. The section also contains discussions on factors which affect crop water use efficiency and the opportunities available for increasing it.



## CHAPTER TWO

### 2.0 LITERATURE REVIEW

#### 2.1.0 Pioneering studies in crop water use efficiency.

Research in crop water use efficiency dates back to the late seventeenth century. The first of these studies quantitatively relating plant growth to transpiration was reported by Woodward (1699). Following this study Lawes (1850) conducted the first outdoor container experiment of transpirational water use efficiency of crop plants (wheat, barley, bean, pea and clover) under fertiliser treatments. On both a yield and total dry matter production basis, it was found that clover had the lowest value of water use efficiency and the maximum was observed for barley. The two cases were observed from plants receiving the heaviest fertiliser treatments. High rates of fertiliser application leads to rapid growth and accumulation of crop dry matter. Without an accompanying increase in transpirational water loss, increase in dry matter accumulation will trigger an increase in water use efficiency. Further, rapid development of vegetative material caused by high fertiliser application covers the ground rapidly and lowers the soil evaporation component of plant water use. From these observations, Lawes concluded that there exists some definite relationships between the passage of water through and the fixation in it of some of its constituents. However, he noted that extrapolation of his results to a field scale resulted in too high crop water

requirements.

King in 1890 researched on the water required to produce field crops, using small lysimeters in glasshouses and fields (Sinclair and Tanner, 1983). Briggs and Shantz (1913a) compiled much of the early water requirement data from container experiments beginning in 1910. Although container experiments on water use efficiency aroused much interest, their practical field application was limited. The limitation was exerted by the need to permit for plant exposure, climate, soil evaporation and fertility.

In view of the limitations above, subsequent research work on water use efficiency shifted to the field, predominantly in semi-arid regions where water was yield limiting. In these studies water use efficiency was usually expressed as the transpiration per unit marketable yield, or more often as its reciprocal, called evapotranspiration ratio (Stanhill, 1986). The large variations in evapotranspirational water use and efficiency from site to site as well as from year to year reported for the same crop cast doubts on the agricultural usefulness of the evapotranspirational water use efficiency. These uncertainties were later reinforced by the advances in the meteorological approach to the study of crop evapotranspiration. In this approach, Penman (1948) reported that water loss to the atmosphere could be treated as a purely physical process, primarily controlled by the radiative and aerodynamic characteristics of the crop surface.

Penman and Schofield (1951) applied the same physical approach to calculate the potential net carbon dioxide flux to

a crop surface, ie, its dry matter increase. This was a pioneering theoretical basis for the transpiration ratio under field conditions. de Wit (1958) re-analysed the early container experiments in an attempt to rehabilitate the transpiration ratio. He demonstrated that the values of water use efficiency obtained could be extrapolated to field crops by normalising for open water evaporation. He also noted that the conversion coefficient thus obtained was also valid under conditions of limiting water supply. Arkley (1963) demonstrated that one could also allow for fertility differences between container and field conditions.

In the recent decades, water use efficiency ratio has assumed a central role in the modelling of crop yield and the simulation of its response to water supply both from rain and irrigation. A variety of models of differing complexity have been developed (de Wit, 1958 ; Arkley, 1963 ; Bierhuizen and Slatyer, 1965 ; Stewart, 1972 ; Hanks, 1974).

Sinclair et al. (1975) investigated the validity of the then hypothesis that water use efficiency of  $C_4$  species decreases with increasing stomatal resistance. They conducted their work on a pure maize crop stand. Results from both computer simulations and field experiments were compiled for varying stomatal resistances. The hypothesis above was confirmed by the results from the two approaches. The researchers concluded that both crop photosynthetic productivity and water use efficiency of maize can be reduced by management practices which induce moisture stress

conditions resulting in increased stomatal resistance.

Lomas et al. (1974) studied the effect of environmental and crop factors on the evapotranspiration rate and water use efficiency of maize on a field of 1.6 hectares. The study was conducted in Israel under different radiative conditions with an aim of identifying their effects on crop behaviour. The results from this study indicated that water use efficiency appeared to be adversely affected by high values of total radiation and soil fertility, which has a positive effect on water use efficiency. These authors noted that the latter finding can be used as a criterion in determining the fertiliser application quantities in regions with limited water resources and high fertiliser costs.

Hagen and Skidmore (1974) presented some findings on increasing water use efficiency by reducing turbulence transfer over the crop canopy. In their efforts to understand the effect of wind speed on water use efficiency, they employed both the energy budget and the photosynthetic rate. They noted from this work that increasing wind speed may increase, decrease, or have no effect on transpiration depending on the stomatal resistance of the leaf. These authors also documented that, using shorter crops or sheltering crops with windbreaks or a few interspersed tall plants can reduce turbulent exchange within the crop and hence improve on the water use efficiency.

Namken et al. (1974) examined the cultural and genetic approaches to moderating adverse temperatures that limit water use efficiency in crop production. They used a short-season

cotton production system as an example of the cultural and genetic advances that have been capitalised on for one major field crop. It was suggested from this work that cultural and genetic modifications that shorten the growing season or allows the growing season to be shifted to a cooler or low potential evapotranspiration part of the year offer practical approaches for improving water use efficiency.

Shih (1983) researched on lysimetrically determined evapotranspiration and water use efficiency of sweet corn in relation to three water table depths. The sweet corn evapotranspiration and water use efficiency were found to be inversely related to the water table depths. Examination of the influence of plant water stress on photosynthesis, evapotranspiration and water use efficiency by Dennis et al. (1985) gave interesting results. Carbon dioxide intake within a fully developed canopy in the field was found to be strongly correlated with stomatal resistance, decreasing logarithmically with increasing stomatal resistance. They noted that extremely low leaf water potentials, which occur when stomatal resistance is high, may limit carbon dioxide uptake by affecting enzymatic reactions associated with photosynthesis. The water stress induced stomatal closure reduces evapotranspiration and influence partitioning of net radiation. This lowering of evapotranspiration will result into an increase in water use efficiency.

Baldocchi et al. (1985) studied the water use efficiency in a soybean field under the influence of plant water stress.

The responses of the soybean to changes in stomatal resistance under conditions of strong irradiance were reported on the basis of carbon dioxide-water flux ratio, carbon dioxide and water vapour exchange. Carbon dioxide exchange was found to be strongly correlated with stomatal resistance, decreasing logarithmically with increasing stomatal resistance. Water vapour loss from the canopy was limited by the increase in stomatal resistance induced by increasing water stress. Under strong irradiance these researchers noted that the carbon dioxide-water flux ratio decreased with increasing stomatal resistance. Findings from this work were similar to the experimental findings of Rawson et al. (1978) and the modelling predictions made by Cowan and Troughton (1971), Sinclair et al. (1975), Jones (1976) and Campbell (1977).

Stewart et al. (1982) developed water/production functions for maize, beans and their intercrop. In their study, they defined water production functions as the resultant plots of actual yields against actual use of water expressed in terms of evapotranspiration. From their definition, it is evident that water production functions are synonymous to the plots of water use efficiency in this study. They observed that maximum total evapotranspiration by the intercropped maize and beans was 655mm and 374mm respectively.

#### 2.2.0 Factors affecting plant water use efficiency.

The water use efficiency ratio is controlled by a variety of factors which may operate in part or in combination. The latter case ensues as a result of the interaction between

factors, that may occur within the soil-plant-atmosphere continuum. The said factors affecting water use efficiency range from climatic, through soil to plant. In addition to these factors, Stanhill (1986) discussed the role the economic factor plays in modifying the plant water use efficiency. The various factors are presented in the following sections.

#### 2.2.1.0 Climatic factors.

Climatic factor operates on water use efficiency of plants through its influence on the atmospheric and soil water content, carbon dioxide concentration in the atmosphere, irradiance, wind speed and ambient temperature. All these factors are prevalent in the environment of the plant and constitute the plant microclimate which dictates plant behaviour, plant productivity and hence water use efficiency.

##### 2.2.1.1 Vapour pressure

Water vapour saturation deficit through its influence on leaf-to-air concentration gradient for water vapour, has a major effect on water use efficiency. From theory (Fischer and Tanner, 1978) and measurement (Rawson et. al., 1977 ; Bierhuizen and Slatyer, 1965), water use efficiency is related to the reciprocal of concentration gradient for water vapour between the leaf and the air. Arkley (1963) in his early container experiments, showed that for a given crop and soil fertility, about 90% of both the interannual and intersite variation in the transpiration ratio could be allowed for by a correction based on air humidity ratio. The same argument

holds for the case of water use efficiency since transpiration ratio is simply the reciprocal of water use efficiency.

The saturation vapour pressure deficit affects water use efficiency through its influence on the leaf transpiration, driven by the vapour pressure gradient between the leaf and the air. Changes in the diurnal water use efficiency in two field studies of soybean crops were reported to be highly correlated with the saturation vapour pressure deficit, above given light and internal water stress thresholds (Zur and Jones, 1984); Baldocchi et. al., 1985a). Lowering of the saturation vapour pressure deficit of the leaf atmosphere will proportionately lower the transpiration rate of the leaf. However, photosynthesis will only change if we have stomatal closure which may result due to direct effect of humidity on stomata or indirectly through lowering of leaf water potential. Thus, unless a compensating closure of stomata occurs, a decrease in humidity will decrease the water use efficiency of the plant.

#### 2.2.1.2 Air Temperature

Fischer and Tanner (1978) reported that air temperature influences water use efficiency through its effect on atmospheric humidity. The relationship between air temperature and humidity has also been presented by other researchers (Kramer, 1969 ; Schulze et al., 1973 ; Jones et al., 1985b). Kramer (1969) noted that atmospheric temperature affects transpiration through its influence on leaf temperature and hence on leaf water vapour pressure. Schulze et al. (1973)



pointed out that the concentration difference for water vapour between the leaf and the air is usually closely coupled to air temperature in field crops. Therefore based on these findings, increased air temperature will reduce water use efficiency, unless leaf temperature is markedly suboptimal for photosynthesis. Jones et al. (1985b) studied the effect of increased air temperature on a soybean crop canopy growing under ambient and elevated carbon dioxide concentrations. They observed increasing transpiration with rising air temperature at both  $\text{CO}_2$  concentration levels. They however noted that, the dry matter production rate was not significantly affected over the 28 to 35°C range studied. They attributed the observed increases in transpiration to the increase in saturation vapour pressure deficit and hence vapour gradient. From this, we can infer that, water use efficiency of the soybean crop canopy decreases with significant change in the dry matter accumulation and elevated transpiration rates.

### 2.2.1.3 Carbon dioxide Concentration

Increasing  $\text{CO}_2$  in the air causes increased water use efficiency. Carbon dioxide operates through its effect on the photosynthetic rate. Bierhuizen and Slatyer (1965) reported that with constant light intensity, relative humidity and wind speed over cotton leaves, the transpiration ratio declined rapidly with increasing  $\text{CO}_2$ . This observation is synonymous to rapidly increasing water use efficiency with increasing carbon dioxide concentration. Similar findings were documented by

Morrison (1985). He associated the decreasing response of the transpiration ratio to  $\text{CO}_2$  increase in single-leaf, plant and crop levels to the secondary and feedback mechanisms. Gifford (1979) examined the effect of increased  $\text{CO}_2$  concentration on the transpiration of two wheat cultivars grown at four levels of growth limiting water supply conditions. He found that the transpiration ratio was less for both cultivars grown in the  $\text{CO}_2$ -enriched atmosphere with the relative difference increasing as the water supply became more restrictive. The observed difference in the transpiration ratio was attributable to the  $\text{CO}_2$ -induced increase in dry matter production.

#### 2.2.1.4 Solar Radiation

Solar radiation is the primary source of energy for atmospheric, soil and plant processes. This factor therefore exerts a direct influence on plant water use efficiency. Several researchers (Jones, 1976 ; Downes, 1970 ; Bierhuizen and Slatyer, 1965) have noted that there is an optimum irradiance for maximum water use efficiency. Jones (1976), however noted that this optimum irradiance is usually less than the irradiance incident on a leaf oriented normal to the sun. Transpiration is always positive showing a relationship which is linear or curvilinear upwards with increasing irradiance. Fischer and Tanner (1978) explained this observation in terms of the rising leaf temperature and falling stomatal resistance. These researchers also noted that net photosynthesis especially of  $\text{C}_3$  plants show downward

curvilinearity with increased irradiance and is negative at zero irradiance. From this review we can infer that increased irradiance above an optimum value is accompanied with a reduction in water use efficiency. This inference is further supported by the work of Jones (1976). He proposed that leaf orientation at an appropriate angle to the sun's rays, by reducing the effective incident irradiance can increase water use efficiency.

#### 2.2.1.5 Wind Speed

Wind speed has also been reported to affect plant water use efficiency. Micrometeorological measurements of wind speed within the maize crop canopy have shown that water use efficiency increases substantially with increasing wind speed (Lemon, 1963). Wind speed operates through its influence on the boundary layer resistance of the plant. Boundary layer resistance decreases with increasing wind speed. Water use efficiency has been reported to increase with decreasing boundary layer resistance, except under conditions of low radiation and high air temperature and saturation deficit (Parkhurst and Loucks, 1972 ; Jones, 1976).

Wind serves to regulate the temperature of the foliage. Foliage temperature decreases with increasing wind speed (Monteith et al., 1991). These authors also noted that increasing wind speed enhances saturation water vapour pressure deficit and therefore results in increased leaf transpiration.

## 2.2.2.0 Plant factors

### 2.2.2.1 Carbon Fixation Pathways

The major plant factor contributing to the differences in the efficiency of water use is the method of carbon fixation by plants. Plants possessing the four-carbon dicarboxylic acid ( $C_4$ ) pathway of photosynthesis usually have lower mesophyll resistance and low  $CO_2$  compensation points compared with  $C_3$  species.  $C_3$  plants use the Calvin-Benson pathway of photosynthesis. Downes (1970) and Tanner (1974) attributed the lower water use efficiency values of the  $C_3$  plants as compared with the  $C_4$  and CAM (those using the crassulacean acid metabolism pathway) to their high mesophyll resistances and low stomatal resistance. The high mesophyll resistance inhibits  $CO_2$  assimilation and lowers the photosynthetic rate. On the other hand the low values of stomatal resistance enhances transpiration rate. Thus, the water use efficiency of the plant will decrease. Neales et al. (1968) explained the diurnal behaviour of CAM plant stomates. They attributed the opening of CAM plant stomates during the night and closing during the day to their metabolism. The metabolism in CAM plants enables them to open their stomata at night when the vapour pressure gradient between the leaf and the atmosphere is smaller than during day, thereby increasing water use efficiency. It is worth noting that  $C_3$  species is not necessarily less efficient in water use than  $C_4$  species. Bull (1971) working on sunflower ( $C_3$  species) and, sorghum and maize ( $C_4$  species) found that the  $C_3$  species was more water

use efficient than the  $C_4$  species.

CAM plants often have high water use efficiency. They keep their stomata open at night (Nishida, 1963) so that  $CO_2$  is transported inward and fixed into and stored as organic acids. But during the day the stomates remain closed while the  $CO_2$  is released from the stored organic acids and refixed via the  $C_3$  pathway as photosynthetic products (Kluge, 1971 ; Black, 1973).

#### 2.2.2.2. Stomatal resistance

Stomatal movement affects the transpiration and assimilation characteristics of a leaf and/or plant canopy and can also affect the plant water use efficiency. Cowan and Troughton (1971) investigated the relative role of stomata in transpiration and assimilation and noted that both the two processes are equally sensitive to changes in stomatal aperture. Shimshi (1963) observed that induced stomatal closure in maize by phenylmercuric acetate (PMA) reduced transpiration more than it reduced photosynthesis, implying an increase in water use efficiency. Jones (1976) found that water use efficiency increases with increasing stomatal resistance, except for situations in which the ratio of mesophyll resistance to boundary layer resistance is less than a given critical value. However, the latter condition as pointed out by Fischer and Tanner (1978) is not common. Increase in stomatal resistance has a number of consequences for the crop, namely, reduction in the rate of transpiration, changes in the crop energy balance and a reduction in the rate

of carbon dioxide assimilation.

### 2.2.2.3 Leaf size and Leaf structure

The size of the leaf may also confer some influence on plant water use efficiency. This may be effected through its influence on the thickness of the leaf's boundary layer. Leaf structure is also of greater significance in plant water use efficiency. Water use efficiency can be expected to increase as the ratio of the leaf's internal assimilating surfaces to its internal transpiring surface increases.

### 2.2.2.4 Leaf Orientation

Diurnal changes in foliage orientation can also affect water use efficiency as has been shown for a number of crop species. Alfalfa, cowpeas, and beans reduce their radiation absorption under conditions of high irradiance by leaf movements which affect solar radiation, paraheliotropism (Ehleringer and Forseth, 1982 ; Travis and Reed, 1983). The above leaf movements at an appropriate angle to the sun's rays thus reducing the effective incident irradiance, has been noted to increase water use efficiency (Jones, 1976). Fischer and Tanner (1978) proposed plant adaptations leading to increased water use efficiency. They highlighted that leaf movements which orient the leaf parallel to the sun's rays, leaf rolling and flagging, erect leaves and needle like leaves may serve to increase water use efficiency.

#### 2.2.2.5 Crop Canopy Albedo

Water use efficiency has also been found to vary with the albedo of the crop surface. Fischer and Tanner (1978) noted that increased reflection of incident radiation would for a similar reason as above tend to increase water use efficiency. This may arise due to the reduced leaf temperature and the energy load of the leaf system that will occur. Other researchers have indicated the effects of reflectivity on the water use efficiency ratio. Blum (1975) working on sorghum leaves with normal wax bloom, which increases reflectivity observed higher water use efficiency values than in the study involving bloomless leaves by Chatterton et al. (1975). Njihia (1978) noted that changes in the reflection coefficient of the soil surface will influence the loss of soil moisture by evaporation. This observation can be extended from the soil surface level to the crop canopy scale. An increase in the reflection coefficient at the crop canopy will then serve to conserve water through reduced amount of energy absorbed which could drive the evaporative and/or transpiration process. This reduction in transpirational water loss will then enhance water use efficiency.

#### 2.2.2.6 Position and age of plant leaves

The position and age of plant leaves may also contribute quite significantly to the plant water use efficiency. Their effects are felt in the photosynthetic rates and hence dry matter accumulation. Research on maize revealed that as the leaves age, maximum potential rate of photosynthesis decreases

(Blaine, 1986). Differences in the photosynthetic rate among individual leaves on a maize plant do exist. The reasons for the observed differences have been attributed to the old age of bottom leaves and shading by other leaves. These differences are however, less in young plants when the canopy has not yet closed, and are greatest as the plant approaches maturity. Thus, for maize, a functional relationship between photosynthetic rate and, leaf area and plant age is evident.

#### 2.2.2.7 Planting density

The contribution of planting density to plant water use efficiency is of prime concern, as it affects other plant characteristics like leaf area index (LAI). Plant density or leaf area index determines the loss of soil moisture. Turner (1965) found that plots planted with higher maize densities had a tendency to dry more rapidly than those with lower densities. Other researchers have documented similar findings : grain sorghum hybrids (Blum, 1970), dry land cotton and grain sorghum (Ritchie and Burnet, 1971 ). Ritchie and Burnet (1971) found that use of higher plant densities and closer row spacing decreases soil evaporation, thus improving on water use efficiency of dry land crops. The differences in plant water use efficiency at different plant densities can be accounted for by the leaf area index since the higher the plant density the higher the leaf area index. Water use efficiency has been found to increase with leaf area index (Ritchie, 1974). When soil moisture is not limiting closer row spacings of sorghum crops use water more efficiently and



increase grain yields (Stickler, 1964 ; Blum, 1970). However, it is worth noting that narrow spacing does not necessarily lead to increased yields. Alesi et al. (1974) and Mitchell (1970) found that under limited moisture (less than optimal), narrow rows do not necessarily result in yield increases. Further, Cummins et al. (1973) noted that narrow rows for maize being raised for silage is not necessarily advantageous. Prior and Russell (1975) reported an increase in kernel yield of maize with plant population density upto 51,000 plants per hectare, followed by decreasing yields with further increases in plant population density upto 72,000 plants per hectare, ie, a parabolic response.

Nadar et al. (1982) investigated on maize populations at three row spacings at both Katumani and Kampi-ya Mawe research stations during the long rains season of 1978 and the short rains season of 1978/79. In their study maximum yields were realised at populations between 58,000 and 70,000 plants per hectare. They noted that under favourable rainfall conditions, increasing the maize plant density from 20,000 to 70,000 plants per hectare would result in yield increase of 200% (from 2.0 tons/ha to 6.0 tons/ha). However, the expected yield decrease when rainfall conditions are not favourable, on increasing the population from 20,000 to 70,000 plants per hectare would be 22.5% (from 2 tons/ha to 1.55 tons/ha).

Tetio-Kagho and Gardner (1988) examined the responses of maize plant population density in the light of reproductive development, yield and consequently yield adjustments. From their work it was inferred that maize reproductive response to

plant population density indicate that individual plant yields decrease with increasing plant population density whereas yields per unit area increase.

#### 2.2.2.8 Crop height.

Crop height influences the rate at which water is depleted from the soil. Mitchell and Kerr (1966) reported higher evapotranspirational rates for tall than for short ryegrass and clover. Plant height operates through its influence on the roughness and hence the aerodynamic characteristics of a crop surface. This may in turn modify the response of a crop to soil moisture.

#### 2.2.3.0 Soil factors

Soil factors which do affect plant water use efficiency may be classified as being, both physical and chemical in nature. They exert direct influences on nearly every phase of the agricultural hydrological cycle. The effects may be viewed in terms of determining infiltration into, and runoff from the soil surface, downward drainage and upward capillary movement through the root zone, as well as availability of the stored soil water. The latter is the component that is potentially available for crop exploitation in transpiration.

#### 2.2.3.1 Soil temperature and Salinity

The temperature and salinity of the soil can limit water uptake by a crop's root system and so transpiration from the canopy (Blaine, 1986 ; Stanhill, 1986). Dynamically the same factors can influence the growth of the crop's root and canopy

system and thus also limit crop transpiration. Bierhuizen (1973) documented that at suboptimal temperatures the water uptake by roots during vegetative and generative phases increases as soil temperature increases. The high concentration of salts at the soil-root interface can affect the osmotic potential and decrease the ability of the roots to take up water. In maize it has been found that the salinity tolerance limit is greatly influenced by the amount of transpirational demand occurring during the growing season (Blaine, 1986).

#### 2.2.3.2 Soil Nutrients

The nutrient status of the soil has also been reported to affect water use efficiency. However, container studies indicated that the effects of nutrient deficiency on water use efficiency were generally small (Anderson and Read, 1966 ; de Wit, 1958).

#### 2.2.3.3 Soil Moisture

Soil water content plays a vital role in influencing water use efficiency of plants. Changes in the available soil water for plants affects plant water use efficiency. Water use efficiency decreases even with mild soil water stress, presumably as the stomatal resistance increases (Lemon, 1963 ; Sinclair et al., 1975). In the study by Sinclair et al. (1975) the measured response of canopy water use efficiency to the change in stomatal resistance agreed with that predicted from a single leaf model of water use efficiency. For maize crop

severe water deficits at the fertilisation and the grain filling stages resulted in marked yield reduction (Stewart and Wang'ati, 1986). Water stress at the tasselling stage not only hinders the plant's ability to flower and shed pollen, but also can greatly affect the viability of plant's pollen especially when the drought is accompanied by high temperatures. Turner (1966) in his investigation into the causes of low yield in late planted maize noted that the low yields were due to a greater proportion of barren cobs, fewer grains per harvestable cob, and smaller grain size. As pointed out in the foregoing lines these observations are consequences of water deficits as from floral initiation stage. Denmead and Shaw (1960) found that water stress in maize reduces grain yield by 25% when prior to silking, by 50% when occurring at silking, and by 21% after silking. Changes in yields result into changes in water use efficiency.

#### 2.2.4.0 Economic factor

Water use efficiency is characterised by the plant's ability to produce dry matter for every available unit of water. Besides this ratio being dictated by the varied factors discussed in the foregoing sections, the economic level of the farmer or the farming organisation to a considerable extent has a bearing on the optimum level of water use efficiency. In both commercial and subsistence farming, the objective is to attain maximum yield with minimum inputs such as water, especially in irrigated agriculture. On the basis of these highlights the overall goal is increased water use

efficiency.

To achieve increased yields, use of advanced agronomic practices such as high rates of fertiliser application, use of improved seed varieties, mechanisation, minimisation of the runoff component, and reduction of the evaporative water losses are priorities. These operations are nevertheless very expensive. Low income generators may definitely be unable to finance these operations. Consequently, low yields accompanied by high water losses will be encountered and hence low water use efficiency.

In irrigated agricultural systems, purchase of irrigation equipments (pumps, pipes), repair and maintenance costs, energy for operating the system together with labour charges solely depend on the economic status of the farmer. Failure to avail these facilities implies low to no production at all and therefore very low water use efficiency. Intuitively, water use efficiency in this respect may be expressed as a function of the economic factor.

In line with minimisation of the water used by the crops under natural conditions, improved cultural management practices must be employed. This involves use of antitranspirants such as phenylmercuric acetate (PMA) to minimise water loss from the plant through transpiration, and use of mulches to conserve soil water. Through decreased leaf transpiration, PMA may help make available large quantities of water to the plant and therefore result into increased biomass production. To meet these demands, materials for these purposes though expensive need to be acquired in order to

sustain production. Absence of such techniques will render extravagant losses of water by crops, thus lowering its productivity. It is with no doubt that reduced productivity coupled with increased water consumption will result in diminishing water use efficiency ratio. It is therefore worth noting that water use efficiency of any crop farming system may be manipulated via the economic factor of the operating system.

### 2.3.0 Steps towards improved water use efficiency.

The opportunities available for improving water use efficiency may be viewed in two ways. These may be classified under differential reduction in the rates of plant water loss and under increment in rates of dry matter production. These techniques are discussed in the sections that follow.

#### 2.3.1.0 Reduction of plant water loss.

In this section, two approaches to minimising transpiration on a field scale without hampering growth will be examined. These approaches involve increasing the diffusive resistance to water vapour and increasing the albedo of the crop surface. Diffusive resistance in this context refers to the opposition offered by the stomates to the passage of water vapour through them.

##### 2.3.1.1 Manipulation of leaf diffusive resistance

Increasing the diffusive resistance to water vapour in the stomatal, cuticular, and boundary layer pathways between the surface of the stomatal cells which are the vapour source and

the free air, the vapour sink, has been reported to reduce transpiration more than it does reduce carbon dioxide exchange (Sinclair and Tanner, 1983 ; Stanhill, 1986). The reasons underlying this may be viewed in the difference between the total diffusion pathway to water and that for carbon dioxide, the diffusion pathway of water being less. Higher reduction in transpiration more than  $\text{CO}_2$  exchange implies increased water use efficiency. This will occur through increased photosynthetic rate.

To achieve increased stomatal resistance in the water vapour diffusion pathway, chemical, stomatal-closing, and sealing agents have been used. However, Stanhill (1986) presented difficulties which limit future prospects of reducing transpiration through manipulation of stomatal resistance. He noted non-availability of cheap and non-toxic specific stomatal-closing agent which could be taken up by the plant to avoid frequent applications to cover stomatal-bearing of a growing crop canopy. According to this author, there exists a gap in the knowledge concerning optimum level of stomatal resistance to minimise transpiration ratio for a given crop stage and environment. Thus, if such a chemical was available its practical field application could still be limited.

Another drawback associated with increasing diffusion resistances with an aim of reducing transpiration is the higher equilibrium temperature at the leaf surface that will result. The saturation vapour pressure at the transpiring

surface will in turn increase and therefore result in increased transpiration potential. The resulting higher temperatures in arid regions may be supraoptimum for dry matter production. The entire operation may then be considered as a negative feedback effect, whose field application should be restricted to situations where the modification is most required.

#### 2.3.1.2 Use of anti-transpirants

Another aspect of reduction of transpirational water loss is by reduction of radiation energy absorption. This is effected by providing for reflectivity from the crop surface. Under this the conserved energy is radiated back into space rather than convected into the lower atmosphere. By so doing the negative feedback effect above is avoided, although another problem may ensue if radiation reduction is not spectrally selective. Through unselected spectral reflectivity, the photosynthetically active radiation (PAR) may be restrictive and thus dry matter production will be reduced, unless the crop canopy is saturated.

For a wider scale, application of spectrally neutral reflectant enhancement appears to be the possibility of artificial cloud generation. Stanhill (1986) remarked that this approach is technically possible at the crop level during selected seasons and hours of maximum potential transpiration, or at critical stages of crop sensitivity to water stress.



### 2.3.2 Increasing dry matter production.

Another method available for increasing water use efficiency lies in the opportunity in increasing dry matter production without initiating an increase in transpirational water loss. Three possible methods aimed at meeting this expectation are presented in the succeeding sections.

Where total dry matter production has increased, this has nearly been achieved through larger and longer lasting leaf canopies, which are the photosynthetic apparatuses. The larger crop canopies serve to decrease soil evaporation through shading the bare portions of the soil surface. Through such a practice a lot more water is made available to the crop. On the other hand we may expect that large canopies will provide a large surface for increased transpiration and hence decreased water use efficiency. This however, will not necessarily happen because the effective evapotranspiration over the entire canopy will be reduced as a result of decreased soil evaporation.

Improved agronomic practices such as use of new crop varieties known to be high yielding, improved fertiliser application, irrigation and plant protection measures against diseases and pests aid in increasing yields and therefore water use efficiency. These practices lead to development of large crop canopies which shade the soil and lower soil evaporation. Development of large canopy stands implies incremental changes in dry matter accumulation. This coupled with the accompanying reduction in soil evaporation and

therefore evapotranspiration results into increased water use efficiency.

While the adequacy of a region for producing a crop is determined by the climate, the crop yield and therefore water use efficiency is dictated by weather conditions. In line with this fact we view weather as an integrator of crop yield. Knowledge of the factors influencing crop water use efficiency and a hope to improve the efficiency has continued to be an objective in many recent investigations. In retrospect to the previous century research, much work yielded in empirical conclusions that seemed confusing and even contradictory. However with recent developments in the understanding of the physical and physiological processes regulating crop growth and water loss, analysis of crop water use in quantitative mechanistic terms has been made possible (Sinclair and Tanner, 1984).

The significance of water use efficiency is great particularly in regions where water demand, potential evapotranspiration, exceeds water supply. This is a problem quite prominent in the dryland areas, commonly termed as the Arid-semi-arid lands (ASAL). Even in the absence of water shortage on annual basis, water in such environments is often limiting on a short term seasonal basis. Stanhill (1986) remarked that in dryland areas where water is the primary limiting factor in crop growth, increases in water use efficiency achieved by eliminating or reducing non-productive water use will lead to an increase in transpiration and yield. However, in rain-fed agricultural systems an increase in crop

CHAPTER THREE.

water use efficiency can be achieved by water conservation measures which decrease surface runoff, increase water storage capacity and by cultivation practices which reduce transpiration by weeds and evaporation from the soil. This study looks at water use efficiency of maize in semi-arid lands of Kenya with the hope of increasing food production through better cultural practices.

The chapter that follows presents the experimental layout, and materials and methods used in this study.

## CHAPTER THREE.

### 3.0 MATERIALS AND METHODS.

#### 3.1 Site of Study

The study was conducted on a 2-acre plot located within 12,188 acres of land at the Kibwezi dry land field station of the University of Nairobi. The field is situated in Machakos District within latitude  $1^{\circ} 35'S$  and longitude  $37^{\circ} 59'E$ . It is about 250km south east of Nairobi.

The land is comprised of gently undulating terrain ranging in altitude from 700 to 780 metres above sea level. The land slopes south eastwards and is traversed by several dry valleys. The Kibwezi river borders the field experimental station in the south. Figure 1 drawn to a scale of 1:50, 000 is a sketch map representing the University of Nairobi, Kibwezi Dryland Field Station.

The climate of the study area is characterised by a bimodal rainfall distribution, colloquially termed as the 'long' and 'short' rainy seasons. The long rains which occur in the period 'March to May' average at 229mm. The short rain component (October to December) is characterised by an average rainfall of 349mm. The long and short rain seasons are mediated by the driest period within a year (June-September). Mean annual rainfall over the region is 663mm. Table 1 below, obtained from the Kenya Meteorological Department illustrates the citations presented in this section.

The soils in the study region are derived from

SKETCH MAP

SCALE 1 : 50,000

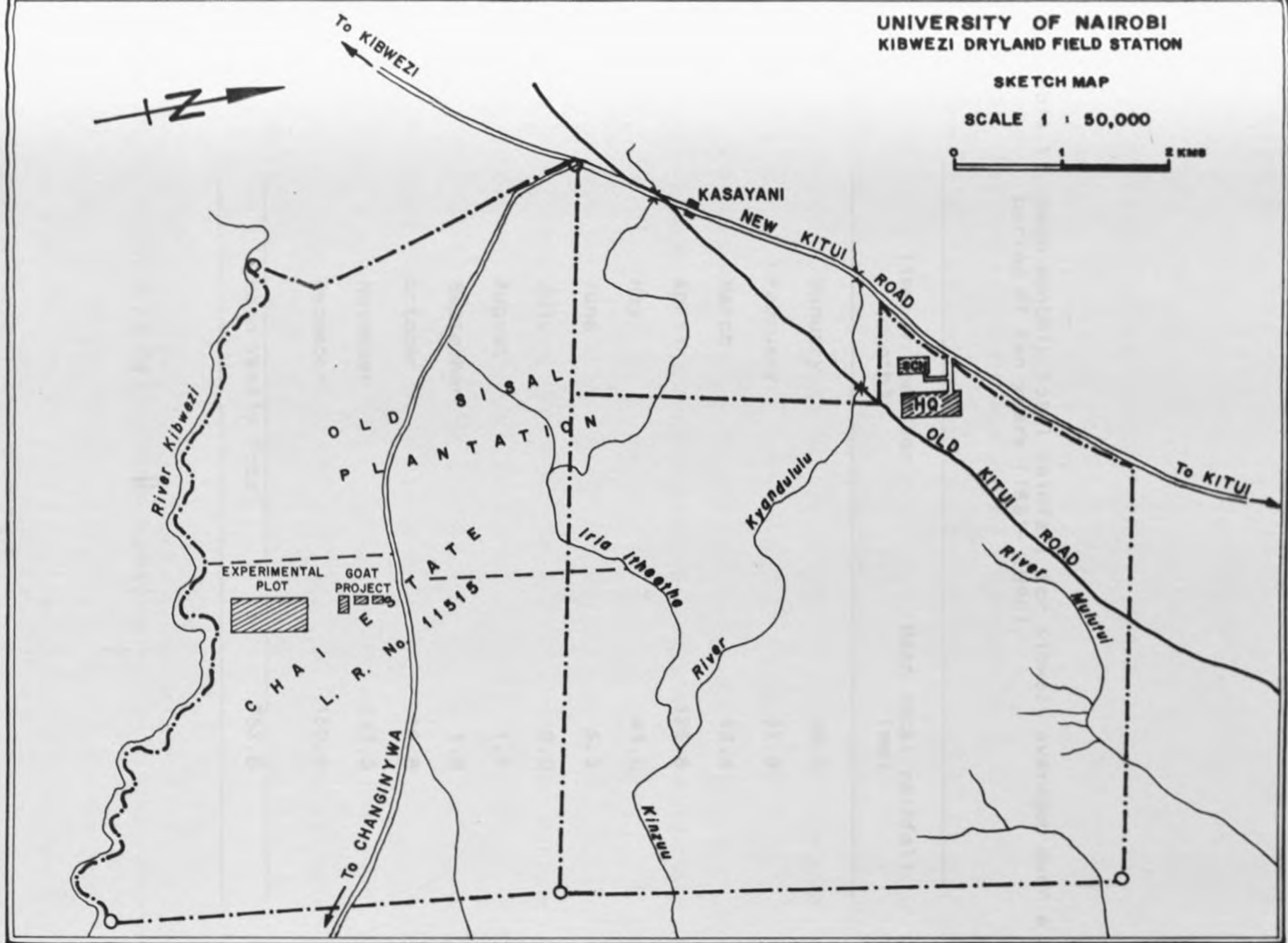
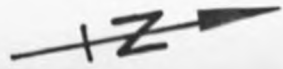


FIG. 1 - MAP OF THE STUDY AREA

Table 1: Mean monthly total rainfall for Kibwezi averaged over a period of ten years (1981- 1990).

Time of the Year (month)	Mean total rainfall (mm)
January	38.8
February	37.9
March	53.4
April	126.8
May	43.0
June	5.3
July	0.0
August	1.5
September	1.9
October	60.8
November	237.3
December	150.9
Mean Yearly Total	753.8

metamorphic rocks composing the basement complex. They are fairly well drained, sandy to medium textured, deep, and slightly acidic to acidic. Some profiles are however, laden with laeteritic concretions ( Touber, 1983).

### 3.2 Instrumentation.

Meteorological parameters were measured at an agrometeorological station situated at about 500m from the crop field. Since the station was already in operation at the time of the experiment, all the instruments for meteorological observations were considered already calibrated and were made use of the way they had been installed. The meteorological parameters considered were sunshine hours, maximum temperature, minimum temperature, pan evaporation, wind run, relative humidity and rainfall.

Soil moisture content was monitored by use of the neutron probe. Though the equipment was tested for operation, factory calibration could not be used for experimental purposes in this study. The reason for invalidating the use of the factory calibration could be viewed in terms of the possible difference in performance of the neutron probe in this study as compared with the factory conditions. This disparity could emanate from the difference between soil properties and type of access tubes used in factory calibration and those of this experiment.

In the light of the above limitations of factory calibration, field calibration of the neutron probe was done. Soil samples from the field were collected in increment cores

of 15cm depth, corresponding to those which were sampled with the neutron probe. Six samples per depth were taken for gravimetric determination of soil water content. Water content of each soil sample collected was determined and expressed in units of centimetre depth of water per 30cm depth of soil (cm/30cm). Correspondingly, count rates were taken by the neutron probe. From these two observations, a plot of water content of the soil samples against the corresponding count rates was made. The slope and intercept obtained from the graph were then entered into the calibration unit of the neutron probe to be used for subsequent measurement of soil water content. Figure 2 shows a typical calibration graph of the neutron probe under the Kibwezi soils.

### 3.2.1 Field Experimentation.

The experimental design was of complete block design with two blocks and three treatments per block. Two maize varieties namely, makueni and katumani composites formed blocks whereas three planting densities viz. low, medium and high were the treatments. The field study was conducted for three months starting from 10<sup>th</sup> of November 1990 to 15<sup>th</sup> of February 1991. Field plots were never irrigated. Throughout the growing season the crop relied on rainfall and stored soil water only.

Two dry land varieties of maize (*Zea mays* L.) viz. Katumani and Makueni composite B were planted in separate plots and rows oriented in an East-West direction at three different spacings. This step ensured easy penetration of the



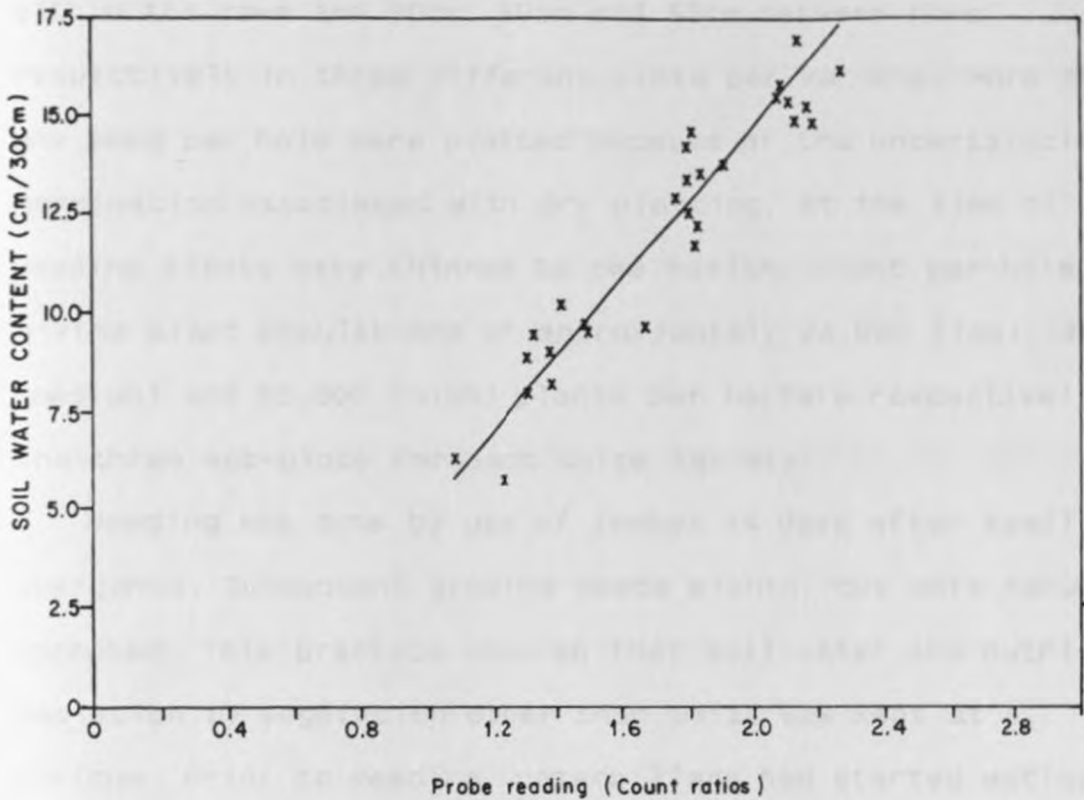


FIG. 2 — CALIBRATION GRAPH OF NEUTRON PROBE TYPE 503 DR.

sun's rays into the crop canopy. Two to three seeds of each variety were dry-planted using spacings of 45cm, 30cm, 20cm within the rows and 90cm, 90cm and 60cm between rows respectively in three different plots per variety. More than one seed per hole were planted because of the uncertainties in germination associated with dry planting. At the time of weeding plants were thinned to one healthy plant per hole, giving plant populations of approximately 24,000 (low), 36,000 (medium) and 83,000 (high) plants per hectare respectively for the three sub-plots for each maize variety.

Weeding was done by use of jembes 14 days after seedling emergence. Subsequent growing weeds within rows were manually uprooted. This practice ensured that soil water and nutrient depletion by vegetation other than maize was kept at a minimum. Prior to weeding, caterpillars had started eating part of the foliage causing scarifications and windowing on them. After weeding, destruction of maize by these pests was checked.

In this study only one crop season investigation was made. The reasons of which were twofold: inadequate time for setting up another similar field experiment and lack of funds to operate field experiments in the succeeding cropping seasons. However, it is hoped that findings obtained in this study will be useful to the farming communities in the study region and to other dryland regions where transferability of these results is possible. This may be so based on the fact that the short rainy season so utilised for the experiment is the most reliable in the region of study.

### 3.3.0 Sampling and field measurements.

#### 3.3.1 Soil moisture measurements.

A neutron scatterer was used to measure soil moisture in the experimental field. Six aluminium access pipes were located in the field, distributed within rows of maize and at the centre of each plot representing a particular planting density. Soil water content was measured at 15cm intervals to a depth of 90cm beginning at 15cm below the soil surface. Soil water content in the upper 15cm of the soil was determined gravimetrically.

Measurements were made at weekly time intervals from the first week after crop emergence through harvest. The depth of 90cm was chosen on the strength of the previous research findings (Russell and Danielson, 1956) that showed that the bulk of the soil water withdrawal took place in the top 90-120cm of the soil. However, soil depths in excess of 90cm could not be explored because access pipes were available in metre lengths. As such drilling of holes whose depths were 100cm or more could permit for accumulation of surface water after rains into them. The pipes therefore had to protrude 10cm above the ground to avoid this menace. The end result of the accumulation of water into the holes could be markedly high exaggeration of soil moisture content values. Figure 3 illustrates the field experimental layout that was adapted in this study.

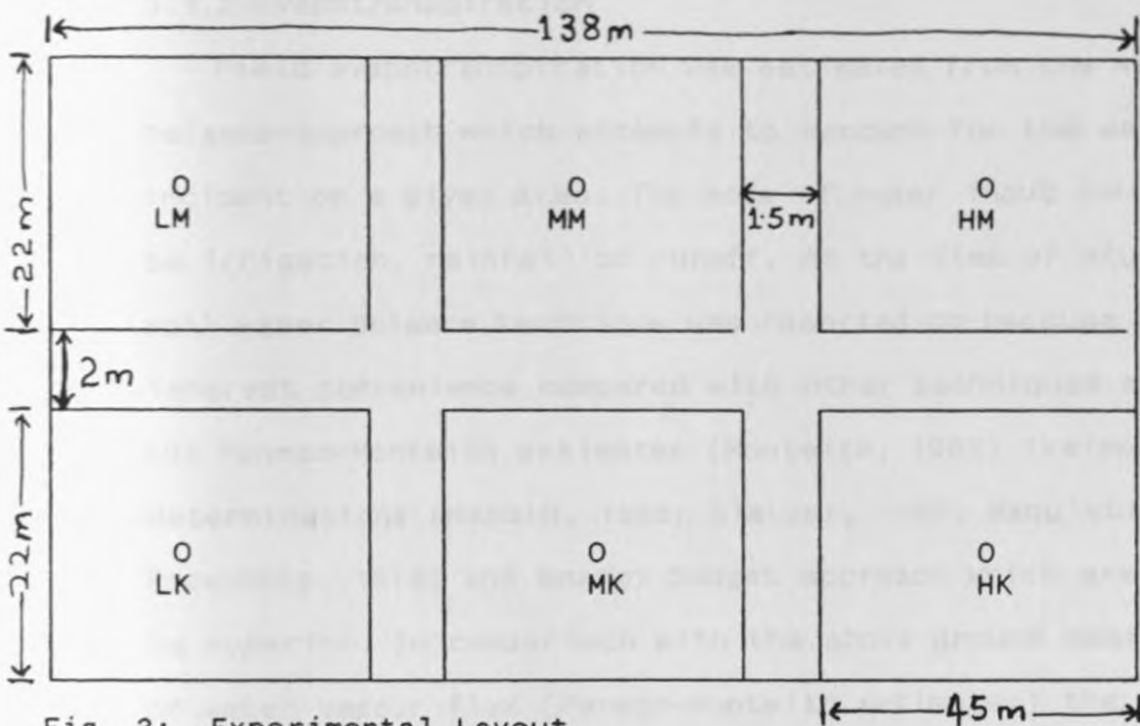


Fig. 3: Experimental Layout.

Legend to Fig. 3.

- O access pipe
- LM makueni low planting density.
- MM makueni medium planting density.
- HM makueni high planting density.
- LK katumani low planting density.
- MK katumani medium planting density.
- HK katumani high planting density.

### 3.3.2 Evapotranspiration

Field evapotranspiration was estimated from the water balance approach which attempts to account for the water incident on a given area. The mode of water input could either be irrigation, rainfall or runoff. At the time of study the soil water balance technique was resorted to because of its inherent convenience compared with other techniques such as the Penman-Monteith estimates (Monteith, 1963) lysimetric determinations (Harold, 1966; Slatyer, 1967; Wang'ati, 1972; Rosenberg, 1974) and energy budget approach which are known to be superior. In comparison with the above ground measurements of water vapour flux (Penman-Monteith estimates) the water balance technique presents ease of data processing and the integration, by the soil water reservoir, of extraction rates between observations. Further, the method is useful where instrumentation to measure the flux of water vapour from the soil to the atmosphere is unavailable.

Another advantage of the soil water balance approach is manifested in its capability in demonstrating the relative rates at which soil water extraction is taking place from different soil zones. This information is of particular value in understanding root distribution, problems of competition between species, and reasons for species persistence or failure under extreme environmental conditions.

Rijks (1973) pointed out the limitations associated with use of lysimeters in determining evapotranspiration in the field. He noted that evapotranspiration from crops grown in lysimeters could very well be different from that of the

surrounding crops in the same field. The difference could be due to the effects of edging, advection and difference in soil physical characteristics resulting from excavating and filling. It therefore becomes impossible to simulate the natural environment inside the lysimeter especially when the mixed nature of the species composition, the spatial distribution of the vegetation, the depth and ramification of the root system exist. In addition to the above limitation, the use of lysimeters could not be effected because of the high initial costs of the equipment and installation, and high expertise involved. This could not be possible at the time of the experiment.

The water balance approach is extensively discussed in the section that follows. The basic assumptions underlying its field application in this study are also presented.

$$\frac{dW}{dt} = P - E - R - G - \Delta S \quad (2)$$

- $P$  is the precipitation
- $E$  is the evaporation
- $R$  is the runoff
- $G$  is the groundwater
- $\Delta S$  is the change in soil water content

### 3.3.2.1 Specification of the Water balance Model.

An equation describing the water balance technique may be written as

$$P + \Delta SW + D - U_z - E_t = 0 \quad (1)$$

Where P is precipitation and/or irrigation

D is runoff

$U_z$  is percolation or deep drainage

$\Delta SW$  is change in the water content of the soil

$E_t$  is evapotranspiration.

It is worth noting that all the symbols in equation (1) have dimensions of length. In this study depth units of millimeters (mm) were used.

Because observations were to be made over discrete time intervals, equation (1) above was modified in line with previous research recommendations ( Slatyer, 1968 and Rose, 1966) expressed as

$$\int_{t_1}^{t_2} [(P + D) - E_t - U_z ] dt = \int_{t_1}^{t_2} \int_{z_0}^z \frac{\partial \theta}{\partial t} dzdt \quad (2)$$

Where  $t_2 - t_1$  is the time interval of measurement

$z_0$  is the depth to the lowest point of measurement

$U_z$  is the net downward flux of water at depth Z

$\theta$  is the volumetric soil water content

The above equations may be used on scales ranging from continental

landmasses (Malhotra and Brock, 1970) and hydrologic catchments (Lettau and Baradas, 1973; Woolhiser et al., 1970; Baumgartner, 1970) down to small fields or even small plants (Slatyer, 1968).

In this study an approximate flat field was chosen for the experiment. This step was undertaken for the purpose of enhancing infiltration rate and curtailing the amount of runoff into or out of the plots. Runoff which is dependent on the slope of the land plays a significant role in determining the pattern of soil water recharge. Drainage channels were dug along sides of the field which appeared to be lower than the neighbouring elevated grounds. This was a check on the flow of rain water into the experimental field. Based on the above attempts of minimisation of the runoff component, the study neglected the effect of this parameter. Equation (2) above, then assumed the form

$$\int_{t_1}^{t_2} [P - E_t - U_z] dt = \int_{t_1}^{t_2} \int_{z_0}^z \frac{\partial \theta}{\partial t} dz dt \quad (3)$$

Rainfall (P) was measured on daily basis by use of a rain gauge and weekly totals expressed in millimetres determined. Changes in soil water content were determined from the difference in consecutive soil water content measurements made by the use of the neutron moisture meter discussed in the foregoing section. In this study it was assumed that all the water input into the soil through rainfall remained within reach of the crop root system. The deep percolation component



of the water balance equation was therefore neglected and the resulting water balance equation could then be expressed as

$$\int_{t_1}^{t_2} [P - E_t] dt = \int_{t_1}^{t_2} \int_{z_0}^z \frac{\partial \theta}{\partial t} dz dt \quad (4)$$

Consequently from equation (4) above, evapotranspiration could be estimated from equation (5) below

$$\int_{t_1}^{t_2} E_t dt = \int_{t_1}^{t_2} P dt - \int_{t_1}^{t_2} \int_{z_0}^z \frac{\partial \theta}{\partial t} dz dt \quad (5)$$

The left hand term of equation (5) stands for the total amount of evapotranspiration that took place between the sampling dates. The first and second terms on the right hand side represent the corresponding amount of rainfall and change in stored soil water respectively.

From the set-up of equation (5) we may note that in the absence of precipitation in rainfed farming systems or irrigation during any one sampling interval, then, the amount of evapotranspiration will equal the change in profile soil water content.

### 3.3.3 Yield Dry Matter.

Field measurements of dry matter were made every week by harvesting 2 plants chosen at random in the neighbourhood of the installed aluminium access pipes from each of the six plots. The neighbourhood of the sites of measurement was chosen in order to avoid the edge effects which could otherwise influence the results. During harvesting of the plant material, all shoot material of the plant chosen within each plot were clipped at ground level by shears. The woody plant material was cut by pangas. The harvested material was dried to constant weight at  $80^{\circ}\text{C}$  in a forced draught oven. The constant weight attained gave the amount of dry matter accumulated by the plant since seedling emergence.

As from grain filling stage of the maize crop, the harvested plant material was separated into two components. Biological yield comprising the leaves, stalks, husks, silks, tassels and cobs formed the first component. The economic yield consisting the grains constituted the second category of the yield. As stated above, both the biological and economic yields were dried to constant weight to give their dry matter weights accumulated up to the sampling time. This practice was carried out up to harvesting time.

### 3.3.4 Water Use Efficiency.

Water use efficiency in this study was calculated using both the biological yield-to-evapotranspiration and economic yield-to-evapotranspiration ratios. Crop yield was invoked into this study

because it is an important determinant of how efficiently water is used. Weekly water use efficiency ratios for the two cases above were obtained. The biological yield-to-evapotranspiration and the economic yield-to-evapotranspiration ratios give relative quantities of the amount of dry matter accumulation for every unit of water used productively through evapotranspiration by the plant to produce the biological and economic yields respectively.

In general the water use efficiency ratio may be expressed in terms of its components by the relationship of the form:

$$WUE = \frac{Y}{E_t} \quad (6)$$

Where Y is the yield dry matter

$E_t$  is the amount of water used productively by the plant through evapotranspiration.

WUE is the water use efficiency

### 3.3.5 Meteorological Data.

Meteorological parameters were recorded at an agrometeorological station situated 500m away from the crop field. Temperature and relative humidity were recorded by a thermohygrograph in a standard screen at a height of 2m and averaged over 24 hours to give daily means. Within the same framework, dry bulb, wet bulb, maximum and minimum temperatures were recorded.

24-hour totals of evaporation from an open class A pan with a protective wire screen were estimated from the equations that follow

$$E = R + 0.5 N_c \quad (7)$$

where  $E$  is evaporation

$N_c$  is the number of full cups that were added to the pan when evaporation was greater than rainfall

$R$  is the rainfall

In cases where the amount of rainfall within the 24 hours exceeded the daily evaporation, the pan evaporation was determined from

$$E = R - 0.5 N_c \quad (8)$$

$N_c$  in this case stands for the number of full cups taken out to bring the water level to datum level. However, in cases where no cups of water were added or taken out of the pan, evaporation was taken to be equal to the amount of rainfall in that day.

Sunshine hours were determined from the Campbell-Stokes sunshine recorder. From the derived sunshine hours, values of net radiation were estimated from the algebraic difference between net short wave radiation and net long wave radiation. This operation may be represented by the equation below

$$R_n = R_{ns} - R_{nl} \quad (9)$$

where  $R_{ns}$  is the net short wave radiation, and  $R_{nl}$  is the net long wave radiation, and  $R_n$  is the net radiation.

The quantity of net short wave radiation reaching the earth's surface was estimated from the equation that follows

$$R_{ns} = (1-\alpha)R_s \quad (10)$$

where  $\alpha$  is the albedo of the crop surface [ assumed to be 0.25 (Stewart and Mugah, 1982)] and  $R_s$  is the solar radiation incident on the earth's surface. The value of  $R_s$  is given by the equation

$$R_s = (0.25 + 0.50 n/N) R_a \quad (11)$$

where  $R_a$  is the extra-terrestrial radiation expressed in equivalent evaporation in mm/day.

$n/N$  is the ratio between actual measured bright sunshine hours and maximum possible sunshine hours.

Values of  $N$  for different months and latitudes were obtained from standard tables extracted from the work of Doorenbos and Pruitt (1977). From similar work values of  $R_a$  in mm/day for different months and latitudes were obtained. These tables are presented in the appendix.  $R_s$  was obtained in mean equivalent evaporation in mm/day for the period considered.

Net long wave radiation was estimated from the equation proposed by Doorenbos and Pruitt (1977) given as:

$$R_{nl} = \delta TK^4 (0.34 - 0.044/e_a) (0.1 + 0.9 n/N) \quad (12)$$

where  $\delta$  stefan boltzman constant ( $= 1.98 \times 10^{-9}$  mm/day/k<sup>-4</sup>)

TK mean air temperature in degree Kelvin

$e_a$  actual vapour pressure at the prevailing

temperature

$e_a$  was obtained from psychrometric tables using dry bulb temperature ( $T_{db}$ ) and the corresponding wet bulb depression ( $T_{db} - T_{wb}$ ).

### 3.4 Relative Dry Matter Accumulation rate.

The relative growth rate serves as a fundamental measure of dry matter production (Blackman, 1919; Evans, 1972; Couston and Venus, 1981 ; Beadle, 1986; Chiariello et al.,1989) and was therefore used to compare the performance of Katumani and Makueni composites, and the effects of planting densities on the two maize varieties. However in this study, the rate of accumulation of dry matter but not the growth rate was considered. Therefore in the succeeding portions of this section the term rate of dry matter accumulation will be used in place of growth rate.

The relative accumulation rate (R) at any instant in time (t) may be defined as the instantaneous rate of increase relative to the productive mass of the plant material present. It is the only component of growth analysis which does not require knowledge of the assimilatory system. The expression for the relative dry matter accumulation rate is of the form

$$R = -\frac{1}{W} \frac{dW}{dt} = \frac{d}{dt} (\ln W) \tag{13}$$

where R is the accumulation rate and W is the total individual plant

dry weight (g) of the biomass and  $t$  is the time. The relative accumulation rate was used but not the absolute accumulation rate because the latter does not give much information concerning the physiological performance of the plant in dry matter production. On the other hand relative accumulation rate measures the average efficiency of each unit of dry matter in the rate of production of new dry matter (Causton and Venus, 1981; Blackman, 1919).

Longer time units are used rather than the second for time measurements because they are more meaningful biologically and experimentally (Chiariello et. al, 1989) These authors also noted that the typical and minimum time unit for growth parameters is the day since physiological processes contributing to growth have diurnal rhythms.

Since observations for dry matter yields were made at discrete time intervals, equivalent one week, the mean relative accumulation rate for each interval was used. The mean accumulation rate for time period not less than one day was recommended by Beadle (1986) and Chiariello et al. (1989). If therefore the dry biomass varies continuously from time  $t_1$  to  $t_2$ , then the mean relative accumulation rate may be defined as

$$R = \frac{1}{(t_2 - t_1)} \int_{W_1}^{W_2} d(\ln W) = \frac{[\ln W_2 - \ln W_1]}{[t_2 - t_1]} \quad (14)$$

Equation (14) was then used to compute the weekly mean relative dry

matter accumulation rates for both varieties and plant populations. However, this equation is independent of changes in the relative dry matter accumulation rate during the time interval.

W increases exponentially with time and therefore we may write

$$W_2 = W_1 e^{R(t_2 - t_1)} \quad (15)$$

where  $W_1$  and  $W_2$  are the initial and final plant dry weights respectively, during the observation interval. On taking natural logarithms on both sides of equation (15) above, and making R the subject of the equation we get

$$R = \frac{[\ln W_2 - \ln W_1]}{[t_2 - t_1]} \quad (16)$$

It is therefore observed that equation (16) is the same as equation (14). The inference we make from this is that the mode of change in the relative accumulation rate is independent of the path followed by variations in the dry weight of the plant. In both circumstances of the two equations, it is the initial and final dry weight accumulations that are really important.

In determination of relative dry matter accumulation rates, it was assumed that all the plants were growing at the same rate. The sampling procedure used was destructive and therefore errors could



have arisen due to the above assumption, since different plants were used.

In this section the two questions we address ourselves to are; whether there is a significant difference in

1. dry matter accumulation rate between the two varieties of maize, and
2. dry matter accumulation rate between planting densities.

To facilitate for the analysis described above, mean relative dry matter accumulation rates during vegetative stage and grain filling stage were considered in the analysis of variance. In addition to the mean accumulation rates of dry matter, the accompanying water uses ( evapotranspiration rates) and water use efficiencies were also subjected to the analysis of variance, which is discussed in the following section.

#### 3.4.1 Analysis of Variance.

The analysis of variance is essentially an arithmetic process for partitioning a total sum of squares into components associated with recognized sources of variation. In this study there are three possible sources of variation in the measured physical quantities, ie. dry matter accumulation, evapotranspiration and subsequently water use efficiency of maize varieties. The sources of variation include maize varieties which form the blocks, planting densities constituting the treatments, and the inherent error.

Before examining the procedure that was adapted in the analysis of variance, a brief account of the symbols and notations used is first presented. We shall examine a general case and consider a situation in which  $k$  treatments are subjected to  $r$  blocks.

The observation  $Y_{ij}$  denotes the response of the  $i^{\text{th}}$  treatment applied to the  $j^{\text{th}}$  block,  $i = 1, \dots, k$  treatments and  $j = 1, \dots, r$  blocks. Dot notation will also be used. We therefore, define

$$Y_{i.} = i^{\text{th}} \text{ treatment total}$$

$$Y_{..} = \text{overall total}$$

$$Y_{.j} = j^{\text{th}} \text{ block total}$$

$$\sum_j Y_{ij}^2 = \text{sum of squares for treatments}$$

$$\sum_i Y_{ij}^2 = \text{sum of squares for blocks}$$

$$\sum_{i,j} Y_{ij}^2 = \text{sum of squares of treatment and block totals}$$

$C = \text{correction term}$

The above parameters were computed following the procedure outlined by Steel and Torrie (1981) presented as follows.

The raw data was arranged as shown in Table 2. Treatment totals,  $Y_{i.}$ , block totals,  $Y_{.j}$  and the grand total,  $Y$  were obtained. Simultaneously,  $\sum Y^2$  for each treatment and block were obtained, i.e.,

$$\sum_j Y_{ij}^2, \quad i = 1, \dots, k$$

Table 2: Arrangement of Raw Data.

Treatment	Blocks		Treatment Total		
	1	2	$Y_{i.}$	$\sum_j Y_{ij}^2$	
1	11	21	$Y_{1.}$	$Y_{1.}^2$	
2	12	22	$Y_{2.}$	$Y_{2.}^2$	
3	13	23	$Y_{3.}$	$Y_{3.}^2$	
Block Totals	$Y_{.j}$	$Y_{.1}$	$Y_{.2}$	$Y_{..}$	-
	$\sum_i Y_{ij}^2$	$Y_{.1}^2$	$Y_{.2}^2$	-	$Y_{..}^2$

$$\sum_i Y_{ij}^2, \quad j=1, \dots, r$$

The grand total was obtained by summing treatment totals and block totals separately. The sum of squares of these totals was simultaneously obtained.

The adjusted sum of squares were computed as follows. The correction term, C, was first computed from

$$C = \frac{Y_{..}^2}{rk} \quad (17)$$

Below are the computations of the adjusted sums of squares.

$$\text{Total sum of squares (SST)} = \sum_{i,j} Y_{ij}^2 - C$$

$$\text{Block sum of squares (SSB)} = \frac{1}{k} \sum_j Y_{.j}^2 - C$$

$$\text{Treatment sum of squares (SSt)} = \frac{1}{r} \sum_i Y_{i.}^2 - C$$

$$\text{Error sum of squares (SSE)} = \text{SST} - \text{SSB} - \text{SSt}$$

According to Myers and Walpole (1978), to determine if part of the variation in our observations is due to differences among the treatments, we consider the test

$$H_0' : v_1 = v_2 = \dots = v_k = v$$

$$H_1' : v_j \text{'s are not all equal}$$

where  $H_0$  is the null hypothesis and  $H_1$  is the alternative hypothesis. To test the null hypothesis that the treatment effects are all equal to zero, we compute the ratio

$$f_1 = \frac{S_1^2}{S^2} \quad (18)$$

where  $S_1^2$  and  $S^2$  are mathematically given by the relationships that follow;

$$S_1^2 = \frac{SSt}{k-1}$$

and 
$$S^2 = \frac{SSE}{(k-1)(r-1)}$$

The ratio in equation (18) is a value of the random variable  $F_1$  having the F-distribution with  $(k-1)$  and  $(k-1)(r-1)$  degrees of freedom when the null hypothesis is true. The null hypothesis is rejected at the  $\alpha$  level of significance when

$$f_1 > f_\alpha [k-1, (k-1)(r-1)]$$

Similarly, to test the null hypothesis that the block effects are all equal to zero, we compute the ratio

$$f_2 = \frac{s_2^2}{s^2} \quad (19)$$

where  $s_2^2 = \frac{SSB}{r-1}$

Table 3. Specific Analysis of Variance.

The ratio in equation (19) above is a value of the random variable  $F_2$  having the F-distribution with  $(r-1)$  and  $(k-1)(r-1)$  degrees of freedom when the null hypothesis is true. In this case the null hypothesis is rejected at the  $\alpha$  level of significance when

$$f_2 > f_{\alpha} [r-1, (k-1)(r-1)]$$

In conclusion, the computations in an analysis of variance problem for a randomized complete block design may be summarized as shown in table 3.

#### 3.4.2 Validity of Sampling procedure.

The representativeness of the entire plant population by the two plants harvested weekly from each plot was determined by the method of least significant difference (lsd). Under this we computed the smallest difference that would be declared significant and compared the absolute value of each observed difference with it. A total of five plants were used in this investigation.

Table 3: Symbolic Analysis of Variance.

Sources Variation	Sum of Squares	Degrees of freedom	Mean Squares	Computed f
Treatment	SSt	k-1	$S_1^2 = \frac{SSt}{k-1}$	$f_1 = \frac{S_1^2}{S^2}$
Blocks	SSB	r-1	$S_2^2 = \frac{SSB}{r-1}$	$f_2 = \frac{S_2^2}{S^2}$
Error	SSE	(k-1)(r-1)	$S^2 = \frac{SSE}{(k-1)(r-1)}$	
Total	SST	(kr-1)		

The five plants were combined in sets of two plants and the mean weight of each set obtained. The mean weight of all the five plants served as a basis for computing the least significant difference.

The least significant difference (lsd) as presented by Steel and Torrie (1980) may be given as

$$lsd = t_{\alpha/2} S_{Y_i - \bar{Y}} \quad (20)$$

where  $t$  is the tabulated Student's t-value

$\alpha$  is the level of significance

$Y_i$  is the mean of the  $i^{\text{th}}$  set

$\bar{Y}$  is the mean of all the plants (reference mean)

$S_{Y_i - \bar{Y}}$  is the standard deviation of the differences

between the means of the sets and the reference mean.

Significant differences were declared when the criterion below was fulfilled.

$$| Y_i - \bar{Y} | \geq t_{\alpha/2} S_{Y_i - \bar{Y}} \quad (21)$$

If the condition above was not met, then, lack of significant difference implied that the two plants harvested at random were representative of the entire plot.

### 3.4.3 Harvest Index.

The harvest indices for the two varieties of maize were computed to ascertain the variety and planting density that meets the



requirement of maize production for food and that which meets forage requirements. The harvest index (HI) may be defined as the ratio of grain yield (or economic yield) to total above-ground dry matter expressed as a percentage. Thus, we may express the harvest index mathematically as:

$$HI = \frac{\text{economic yield}}{\text{total dry matter}} \times 100\% \quad (22)$$

The harvest indices were based on the harvests at crop maturity. Tivy (1990) reported values of harvest indices of less than 50% for cereals and remarked that they vary within a particular cultivar or crop strain depending on density of planting, and variations in the supply of nutrients and water.

A higher harvest index implies suitability of growing the crop for food purposes. Conversely, a lower value indicates suitability of raising the crop for fodder.

#### 3.4.4 Meteorological Data.

The meteorological data recorded at the agrometeorological station around the experimental field is presented in Table 4.

The chapter that follows presents the results of this study and the discussions.

CHAPTER FOUR.

Table 4 : Meteorological parameters recorded at the agrometeorological station at Kibwezi Dryland Field Station.

Date (week)	Daily mean temp. (°C)	Daily max. temp. (°C)	Daily min. temp. (°C)	Daily sun-shine hours	rainfall (mm)	Wind run (km/day)	Net radiation (mm/day)	Relative humidity (%)
1	25.3	30.3	20.4	9.1	91.2	56.1	5.6	69.5
2	24.8	29.4	20.3	8.8	102.0	65.4	5.5	74.0
3	24.7	27.5	21.9	6.4	21.7	78.8	4.6	74.5
4	24.0	28.0	20.4	7.9	113.0	46.3	5.1	67.5
5	23.9	29.0	18.8	9.3	1.5	68.4	5.6	70.0
6	24.7	28.2	20.7	9.0	25.5	62.6	5.6	73.5
7	24.7	29.1	20.8	9.5	5.0	54.1	5.7	74.5
8	24.0	28.9	18.8	10.0	0.5	47.5	5.9	66.0
9	26.4	30.9	23.9	9.2	1.7	63.6	5.6	68.0
10	24.6	31.0	22.3	9.2	0.0	90.0	5.9	65.0
11	26.0	31.7	20.3	10.2	0.0	92.4	6.2	56.5

## CHAPTER FOUR.

### 4.0 RESULTS AND DISCUSSION.

#### 4.1 Total above-ground Dry Matter.

Mean total above-ground dry matter for the two maize varieties during vegetative stage, grain filling stage and harvesting stage are given in Table 5. For both varieties and planting densities, the pattern of total above-ground dry matter was the same, only differing in their relative magnitudes. The curves representing the temporal variation of total above-ground dry matter in all the cases (Fig.4 and 5) were sigmoid in nature. Expressed on a kilogram per hectare basis, the magnitudes of the total above-ground dry matter for both Katumani and Makueni composite B were found to increase with planting density within the plant population range considered. However, on the basis of individual plant performance, the total above-ground dry matter was observed to decrease with increasing planting density.

The high value of total above-ground dry matter yield for the highest planting density treatment expressed in kilograms per hectare could be attributed to the high plant population. On the other hand, the pattern depicted by individual plants is likely to be a consequence of inter-plant competition for soil water and nutrients. The end result in this case being low individual plant dry weight in the highest planting density treatment as compared with the low and intermediate planting densities.

Table 5: Total above-ground yield dry matter.

Time (weeks after Planting)	Planting density	Makueni composite (kg/ha)	Katumani composite B (kg/ha)
4	Low	920.4	774.0
	Medium	1242.8	970.2
	High	2730.7	1601.9
7	Low	2577.6	2070.1
	Medium	3704.8	2981.2
	High	7378.7	5996.8
11	Low	4029.6	3492.8
	Medium	5584.0	4800.6
	High	10852.2	9806.5

Legend.

- 4 weeks represents the vegetative growth stage
- 7 weeks stands for the grain filling stage
- 11 weeks represents the harvesting stage.

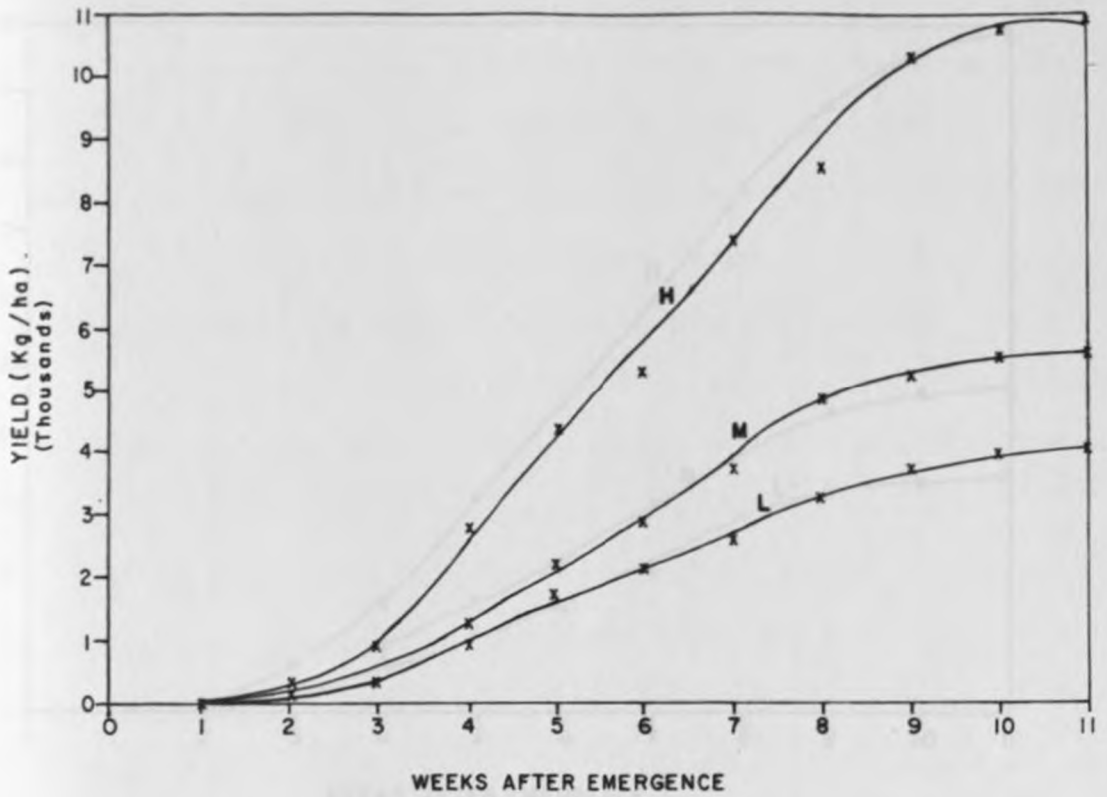


FIG. 4 - VARIATIONS OF WEEKLY TOTAL ABOVE-GROUND DRY MATTER OF MAKUENI COMPOSITE FOR THE PLANTING DENSITIES LOW (L), MEDIUM (M) AND HIGH (H).

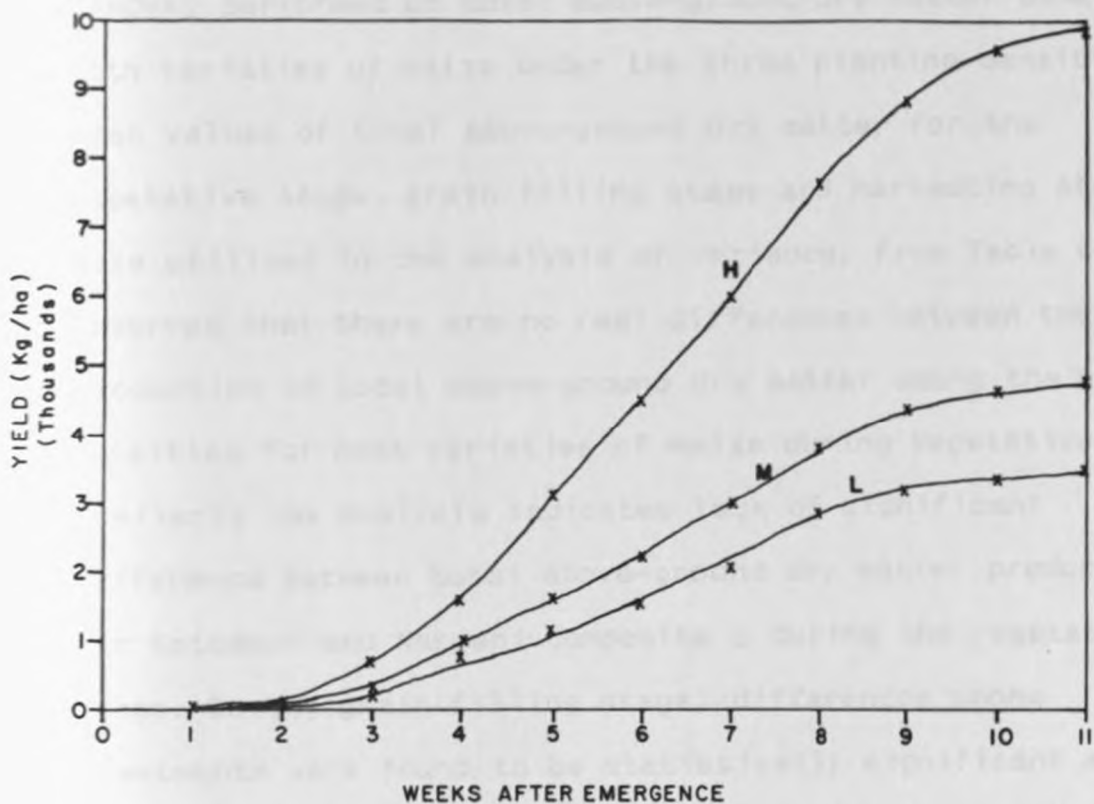


FIG. 5—VARIATIONS OF WEEKLY TOTAL ABOVE-GROUND DRY MATTER OF KATUMANI COMPOSITE FOR DENSITIES LOW(L) , MEDIUM(M) AND HIGH(H) .

Table 6 shows the results of the analysis of variance (ANOVA) performed on total above-ground dry matter data for both varieties of maize under the three planting densities. Mean values of total above-ground dry matter for the vegetative stage, grain filling stage and harvesting stage were utilised in the analysis of variance. From Table 6, it is observed that there are no real differences between the production of total above-ground dry matter among the planting densities for both varieties of maize during vegetative stage. Similarly the analysis indicates lack of significant difference between total above-ground dry matter productivity for Katumani and Makueni composite B during the vegetative stage. During grain filling stage, differences among treatments were found to be statistically significant at both 1% and 5% level of the F-distribution. Differences between variety total above-ground dry matter productivity were not significant at both 5% and 1% levels of the F-distribution. At harvesting time, variety differences in total above-ground dry matter were found to be statistically significant at the 5% level of the F-distribution. Inter-planting density differences in total above-ground dry matter were statistically significant at the 1% level of the F-distribution.

Figures 6 to 8 give direct comparisons between the total above-ground dry matter productivity of Katumani and Makueni composites for the three planting densities. It is observed that throughout the growing season, the curves representing Makueni composite lie above those for Katumani composite. At

Table 6: Analysis of variance total above-ground yield dry matter.

Time (weeks)	Source of variation	Degrees of freedom	sum of squares	Mean square	F ratio
4	Treatment	2	1953624.9	976712.4	6.84 <sup>ns</sup>
	Variety	1	399280.8	399280.8	2.79 <sup>ns</sup>
	Error	2	285685.8	142842.9	
	Total	5	2638591.5		
7	Treatment	2	20846428.3	10423214.2	100.5 <sup>**</sup>
	Variety	1	1137961.5	1137961.5	11.0 <sup>ns</sup>
	Error	2	207438.9	103719.5	
	Total	5	22191828.7		
11	Treatment	2	47718616.2	23859308.1	736.8 <sup>**</sup>
	Variety	1	932913.8	932913.8	28.8 <sup>*</sup>
	Error	2	64765.3	32382.7	
	Total	5	48716295.4		

Legend.

- 4 represents the vegetative growth stage
- 7 stands for the grain filling stage
- 11 represents the harvesting stage.
- ns not significant
- \* significant at 5% level
- \*\* significant at 1% and 5% levels



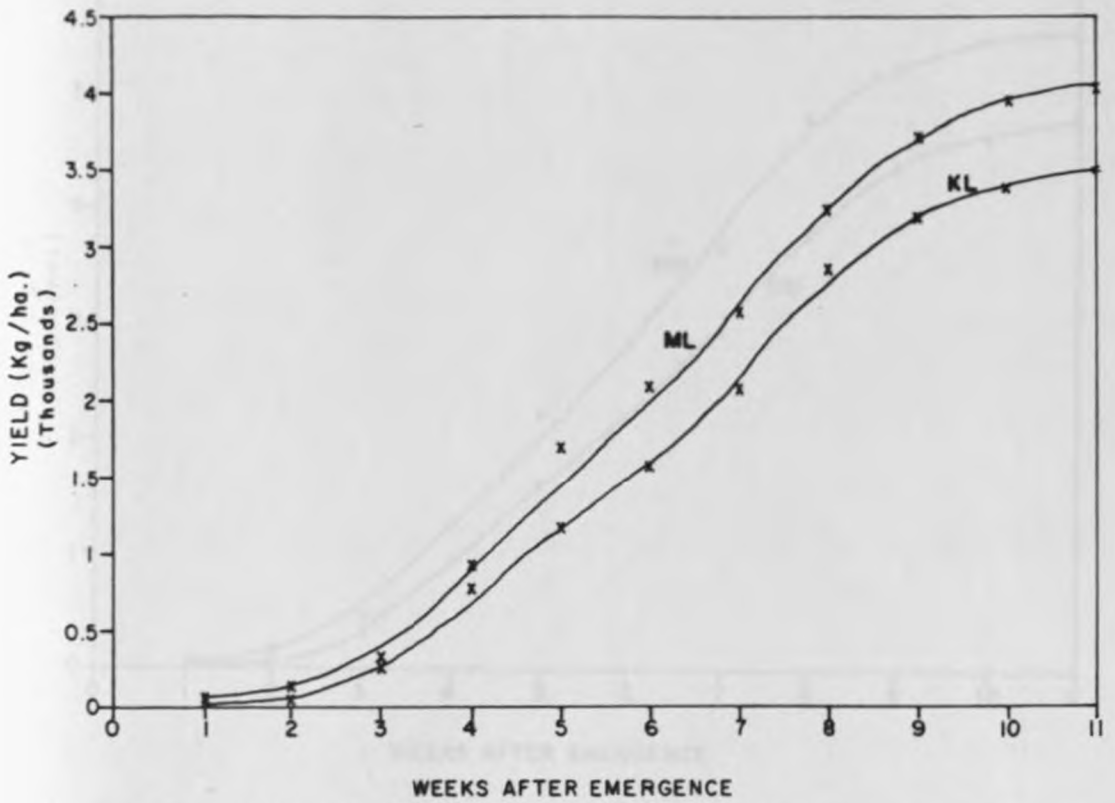


FIG. 6 - VARIATIONS OF WEEKLY TOTAL ABOVE-GROUND DRY MATTER FOR KATUMANI (KL) AND MAKUENI (ML) LOW PLANT DENSITY.

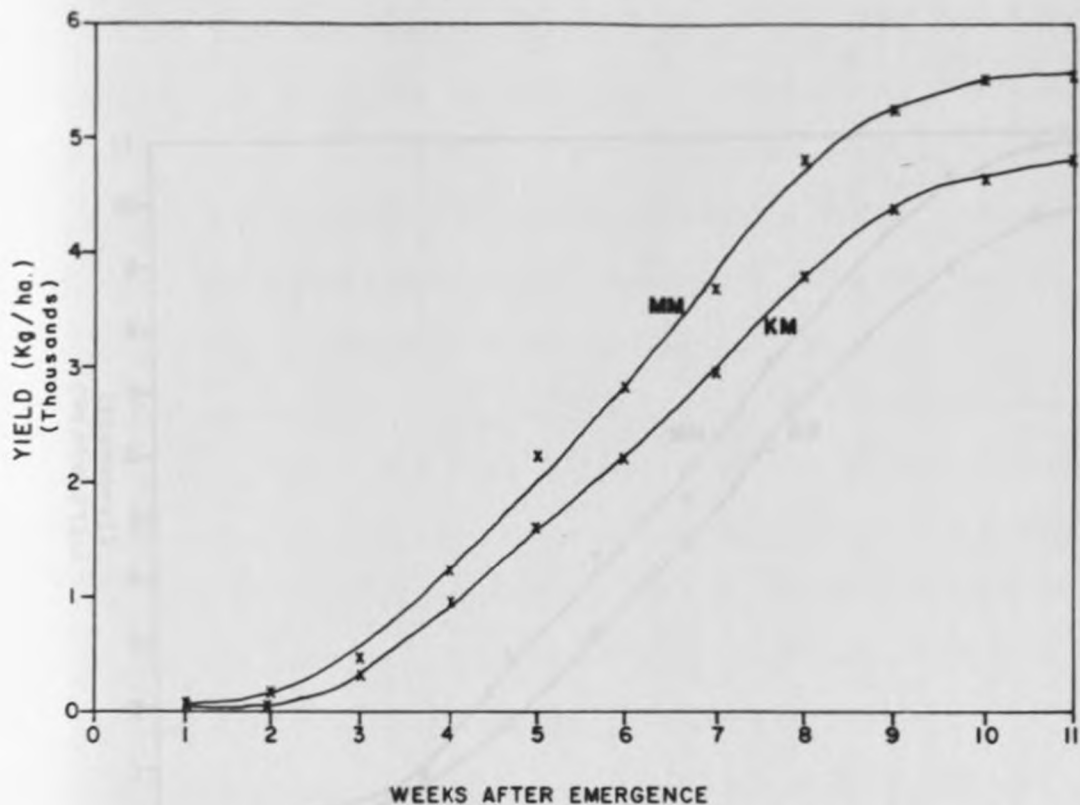


FIG. 7 - VARIATIONS OF WEEKLY TOTAL ABOVE-GROUND DRY MATTER FOR KATUMANI (KM) AND MAKUENI (MM) COMPOSITE MEDIUM DENSITY .

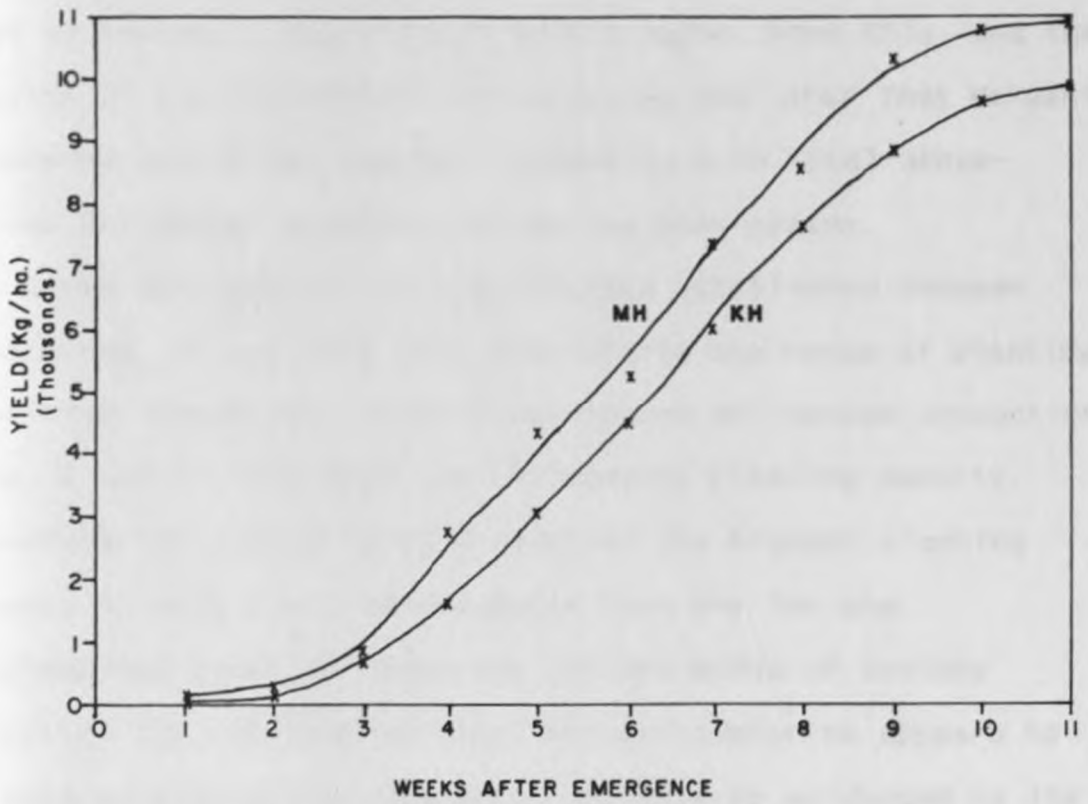


FIG.8 - VARIATIONS OF WEEKLY TOTAL ABOVE-GROUND DRY MATTER FOR KATUMANI (KH) AND MAKUENI (MH) COMPOSITE HIGH PLANTING DENSITY .

harvesting time total above-ground dry matter for makueni composite high planting density was 10852.2 kg/ha compared to that of katumani composite at 9806.5 kg/ha. From this, and the results of the analysis of variance, we can infer that Makueni composite outyielded Katumani composite B in total above-ground dry matter productivity during that season.

Given the statistical significance established between treatments, we may note here that within the range of planting densities considered, total above-ground dry matter production (Fig. 4 and 5) increased with increasing planting density. Therefore for forage maize production the highest planting density is more yield advantageous than the low and intermediate planting densities. On the basis of variety selection for the same purpose, makueni composite appears to be more promising than katumani composite as evidenced by its higher yield potential. The high yield of makueni composite could be the result of genetic improvement. Makueni composite was bred later than Katumani composite with a possible genetic improvement inclined towards increased yields and heat tolerance. This emanates from the fact that this variety was bred at Makueni, a hot and drier region than Katumani, a centre from which katumani composite B derives its name.

#### 4.2 Grain Dry Matter

Grain dry matter yield was determined as from grain filling stage. Table 7 gives mean grain dry matter yields for the two varieties of maize during grain filling stage, soft dough stage and at harvesting. Grain dry matter yields also

Table 7: Grain yield dry matter.

Time (weeks after planting)	Planting density	Makueni composite (kg/ha)	Katamani composite B (kg/ha)
7	Low	452.0	224.4
	Medium	804.6	340.2
	High	1701.5	489.7
9	Low	1358.9	1046.4
	Medium	2134.8	1519.2
	High	3913.5	2826.2
11	Low	1550.4	1286.4
	Medium	2367.0	1798.2
	High	4299.4	3627.1

Legend.

- 7 represents the grain filling stage
- 9 stands for the soft dough stage
- 11 represents the harvesting stage.

depicted sigmoidal patterns for both maize varieties (Fig. 9 and 10). As illustrated in the figures above, the grain dry matter yields also increased with planting density. The individual plant grain dry matter yield decreased with increasing planting density. The highest grain dry matter yield was obtained from the highest planting density treatment. This observation could be attributed to either the high population and/or the change in the population geometry caused by the change in both row spacing and inter-plant spacing.

The high plant population could lead to faster ground cover, may be, minimising soil evaporation, and could also result into better light interception which may enhance rapid production and storage of the photosynthate within the plant. The reduction in soil evaporation caused by increased solar energy interception by plant canopy may aid in increasing the available soil water for plant growth.

Table 8 shows the results of the analysis of variance performed on the grain dry matter yield of Table 6. From this table it is observed that the difference between the grain dry matter yields of Katumani and Makueni composites was not statistically significant during the grain filling stage. Inter-planting density differences in grain dry matter yield production were also not statistically significant during this growth stage. This may be so because at the initial stage of grain filling, the grain performance of the two varieties is not yet well differentiated. Treatment differences were statistically significant at 5% level during the soft dough

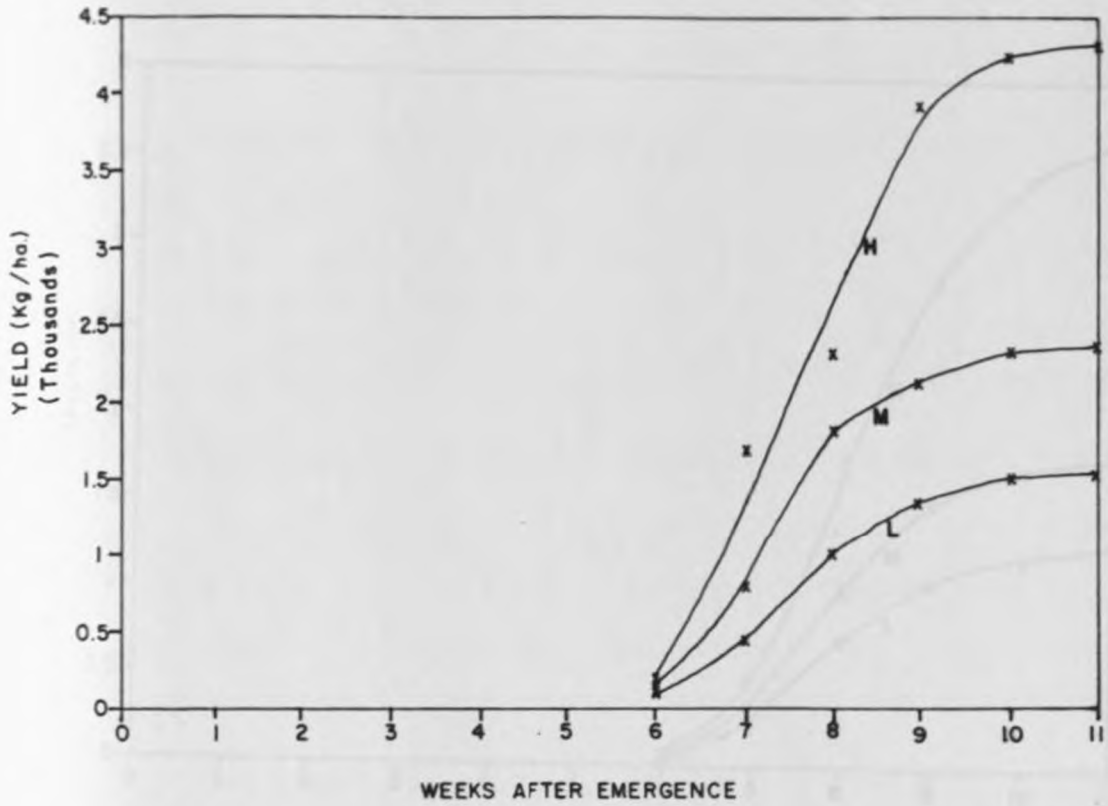


FIG. 9 - VARIATION OF WEEKLY GRAIN DRY MATTER FOR MAKUENI PLANTING DENSITIES LOW (L) , MEDIUM AND HIGH (H) .

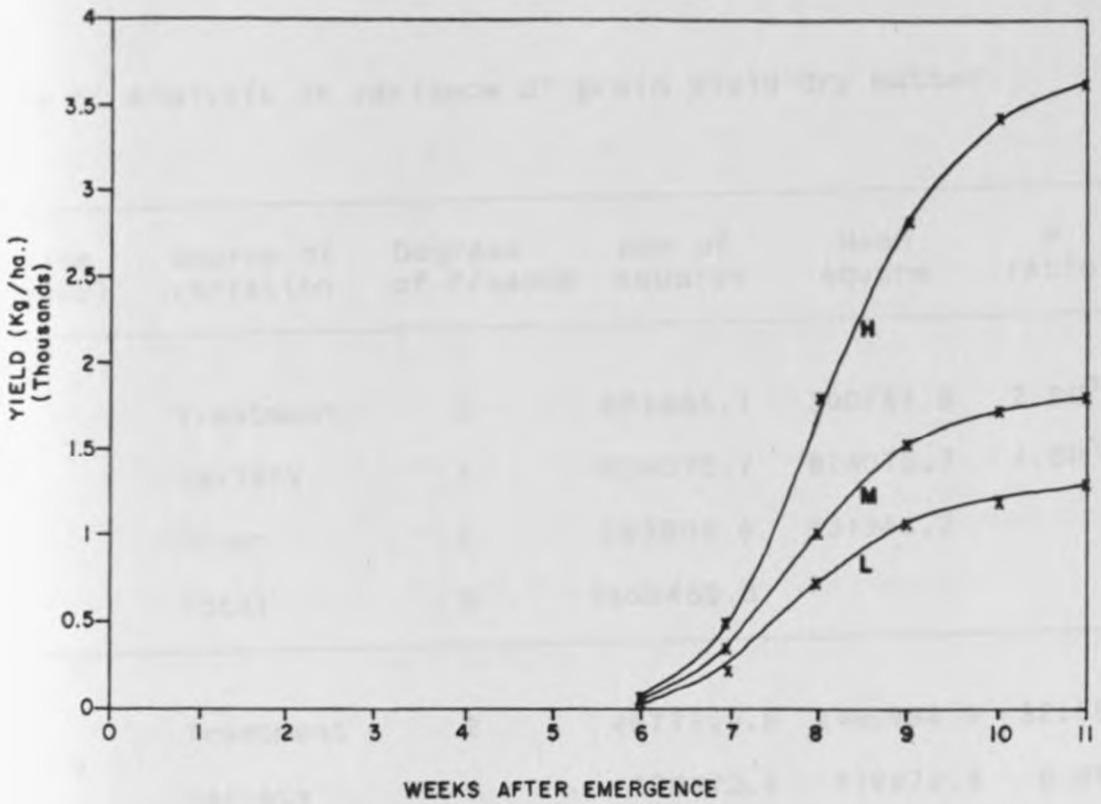


FIG. 10 — VARIATION OF WEEKLY GRAIN MATTER YIELD FOR KATUMANI COMPOSITE LOW (L), MEDIUM (M) AND HIGH (H) DENSITIES.



Table 8: Analysis of variance of grain yield dry matter.

Time (weeks)	Source of variation	Degrees of freedom	sum of squares	Mean square	F ratio
7	Treatment	2	601495.1	300747.5	2.28 <sup>ns</sup>
	Variety	1	604075.7	604075.7	4.58 <sup>ns</sup>
	Error	2	263888.4	131944.2	
	Total	5	1469459.3		
9	Treatment	2	4977969.9	2488984.9	32.65*
	Variety	1	676972.9	676972.9	8.89 <sup>ns</sup>
	Error	2	152447.6	76223.8	
	Total	5	5807390.4		
11	Treatment	2	6969511.7	3484755.9	154.7**
	Variety	1	377554.3	377554.3	16.8 <sup>ns</sup>
	Error	2	45054.0	22527.0	
	Total	5	7392120.1		

## Legend.

7 represents the grain filling stage

9 stands for the soft dough stage

11 represents the harvesting stage.

ns not significant

\* significant at 5% level

\*\* significant at 1% and 5% levels

stage and at 1% level at harvesting time. Differences between varieties at all the three stages were not statistically significant.

Figures 11 to 13 compare the performance of Katumani and Makueni composites in terms of grain dry matter production for the three planting densities. From these figures it is observed that curves representing Makueni composite are in all the cases above those for Katumani composite B. At harvesting, the grain yield for makueni composite high planting density was 4299.4kg/ha compared to that of katumani composite at 3627.1kg/ha. This further indicates that Makueni composite was superior to Katumani composite B in grain dry matter production during that season. Fig. 9 and 10 show that for both varieties, grain yield increased with planting density in the plant population range considered. Thus for the purposes of raising maize for food, preference towards planting Makueni composite and a plant population of 83,000 plants per hectare seem justifiable in this investigation. As noted in the case of total above-ground dry matter, the higher grain yield potential of makueni composite is likely to be an artefact of genetic improvement in makueni composite.

#### 4.3 Relative dry matter accumulation rates

Investigations on the relative dry matter accumulation rates of makueni and katumani composites were carried out to determine the maize variety that is more efficient in accumulating new dry matter per unit of dry matter originally present. Table 9 gives the magnitudes of both relative and

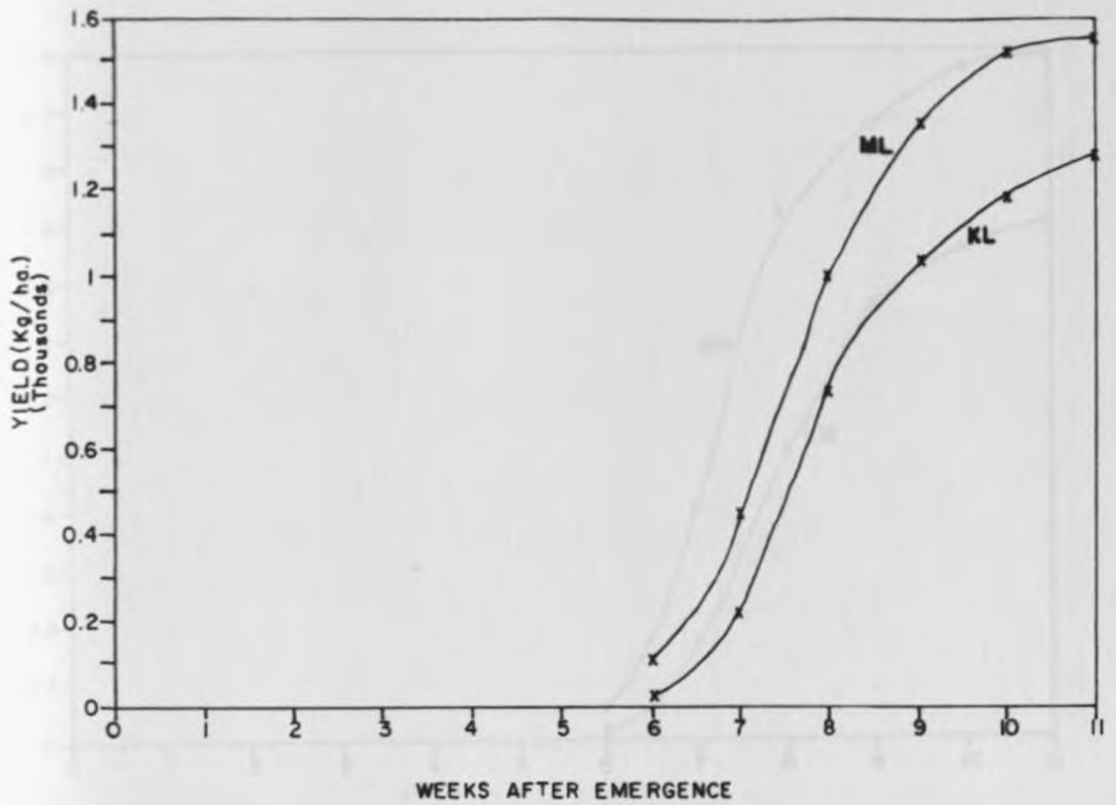


FIG. II - GRAIN DRY MATTER YIELDS OF KATUMANI (KL) AND MAKUENI (ML) COMPOSITE LOW PLANTING DENSITY .

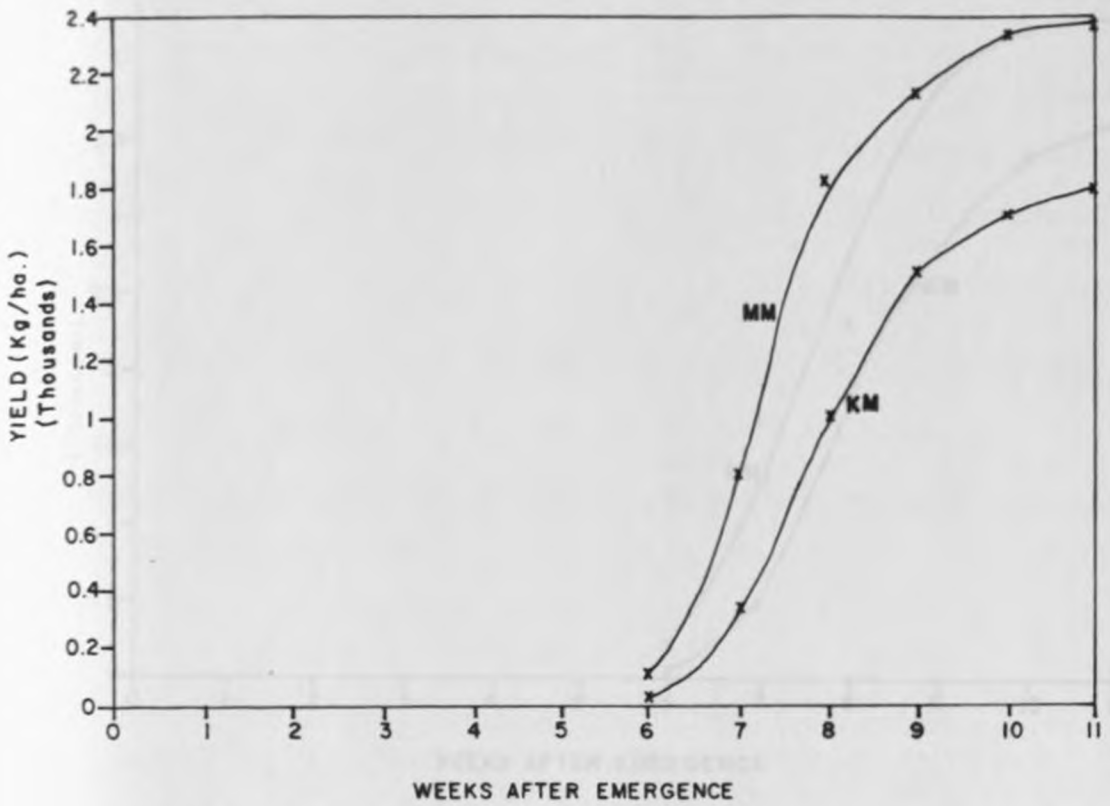


FIG.12 - VARIATION OF GRAIN DRY MATTER YIELD FOR KATUMANI (KM) AND MAKUENI(MM) COMPOSITE MEDIUM PLANTING DENSITY .

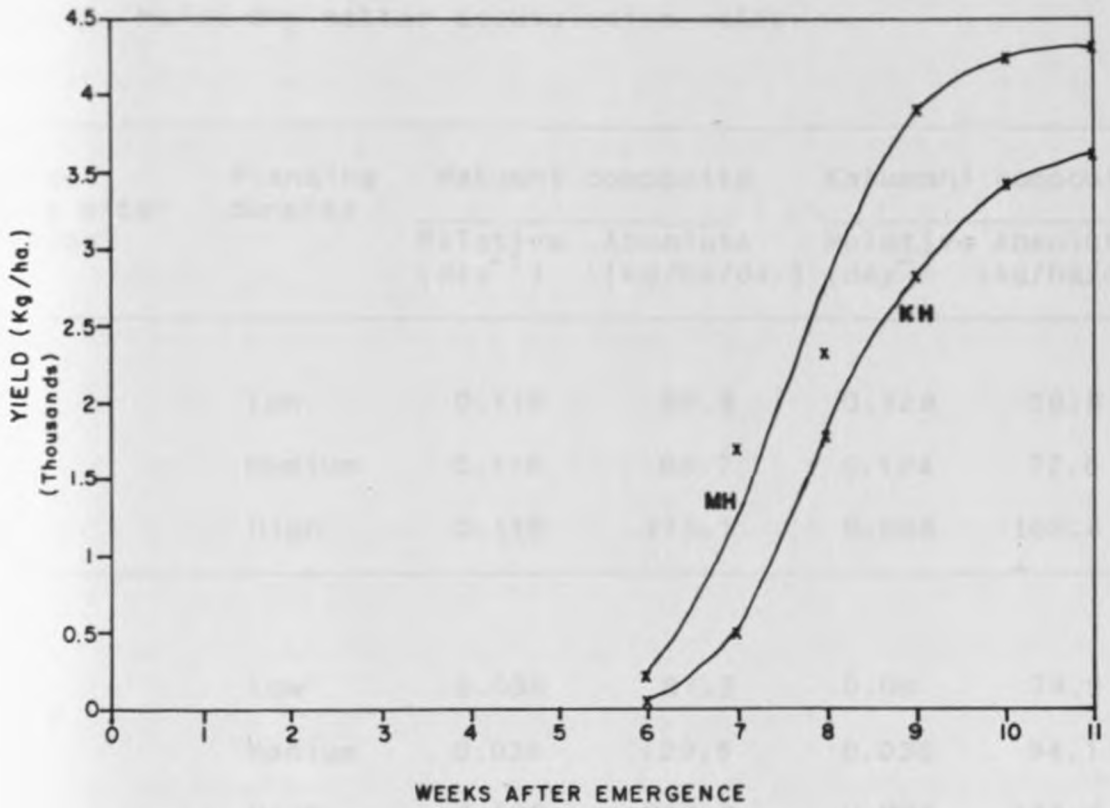


FIG.13- VARIATION OF GRAIN DRY MATTER YIELD FOR KATUMANI(KH) AND MAKUENI(MH) COMPOSITE HIGH PLANTING DENSITY .

Table: 9. Maize dry matter accumulation rates.

Time (weeks after planting)	Planting density	Makueni composite		Katumani composite	
		Relative (day <sup>-1</sup> )	Absolute (kg/ha/day)	Relative (day <sup>-1</sup> )	Absolute (kg/ha/day)
4	Low	0.118	66.9	0.128	58.9
	Medium	0.116	89.7	0.124	72.6
	High	0.116	175.1	0.095	102.4
7	Low	0.036	87.2	0.04	74.9
	Medium	0.036	120.5	0.036	94.1
	High	0.033	213.0	0.035	184.2
11	Low	0.002	9.6	0.003	9.6
	Medium	0.0015	8.4	0.004	19.8
	High	0.0014	15.4	0.0029	29.1

## Legend.

- 4 represents the vegetative growth stage  
 7 stands for the grain filling stage  
 11 represents the harvesting stage.

absolute dry matter accumulation rates. Findings from this study are presented in the following section.

Mean daily relative dry matter accumulation rates during vegetative and grain filling stages were considered in the analysis of variance. The results of the analysis of variance for the two varieties of maize and three planting densities are presented in Table 10a and 10b. The analysis revealed that relative dry matter accumulation rates during the vegetative stage, grain filling stage and harvesting were not significantly affected by varieties and planting densities.

However, absolute dry matter accumulation rate was affected by both maize varieties and planting densities during grain filling stage. During this stage, makueni composite was found to be superior to katumani composite B in absolute dry matter accumulation rate.

#### 4.4 Sampling Procedure

The validity of the sampling procedure was determined based on the fact that, a sample representing the entire population should have the same mean as the population from which it was derived.

Table 11 gives the means of the combinations of two plants and their corresponding deviations from the population mean. The third column of Table 11 gives comparisons of the observed deviations and the computed least significant difference (lsd) given at the bottom of the table.

It is observed from column 3 that the deviations in all the cases are less than the least significant difference,

Table 10a: Analysis of variance mean relative dry matter accumulation rate.

Time (weeks)	Source of variation	Degrees of freedom	sum of squares	Mean square	F ratio
4	Treatment	2	$3.5 \times 10^{-4}$	$1.8 \times 10^{-4}$	1.16 <sup>ns</sup>
	Variety	1	$1.5 \times 10^{-6}$	$1.5 \times 10^{-6}$	0.01 <sup>ns</sup>
	Error	2	$3.0 \times 10^{-4}$	$1.5 \times 10^{-4}$	
	Total	5	$6.5 \times 10^{-4}$		
7	Treatment	2	$1.6 \times 10^{-5}$	$8.0 \times 10^{-6}$	4.00 <sup>ns</sup>
	Variety	1	$6.0 \times 10^{-6}$	$6.0 \times 10^{-6}$	3.00 <sup>ns</sup>
	Error	2	$4.0 \times 10^{-5}$	$2.0 \times 10^{-5}$	
	Total	5	$2.6 \times 10^{-5}$		
11	Treatment	2	$3.6 \times 10^{-7}$	$1.8 \times 10^{-7}$	0.62 <sup>ns</sup>
	Variety	1	$4.2 \times 10^{-6}$	$4.2 \times 10^{-6}$	14.29 <sup>ns</sup>
	Error	2	$5.8 \times 10^{-7}$	$2.9 \times 10^{-7}$	
	Total	5	$5.1 \times 10^{-6}$		

Legend.

- 4 represents the vegetative growth stage
- 7 stands for the grain filling stage
- 11 represents the harvesting stage.
- ns not significant
- \* significant at 5% level
- \*\* significant at 1% and 5% levels



Table 10b: Analysis of variance of absolute dry matter accumulation rate.

Time (weeks)	Source of variation	Degrees of freedom	sum of squares	Mean square	F ratio
4	Treatment	2	6269.4	3134.7	5.111 <sup>ns</sup>
	Variety	1	1594.1	1594.1	2.599 <sup>ns</sup>
	Error	2	1226.7	613.4	
	Total	5	9090.2		
7	Treatment	2	15228.5	7614.3	191.6 <sup>**</sup>
	Variety	1	759.4	759.4	19.1 <sup>*</sup>
	Error	2	79.5	39.7	
	Total	5	16067.3		
11	Treatment	2	164.5	82.2	3.1 <sup>ns</sup>
	Variety	1	105.0	105.0	3.9 <sup>ns</sup>
	Error	2	53.8	26.9	
	Total	5	323.3		

Legend.

- 4 represents the vegetative growth stage
- 7 stands for the grain filling stage
- 11 represents the harvesting stage.
- ns not significant
- \* significant at 5% level
- \*\* significant at 1% and 5% levels

Table 11. Determination of the validity of the sampling procedure by the method of Least Significant difference.

Means of two plants	Deviations from population mean (= 136.8)	Comparison with least significant difference
97.1	-39.7	< 1sd
147.1	10.3	< 1sd
123.9	-12.9	< 1sd
152.8	16.0	< 1sd
124.9	-11.9	< 1sd
101.8	-35.0	< 1sd
130.7	- 6.1	< 1sd
151.8	15.0	< 1sd
180.7	43.9	< 1sd
157.5	20.7	< 1sd

1sd = 58.78

signifying lack of significant differences at the 5% level of the Student's t-test. Therefore the means of each of the two plants considered were not significantly different from the mean of the population from which the samples were obtained. This implies that the two plants which were harvested in any one week were representative of the whole plot.

#### 4.5 Harvest Index

The harvest indices for both varieties of maize and planting densities are presented in Table 12. Two observations can be made from this table. Firstly, Makueni composite shows higher harvest indices than Katumani composite. Secondly, the harvest index shows an increase with planting density upto 36,000 plants/ha and thereafter a decrease with further increase in plant population. However, the analysis of variance (Table 13) indicates lack of significant differences between harvest indices of the two varieties of maize and planting densities. This analysis therefore, suggests that the harvest index was not affected by the maize varieties and planting densities.

#### 4.6 Soil moisture characteristic curves

Fig. 14 ( a to f ) show the soil moisture profile recharge and drying cycles during the period of the experiment. The curves numbered from 1 to 6 in each of the graphs represent the soil water status, every two weeks, starting from the first week after seedling emergence upto harvesting.

It is evident from the plots of the soil moisture

Table 12 : Harvest Indices of makueni and katumani composite for the three planting density treatments.

Treatments (planting density)	Makueni composite (%)	Katumani composite (%)
Low	38.5	36.8
Medium	42.4	37.5
High	39.6	37.0

Table 13: Analysis of variance of the harvest indices.

Time (weeks)	Source of variation	Degrees of freedom	sum of squares	Mean square	F ratio
11	Treatment	2	5.623	2.812	2.065 <sup>ns</sup>
	Variety	1	14.107	14.107	10.36 <sup>ns</sup>
	Error	2	2.723	1.362	
	Total	5	22.452		

Legend.

- 4 represents the vegetative growth stage
- 7 stands for the grain filling stage
- 11 represents the harvesting stage.
- ns not significant

LEGEND TO FIGURE 14(a to f).

- 1 Soil water status at first week of measurement
- 2 Soil water status at the third week
- 3 Soil water status at the fifth week
- 4 Soil water status at the seventh week
- 5 Soil water status at the ninth week
- 6 Soil water status at the eleventh week

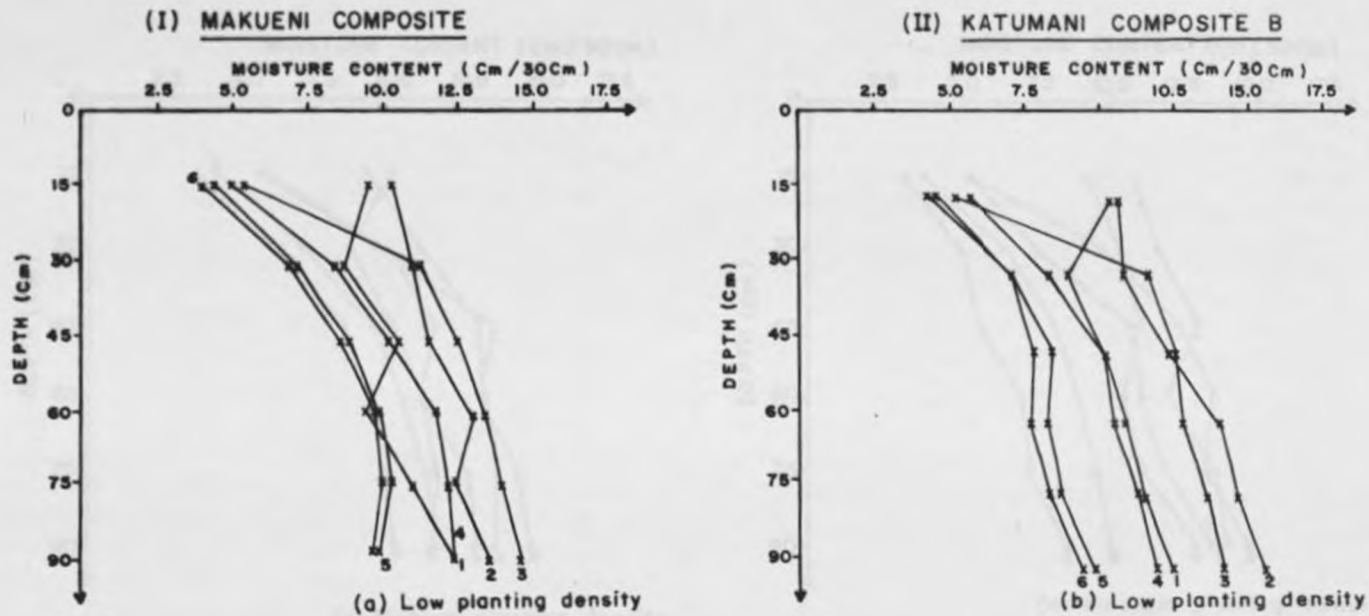
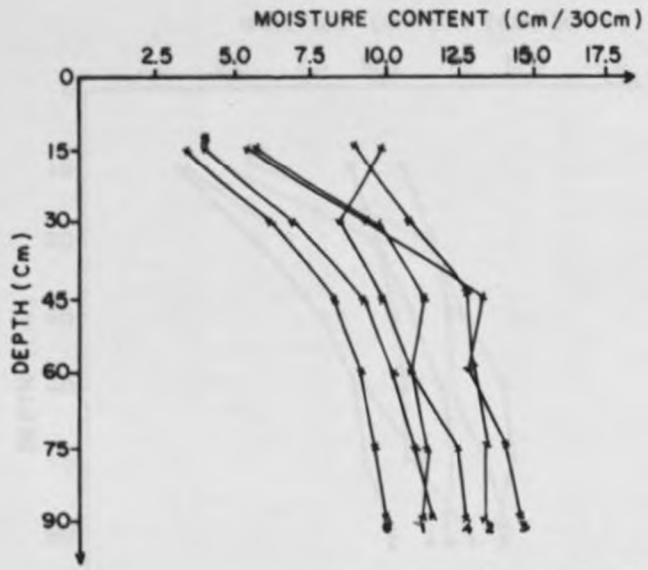
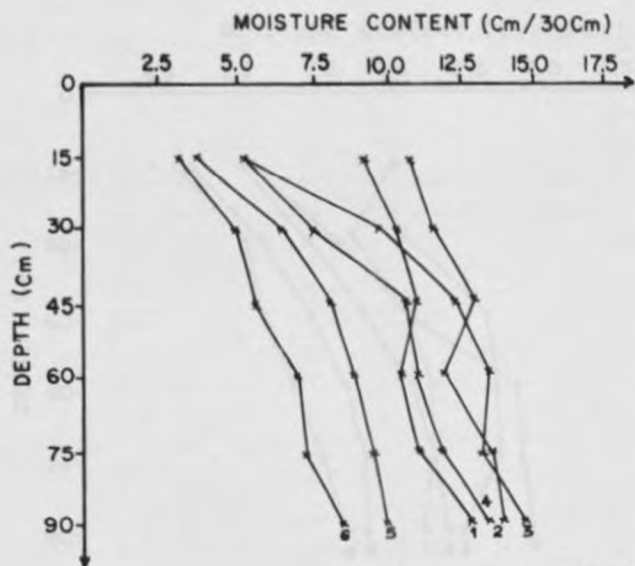


FIG. 14 - VARIATION OF SOIL MOISTURE CONTENT (Cm/30Cm) WITH DEPTH (Cm) AFTER EVERY TWO WEEKS.

FIG. 14 - CONT'D



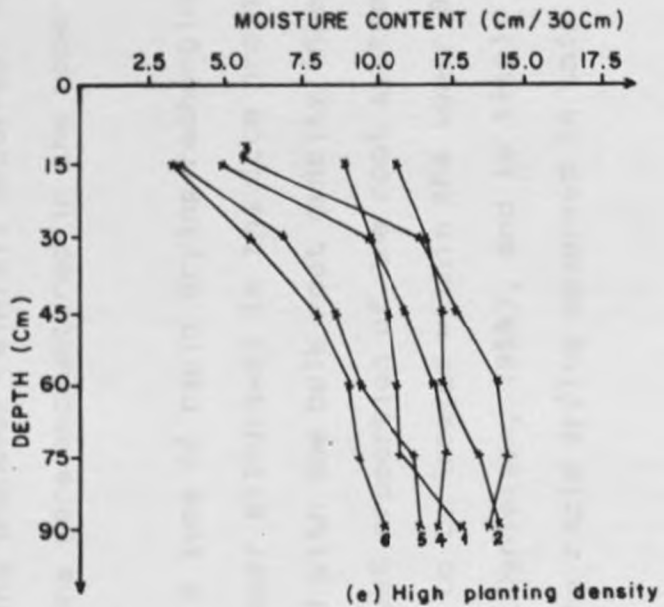
(c) Medium planting density



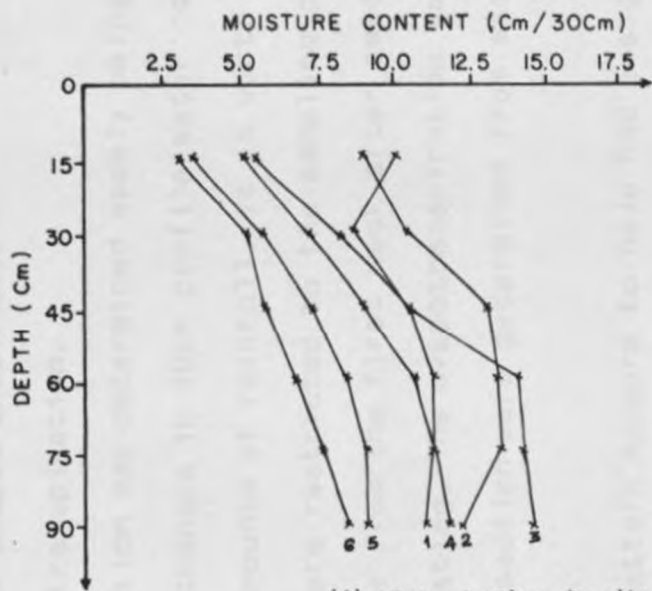
(d) Medium planting density



FIG. 14 - CONT'D



(e) High planting density



(f) High planting density

characteristic curves that the bulk of water extraction took place in the upper 60cm-section of the soil profile. This is the zone which exhibited greater fluctuation in moisture content caused by rapid drying during periods of minimum or no rainfall and wetting whenever rainfall occurred. However, maximum fluctuations were encountered in the upper 30cm of the soil profile.

Besides being a zone of rapid drying-recharging cycles, the marked soil water withdrawal in the 60cm profile depth may also be associated with the bulk root density inherent in this profile. The largest proportion of the root system of maize has been reported to be located within the upper 90cm of the soil (Russell and Danielson, 1956), and is likely to be responsible for the rapid drying observed in this zone.

#### 4.7 Time course of evapotranspiration.

##### 4.7.1 Weekly Evapotranspiration.

Evapotranspiration was determined weekly using equation (5) by monitoring changes in 90cm profile water content and the accompanying amounts of rainfall. It is worth noting that the computations were restricted to the sampling period, reported here to be from the first week after seedling emergence to harvesting. The evapotranspiration values presented in this section were determined from each of the six plots.

The rainfall pattern appears to have had a significant influence on the pattern of evapotranspiration in all the plots throughout the sampling period. Figure 15 shows the

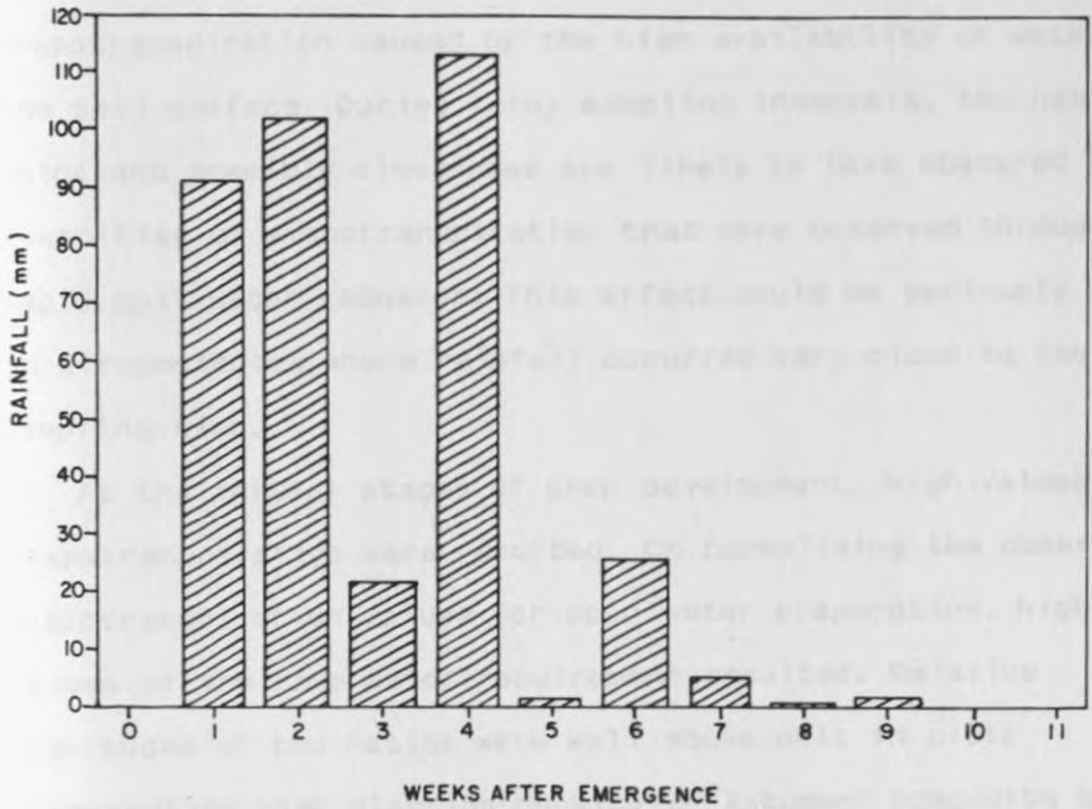


FIG.15 - RAINFALL PATTERN IN THE GROWING SEASON .

variation of the rainfall during the season. Crop water use decreased during time intervals when rainfall was recorded and increased in the subsequent sampling interval. The said increase could be due to increased evaporation component of evapotranspiration caused by the high availability of water at the soil surface. During rainy sampling intervals, the heavy rains and possibly cloudiness are likely to have obscured the quantities of evapotranspiration that were observed through rapid soil water recharge. This effect could be seriously felt in circumstances where rainfall occurred very close to the sampling time.

At the initial stages of crop development, high values of evapotranspiration were recorded. On normalising the observed evapotranspiration values for open water evaporation, high values of the crop water requirement resulted. Relative magnitudes of the ratios were well above unit in plots representing high planting density of katumani composite and low planting density of makueni composite. These observations could be ascribed to two possible causes. Firstly, at the initial crop stages, most of the ground was bare and therefore chances of increased soil evaporation, especially with plenty of water at the surface were high. Secondly, at the beginning of the crop season, the crop canopy was still too open and might have given way to direct impact of rain drops onto the soil surface, making the top soil to attain field capacity status rapidly. As a result the soil water recharge (infiltration) could have appreciably reduced at the expense

of surface runoff within the plots, thus leading to overestimation of evapotranspiration by the water balance approach. However, no significant surface run-off was observed. Pendleton (1966) and Mitchell (1970) noted that a closed crop canopy intercepts more rain drops and thus results into higher infiltration and more effective rainfall utilisation.

Crop water use increased with phenological stages upto silking time (5 weeks after seedling emergence) and then subsided with time until harvesting . Peak amount of rainfall was noted one week prior to silking. We may therefore attribute the high crop water use at this stage to either the phenological stage, high availability of soil water, or both. Peak values of maize crop water use during silking were also reported by Shaw (1963) and Waldren (1983).

Figures 16 to 18 compare the variation of evapotranspiration with time as depicted by the two varieties of maize. On the same axes, the observed trends in the crop water requirement (ET/Epan) are also plotted. The patterns in the above figures indicate higher crop water use for Katumani composite B than for Makueni composite. The ET/Epan ratios followed a similar pattern as that of evapotranspiration, ie, increased steadily to a maximum five weeks after seedling emergence and then declined toward harvesting. The peak ratio occurred during silking time of the two varieties of maize. On subjecting the two sets of crop water use to statistical analysis using the student's t-test as a test criterion for differences between the means, it was found that save for the

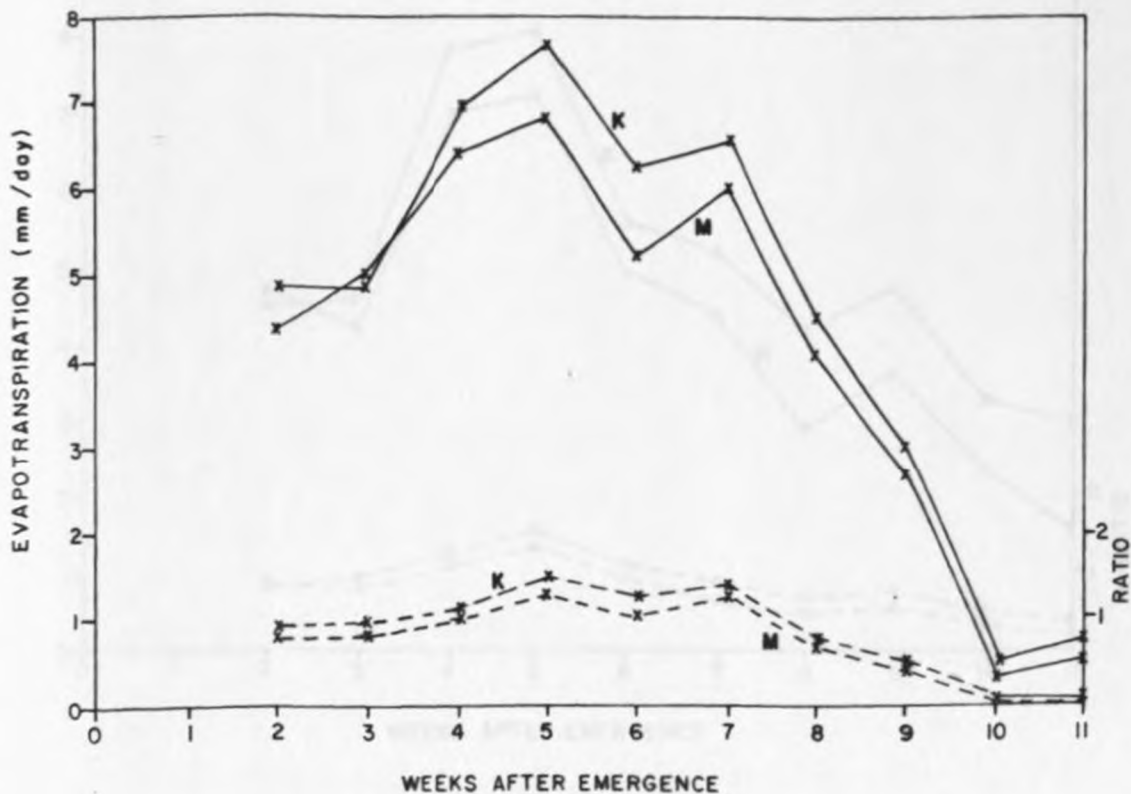


FIG.16 — AVERAGE DAILY EVAPOTRANSPIRATION IN A GIVEN WEEK AND THE RATIO OF EVAPOTRANSPIRATION TO STANDARD CLASS A PAN EVAPORATION FOR THE LOW PLANTING DENSITIES OF MAKUENI (M) AND KATUMANI (K) COMPOSITES .

LEGEND

- x — x EVAPOTRANSPIRATION
- x - - - x EVAPOTRANSPIRATION TO PAN EVAPORATION RATIO .

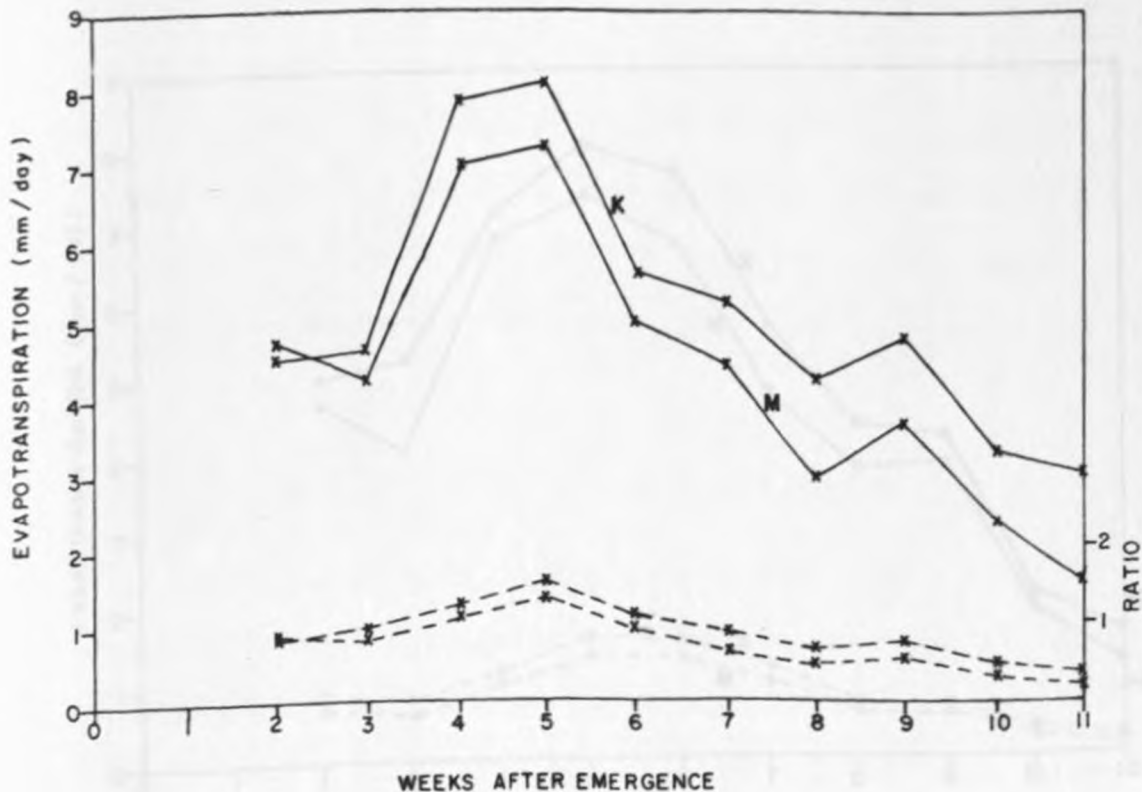


FIG. 17 - AVERAGE DAILY EVAPOTRANSPIRATION IN A GIVEN WEEK AND THE RATIO OF EVAPOTRANSPIRATION TO STANDARD CLASS A PAN EVAPORATION FOR THE MEDIUM PLANTING DENSITIES OF MAKUENI (M) AND KATUMANI (K) COMPOSITES .

**LEGEND**  
x — x EVAPOTRANSPIRATION  
x - - - x EVAPOTRANSPIRATION TO PAN EVAPORATION RATIO



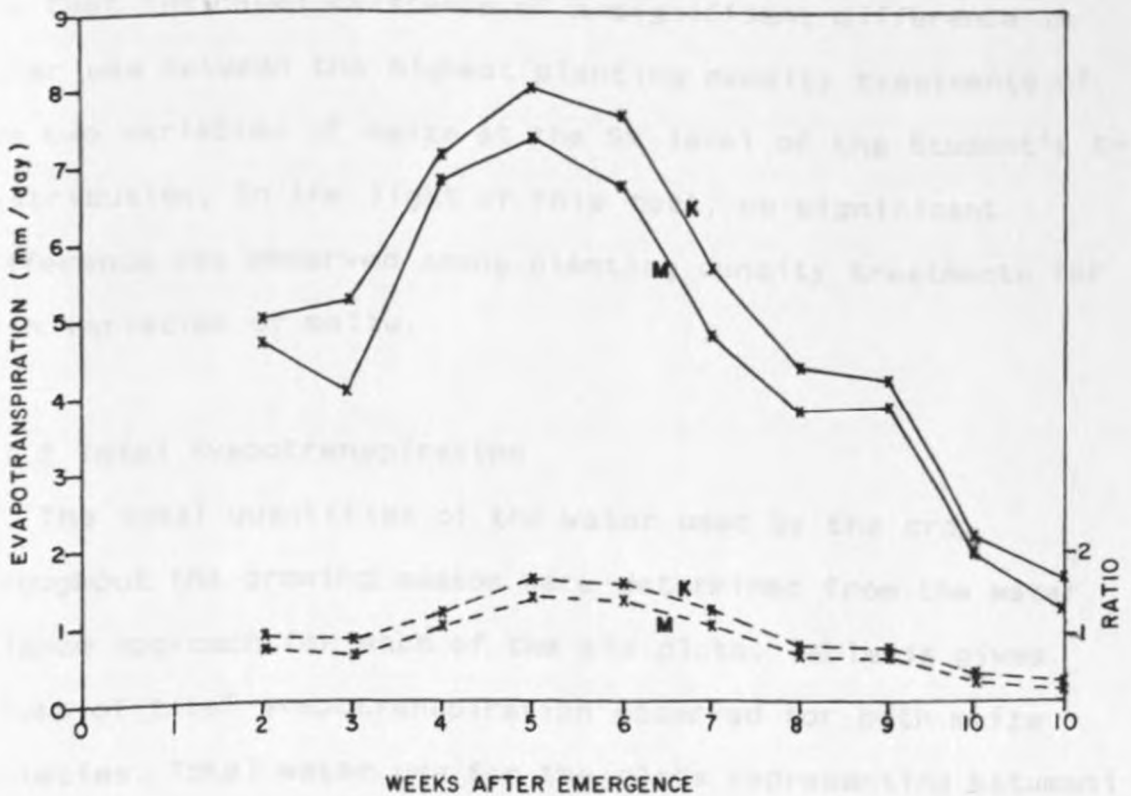


FIG. 18 — AVERAGE DAILY EVAPOTRANSPIRATION IN A GIVEN WEEK AND THE RATIO OF EVAPOTRANSPIRATION TO STANDARD CLASS A PAN EVAPORATION FOR THE HIGHEST PLANTING DENSITIES OF MAKUENI (M) AND KATUMANI (K) COMPOSITES .

LEGEND

- \* — \* EVAPOTRANSPIRATION
- x- - - \* EVAPOTRANSPIRATION TO PAN EVAPORATION RATIO

highest density treatments, the low and medium density treatments had no significant difference in crop water use. The test indicated existence of a significant difference in water use between the highest planting density treatments of the two varieties of maize at the 5% level of the Student's t-distribution. In the light of this test, no significant difference was observed among planting density treatments for both varieties of maize.

#### 4.7.2 Total Evapotranspiration

The total quantities of the water used by the crop throughout the growing season were determined from the water balance approach for each of the six plots. Table 14 gives values of total evapotranspiration observed for both maize varieties. Total water use for the plots representing katumani composite was as shown in the preceding section higher than that for makueni composite. From the table above, there exists an increasing pattern of crop water use with increasing plant population, except for the highest planting density treatment of Katumani composite B which was lower than its intermediate planting density counterpart. However, the analysis of variance (Table 15) suggests lack of significant difference in crop water use between the two varieties of maize and planting densities.

The results of the analysis of variance could be explained as follows. Although plants in the highest population density treatments could extract more soil water than those in the low

**Table 14: Total crop Evapotranspiration**

Planting density	Makueni composite ET.(mm)	Katumani composite ET.(mm)
Low	332.0	367.7
Medium	346.0	408.7
High	359.7	404.6

**Table 15. Analysis of variance of total Evapotranspiration.**

Source of variation	Degrees of freedom	Sum of squares	Mean squares	Computed f
Variety	1	1215.07	1215.07	12.9 <sup>ns</sup>
Treatment	2	3422.49	1711.245	18.167 <sup>ns</sup>
Error	2	188.39	94.95	
<b>Total</b>	<b>5</b>	<b>4825.95</b>		

ns indicates no significance at 5% level.

and intermediate plant densities, there is a likelihood of a compensatory mechanism in the lower plant density treatments which obscured the differences in crop water uses in the three planting densities. This mechanism may be manifested in the capacity of the more open canopy in the lower densities to allow high penetration of solar radiation. Increased penetration of solar radiation into the crop canopy enhances the soil evaporation component of evapotranspiration. Thus, the low quantities of soil water depleted by the plants in the low plant density treatments are compensated for by increased soil evaporation.

#### 4.8 Water Use Efficiency

Water use efficiency in this study is quantitatively expressed as the ratios of total above-ground dry matter to evapotranspiration and grain dry matter to evapotranspiration. The dry matter yields and evapotranspiration are expressed in units of grams and millimetres respectively. This gives rise to the 'g/mm' as our unit for expressing water use efficiency in this study. Both grain and total above-ground dry matter water use efficiencies are reported.

##### 4.8.1 Water Use Efficiency of Grain Dry Matter

The pattern of weekly grain water use efficiency depicted a parabolic like response (Fig.19 and 20). Water use efficiency increased as from grain filling stage to a maximum value which corresponds to the period of maximum grain development. Thereafter, a decreasing trend persisted until

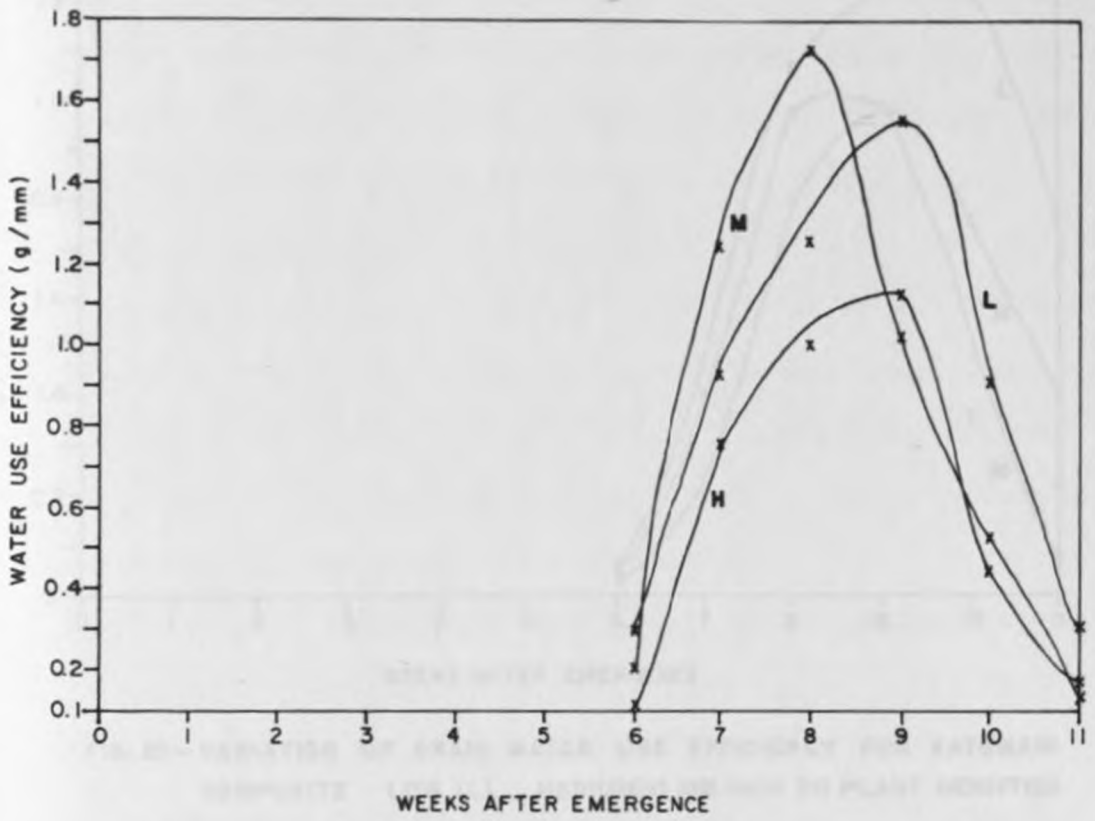


FIG.19— VARIATION OF GRAIN WATER USE EFFICIENCY FOR MAKUENI COMPOSITE , LOW (L) , MEDIUM (M) AND HIGH (H) PLANT DENSITIES .

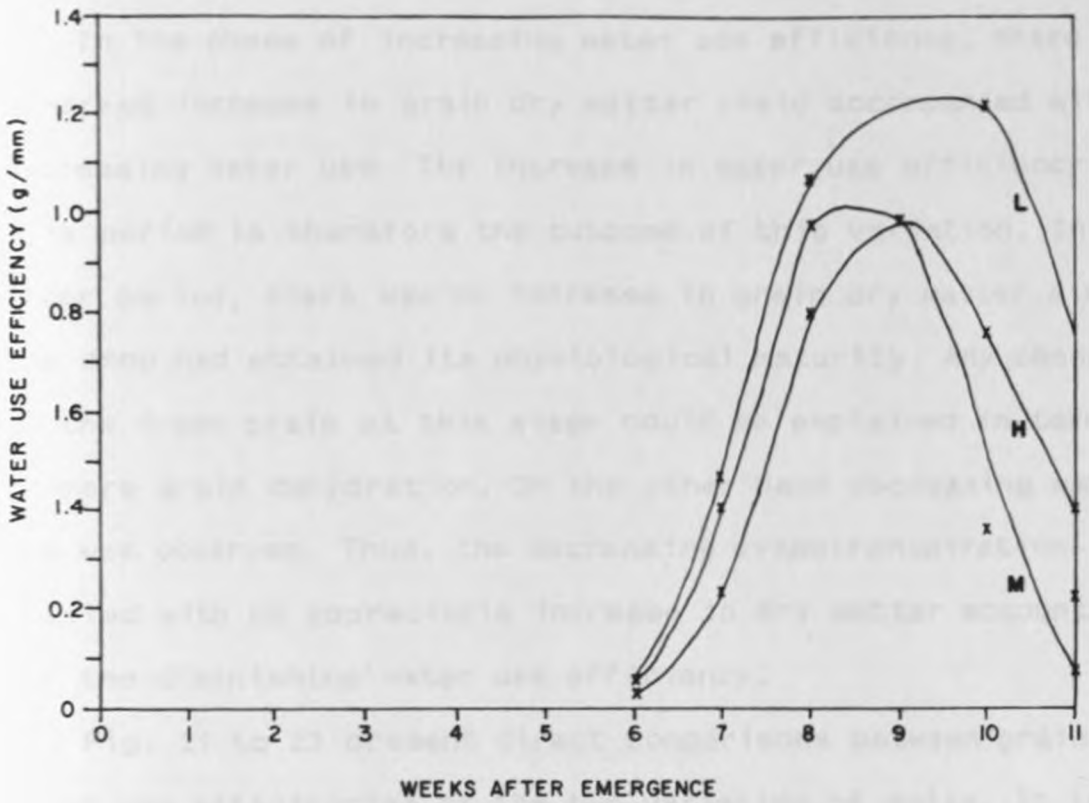


FIG. 20— VARIATION OF GRAIN WATER USE EFFICIENCY FOR KATUMANI COMPOSITE LOW (L) , MEDIUM(M) AND HIGH (H) PLANT DENSITIES.

harvesting.

In the phase of increasing water use efficiency, there was a marked increase in grain dry matter yield accompanied with decreasing water use. The increase in water use efficiency in this period is therefore the outcome of this variation. In the later period, there was no increase in grain dry matter since the crop had attained its physiological maturity. Any changes in the fresh grain at this stage could be explained in terms of mere grain dehydration. On the other hand decreasing water use was observed. Thus, the decreasing evapotranspiration coupled with no appreciable increase in dry matter accounts for the diminishing water use efficiency.

Fig. 21 to 23 present direct comparisons between grain water use efficiencies of the two varieties of maize. It is also noted just like in the earlier considerations, that makueni composite curves persisted above those for katumani composite B upto period of maximum water use efficiency. Beyond this point katumani composite took the lead.

Mean values of grain water use efficiency of both varieties of maize at grain filling stage, soft dough stage and harvesting stage (Table 16) were considered in the analysis of variance. Results from the analysis of variance of variety and planting density effects on grain water use efficiency are shown in Table 17. Lack of significant difference in grain water use efficiency between the two varieties of maize was observed at the soft dough and harvesting stages. Variety effects were only significant at

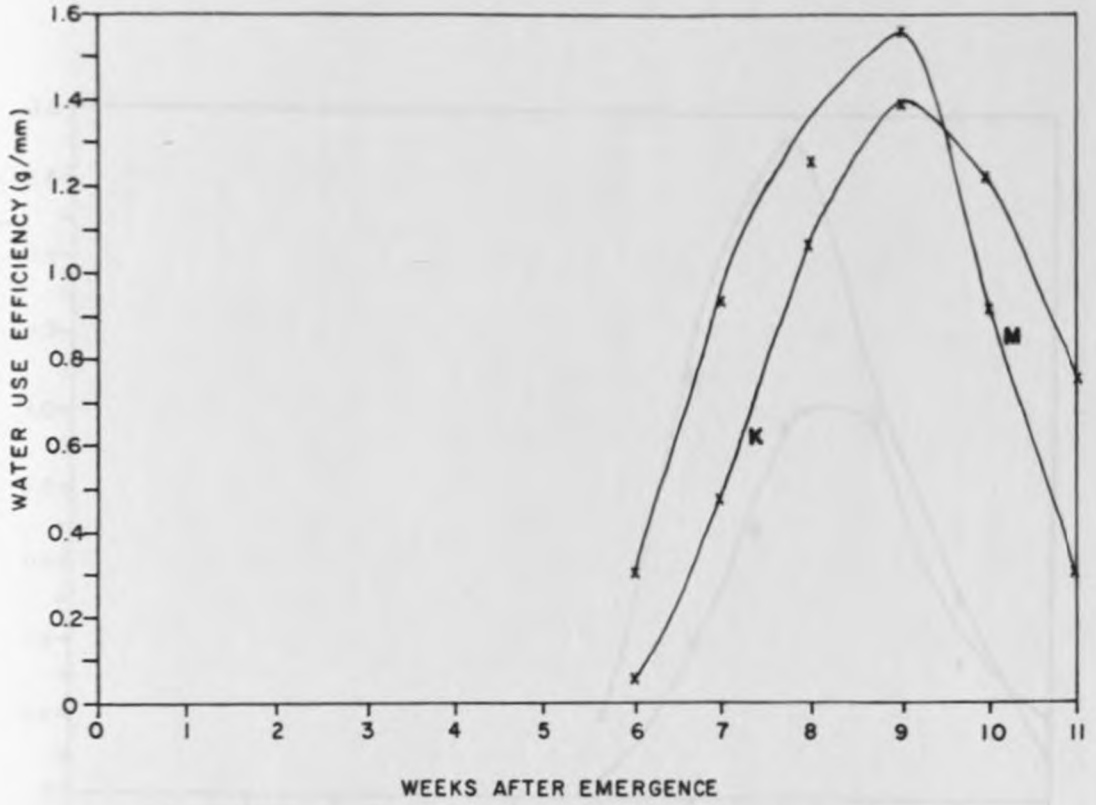


FIG. 21—GRAIN WATER USE EFFICIENCY FOR MAKUENI (M) AND KATUMANI(K) COMPOSITE , LOW PLANTING DENSITY .



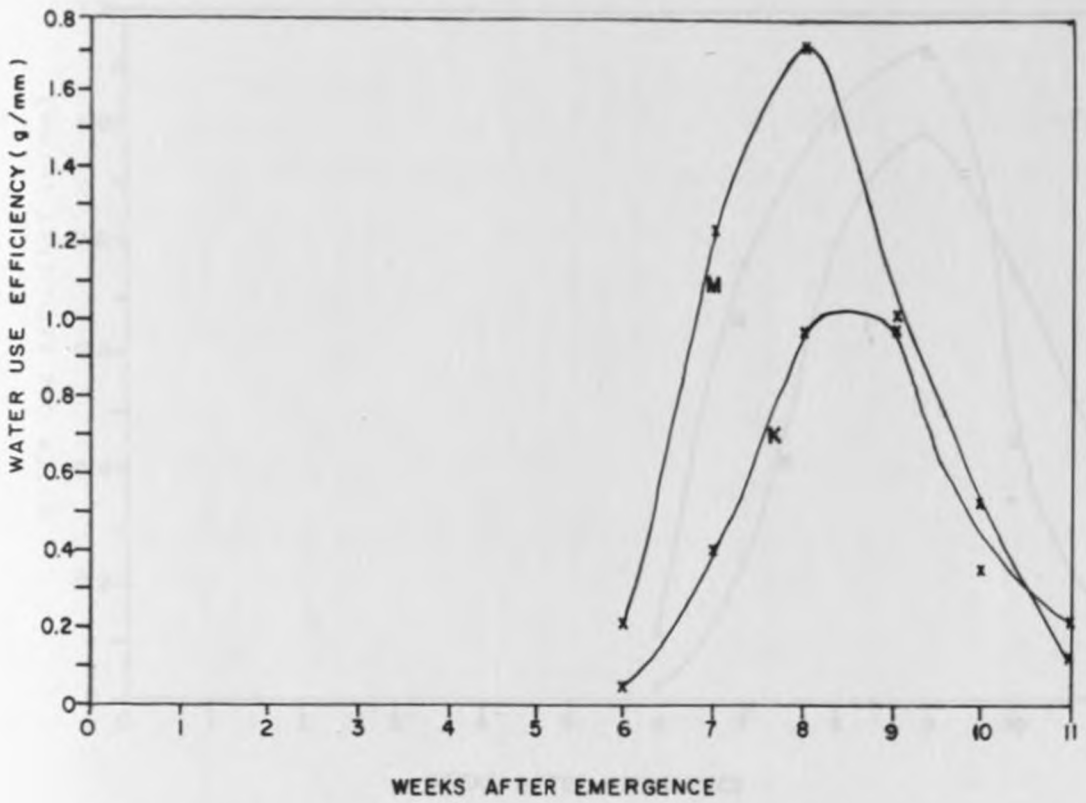


FIG. 22— GRAIN WATER USE EFFICIENCY FOR MAKUENI (M) AND KATUMANI(K) COMPOSITE, MEDIUM PLANTING DENSITY .

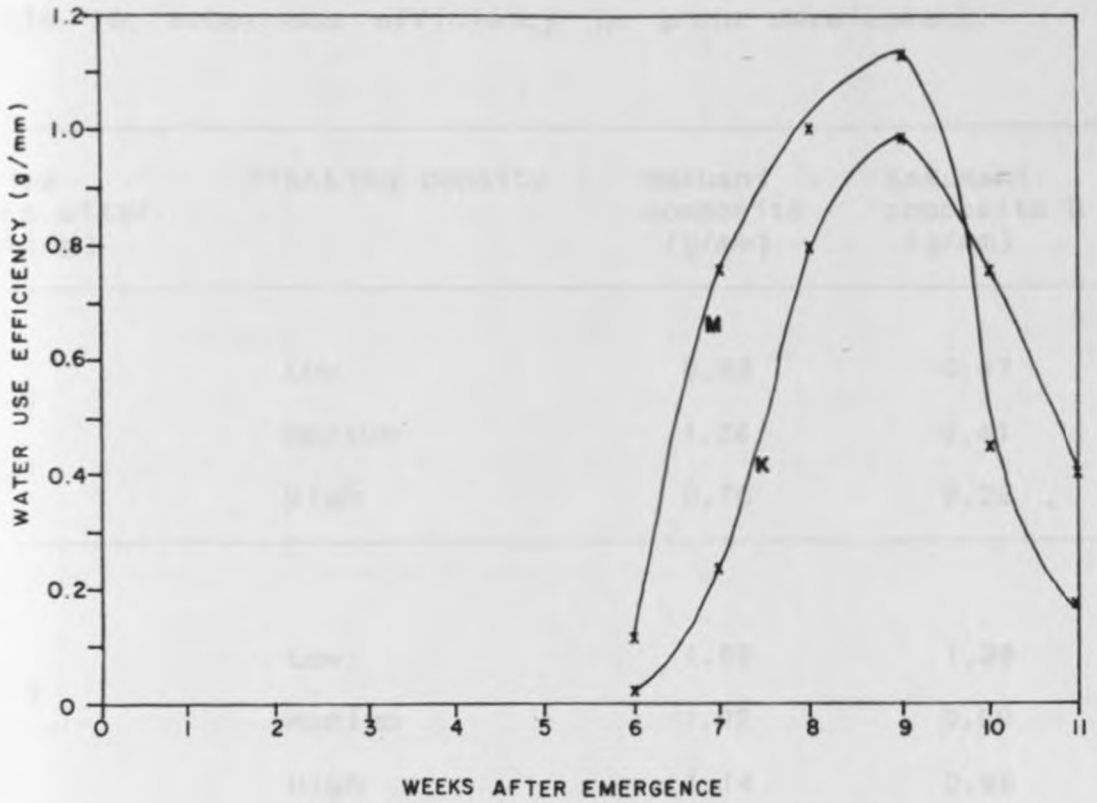


FIG. 23—GRAIN WATER EFFICIENCY FOR MAKUENI (M) AND KATUMANI (K) COMPOSITE HIGH PLANTING DENSITY .

Table 16: Water use efficiency in grain development.

Time (weeks after planting)	Source of variation	Planting density (plants/m <sup>2</sup> )	Makueni composite (g/mm)	Katumani composite B (g/mm)
7	Treatment	2	0.111	0.088
		Low	0.93	0.47
	Variety	1	0.007	0.002
		Medium	1.24	0.41
	Error	2	0.039	0.019
Total	5	0.109		
9	Treatment	2	0.206	0.132
		Low	1.56	1.39
	Variety	1	0.002	0.002
		Medium	1.02	0.99
	Error	2	0.1410 <sup>-13</sup>	0.1410 <sup>-13</sup>
Total	5	0.202		
11	Treatment	2	0.108	0.064
		Low	0.31	0.75
	Variety	1	0.101	0.101
		Medium	0.13	0.23
	Error	2	0.039	0.015
Total	5	0.253		

Legend.

- 7 represents the grain filling stage
- 9 stands for the soft dough stage
- 11 represents the harvesting stage.

ns: not significant

\*: significant at 1% level

Table 17: Analysis of variance of grain water use efficiency.

Time (weeks)	Source of variation	Degrees of freedom	sum of squares	Mean square	F ratio
7	Treatment	2	0.111	0.056	2.874 <sup>ns</sup>
	Variety	1	0.552	0.552	28.58*
	Error	2	0.039	0.019	
	Total	5	0.702		
9	Treatment	2	0.264	0.132	43.29*
	Variety	1	0.022	0.022	7.08 <sup>ns</sup>
	Error	2	6.1x10 <sup>-3</sup>	3.1x10 <sup>-3</sup>	
	Total	5	0.292		
11	Treatment	2	0.128	0.064	4.39 <sup>ns</sup>
	Variety	1	0.101	0.101	6.94 <sup>ns</sup>
	Error	2	0.029	0.015	
	Total	5	0.259		

Legend.

7 represents the grain filling stage

9 stands for the soft dough stage

11 represents the harvesting stage.

ns not significant

\* significant at 5% level

the grain filling stage. Planting density effects were however found to be significant at the 5% level of the F-distribution at the soft dough stage.

On considering water use efficiency in terms of final plant yield and whole crop season water use (Table 18), it was found from Table 19 that inter-variety difference in final grain water use efficiency was significant at the 5% level of the F-distribution. Plant population effects on final grain water use efficiency for both maize varieties were not statistically significant. It may therefore be inferred from the two tables, that Makueni composite was more water use efficient than katumani composite B in grain dry matter yield accumulation over the season.

#### 4.8.2 Water Use Efficiency for Total above-ground dry Matter

Here we report findings on weekly water use efficiency and on the entire crop season water use efficiency. Figures 24 and 25 illustrate the general time pattern of crop water use efficiency observed in this study for makueni and katumani composites respectively. Here we observe an alternating pattern comprising two maxima. The first peak arises after flowering, just before grain filling stage. The second maximum occurs at the period which corresponds to the stage of maximum grain development.

Figures 26 to 28 compare the water use efficiencies of the two varieties of maize under the three planting density treatments. From these figures, it may be noted that for most part of the growing season, weekly water use efficiency values

Table 18: Whole season grain water use efficiency.

Planting density	Makueni composite grain WUE (g/mm)	Katumani composite grain WUE (g/mm)
Low	0.39	0.29
Medium	0.38	0.24
High	0.29	0.22

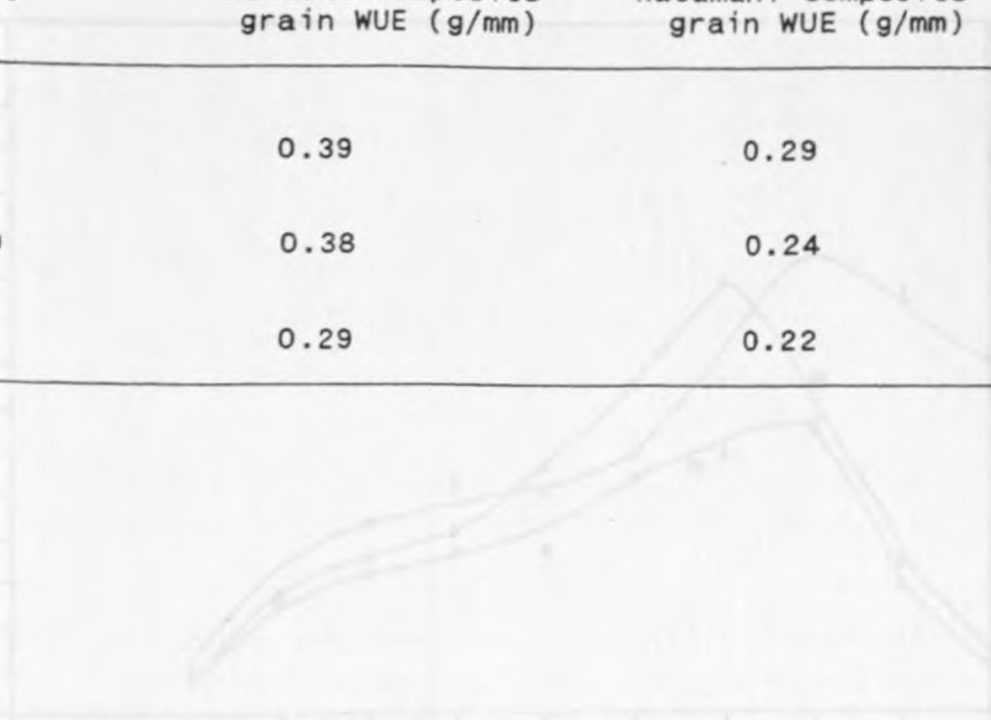


Table 19. Analysis of variance of grain water use efficiency.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	Computed f
Variety	1	0.01600	0.016	25.6*
Treatment	2	0.00745	0.00373	5.96 <sup>ns</sup>
Error	2	0.00125	0.000625	
Total	5	0.02470		

\* indicates significance at 5% level.  
 ns stands for no significance

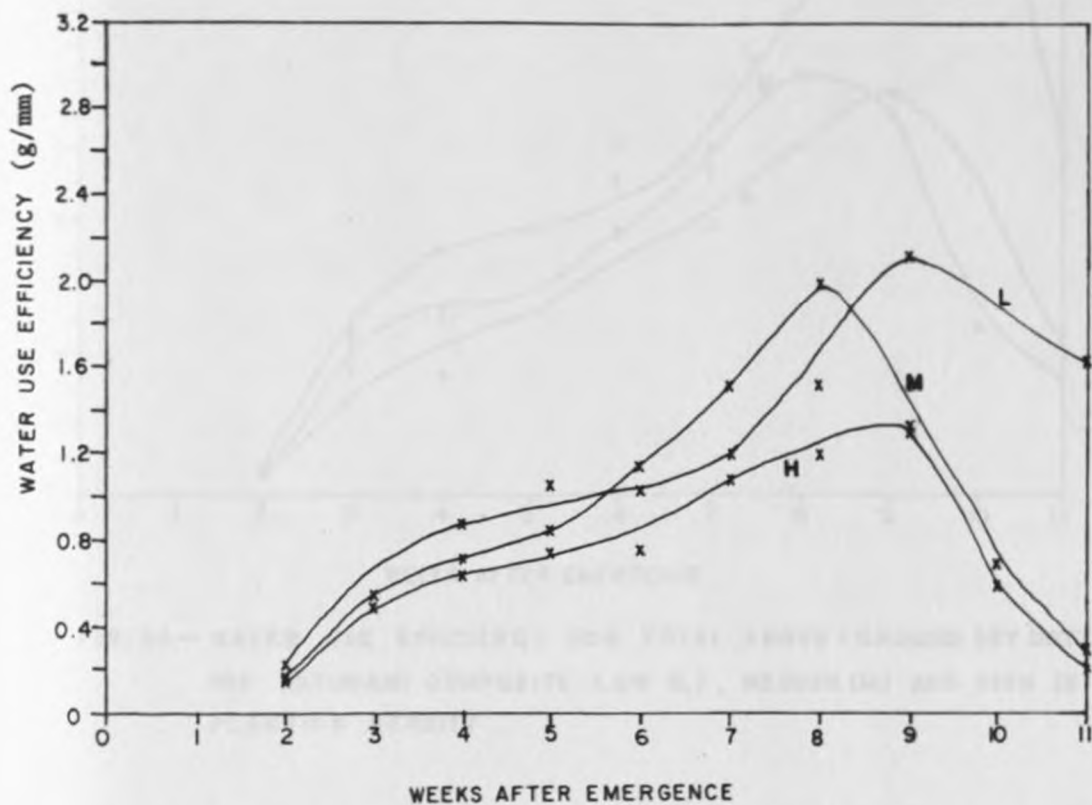


FIG. 24—WATER USE EFFICIENCY FOR TOTAL ABOVE-GROUND DRY MATTER FOR MAKUENI COMPOSITE LOW (L), MEDIUM (M) AND HIGH (H) PLANTING DENSITY .

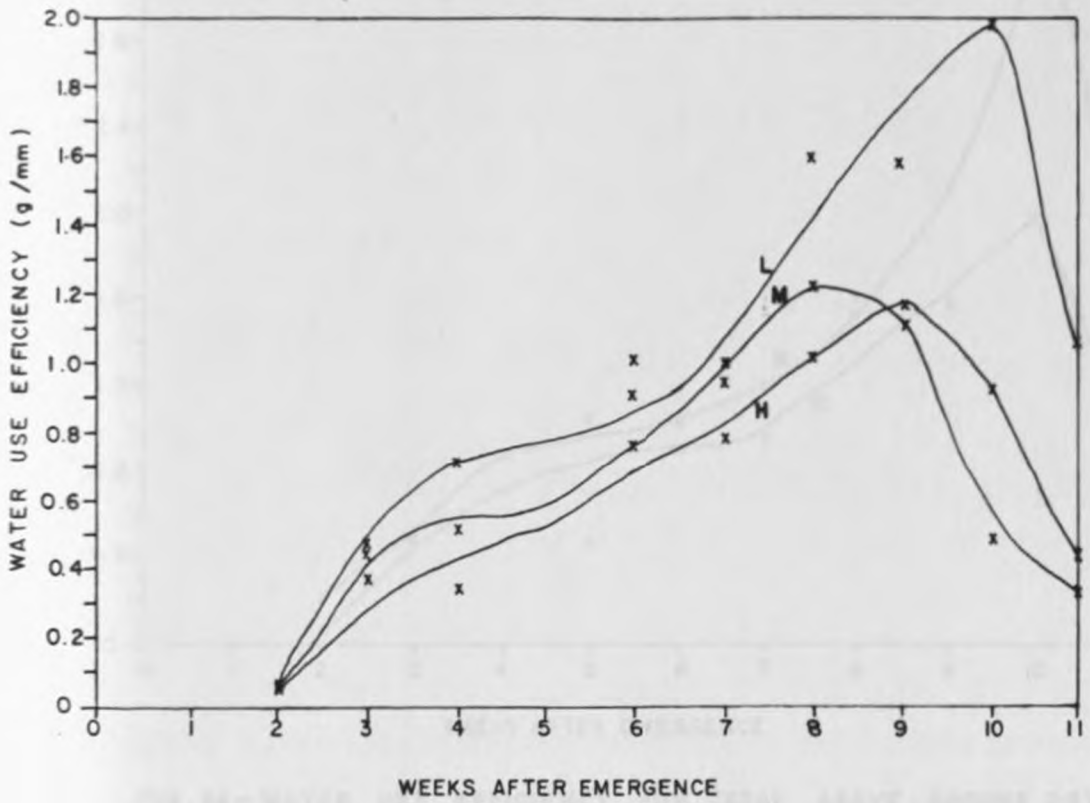


FIG. 25 — WATER USE EFFICIENCY FOR TOTAL ABOVE-GROUND DRY MATTER FOR KATUMANI COMPOSITE LOW (L), MEDIUM (M) AND HIGH (H) PLANTING DENSITY .



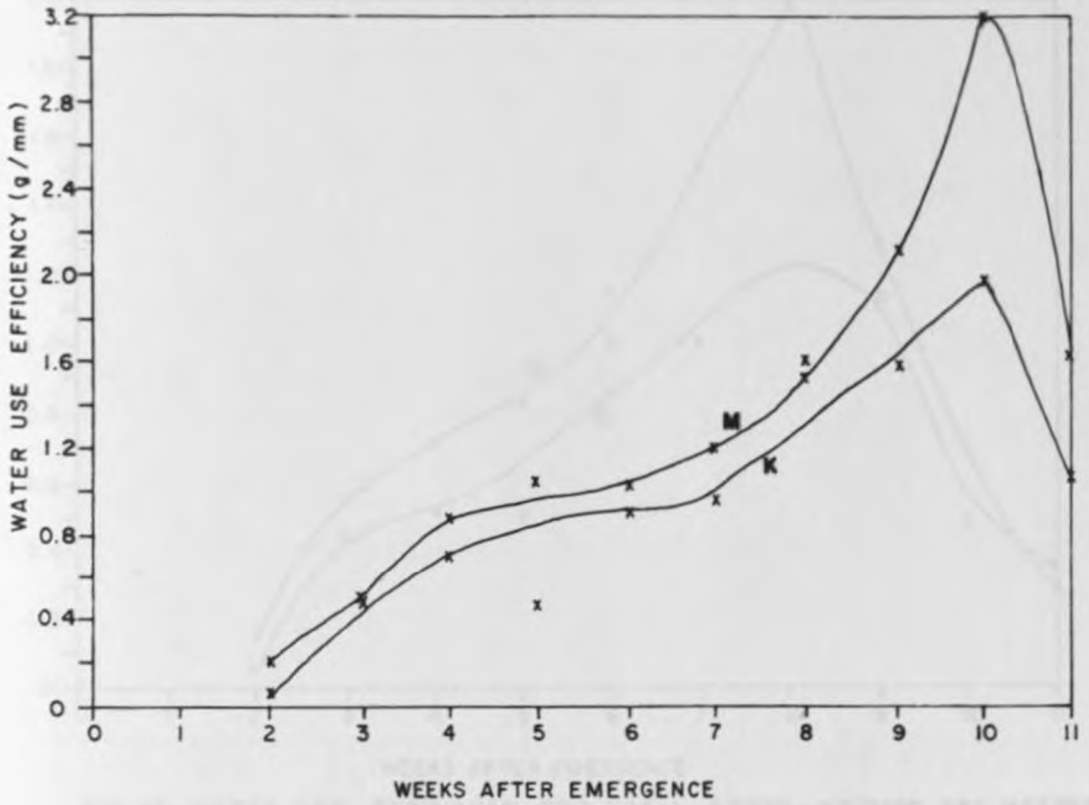


FIG. 26—WATER USE EFFICIENCY FOR TOTAL ABOVE-GROUND DRY MATTER FOR MAKUENI (M) AND KATUMANI (K) LOW PLANTING DENSITY .

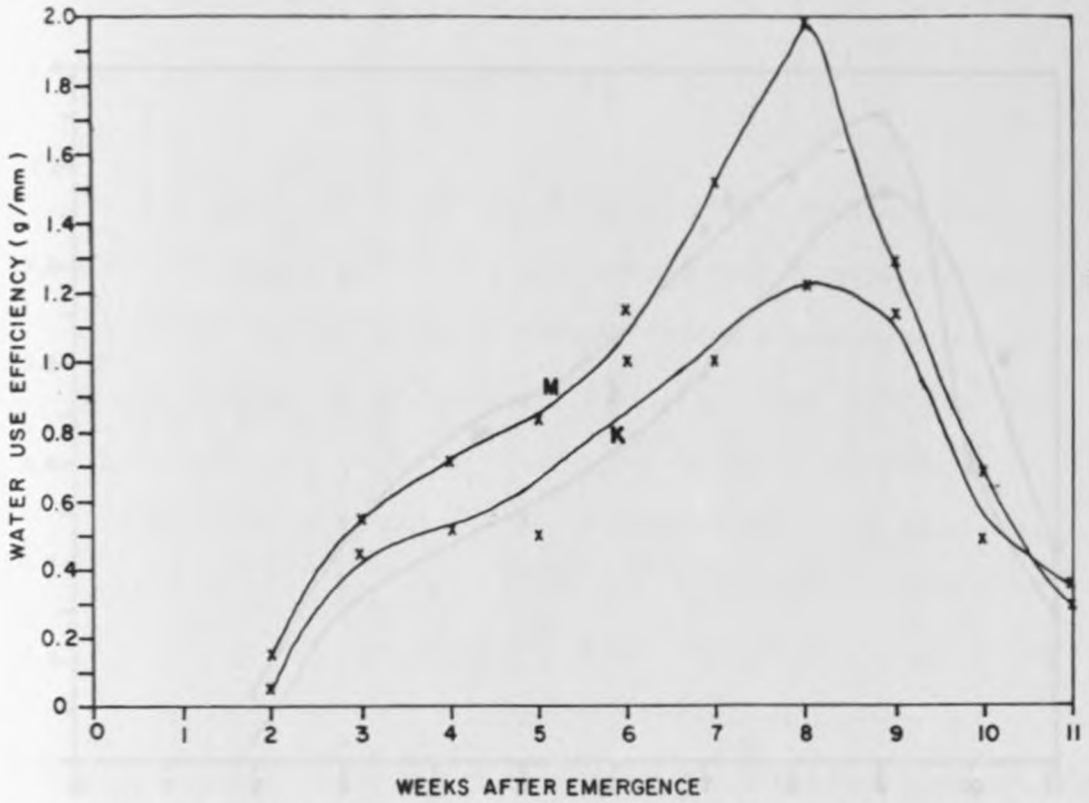
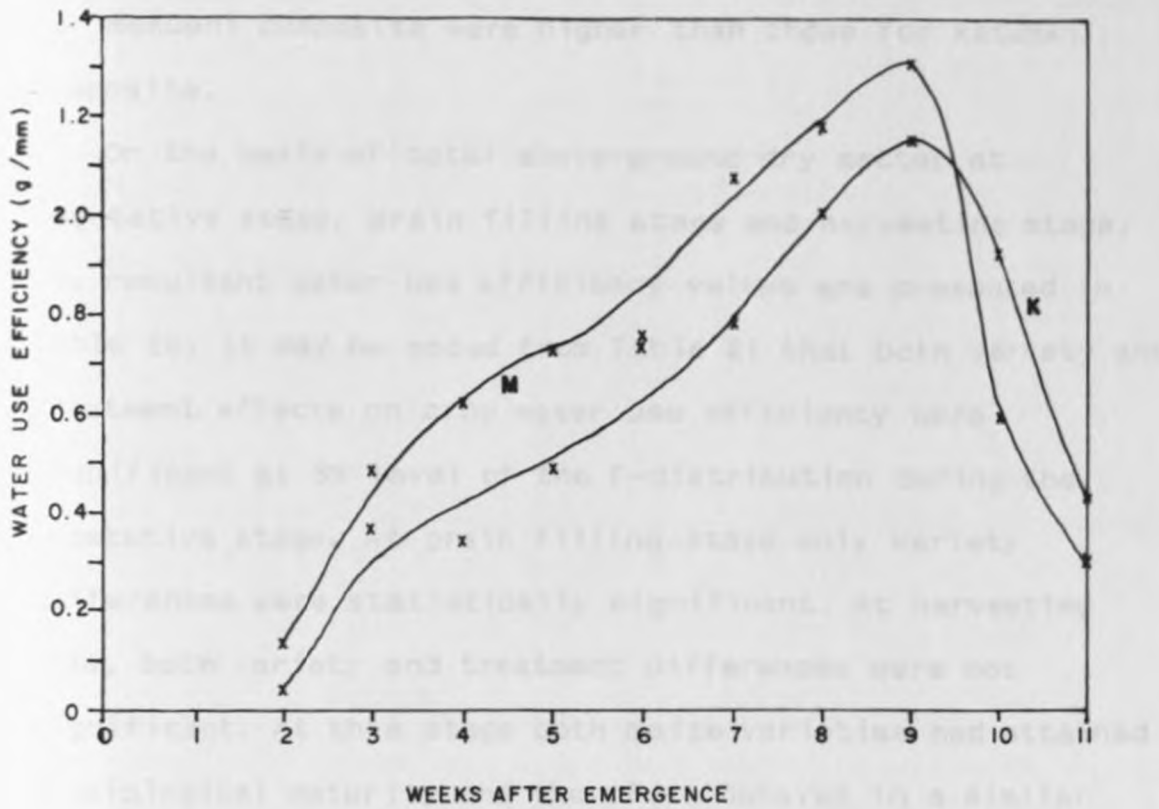


FIG.27—WATER USE EFFICIENCY FOR TOTAL ABOVE-GROUND DRY MATTER FOR MAKUENI (M) AND KATUMANI (K) COMPOSITE MEDIUM PLANTING DENSITY .



**FIG. 28 - WATER USE EFFICIENCY FOR TOTAL ABOVE-GROUND DRY MATTER FOR MAKUENI (M) AND KATUMANI (K) COMPOSITE HIGH PLANTING DENSITY .**

for makueni composite were higher than those for katumani composite.

On the basis of total above-ground dry matter at vegetative stage, grain filling stage and harvesting stage, the resultant water use efficiency values are presented in Table 20. It may be noted from Table 21 that both variety and treatment effects on crop water use efficiency were significant at 5% level of the F-distribution during the vegetative stage. At grain filling stage only variety differences were statistically significant. At harvesting time, both variety and treatment differences were not significant. At this stage both maize varieties had attained physiological maturity and therefore behaved in a similar manner.

Table 22 shows water use efficiency of whole season total above-ground dry matter. The analysis of variance (Table 23) shows that variety and treatment differences in water use efficiency of total above-ground dry matter were both significant at the 5% level of the F-distribution. These results also indicate that Makueni composite was more water use efficient than katumani composite and that, water use efficiency increased with decreasing planting density.

The decrease in water use efficiency with increasing plant population could be explained in terms of increased water depletion and decreased individual plant dry weight in the high plant population density treatments. This could arise due to increased inter-plant competition for both water and

Table 20: Water Use efficiency for total above-ground dry matter.

Time (weeks after planting)	Planting density	Makueni composite ( g/mm)	Katumani composite B ( g/mm)
4	Low	0.87	0.71
	Medium	0.71	0.52
	High	0.62	0.35
	Error		
7	Low	1.21	0.95
	Medium	1.52	1.00
	High	1.08	0.78
	Error		
11	Low	1.63	1.07
	Medium	0.29	0.36
	High	0.30	0.43
	Error		

Legend.

- 4 represents the vegetative growth stage
- 7 stands for the grain filling stage
- 11 represents the harvesting stage.

not significant.

significant at 5% level

Table 21: Analysis of variance of water use efficiency of total above-ground yield dry matter.

Time (weeks)	Source of variation	Degrees of freedom	sum of squares	Mean square	F ratio
4	Treatment	2	0.094	0.047	28.98*
	Variety	1	0.064	0.064	36.63*
	Error	2	$3.2 \times 10^{-3}$	$1.6 \times 10^{-3}$	
	Total	5	0.161		
7	Treatment	2	0.109	0.055	5.57 <sup>ns</sup>
	Variety	1	0.194	0.194	19.84*
	Error	2	0.020	$9.8 \times 10^{-3}$	
	Total	5	0.323		
11	Treatment	2	1.348	0.674	9.23 <sup>ns</sup>
	Variety	1	0.022	0.022	0.30 <sup>ns</sup>
	Error	2	0.146	0.073	
	Total	5	1.516		

Legend.

- 4 represents the vegetative growth stage
- 7 stands for the grain filling stage
- 11 represents the harvesting stage.
- ns not significant
- \* significant at 5% level

Table 22: Whole season total dry matter water use efficiency.

Planting density	Makueni composite total WUE (g/mm)	Katamani composite total WUE (g/mm)
Low	1.01	0.79
Medium	0.90	0.65
High	0.73	0.58

Table 23. Analysis of variance of total water use efficiency.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	Computed f
Variety	1	0.0639	0.0639	51.12*
Treatment	2	0.0606	0.0303	24.24*
Error	2	0.0025	0.00125	
Total	5	0.127		

\* indicates significance at 5% level.

nutrients.

#### 4.9 Variation of Water Use Efficiency with Meteorological Parameters.

An attempt was made to investigate the variation of water use efficiency of the two varieties of maize with the meteorological parameters observed near the experimental site. Water use efficiency in both grain development and total above-ground dry matter were considered. The meteorological Parameters analysed include; mean air temperature, net radiation, Sunshine hours, wind speed and rainfall.

Simple regression lines were generated for water use efficiency components and each of the meteorological parameters. Except for water use efficiency in the production of total above-ground dry matter of the high planting density of katumani composite and rainfall relationship, all the regression lines were found to be statistically insignificant.

Under the conditions of the experiment in this study, weekly rainfall in the case named above appeared to have had an inverse association with the observed crop water use efficiency. This could have come up as a result of increased evapotranspiration which may have occurred following high availability of soil water after rains. This stems from the fact that water use efficiency is a function of evapotranspiration. Lots of rain-water may also have led to surface runoff within the plots and may be deep drainage, thus resulting into overestimation of evapotranspiration by the water balance approach, particularly in the early crop stages



when high rainfall amounts were recorded.

On the whole, no definite association was found between the meteorological parameters recorded and the observed crop water use efficiency. Other factors such as crop genetic ability to accumulate high yields and/or crop phenological stages could have possibly accounted for the pattern of water use efficiency noted in this study.

Relaxant composite proved to be more dry matter yield abundant than Reliant composite for all planting densities studied and for both grain and total above-ground matter. At harvesting, the grain yield dry matter for relaxant composite plots were higher than those for Reliant composite by 22.5%. Total above-ground dry matter yields for relaxant composite plots were higher than for the corresponding Reliant composite yields by 16.4%.

Harvest indices increased with planting density upto 100 plants/ha and later decreased with further increase in the population. Relaxant composite gave higher harvest index than Reliant composite for all the plots although the differences between both varieties and planting densities were statistically significant.

Relative dry matter accumulation rates for both Reliant and Relaxant composites at the vegetative stage, grain filling and at harvesting stage were not significantly different. However, the absolute dry matter accumulation rate of Relaxant composite was higher than that of Reliant composite during grain filling stage. It may therefore be

## CHAPTER FIVE.

### 5.0 SUMMARY AND CONCLUSIONS.

The aim of this study was to investigate the variations of water use efficiency of two varieties of maize (*Zea mays* L.), viz. makueni and katumani composite B under rainfed farming conditions. The findings of this study are presented in the following section.

Makueni composite proved to be more dry matter yield advantageous than katumani composite for all planting densities studied and for both grain and total above-ground dry matter. At harvesting, the grain yield dry matter for makueni composite plots were higher than those for katumani composite by 23.5%. Total above-ground dry matter yields for makueni composite plots were higher than for the corresponding katumani composite yields by 14.4%.

Harvest indices increased with planting density upto 36,000 plants/ha and then decreased with further increase in plant population. Makueni composite gave higher harvest indices than katumani composite for all the plots although the differences between both varieties and planting densities were not statistically significant.

Relative dry matter accumulation rates for both katumani and makueni composites at the vegetative stage, grain filling stage and at harvesting stage were not significantly different. However, the absolute dry matter accumulation rate of makueni composite was higher than that of katumani composite B during grain filling stage. We may therefore note

that the two maize varieties had the same potential of accumulating new dry matter per unit of dry matter originally present.

Total evapotranspiration for whole crop season for katumani composite plots were higher than the corresponding values of makueni composite plots. The three plots of makueni composite in order of increasing plant population used 332, 346 and 360mm of soil water whereas the katumani composite plots respectively utilised 368, 409 and 405mm of soil water.

The ratio of actual evapotranspiration to standard class A pan evaporation increased to a maximum during silking period and declined thereafter as the crop approached maturity.

Mean weekly grain water use efficiency was affected by varieties at grain filling stage. Planting densities showed significant effects on mean weekly grain water use efficiency during soft dough stage. Both variety and planting density effects on total above-ground dry matter water use efficiency were significant at the 5% level at the vegetative stage. At grain filling stage, water use efficiency was different for the two varieties of maize. On crop season basis, both varieties and planting densities had significant influences on water use efficiency of total above-ground dry matter. Only variety effects on whole season grain water use efficiency were significant. Makueni composite exhibited higher water use efficiency than katumani composite B. Water use efficiency decreased with increasing plant population.

In line with the findings of this study, we may advance

the following suggestions. Though subject to further investigation in other cropping seasons, the makueni maize variety appears to be superior to katumani composite B and may therefore be adapted in the study area. Although long term studies recommended a planting density of 90cm between the rows and 30cm within the rows for maize in dryland areas, this study shows that it is possible to get higher yields with a planting density of 60cm between the rows and 20cm between plants.

#### 6.0 SUGGESTIONS FOR FUTURE WORK.

Water use efficiency of maize in the dryland areas of Kenya had not been studied in the previous years in the Kibwezi region of Kenya. This study analysed this problem in this area of Machakos district of Kenya for one cropping season, given the limited amount of time and finance.

In this project, an attempt was made to study the influence of plant density on water use efficiency of katumani and makueni varieties of maize. Due to lack of recording instruments and aluminium access tubes in sufficient numbers, the experimental plots were not replicated. Mean values of water use efficiency from replicates could give a better insight into the problem than a single replicate.

Further, because of lack of meteorological instruments in sufficient numbers, it was not possible to carry out micrometeorological measurements of solar radiation, soil temperature and leaf temperature within the crop canopy in each of the treatment plots.

ACKNOWLEDGEMENTS

Adoption of results from only one season investigation may not be appropriate. Several seasons studies are essential as they consider contributions of variability in meteorological conditions of the study area over long periods. The season utilised for the experiment may not have been representative of the climatic conditions of the study site. It is therefore suggested that this work be continued in other crop seasons, taking into consideration, the limitations presented above. Findings from many seasons determinations of water use efficiency may enable us draw more sound conclusions that may aid in planning agricultural systems aimed at maximising maize productivity.

So to register my appreciation to my father Joseph Lularika, my mother Margaret Mwikiche, sister Beatrice Muthali and the whole family for bearing with me since from home, particularly on occasions when the entire family wished to be together.

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## Appendix A.

Table 24

Extra Terrestrial Radiation (Ra) expressed in equivalent evaporation in mm/day

Northern Hemisphere												Lat	Southern Hemisphere											
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2	50°	17.5	14.7	10.9	7.0	4.2	3.1	3.5	5.5	8.9	12.9	16.5	18.2
4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7	48	17.6	14.9	11.2	7.5	4.7	3.5	4.0	6.0	9.3	13.2	16.6	18.2
4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3	46	17.7	15.1	11.5	7.9	5.2	4.0	4.4	6.5	9.7	13.4	16.7	18.3
5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7	44	17.8	15.3	11.9	8.4	5.7	4.4	4.9	6.9	10.2	13.7	16.7	18.3
5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2	42	17.8	15.5	12.2	8.8	6.1	4.9	5.4	7.4	10.6	14.0	16.8	18.3
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8	15.7	13.9	11.6	9.5	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

## Appendix B.

Table 25

Mean Daily Duration of Maximum Possible Sunshine Hours (N) for Different Months and Latitudes

Northern Lats	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Southern Lats	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
50	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1