A STUDY OF WATER USE EFFICIENCY IN FIELD CROPS OF MAIZE AND BEANS

by

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A THESIS SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
IN THE UNIVERSITY OF EAST AFRICA

MAY 1970

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Declaration

I declare that this thesis has not been submitted for a degree in any other University.

21/4/70

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SUMMARY

Crop water use efficiency may be defined as the ratio of total dry matter produced to total evaporation from the crop and the soil. In East Africa, the areas of high photosynthetic potential (highest number of sunshine hours) are also the driest. Success in growing annual food crops like maize and beans in these areas is therefore heavily dependent on the date of planting and the ability of the crop to complete all its stages of growth within the short rainfall seasons. While breeding of short term and high yielding varieties has been emphasized, little has been done in finding out the water use patterns of the varieties.

Experiments were therefore designed to provide information on the water use patterns of one hybrid of maize (H 511) with a medium maturity period (4 months) and one popular variety of field bean (*Phaseolus vulgaris* var. Canadian Wonder), in all stages of growth, and to observe the effect of reduced soil moisture on the water use and rate of growth of these two crops. Ratios of crop water use (Et) to Penman estimate of open water evaporation (Eo) gave values as high as

1.4 - 1.5 for maize and 1.3 - 1.4 for beans under wet conditions. It is shown that the excess water use, at least in the maize crop, may be due to the combination of large net interception of rain and low aerodynamic resistance. There was a reduction of ~ 20% in water use and ~ 40% in yield in the dry treatment of the maize experiment.

Measurement of soil moisture in situ by the neutron scattering technique was studied with the intention of using the method for routine determination of crop water use in the field. Although reliable calibrations were obtained for two makes of neutron moisture meters, E.A.L. and N.I.V.-I, the method was shown to be successful only in the absence of drainage. Because of errors in calibration and spatial variations in moisture contents, the precision of soil moisture determination by the neutron moisture meter is not adequate for small differences and the interval between measurements should be at least 7-10 days. In irrigated fields, the inherent poor distribution of irrigation water is a major limitation. Attempts to derive drainage correction data from tensiometer readings were not successful.

Theoretical estimates of gross photosynthesis have been successfully correlated with measured dry matter production in maize and beans. The correlations suggest that in the local environment respiration loss for the two crops is a constant proportion of gross photosynthesis in all stages of growth. This result enables the prediction of the maximum yields of these crops from meteorological data, mainly solar radiation.

Studies of partition of energy in field crops of maize and beans have shown that in the local environment, when the crops are supplied with adequate water, all net radiation may be converted into latent heat, and for periods of 1-2 hours during the day, latent heat may greatly exceed net radiation, the extra energy being derived from the air.

Finally the implications of the above findings on plant breeding and agronomic techniques for maximum water use efficiency are discussed.

ACKNOWLEDGEMENTS

A considerable amount of work had been carried out in the preparation of the experimental site and equipment before the experiments started. I am therefore pleased to acknowledge the efforts of Mr. J. Forsgate, who organized the initial installation of the lysimeters, and those of Messrs. J. R. Blackie and E. A. Ripley in the siting and installation of meteorological instruments.

A field experiment of this kind would not have been possible without the valuable assistance provided by the Management of the Mwea Irrigation Settlement. I am therefore grateful to Mr. J. J. Veen, Manager, Mr. Joseph Njeru and many others for their assistance in land preparation and the repairs on irrigation equipment.

Regular recording of meteorological and other numerous observations would not have been adequately fulfilled without the valuable assistance of

Mr. Stephen Magondu Mwera. I wish to acknowledge his willingness to work efficiently often under very difficult conditions. The assistance of Messrs. D. Mugunu and J. Mwirigi in data processing, and Mr. P. Ngugi in the preparation of diagrams, is gratefully acknowledged.

This project was sponsored jointly by the International Atomic Energy Agency and the East African Agriculture and Forestry Research Organisation. I therefore wish to acknowledge the financial support from these two organisations and also the generous study grant provided by the Rockefeller Foundation. The loan of neutron moisture meters from the Institute of Hydrology, U.K., and the Ministry of Agriculture, Kenya, is gratefully acknowledged.

Finally, I am specially indebted to Dr. M. Dagg for his counsel and encouragement throughout, both as senior investigator on the I.A.E.A. contract project and as one of my supervisors. I would also like to thank Professor D. H. Parish, my second supervisor, for his encouragement and guidance in the preparation

of the thesis. I also wish to thank Mrs. M. Windsor for typing the thesis.

This work is published with the kind permission of the International Atomic Energy Agency and The Director, East African Agriculture and Forestry Research Organization.

CHAPTER I

INTRODUCTION

The Climate of East Africa

The three territories which comprise East Africa lie between latitudes 5° North and 12° South. The climate of East Africa is therefore tropical with 11-12 hours of daylight throughout the year. However, because of the tremendous variation in altitude, air temperatures and average rainfall vary over wide limits from place to place. Mean air temperatures decrease from 25-28° C at the coast to 13-15° C at 2,500 metres and less than 0° C on top of mountains rising above 5,000 metres. Except for the coast and the area around Lake Victoria where total rainfall is higher, average rainfall in East Africa increases with altitude and is bimodal, falling in two distinct seasons with periods of varying length and degree of drought in between. Uganda is much wetter than Kenya and Tanzania, but as a region, only about 3 per cent of the East African land surface has average rainfall greater than the potential open water evaporation in four years out of five (Dagg, Woodhead and Rijks, 1970).

Over most of East Africa, therefore, one of the major factors limiting agricultural productivity is inadequate soil moisture during critical stages of plant growth. With valuable perennial crops like coffee and tea, supplementary irrigation during the dry season has proved economical but for annual crops of less economic value, the answer seems to be in matching the crops to rainfall regimes and the breeding of drought resistant and drought escaping varieties.

Need for research in crop water use

Maize, Zea mays, is one of the most important food crops in East Africa. This is obvious from the tremendous efforts made by local people, particularly in Kenya and Tanzania, who insist on growing maize even under very unfavourable environmental conditions. This results in unnecessary wastage of seed and labour. The logical solution to this problem may be the intensification of maize production in high potential areas, but for a variety of reasons, mostly connected with marketing, it seems that this will take some time to operate successfully. Farmers in the low potential areas will therefore continue to grow maize and the best that can be done to help them at present is to provide them with high yielding varieties and devise agricultural methods which would minimize input costs and changes of crop failure.

There is another important reason why the problem of growing maize - and other grain crops - in the low potential areas of East Africa should be given sufficient attention. The rangelands of East Africa are ideal for animal production, particularly beef cattle; but one of the problems which must be solved before these areas can be fully utilised is how the animals can be supplied with sufficient feed during the dry seasons. Cereals such as maize, sorghum and millet would fulfil this need provided they can be grown under such conditions of low and erratic rainfall.

Rational approach to matching crops to environment

Unlike the sorghums and millets which have over the years evolved several varieties naturally adapted to the different local climatic regimes, maize is not indigenous to East Africa and was only introduced in the 19th century. However, because of its greater resistance to bird damage, maize has achieved such popularity that it has become necessary to produce seed suited to different rainfall regimes.

Significant progress has been achieved in breeding high yielding and drought escaping varieties of maize for areas with short, medium and long rainfall seasons. Much breeding work has also been carried out with sorghum and millet which are more drought resistant than maize.

In his paper entitled "A rational approach to the selection of crops for areas of marginal rainfall in East Africa", Dagg (1965) showed how success or failure in growing a crop of maize requiring 210 days to reach maturity at Muguga was governed not by the heavy long rains concentrated in the months of April and May, but by the small amounts of rain received in June, July and

August. The validity of the above prediction is borne out by the frequent failure of the local long maturity varieties of maize and the reliable performance of the Katumani short-term (3 months) variety. This approach would therefore be very helpful in land-use planning provided there are sufficient data on rainfall reliability, crop water use in all stages of growth and soil moisture storage capacity. Significant progress has been achieved in calculating rainfall variability (Manning 1965; Walker and Rijks 1967; Huxley, Turk and Mitchell 1969), and where soil data are not available, it is a relatively simple job to take soil samples and work out soil moisture storage capacity. Few data are however available on the water use of crops in all stages of growth. It is therefore one of the main objectives in this thesis to examine the water use patterns obtained for maize in different experiments and to find out what additional information, if any, is required for the valid application of these results.

Water use of maize

Numerous studies have been carried out on the water use of maize (Zea mays). Results from these experiments have not, however, always been comparable because of varying and often unspecified experimental conditions, e.g. fertilizers applied, plant population and climatic conditions.

Haynes (1948) concluded from his experiments that available soil moisture affected vegetative growth, but did not affect transpiration rate per unit of plant dry weight. This result suggests that transpiration rate is reduced in the same proportion as the loss of dry matter production due to water stress. From their studies on supplementary irrigation for maize, Letey and Peters (1957) concluded that while maintenance of soil moisture tension well above 15 atmospheres tension was desirable, adequate water reserve in the soil profile at planting was also important. Supplementary irrigation for deep rooted crops was then required only when weather conditions favoured a serious depletion of water in the upper two feet of soil.

Denmead and Shaw (1962), however, showed that when potential transpiration was about 6-8 mm/day and soil water potential was greater than ½ atmosphere, maize was unable to maintain either full transpiration rate or full turgor. Fuehring <u>et al</u>. (1966) also showed that increasing soil moisture stress within the upper half of "available water" decreased transpiration. In their experiments, crop water use in the first week after irrigation was greater than in the second week, and yields were depressed by 4% when a weekly irrigation interval was increased to two weeks.

Evaporation from bare soil is also an important factor in the water use of a maize crop. Peters and Russell (1959) found that in a crop of maize evaporation from bare soil accounted for 50-70% of total water use. They used polyethylene plastic covers to separate transpiration from bare soil evaporation in field crops of maize. Similar results were obtained by Harrold _et al_. (1959) in lysimeters covered with plastic. In studies on the influence of soil moisture, nitrogen fertilisation and plant density on evapotranspiration and yield of maize, Carlson _et al_. (1959) also found that because of the effect of surface wetness on evaporation from bare soil, evapotranspiration from irrigated plots was considerably greater than water use in the non-irrigated plots.

Bare soil evaporation also interferes with meteorological estimates of crop water use. Garber and Decker (1961) compared water balance from a ten-acre maize field with heat budget estimate of evapotranspiration by the method of Penman (1956). The two estimates were in agreement when the soil surface was wet, but not when the soil surface was dry even though there was sufficient water available in the soil profile. These workers suggested that under dry surface conditions, surface temperature and hence sensible heat were underestimated.

In spite of the uncertainties in the experiments described above there seems to be a general pattern of water use for maize which shows a gradual increase in the early part of the crop, a plateau of varying duration after tasselling and a decline as the crop matures. Such a pattern is shown by Denmead and Shaw (1959) in their analysis of water use data covering 5 seasons at 11 sites in Iowa. Most of these data, based on State Soil Moisture Survey, were necessarily of low accuracy, and assumptions on runoff and deep drainage may be in error. The resulting pattern of the ratio of water use (Et) to pan evaporation (E_p) should, however, be representative. Et/E_p ratios increased in sigmoid manner from a value of 0.36 at planting to 0.81 at silking. The value 0.81 remained constant for 16 days and then decreased, apparently due to declining physiological activity of the crop.

Similar patterns of water use for maize, showing a maximum during pollination, have been observed by Fritschen and Shaw (1961), England (1963), and in studies conducted over two seasons by Cackett and Metelerkamp (1964). In the latter study, water use was estimated from soil moisture sampling, but excluded 3 days after each irrigation to minimise errors due to drainage. The recorded maximum ratio of Et to Penman Eo was nevertheless 1.10. This figure would be an underestimate if there was water extraction by maize roots beyond the 48 inches depth of soil profile sampled. These data were also used to formulate seasonal trends in Et/Eo as quadratic functions of the age of the crop in weeks (x) in equations of the form

$$\frac{Et}{Eo} = ax - bx^2 - c.$$

It is, however, difficult to find any physical basis for such an equation, and hence its usefulness in predicting water use of maize in a different environment is limited.

Water use of beans (Phaseolus vulgaris)

Field beans are a popular and common food crop in East Africa. The seed has a high protein content and is a useful supplement to the maize diet. Research work on field beans has, however, lagged far behind that on maize and relatively little is known about the water requirements of beans.

Cackett and Metelerkamp (1963) working in Sabi Valley, Rhodesia, and using a technique similar to that used for the maize crop as discussed earlier, found that the water use pattern for variety Red Canadian Wonder beans was similar to that of maize, except for a much flatter peak; maximum consumption occurred during the period from 9 to 12 weeks after planting. The highest Et/Eo was approximately 0.90, average for the season was 0.72. These data are subject to the same limitations observed for the maize data.

Extension of evaporation formulae to estimate of crop water use

Water use by crops is primarily an energy dependent process. The rate of vapour transfer away from the site of evaporation, and in some cases, the rate of supply of liquid water to such sites, serve to modify the energy dependence of evaporation from the soil and leaf surface.

Since the pioneering work of Dalton (1834), Rohwer (1931), Briggs and Shantz (1914-1917), and others, good progress has been made in the understanding of the evaporation process, especially evaporation at an open water surface. The methods of Thornthwaite (1948), Penman (1948), Blaney and Criddle (1950), and Olivier (1961) have all been tried in East Africa, but Penman's formula has provided the best correlation with data from pan evaporimeters in the tropical climate of East Africa.

The basic Penman equation combines energy balance with the efficiency of vapour transfer (sink strength) and can be written as

$$E = \frac{\Delta Rn + \gamma Ea}{\Delta + \gamma} \qquad .....(1:1)$$

where E = evaporation rate (mm/day),

Rn = net radiation (equiv. mm water/day),

Δ = slope of saturation vapour pressure-temperature curve (mb $^{o}C^{-1}$),

γ = psychrometric constant (mb $^{o}C^{-1}$),

and Ea is the equivalent of

$$0.35\ (es - ed)(1 + \frac{u}{100})$$

with es replaced by ea, the saturation vapour pressure at the air temperature.

u is windspeed (miles/day).

With the above approach, it is possible to estimate with an error less than 20 per cent for periods longer than 10 days, the evaporative loss from a free water surface through a relatively simple integration of simple meteorological observations (McCulloch, 1965). Maps of monthly and annual potential open water evaporation based on Penman's formula have been prepared for Kenya and Tanzania by Woodhead (1968) and for Uganda by Rijks and Owen (1965). Reliable estimates of open water evaporation can also be made for periods less than a day, but proper measurement and integration of meteorological parameters become much more complex.

Application of Penman's formula to evaporating surfaces, other than open water, has met with difficulties. Penman (1948) found that his meteorological estimates of open water evaporation Eo were well correlated with evaporation from well watered, short homogeneous grass at Rothamsted. The normal field crop is, however, neither short nor well watered, nor does it completely cover the ground. Fortunately there is general agreement on the shape of the evaporation-time curve for bare soil surface drying from initial thorough wetting (Penman, 1941; Philip, 1956; Veihmeyer and Brooks, 1954). These curves are based largely on experimental data and although the role of soil capillary conductivity in evaporation from bare soil has been recognised and attempts have been made to include this factor as an additional resistance in the evaporation or transpiration process (van den Honert, 1948; Cowan, 1965; Wangati, 1966), it has not been possible to find representative values of this factor for incorporation in the evaporation formula.

~~Penman and Schofield (1951) estimated the ratio of evaporation from plant cover to that of open water by~~

Penman and Schofield (1951) estimated the ratio of evaporation from plant cover to that of open water by assuming that the crop canopy could be regarded as part of a large flat leaf, with the stomata fully open during the day and fully closed at night. The effective "length" over each cm^2 of surface, a parameter defining the efficiency of vapour transfer by turbulent mixing, was therefore assumed to be the same for open water as for continuous crop cover and had the same effect on transpiration as well as carbon dioxide assimilation. The additional stomatal resistance was therefore calculated on the basis of stomatal dimensions and their population.

The final equations arrived at predicted that evaporation from well watered turf was less than open water evaporation. This prediction was supported by experimental data and energy balance estimates, and the influence of day length on Et/Eo indicated that where the above assumptions applied Et/Eo was equal to a constant, f, which varied between 0.6 and 0.8 according to seasons (Penman, 1956). Penman calculated irrigation requirements in Britain on the basis of the above Et/Eo ratios. The approach was successfully applied by Pereira (1957) in estimating requirements for supplementary irrigation in mature rain grown coffee in Kenya, and Wallis (1963) found the same procedure applicable in predicting soil moisture deficits under irrigated coffee. Mitchell (1965) however found that coffee fields in northern Tanzania could vary in their irrigation requirements, suggesting that there was no simple formula for estimating the frequency and quantity of irrigation water. Evaporation data estimated from catchment area water balance in East Africa (Blackie, 1964; Dagg and Blackie, 1965) suggest that in high rainfall areas where evaporation is not limited by soil moisture deficits, Et/Eo values for perennial vegetation like high montane forest and tea plantation at full cover are relatively constant, varying between 0.7 and 0.9.

Complications arise, however, when the fraction of ground covered by the crop changes with crop development and where available soil moisture is not sufficient to meet potential evaporative demands on the crop. The resulting changes in Et/Eo-time curves can be very large but there is no method as yet which can be used to make the necessary quantitative allowance in the factor f. There is a further problem, this time arising from Et/Eo ratios greater than unity. Values of Et/Eo ranging from 1.0 to 1.8 were reported by Prescott (1938), Stanhill (1958), Mather (1954), McCloud and Dunavin (1954), and Hutchison, Manning and Farbrother (1958). Although there is some doubt on the procedures used for estimating open water evaporation, Eo, it is evident that some crops can be more efficient than open water surfaces in the conversion of net energy into latent heat.

A review of the relative importance of various constants in the Eo formula (Sibbons, 1962), indicates that Et/Eo ratios greater than 1.0, and the obvious differences between crops, might be more related to the physical properties of the crop canopy, especially the aerodynamic resistance referred to earlier. The derivation of Penman formula in a somewhat different way by Monteith (1963) emphasized the role of the aerodynamic resistance (r_a) and the additional stomatal resistance (r_s) introduced in a crop when the leaf surfaces are not wet. Measurement of aerodynamic resistance for crop canopies has, however, proved difficult, requiring large representative areas for proper determination of windspeed profiles. Numerous measurements with diffusion porometers are also required for determination of r_s. However, in spite of the difficulties cited above, this approach provides the best method to date of defining expressions for crop water use in terms of crop parameters and could be extended in the future to include other factors connected with soil moisture availability.

In conclusion to the above review of present status on the application of evaporation formulae to crop water use, it is perhaps a fair observation that interpretations of many results of crop water use measurements have been biased by the underestimation of the part played by the roughness of crop canopies in the extraction of sensible heat from the air, and the conversion of this energy into latent heat. Values of Et/Eo which turned out to be greater than unity were therefore in some cases too readily explained in terms of advection of heat from surrounding areas, with a suggestion that actual water use in the middle of very large, uniform field crop would always be less than potential evaporation from open water in the same environment. Even after the difference in r_a between crop and water surfaces was recognised, it was still maintained that the probable increase in Et would at most just balance the decrease due to surface albedo (0.25 for crop, 0.05 for water). Advection is, however, a factor to be considered seriously in designing experiments for crop water use measurements. The experiments of Fritschen and Van Bavel (1964), with lysimeter crops of Sudan grass protruding well above the surrounding crop, have provided a good demonstration of the importance of a uniform crop in water use experiments.

Other methods of estimating crop water use - neutron moisture meters

Direct measurement of soil moisture under field crops is not only necessary for checking the validity of meteorological estimates of crop water use, but also such measurements provide useful information on the soil moisture profile at all stages of crop growth. These data should therefore lead to a better understanding of root activity and hence the optimum frequency of irrigation and depth of placement of fertilisers for maximum uptake by the plants.

The conventional method of soil moisture measurement requires soil sampling in the field, weighing, drying for a standard period, usually 48 hours, in an oven at 105°C, followed by cooling in a desiccator and re-weighing. This technique is tedious because heterogeneity of soil moisture conditions in the field requires large numbers of samples for a reasonable degree of accuracy to be achieved. Soil sampling also tends to destroy the soil profile to the extent that in time, sampling sites become channels of preferential drainage. A further source of error in this method is the necessity to determine soil bulk density or extraction of core samples of known volume for the conversion of gravimetric to volumetric moisture contents.

Specially made nylon resistance units can be used to measure soil moisture. Calibration of these units is, however, difficult and is usually not possible to check either during or after lengthy field experiments. This limitation applies especially to the cheaper gypsum blocks available commercially.

Considerable and fast development of an alternative method of measuring soil moisture content <u>in situ</u> by the neutron scattering technique has taken place in the last 18 years. Gardner and Kirkham (1952) considered that hydrogen present in the soil, mainly as water, was the only material which would slow down fast neutrons. They developed a theory and a method of measuring soil moisture content based on this property and tests indicated that the method was applicable in the range of soil moisture contents between oven-dryness and water saturation. Holmes (1953) presented results of similar tests carried out in Australia and among these early experiments the work of van Bavel, Hood and Underwood (1954) was directed on methods of increasing vertical resolution of the equipment.

Most of the early work on the use of neutron and gamma radiation for this purpose is extensively reviewed in the Commonwealth Bureau of Soils Bibliography, "The Determination of Soil Moisture Using Neutron Probes (1963-1951)". The later developments are mainly in instrument design for both better resolution and reliability in field operations (Bell and McCulloch, 1966), methods of minimising errors in calibration and measurements (Bell and Eeles, 1967), and operational precautions for accurate evaporation measurement (Van Bavel and Stirk, 1967).

As a result of successful calibration and field tests of the neutron moisture meters, a meeting of a panel of experts on radiation techniques in soil physics and irrigation studies, held in Vienna in October 1964, considered that the neutron moisture meter represented a considerable advance in technique over any previous soil moisture measuring device, and held promise of being able to yield useful quantitative measurements of crop water use. Accordingly, it was decided to set up a co-ordinated experiment in which the water balances of the same crop under irrigation in different countries would be compared. The crop water use measurements with neutron moisture meters reported here were part of this co-ordinated experiment.

<u>Dry matter production in relation to crop water use</u>

Crop water use efficiency may be defined as the weight of dry matter produced per unit of water lost by evaporation in a unit area of field crop (Haise and Viets, 1957). Since in most cases only a fraction of total dry matter is of economic interest in agriculture, a more practical definition would be in terms of marketable crop produced for a unit depth of water used in evapotranspiration. Both evaporation and dry matter production are dependent on energy derived from solar radiation. Crop water use efficiency can therefore also be defined in terms of the partition of net energy between latent heat and chemical energy stored in the form of dry matter. Several accounts of this approach have appeared in literature: Allen, Yocum and Lemon (1964) obtained photosynthetic efficiency of 6.8% in the utilisation of radiation in the 0.4–0.7 wavelength range. Using Beer's Law for light absorption, they calculated potential photosynthesis and compared this value with potential evapotranspiration Et calculated from net radiation data. The result was that 16 times more energy was used in evaporation than in photosynthesis.

Amongst the more interesting data, Yao and Shaw (1964) found that water use efficiency in maize was also sensitive to plant population, being highest (571 lbs/inch) in maize planted two seeds per hill in rows 21 inches apart, and falling to 414 lbs/inch when inter-row spaces were increased to 42 inches. The same workers (1964b) found that net radiation 1 metre above the crop was higher in 42 inch row crops than in 21 inch row crops, implying greater storage of radiant energy in the denser crop.

The subject of energy conversion in photosynthesis and evaporation is reviewed by Lemon (1966). It turns out that the better the understanding of the physics of energy exchange and the morphology and physiology of plants, the less can be said about water use efficiency in such general terms as the "transpiration ratio". Each crop, on each site at a particular time, follows the laws governing the interaction crop and environmental factor. The study of crop water use efficiency described here is therefore not meant to provide more data on the weight of dry matter produced per unit of water used, but to find logical and convenient means of estimating both optimum crop productivity and crop water requirements under field conditions from measurable environmental and crop factors. The task of combining crop productivity with crop water use for maximum water use efficiency will be left to the agronomist to work out according to circumstances - environmental, social and economic - prevailing at each location.

Evaporation reduction in field crops

While a better understanding of the pattern of crop water use can be used to minimise wastage of water in irrigation and would, of course, be very useful in the extension of crop agriculture to drier areas, the scope for control of Et is limited by the necessity to keep stomata open as long as possible for CO_2 assimilation. Studies carried out on chemical anti-transpirants are reviewed by Waggoner (1966). It appears that although there are chemical sprays which would control stomatal opening and in a few cases these have been found to decrease transpiration relatively more than photosynthesis, little is known about the feasibility of using these techniques under field conditions. Experience will therefore indicate that at present, the most promising approach to evaporation reduction in field crops lies in finding out the crop water requirement at all stages of growth and the most economic methods of satisfying this requirement.

Estimates of gross photosynthesis in field crops

Scientific studies of crop yields date as far back as the earliest fertiliser trials in Britain and America in the 19th century. These studies were confined to final yields of the economically important components, viz. grain, tubers or hay. Interest in the relationships between plant populations and yields subsequently developed, followed by studies of growth rates, which led to the introduction of Leaf Area Index by Watson (1947). Parallel studies of carbon dioxide assimilation in leaves were being carried out in controlled environments, pioneered by the work of Blackman (1895), Brown and Escombe (1905), Maskell (1928), and following experiments by Heath (1951) and Gaastra (1959) and others, there has been a welcome but gradual extension of laboratory methods to field crops by workers such as Hesketh and Moss (1963).

Carbon dioxide concentration and light intensity are the two major limiting factors to photosynthesis under field conditions. There is little one can do to increase either the CO_2 concentration in the free atmosphere or CO_2 availability to the leaves, the latter being dependent on windspeed and aerodynamic properties of the crop. Much field work has therefore been directed at the description of the pattern of light interception in the crop canopy and attempts to calculate gross photosynthesis from these profiles using photosynthesis-light curves for single leaves as determined in the laboratory.

Some of the original work (Davidson and Philip, 1958; Saeki, 1960) assumed light profiles based on Beers' Law of light extinction in a homogeneous medium:

$$I_L = I_o e^{-kL} \qquad \text{.....(1:2)}$$

where I is the incident light intensity

I_L is the light intensity at depth L in the medium

k is the light extinction coefficient in the medium.

In the case of crop canopies, k is dependent on transmission through single leaves and on their geometric arrangement on the plant. The changing spectral composition of radiation due to absorption, transmission and reflection by leaves in the canopy was neglected. de Wit (1959) based his calculations on a model assuming random distribution of leaf angles within a canopy which absorbed all radiation falling on it. This approach was modified later (de Wit, 1965) by dividing up the canopy into an infinite number of sections oriented at all angles to direct solar radiation, with a secondary radiation component based on contribution from diffuse sky radiation. The total area of canopy receiving light was obtained by a series of integrations based on the above factors. Success of de Wit's method has been demonstrated for complete canopies of alfalfa (Stanhill, 1962), pasture (Alberda and Sibma, 1962), kale (Watson and Witts, 1959), subterranean clover (Davidson and Donald, 1958; Black, 1963) and rice (Takeda, 1961), but serious discrepancies have also been observed with corn (Williams, Loomis and Lepley, 1965), mixed pasture (Brougham, 1956) and sugar beets (Watson, 1958).

Monteith (1965) criticised the use of mean light intensities in estimates of photosynthetic rates in crop canopies and the neglect of the changing spectral composition of light as a result of reflection and transmission in the canopy. In order to minimise such errors, Monteith, in the same paper, proposed a new model for light interception in field crops. In this model, the canopy is divided into layers of unit leaf area index, L, and the light distribution is given by the binomial expansion of the equation

$$I_L = I_o(s + (1 - s)\tau)^L \qquad .....(1:3)$$

where s is a parameter characteristic of the average arrangement and orientation of leaves, and is equal to the fraction of incident radiation that passes through a layer without interception. τ is the average transmission coefficient of the leaves over the spectral range of the incident solar radiation.

The model has been criticized on the basis that it stops at fractional areas of sunflecks which are not as accurate in predicting photosynthesis as are the fractional areas of leaves in each layer receiving light at various angles of inclination to their surfaces.

Other models, e.g. Duncan _et al_. (1967), have been proposed, but the main differences are in the degree of detail the authors consider necessary for proper evaluation of the light and carbon dioxide functions and effects on overall estimates of gross photosynthesis. The work described here placed emphasis on Monteith's model as the simplest, consistent with reasonable accuracy, for estimating potential productivity of field crops in the local environment.

CHAPTER II

WATER USE OF MAIZE AND BEANS

Site

The experiment was situated on the Mwea Irrigation Settlement (latitude 0°38'S, longitude 37°22'E, altitude 1,300 metres), some 110 km from the home base of E.A.A.F.R.O. Although this distance raised many problems in day-to-day supervision, the site itself was excellent for the purposes of the study.

With some 3,000 hectares under furrow rice irrigation, the site was sufficiently large to give uniform conditions of fetch over a considerable distance.

The position of the experimental plots with respect to the irrigated area is shown in Figures 1a and 1b. Figure 2 shows a comparison between Penman Eo and evaporation from a raised gridded pan in the meteorological enclosure. Over the period April to November when the rice fields were flooded, Penman Eo was consistently higher than pan evaporation but when the fields dried out in December, pan evaporation was more than Penman Eo, indicating that there might well be an appreciable advected component of evaporation during the period when the rice fields are not flooded. There may be a residual advection component also when the fields are flooded, but this is likely to be less than 10%.

The Mwea Irrigation Settlement has two main soil types both derived from massive volcanic lava flows from Mount Kenya. On well drained sites highly permeable red kaolinitic clays have been formed and in areas with impeded drainage, heavy black montmorillonitic clays are found. The experimental site is on an area of level red soil underlain at depths varying from 1.8 to 2.3 metres by tuff rock. Chemical analyses of the experimental soils (Appendix 1) showed no sign of salinity problems. The experimental area had been levelled in the past and it is evident that some 15 cm of soil had been moved from the profile in field B on to that in field A. Results of a physical analysis of pore space and water holding capacity are shown in Table 1. The soil is extremely permcable down to the rock base with a moderately high water holding capacity.

The average rainfall is 800 mm falling in two seasons, April-May and November-December. The annual evaporative demand (Penman Eo) is about 1,800 mm.

Methods and Procedure

The experimental field was divided into 2 one-hectare plots (Fig. 1a). A hydraulic weighing lysimeter was set in the middle of each plot and a central plot 12 metres square was marked around each lysimeter. Four sub-plots 2 m x 2 m were marked at the corners of each central plot and neutron moisture meter access pipes were installed to a depth of 180 cm in the sub-plots and 170 cm in the lysimeters. Tensiometers were installed at 170 cm, 150 cm and 70 cm depths in the central plot and at 170 cm and 150 cm in the lysimeters.

Lysimeters

The lysimeters used in this experiment were 2 m x 2 m x 2 m deep, the design, construction and operation

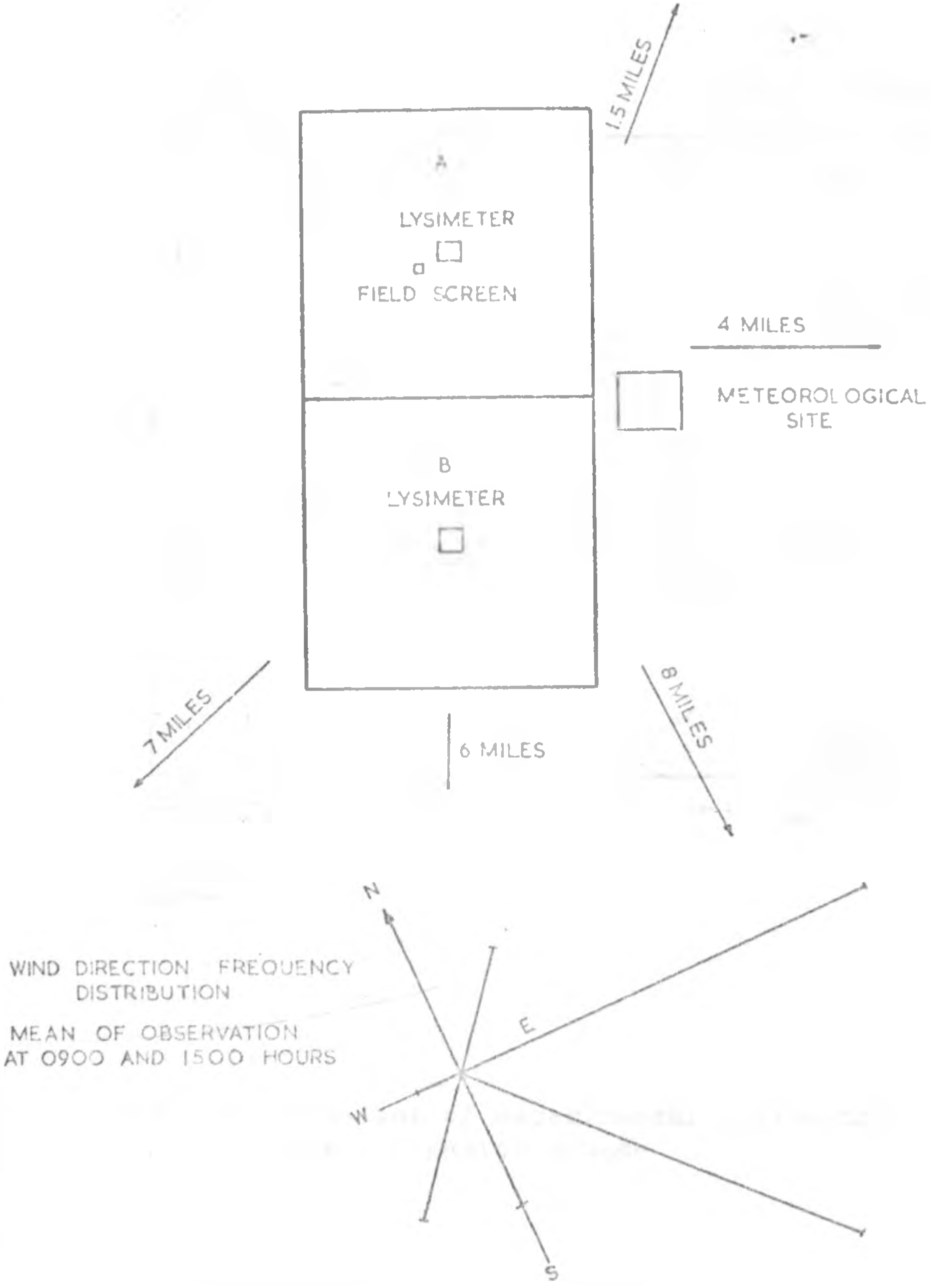


Fig. 1a: Layout of the experimental field showing direction of prevailing wind. The arrows indicate extent of fetch over flooded paddy fields.

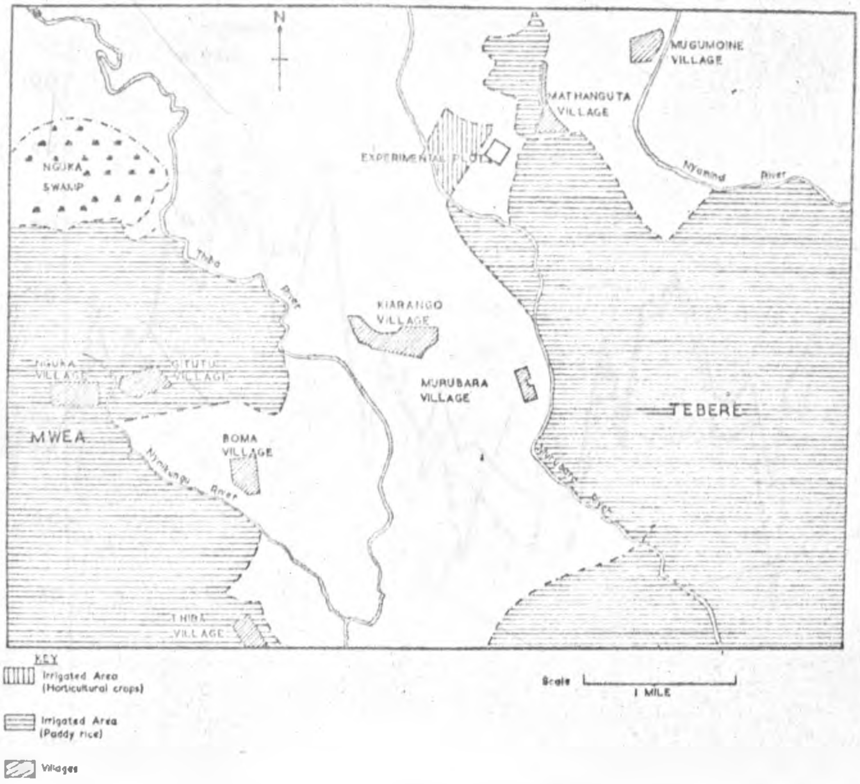


Fig. 1b. Position of experimental plot within the irrigation scheme

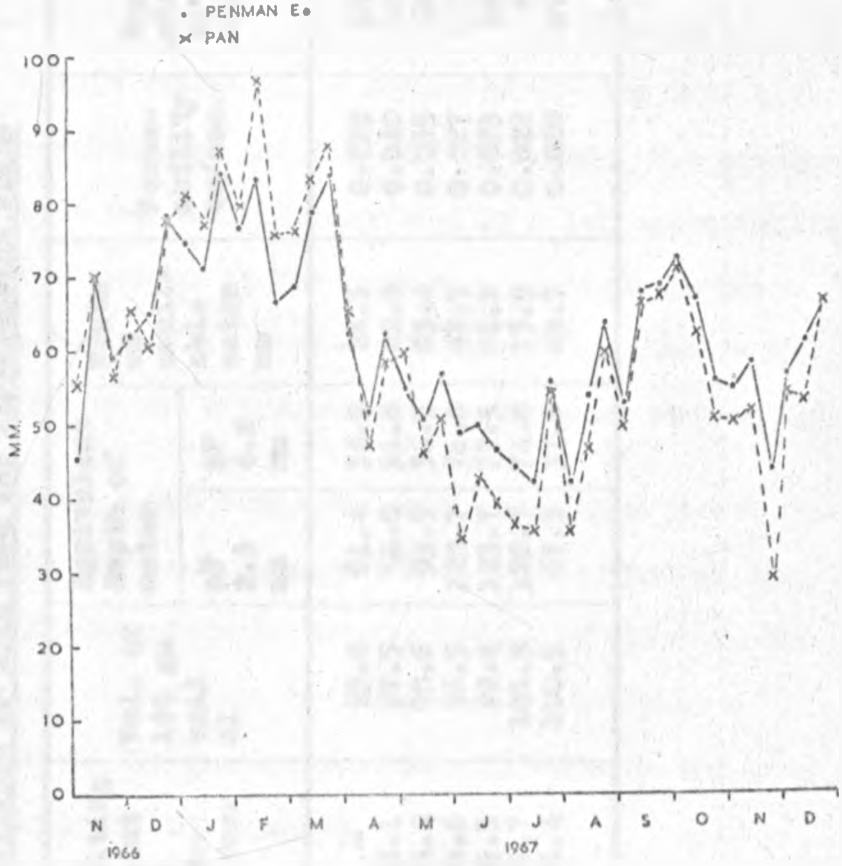


Fig. 2. Comparison between Penman Eo and evaporation from raised gridded pan in the meteorological enclosure

TABLE 4

PHYSICAL ANALYSIS OF SOIL FROM THE EXPERIMENTAL FIELD

Depth cm	Gravimetric moisture content		Wilting point by sun-flower %	Vol. of 100 gm soil ml	Equivalent depth of water		Depth of avail-able water mm	Perme-ability cm/sec.	Percol-ation rate cm/hr.
	pF 2.5 %	pF 4.2 %			pF 2.5 mm	pF 4.2 mm			
0-15	38.4	23.1	-	93.8	61.4	36.9	24.5	0.039	140
15-30	38.2	23.4	23.1	97.5	58.8	36.0	22.8	0.040	144
30-45	39.4	24.0	24.2	98.6	59.9	36.5	23.4	0.035	126
45-75	39.7	24.4	24.6	96.3	123.7	76.0	47.7	0.027	97
75-105	41.0	25.0	25.5	99.4	123.7	75.5	48.2	0.029	104
105-135	43.7	25.4	25.7	101.9	128.7	74.8	53.9	0.024	86
135-150	45.3	25.3	26.4	100.9	67.3	37.6	29.7	0.028	101

of this type of lysimeter being described by Foregate, Hosegood and McCulloch (1965).

A tank of soil containing the crop planted to match that in the field is supported on flat flexible metal bolsters that are filled with water. The pressure of the tank and soil is supported by a balancing column of water connected to the bolsters. Changes in the water content of the tank are reflected by changes in the height of the balancing column which is read daily.

Several weeks after the lysimeters were first installed, it became apparent that the lysimeters were not performing properly and the levels of water in the balancing columns were rising steadily, implying a reduction in the bearing surface area between the lysimeter tank and the bolsters.

It was suspected that this trouble was caused by stretching the bolsters beyond the elastic limit of the material during installation, and this was partially confirmed by preliminary tests on specimen bolsters. A test rig set up at Muguga was used to subject the bolsters to cycles of pressure up to half an atmosphere to check for leaks and for consistency in performance.

The test rig was made of two concrete slabs 2 m x 1.2 m x 15 cm cast round flat hoops of steel bar such that one slab was suspended 5.7 cm above the other. Bolsters could then be pushed into the slot and considerable pressures imposed without any danger of the bolster swelling excessively. On initial subjection to pressure of half an atmosphere, the bolster took some days to settle down but less time was required on subsequent recycling. All the new bolsters for the experimental lysimeters were tested in this rig before they were used to replace the faulty bolsters. The trouble did not recur and has not been observed in other lysimeters with bolsters treated in the same way.

After a few months of satisfactory performance, the lysimeters showed signs of leakage in the measuring system and were once more excavated. The hard plastic connecting pipes between the bolsters were found to have developed fine cracks at sharp bends. All pipes were replaced with more pliable but durable plastic hosepipe which subsequently proved satisfactory. The lysimeters were back-filled with fresh soil excavated from pits at the edge of the field. The initial test period under a waterproof tarpaulin was shortened by the necessity to plant the maize crop on time, but this and later tests after harvest indicated a reasonably satisfactory level of performance.

Both lysimeters were functioning properly when the bean crop was planted at the end of February 1968, but after three weeks one of the lysimeters developed a leak in the weighing system and had to be excavated and lifted out. The leak was traced to pin holes on one bolster, apparently caused by electrolytic corrosion in the metal. This bolster was replaced and the lysimeter tank refilled with soil but although performance was good at the beginning, sudden drops in column height continued to occur at random, making estimates of crop water use from this lysimeter unreliable.

The lysimeter measuring systems were calibrated using field assistants as weights. Figure 3 shows sample calibration lines for the two lysimeters. The calibrations were always linear with 1 mm change in column corresponding to nearly 1 mm of water on the lysimeter.

A tension drainage system was installed in each lysimeter. This consisted of two sets of 4 ceramic candles, 16 cm long and 4.5 cm in diameter, connected to two plastic tubes dipping in water 100 cm below the level of the bottom of the lysimeter. These candles performed satisfactorily throughout.

Neutron moisture meters

Two different makes of neutron moisture meter, the Electronic Associates Limited (E.A.L.) model and the NIV-I, a Russian make, were tested in this experiment (Figure 4).

Calibration was obtained by digging volumetric soil samples from sets of three profiles 15 cm from neutron probe access pipes placed in dry, moist and wet ground in the same plot. The volumetric moisture contents thus obtained were plotted against neutron count rates in the same soil horizon.

From February 1968, it was possible to use one of the B.A.L. neutron moisture meters made available by the Institute of Hydrology, Wallingford, U.K., for catchment research work in East Africa. Calibration of this instrument in the soil moisture range 0.23 to 0.38 moisture volume fraction is shown in Figure 5a. The special batteries required for the NIV-I moisture meters could only be obtained overseas and this led to considerable loss of time. Calibration for this instrument over the same range of soil moisture contents is shown in Figure 5b.

The range of soil moisture contents used in the above calibrations is comparable with the range of available soil moisture in the top 30 cm (see Table 1). Field capacity figures in Table 1 were obtained by draining core samples under ⅓ atmosphere tension in the laboratory and although these figures agree with field observations for the top 30 cm, there is no real evidence that the higher values indicated for lower depths were achieved under field conditions.

Tensiometers

Tensiometers were made by sealing a small ceramic tensiometer cup 5.5 cm long, 2 cm diameter, on to one end of a 13 mm diameter hard plastic pipe. A glass reservoir with a narrow side tube was fixed to the other end of the plastic pipe. The side tube was connected to a mercury manometer comprising a glass capillary tubing, 2 mm bore, dipping into a mercury reservoir. This use of narrow glass tubing for the manometer reduced response time and the quantity of exchange water between tensiometer cup and the soil. The mercury manometers were mounted inside two wooden shields painted white to reduce heating, and were read only once a day at a time (0900 hours) when day-to-day temperatures were nearly the same. By using freshly boiled water throughout the system, formation of air bubbles was greatly reduced and flushing of the connecting tubes was usually necessary only once every two weeks. All tensiometers were tested in the laboratory to a suction of 47 cm Hg before installation, atmospheric pressure at the site being only 58 cm Mercury.

The tensiometer arrangement is shown in Figure 6. The first attempt to use these tensiometers in the field failed due to the unexpected flattening of the strong plastic tubing where it was exposed to the sun, and later the development of leaks at the joints between the glass reservoirs and the plastic pipes. The leaks were subsequently stopped by sliding close fitting rubber sleeves over the joints and applying grease. The flattening of the plastic tubing persisted, though to a lesser extent, after burying the tube in the soil over as much of its length as possible. In 1968, it was possible to replace the flattened connecting tubes with tough translucent P.V.C. tubing. This tubing proved more heat resistant but was apparently more attractive to rodents which bit holes in the tubing causing frequent losses of data.

When a third treatment was included in the 1968 experiment, additional tensiometers could not be constructed in time and commercial irrometers with vacuum gauges were used. The depths of measurement were, however, restricted to 120, 100 and 50 cm, these being the lengths of the available irrometers. These irrometers had the advantage of registering actual soil moisture tension without the necessity to correct for a hanging column of water, but the vacuum gauges could only be read to 1 cm Hg and they deteriorated quickly under continuous exposure in the field; the indicator mechanism became unreliable due to sticking.

Meteorological site

Measurements of maximum, minimum, wet and dry bulb temperatures, hours of sunshine, run of wind, rainfall and radiation (Gunn-Bellani radiometer) were made in an enclosure established immediately upwind of the experimental site (Fig. 7).

Open water evaporation was recorded in the enclosure from a raised Kenya type evaporation pan 122 cm in diameter and 43 cm deep covered with chicken wire to keep birds off.

A second meteorological screen was mounted on a strong vertical metal pipe in the field near lysimeter A so that screen height could be adjusted to 30 cm above the crop. Maximum, minimum, wet and dry bulb temperatures in this screen were recorded at the same time as the meteorological site screen temperatures at the edge of the field.

Comparison between temperature and humidity records from the two screens (Table 2) over a period of 4 months didnnot reveal any appreciable differences and the difficult operation of the field screen was discontinued.

Data recorded at the meteorological site were used to calculate the Penman estimate of open water evaporation, Eo, using tables published by McCulloch (1965). Monthly means of the above weather parameters are presented in Appendix 2.

Irrigation

Initially water was pumped from an irrigation canal at the edge of the field into an overhead spray system consisting of a single line of seven sprinkler heads covering a strip 10 m x 100 m. The pump was not large and took 1 hour to apply 6 mm on a strip. Uniformity of application over the central area as assessed by 8 small raingauges was reasonably good, but variations of up to 15% were observed.

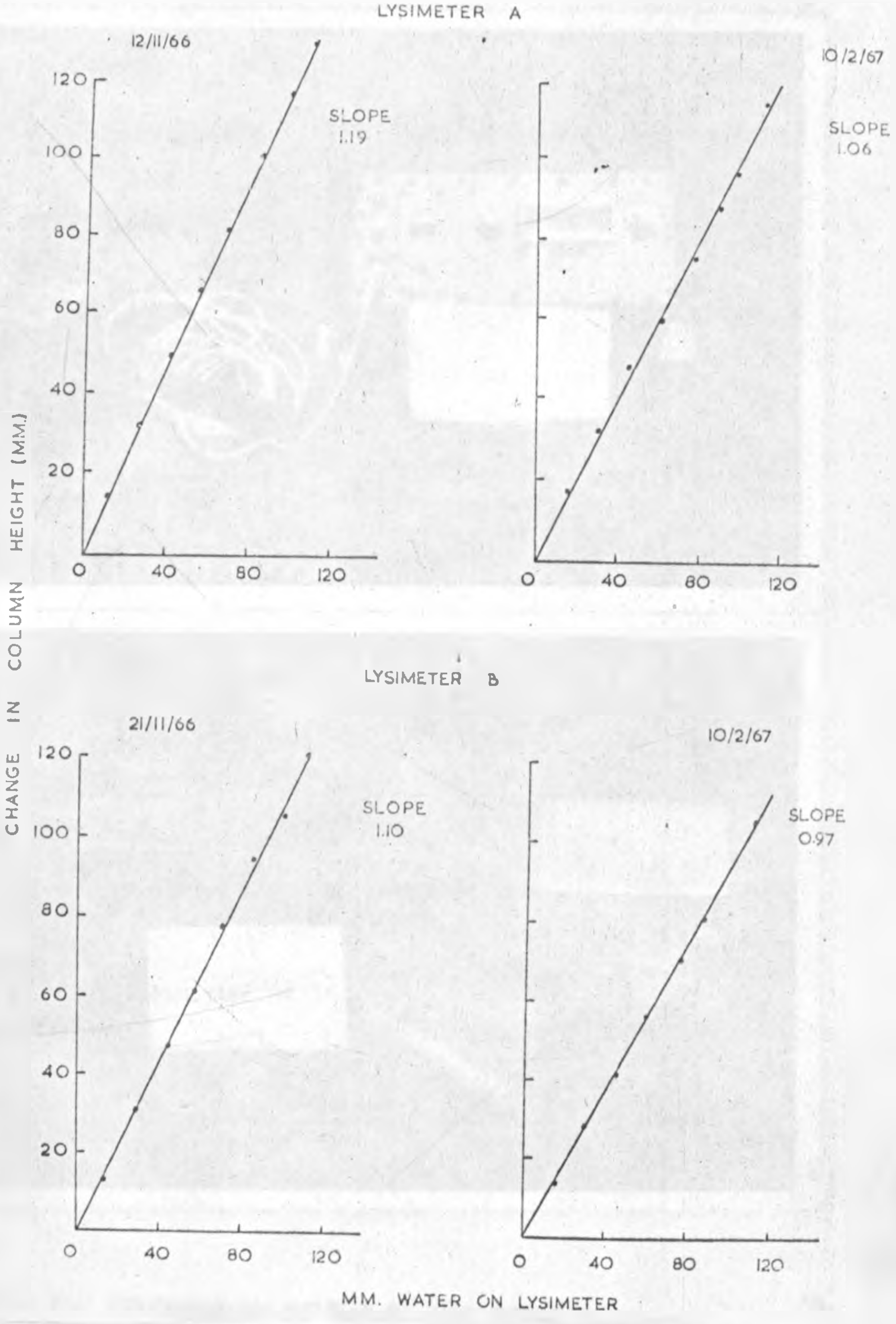


Fig. 3. Sample calibration lines for the two lysimeters

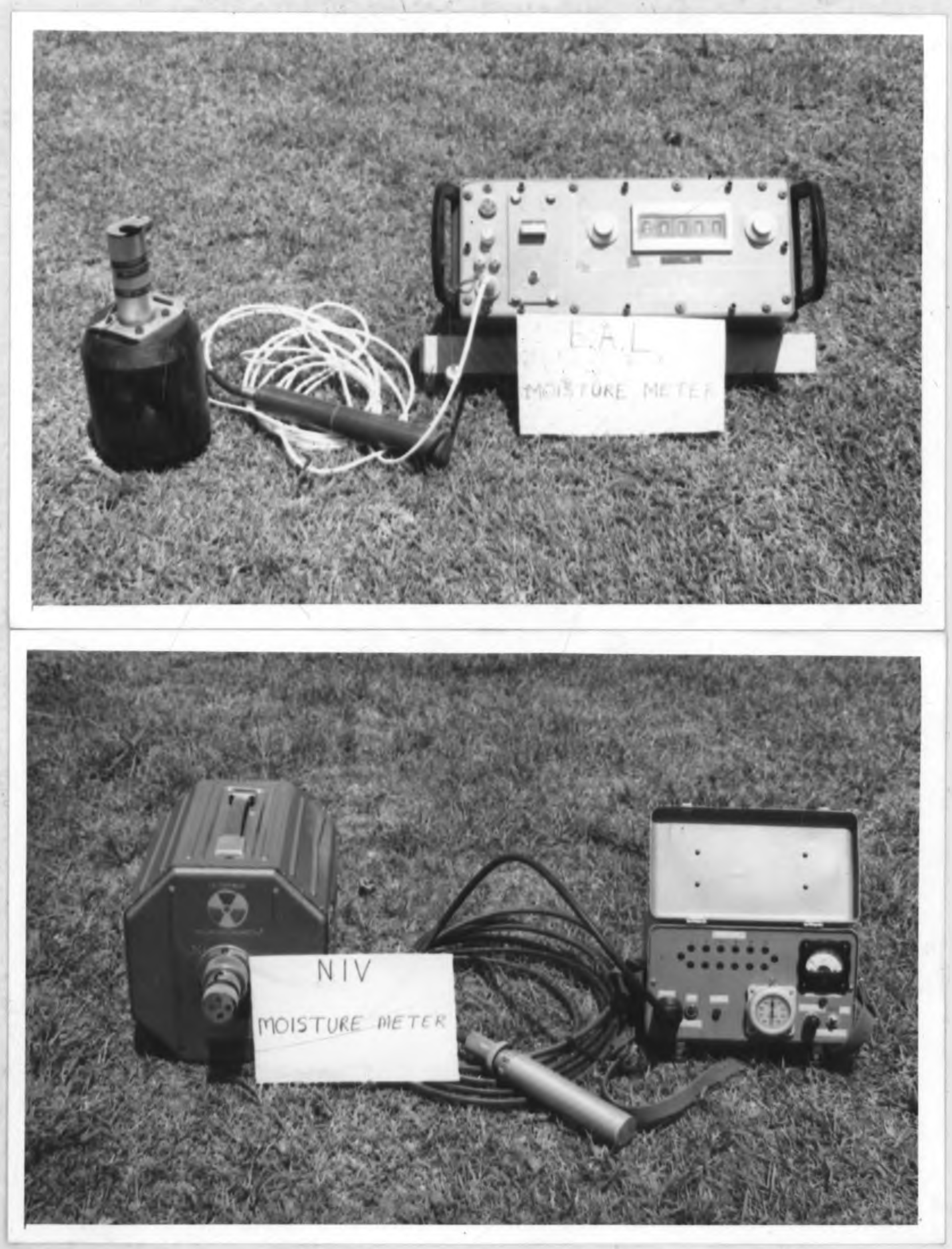


Fig. 4. Photographs of E.A.L. and NIV-I neutron moisture meters

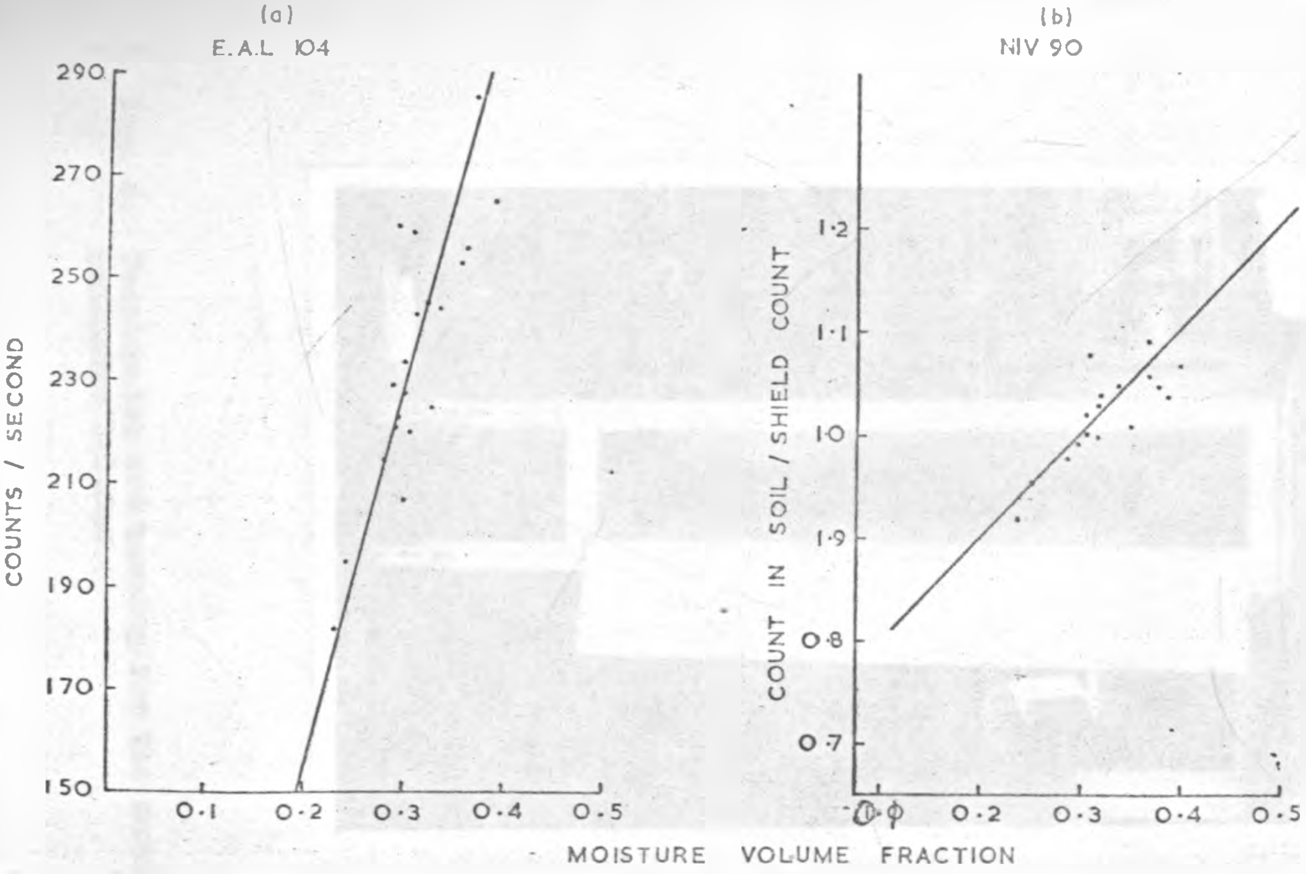


Fig. 5. Calibration of E.A.L. and NIV-I Neutron moisture meter in Mwea soil

Fig. 6. Tensiometer and housing for the mercury manometer columns

Fig. 7. Meteorological enclosure at the eastern edge of the experimental plot. Paddy fields can be seen in the background.

TABLE 2

Comparison between temperature and humidity records from the meteorological site screen (M.S.) and the screen 30 cm above the maize crop (F.S.)

Period 1967	Air temperature						Dewpoint mean of 0900 and 1500 hrs		Saturation deficit mean of 0900 and 1500 hrs		Relative humidity 1500 hrs	
	Max.		Min.		Mean							
	°C.		°C.		°C.		°C.		mm. of mercury		%	
	M.S.	F.S.	M.S.	F.S.	M.S.	F.S.	M.S.	F.S.	M.S.	F.S.	M.S.	F.S.
Sept.	28.2	31.3	14.3	14.7	21.3	22.2	13.4	14.5	7.47	8.68	40	40
Oct.	28.0	27.7	15.8	16.5	21.9	22.1	15.6	17.1	6.42	5.32	48	55
Nov.	26.3	26.6	15.4	16.0	20.9	21.3	17.9	18.3	3.15	3.22	66	66
Dec.	27.2	27.4	12.5	13.2	19.9	20.3	16.2	16.3	3.61	3.97	56	55

Although the capacity of this equipment was sufficient to supply routine irrigation requirements, it soon proved completely inadequate to water the 2 hectares of land within the prescribed experimental schedule and was replaced with a new system. A more powerful motor and more appropriate pump, line pipes and sprinklers were installed. In the new system, two lines of 8 sprinklers covered a strip 25 m x 100 m and applied water at the rate of 10 mm per hour in each strip. The uniformity of water application was reasonable (Table 3) but there was a large discrepancy (approximately 23%) between the amount of water collected in raingauges and the estimated irrigation from the metered application. The flow meter had been calibrated by a commercial firm prior to installation but a check carried out <u>in situ</u> by pumping water into a 490-litre tank revealed that the flow meter overestimated the quantity of water flowing through it by approximately 8%. This left 15% to be accounted for by direct evaporation of the fine sprinkler droplets before they reached the ground. In order to minimise this error, most of the irrigation was therefore

TABLE 3

Uniformity of water application

(a) Typical catches (inches) in nine raingauges distributed in an area 20 ft. x 20 ft. receiving water from four sprinklers spaced 40 ft. x 40 ft. and with spray diameter of 80 ft.; bare ground.

Gauge No.	Irrigation pipe settings					
	1	2	3	4	5	6
1	3.79	5.75	4.39	5.66	4.38	7.34
2	4.59	4.38	9.51	4.42	4.57	5.28
3	3.74	4.39	4.84	3.46	4.14	4.26
4	3.89	3.78	5.55	5.23	4.21	4.04
5	3.68	4.27	4.68	4.93	4.94	5.16
6	3.84	4.32	5.58	4.31	4.88	4.44
7	3.35	3.71	4.98	5.12	5.10	3.79
8	3.65	3.87	5.50	4.52	4.94	5.42
9	4.19	2.81	5.08	4.34	4.85	4.24
Total	34.72	37.28	50.11	41.99	42.01	43.97
Mean	3.86	4.14	5.57	4.67	4.67	4.89
Estimate from flow meter	5.85	5.85	5.85	5.85	5.85	5.85

(b) Catches (mm) in raingauges placed at the subplots in each central plot. Height of maize approximately 30 cm.

Field	Gauge in subplot				Central	Estimate from flow meter
	1	2	3	4		
A	26.4	27.7	29.5	47.8	31.0	57.6
B	20.6	19.8	19.8	21.3	23.1	27.5

carried out at night when evaporation is very low. Suitable exposure for raingauges proved difficult when the maize grew higher than 30 cm, the height of the gauge rim from the ground in normal raingauge exposure.

The first irrigation was applied just before planting and was designed to provide uniform soil moisture conditions throughout the experimental area. After sampling both fields to determine the soil moisture content at all depths up to 180 cm, the profile was brought up to field capacity by irrigation.

The various treatments were intended to be irrigated on the same day each time, applying 1.1 and 0.7 times as much water as had been evaporated in the wet and dry treatments respectively as recorded by the corresponding lysimeter. The above figures were however changed in 1968 from 1.1 and 0.7 to 1.2 and 0.6 to increase the difference in available water in the two treatments. It was not found feasible to irrigate the two fields on the same day, but by shifting the pipes from one field to the other, it was possible to irrigate at least all of the central strips on the same day. The irrigation interval was set at two weeks but varied somewhat because of minor breakdowns in equipment. The sprinkler heads had to be raised on extension pipes as the crop height increased.

Because of heavy rain, no irrigation was necessary during the bean crop.

Cropping seasons

The first crop of maize was planted in September 1967. The maize hybrid H 511, maturing in four months and recommended for altitudes around 5,000 feet, was chosen in an effort to keep the growing season within the period when the surrounding rice fields were flooded, and hence to avoid possible advection effects. All measurements proceeded normally but unusually heavy rain in October removed irrigation treatment effects and the two fields became replicates of the wet treatment. In the following long rains season starting in March 1968, the entire field was planted with beans (*Phaseolus vulgaris* var. Canadian Wonder).

The bean crop was harvested in May and a second maize crop, hybrid H 511, was planted in July 1968.

With the exception of one lysimeter, the equipment did not give trouble and all measurements were made regularly throughout the season. There was very little rain during the major part of the growing season up to maturity and the irrigation treatments were applied throughout.

Land preparation and planting

Before each planting, the land was ploughed and single superphosphate was broadcast at the rate of 382 kg/ha before harrowing. Two maize seeds were planted per hill at 20 cm spacing in rows 1 metre apart. Thinning took place one week after emergence, leaving only one seedling per hill. 560 kg/ha of sulphate of ammonia was applied by hand in two lots - one third as a side dressing on both sides of each maize row at planting and the remaining two thirds along the line halfway between the rows when the maize was 50 cm high. Beans were planted singly at 15 cm spacing in rows 50 cm apart. No fertiliser was applied to the bean crop. The fields were weeded by hand at least twice in the season.

Plant measurements

For each crop of maize, three plants were selected at random in each sub-plot and the lysimeter. Plant heights were measured twice a week and the averages for each plot were calculated.

Crop performance

The 1967 maize crop was adequately supplied with water, germination was 100% and the crop grew uniformly. It was necessary to spray twice with 1% D.D.T. to control stalkborers. The yield from this crop was 5.6 ton/ha. The 1968 maize crop was equally good in germination, uniformity of growth and in yield in the wet and medium treatments. The dry treatment had a good start but growth rate and uniformity of cover were affected after the irrigation treatment was imposed. There was considerable loss of grain due to bird damage and rotting caused by heavy rain at harvest. The bean crop was healthy and grew uniformly. The low yield (1.5 ton/ha) was caused by rotting as a result of heavy rain at harvest time.

Results

Crop water use - lysimeters

Results from the 1967 maize crop are shown in Fig. 8 where Et/Eo is plotted in running averages of two 5-day periods. Lysimeter A received the higher water treatment at the beginning, but the difference was removed by heavy rain later. There was a high peak Et/Eo of up to 1.6 lasting from tasselling to grain formation. A similar presentation (Fig. 9) shows the water use pattern of the bean crop. A broad peak Et/Eo of 1.3 was recorded.

The water use pattern of the 1968 maize crop is shown in Fig. 10. The high peak Et/Eo observed in the 1967 maize crop did not occur; instead there was a gradual increase, with small peaks corresponding to irrigation. It is interesting that the maximum Et/Eo of 1.2 was obtained late in the season when most of the leaves had dried off and hence there was little transpiration, and that this maximum corresponded with the onset of heavy rain (see discussion on evaporation from "wet" and "dry" leaves on page).

The validity of the above measurements is discussed later. In general, the pattern of water use followed the development of leaf area, but the actual relationship between Et/Eo and ground cover was different with each crop. Details of lysimeter data and computation of Et/Eo are contained in Appendices 3, 4 and 5. A neutron moisture meter was not available during the 1967 maize crop. The water use data derived from gravimetric soil sampling are shown in Appendix 6.

Crop water use - neutron moisture meters

The neutron moisture meters used in the 1968 bean crop were the E.A.L. 104 and the NIV-I/90.

Details of estimates of moisture content at different depths in each profile are tabulated in Appendices 7a to 7e.

Taking the NIV-I/90 data first and comparing the data in the last four columns of Table 4, there is little agreement between estimates of Et for both fields and the lysimeter either in individual periods or in totals for the period 1st March to 27th March.

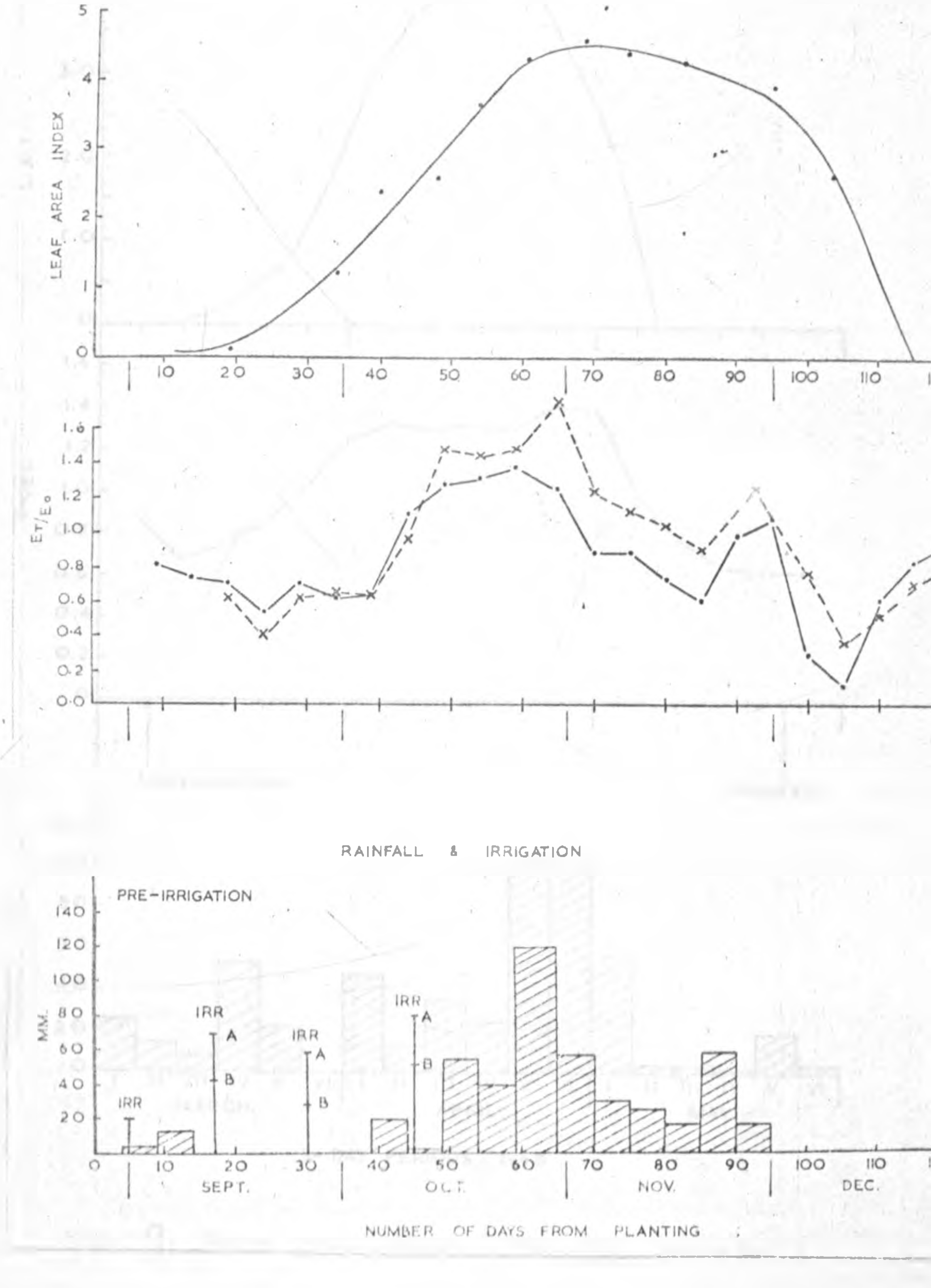


Fig. 8. Water use of maize (1967-68 crop)
in Lysimeter A (.-.) and
Lysimeter B (x----x)

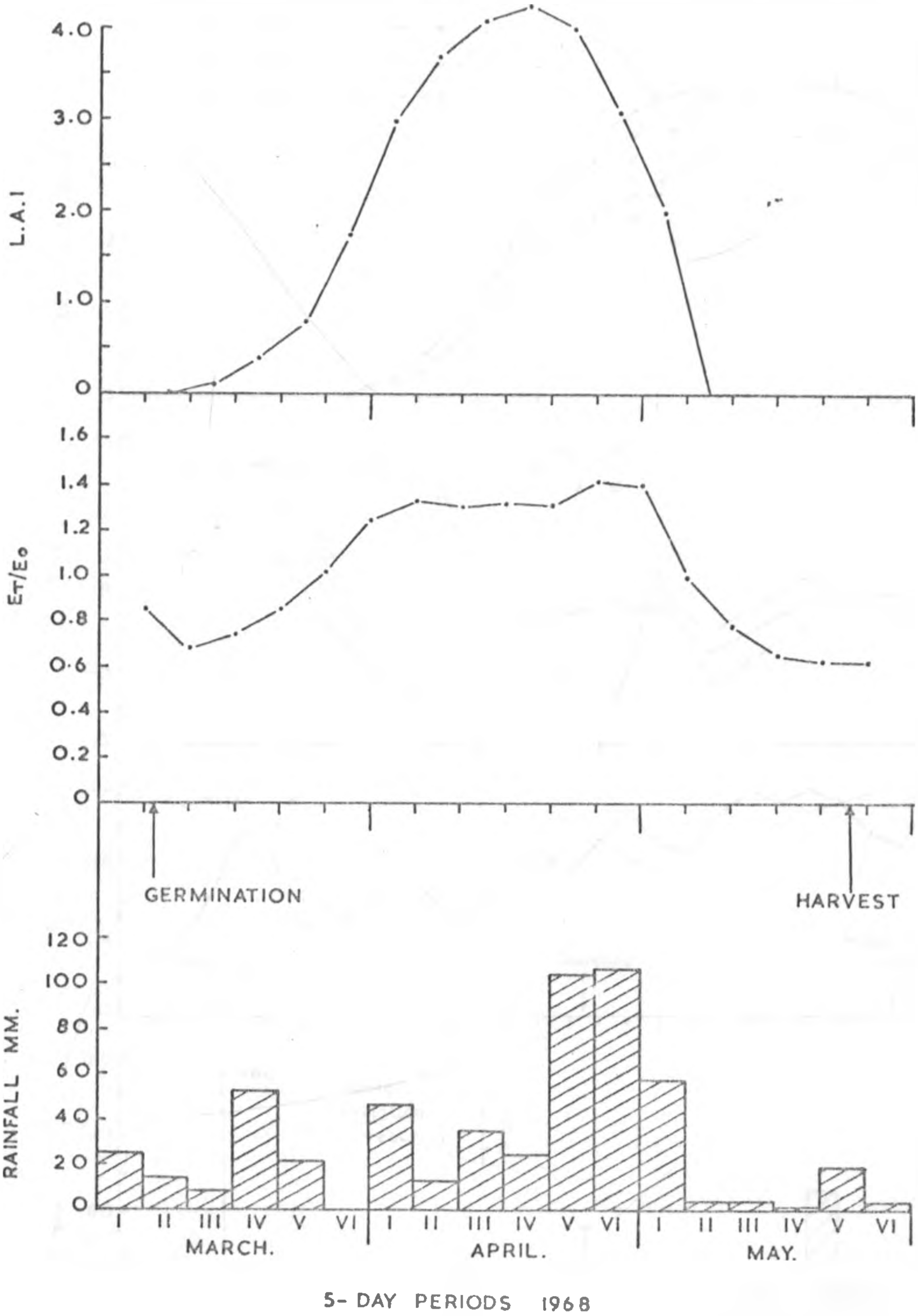


Fig. 9. Water use of beans (1968 crop) Lysimeter A

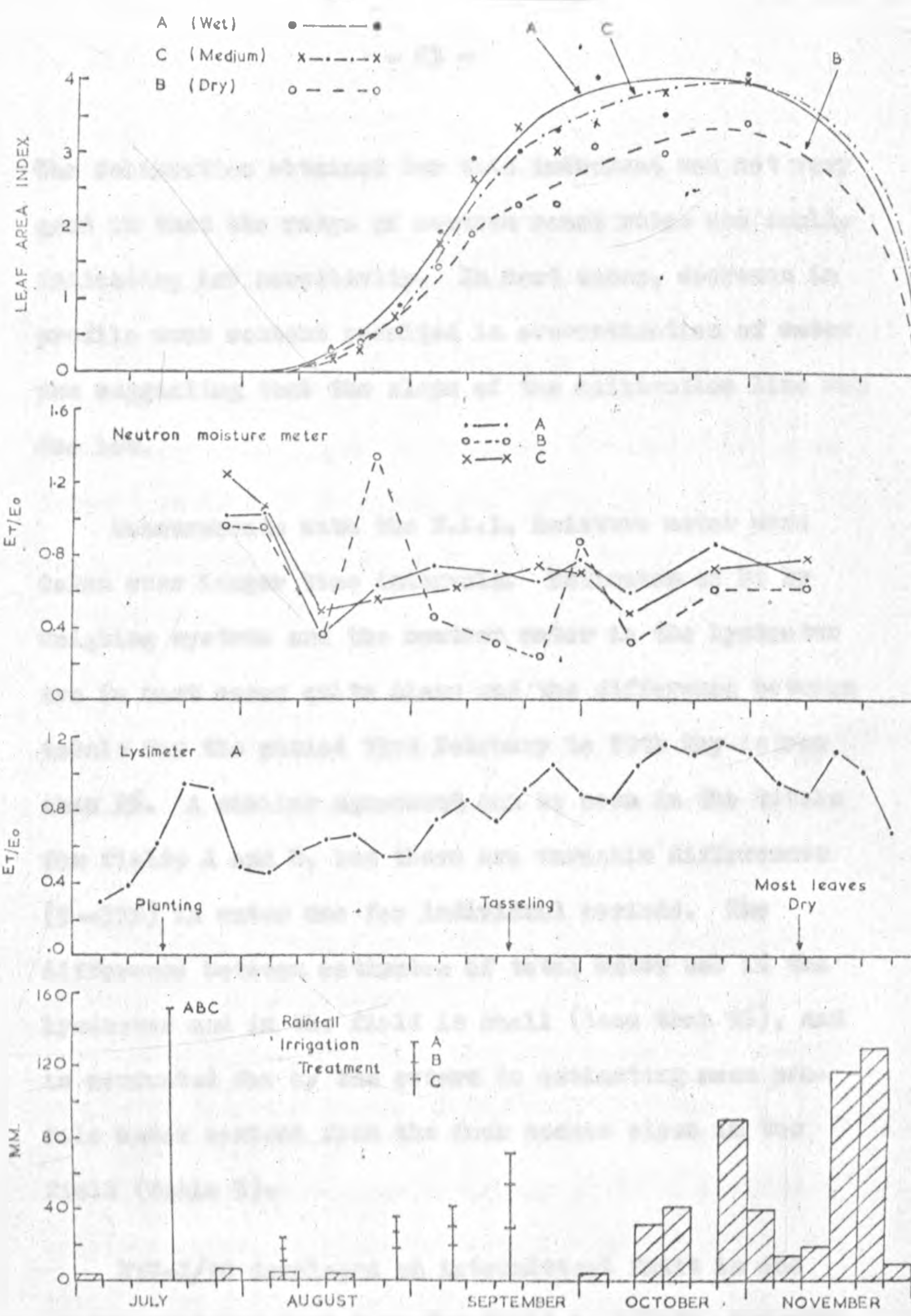


Fig. 10. Water use of maize (1968 crop). Data from Lysimeter A and E.A.L. 104 neutron moisture meter

The calibration obtained for this instrument was not very good in that the range of neutron count rates was small, indicating low sensitivity. In most cases, decrease in profile water content resulted in overestimation of water use suggesting that the slope of the calibration line was too low.

Measurements with the E.A.L. moisture meter were taken over longer time intervals. Estimates of Et by weighing systems and the neutron meter in the lysimeter are in most cases quite close and the difference between totals for the period 23rd February to 29th May is less than 2%. A similar agreement can be seen in the totals for fields A and B, but there are variable differences (3 — 35%) in water use for individual periods. The difference between estimates of total water use in the lysimeter and in the field is small (less than 5%), and is accounted for by the errors in estimating mean profile water content from the four access pipes in the field (Table 5).

NIV-I/90 developed an intermittent fault in one of the switches (see data for field A, 1/3/68, Appendix 7b). NIV-I/96 and E.A.L. 104 were therefore used during the 1968 maize crop. Detailed data for each profile are shown in Appendix 7e. The equivalent NIV-I/90 readings were obtained from the equation

$$\frac{r}{r_s}(\text{NIV-I/90}) = 1.042\,\frac{r}{r_s}(\text{NIV-I/96}) + 0.033$$

derived from an earlier comparison. $\frac{r}{r_s}$ is the ratio of count rate in soil to count rate in shield. The moisture volume fraction was then read off the NIV-I/90 calibration.

Estimates of water use from NIV-I/90 readings proved unsatisfactory and were not comparable with parallel estimates with the E.A.L. moisture meter (Table 6).

The data obtained with E.A.L. 104 are summarised in Table 7, which includes Penman estimate of open water evaporation, Eo, soil moisture tension and tension gradients near the bottom of the soil profile.

A comparison between estimates of Et by neutron moisture meter and lysimeter weighing system (Table 8) shows large differences in individual periods. The

TABLE 4

Comparison between estimates of Et by weighing lysimeter and neutron moisture meters – bean crop 1968

Date 1968	Mean water content of soil profile mm (neutron probe)		Mean w.c. in Lysimeter A mm (probe)	Decrease in total water content mm.			Rainfall mm.	Lysimeter drainage mm.	Et mm.		Et Lysimeter A mm.	
	Field A	Field B		A	B	Lys.A			Field A	Field B	Weighing system	Neutron meter
NIV-90 NEUTRON MOISTURE METER												
1/3	647	644	555*	+53	+18	+25	39.1	-	92.1	57.1	34.6	64.1
9/3	594	626	530	-20	+76	-45	9.1	-	-10.9	85.1	17.1	-35.9
13/3	614	550	575	+13	-66	+17	0.0	-	13.0	-66.0	10.5	17.0
16/3	601	616	558	+24	-2	+7	52.1	-	76.1	50.1	21.2	59.1
20/3	577	618	551	+11	-15	+11	22.9	-	33.9	7.9	28.9	33.9
27/3	566	633	540									
Total							123.2		204.2	134.2	112.3	138.2
EAL 104 NEUTRON MOISTURE METER												
23/2	518	566	509	-118	-122	-130	139.5	-	21.5	17.5	40.8	9.5
6/3	636	688	639	-28	-69	+13	211.6	-	183.6	142.6	231.9	224.6
17/4	664	757	626	-114	-86	-89	198.1	19.8	84.1	112.1	106.7	89.3
2/5	778	843	715	+35	+35	+24	55.9	50.8	90.9	90.9	33.4	29.1
8/5	743	808	691	+67	+78	+36	31.8	8.5	98.8	109.8	73.1	59.3
29/5	676	730	655									
Total							636.9	79.1	478.9	472.9	485.9	411.8

*estimated from Lysimeter B

TABLE 5

Errors due to spatial variation in the estimates of average Et by the neutron moisture meter

1968 Bean Crop

Date 1968	Soil moisture content Average of 4 profiles in Field A		Decrease in total water content		Et	
	mm.	Standard Error ± mm.	mm.	Standard Error ± mm.	mm.	Standard Error ± mm.
N.I.V. 90						
1/3	647	7	+53	9.9	92.1	9.9
9/3	594	7	-20	9.9	-10.9	9.9
13/3	614	7	+13	13.9	13.0	13.9
16/3	601	12	+24	16.3	76.1	16.3
20/3	577	11	+11	21.9	33.9	21.9
27/3	566	19				
Total			+81	20.3	204.2	20.3
E.A.L. 104						
23/2	518	9	-118	15.0	21.5	15.0
6/3	636	12	-28	15.0	183.6	15.0
17/4	664	9	-114	17.5	84.1	17.5
2/5	778	15	+35	21.2	90.9	21.2
8/5	743	15	+67	20.5	98.8	20.5
29/5	676	14				
Total			-158	16.6	478.9	16.6

TABLE 6

Comparison between estimates of Et by the E.A.L. and N.I.V. neutron moisture meters

Period 1968	Field A		Field B		Field C	
	EAL mm	NIV mm	EAL mm	NIV mm	EAL mm	NIV mm
7/8 - 21/8	18.6	200.8	18.1	-27.8	25.0	-
21/8 - 28/8	22.6	13.2	47.5	33.3	19.6	56.0
28/8 - 11/9	61.1	115.5	37.5	190.4	82.8	73.9
Total	102.3	329.5	103.1	195.9	127.4	

TABLE 7

CROP WATER USE ESTIMATED FROM NEUTRON MOISTURE METER READINGS

(EAL 104, MAIZE CROP)

Period 1968	Et (mm)			Penman Eo (mm)	Et/Eo			MEAN soil moisture tension T and Tension gradient $\frac{dT}{dz}$ at 160 cm. depth*					
	Field A	Field B	Field C		Field A	Field B	Field C	Field A		Field B		Field C	
								T	$\frac{dT}{dz}$	T	$\frac{dT}{dz}$	T	$\frac{dT}{dz}$
23/7 - 31/7	31.0	29.1	37.8	30.3	1.02	0.96	1.25	-	-	-	-	242	5.0
31/7 - 7/8	28.0	25.9	29.1	27.2	1.03	0.95	1.07	146	0.4	151	-0.6	251	4.4
7/8 - 21/8	18.6	18.1	25.0	49.7	0.37	0.36	0.50	155	0.5	140	-0.1	279	4.4
21/8 - 28/8	22.6	47.5	19.6	35.2	0.64	1.35	0.56	156	0.9	163	-1.5	312	3.9
28/8 - 11/9	61.1	37.5	84.5	81.8	0.75	0.46	0.63	160	0.7	145	-6.5	315	4.1
11/9 - 19/9	38.5	17.1		53.4	0.72	0.32		163	0.9	120	-7.7		
19/9 - 26/9	53.3	12.7	37.5	50.1	0.66	0.25	0.75	161	1.0	115	-7.5	420	-3.1
26/9 - 3/10	43.0	47.8	38.4	54.1	0.79	0.88	0.71	165	1.3	135	-5.1	416	-0.1
3/10 - 15/10	51.6	27.3	42.8	86.6	0.60	0.32	0.49	170	2.0	143	-5.9	510	-0.7
15/10 - 31/10	84.1	59.5	70.7	96.9	0.87	0.61	0.73	179	3.5	196	2.5	563	-1.2
31/10 - 19/11	71.6	65.5	82.7	106.3	0.67	0.62	0.78	-	-	163	4.7	420	12.8

*110 cm. in Field C

TABLE 8

Comparison between estimates of Et by neutron method (E.A.L.104) and the weighing system in the lysimeter

Period 1968	Et (Lysimeter A)		Et (Field A)
	weighing system mm	neutron meter mm	neutron meter mm
23/7 - 31/7	24.9	1.8	31.0
31/7 - 7/8	9.4	7.1	28.0
7/8 - 21/8	25.8	26.5	18.6
21/8 - 28/8	19.0	33.7	22.6
28/8 - 11/9	61.5	55.7	61.1
11/9 - 19/9	40.1	26.1	38.5
19/9 - 26/9	50.2	62.7	33.3
26/9 - 3/10	52.4	27.8	43.0
3/10 - 15/10	81.3	73.7	51.6
15/10 - 31/10	118.6	80.4	84.1
31/10 - 19/11	101.9	79.4	71.6
Total	585.1	474.9	483.4

totals for the season differ by 20%. As observed earlier, precision in estimating Et in the field by the neutron moisture meter is reduced considerably by spatial variability of soil moisture profiles (see Appendix 7). This variability was increased by the uneven distribution of irrigation water.

Another source of error is the gravimetric determination of soil moisture content in the top 20 cm, where the loss of neutrons imposes a limitation to the use of the neutron moisture meter. In the early stages of growth and whenever the soil surface is wet, evaporation from this layer of soil may constitute as much as 90% of total Et. An experiment was carried out to determine the error introduced in this way. Ten soil samples at 5 cm and ten samples at 15 cm were taken at the same time within an area of 100 cm radius centred on one of the access pipes. The standard error of the mean moisture volume fraction was 0.01, i.e. 2 mm in 20 cm of soil and the standard error of difference between two such estimates would be 0.014, i.e. 2.8 mm in 20 cm of soil. A time interval of at least 10 days at 6 mm/day evaporation is therefore required if error due to this source alone is to be reduced below 5%.

A check was also made on the precision with which moisture content could be determined at a particular level in the soil. Ten readings were taken in succession with NIV-I and E.A.L. moisture meters both at 30 cm depth in soil and in their respective shields. From these readings, means of two successive readings were calculated, this being the normal procedure in the field.

The results summarised in Table 9 suggest that greater precision was achieved with E.A.L. than with NIV-I moisture meters. Since there was no systematic change in shield count rate, calibration of E.A.L. moisture meter was based on count rate in soil, and moisture contents in the field were obtained from this calibration without reference to shield count. The shield count was nevertheless recorded twice on each day of field measurements as a check on the performance of the equipment.

<u>Soil moisture tension</u>

The data obtained with tensiometers are contained in Appendix 8. Average gradients of soil moisture <u>tension</u> have been calculated but, for reasons discussed

TABLE 9

Precision in estimates of profile water content by the neutron moisture meter

Description of error	NIV 96	BAL 104
No. of readings taken	10	10
No. of means of 2 successive readings	9	9
Coefficients of variation		
(a) counts in soil (R)	0.84%	0.65%
(b) counts in shield (R_s)	1.85%	0.67%
(c) $\frac{R}{R_s}$	2.03%	0.935%
Mean $\frac{R}{R_s}$	0.978	0.466
Standard error (S.E.):		
$\frac{R}{R_s}$	0.0066	0.0044
Moisture volume fraction	0.008	0.003
mm/20 cm soil	1.6	0.6
mm/soil profile	12.8	4.8
mm/period, i.e. difference between 2 profiles	18.1	6.8

in the previous section, no attempt has been made to calculate drainage from these data.

Yield

Grain yields obtained in the sub plots and the lysimeters are shown in Tables 10 and 11.

Discussion of Results

Reliability of lysimeters

The validity of the crop water use data and the assessment of the performance of the neutron moisture meters depend on the reliability of the operation of the lysimeter system which is therefore discussed first. There are three main factors involved:

1. The accuracy and sensitivity of the measuring system;

2. The stability of the balancing column over long periods;

TABLE 10

Yield of experimental plots - 1967 maize crop

Treatments and plots	Weight of dry grain kg	Yield ton/ha	Weight of dry stalk kg
Lysimeter A	1.56	3.9	3.4
A-subplots:			
A	1.42		2.4
B	2.19		2.8
C	1.57		4.3
D	1.37		3.4
Average	1.64 (1.45)*	4.1 (3.7)*	3.2
Lysimeter B	1.58	3.9	5.5
B-subplots:			
E	1.27		3.7
F	1.42		3.4
G	1.55		2.4
H	1.62		3.6
Average	1.46	3.7	3.3

Total grain yield from both fields = 10.8 metric ton
Weight of 1,000 grain at 14% mc. = 3.27 kg.

*Excluding the high value of 2.19

TABLE [illegible] 11

Maize yields in the 1968 experiment

Treatment	Field	Plot	gm/plot of 10 plants	kg/ha	weight of 1,000 grains gm	No. of cobs per plant
WET	A	AA	3,018		475.1	1.9
		AB	3,173		446.8	2.1
		AC	2,814		455.6	2.0
		AD	3,572		437.3	2.3
		Mean	3,144	7,860	453.7	2.1
		Yield from 2 rows		4,562		
MEDIUM	C	CI	3,609		447.3	2.0
		CJ	2,943		458.4	2.1
		CK	1,911		455.4	2.3
		CL	3,003		427.8	2.3
		Mean	2,867	7,168	447.2	2.2
		Yield from 2 rows		4,812		
DRY	B	BE	2,779		413.8	2.5
		BF	2,704		424.9	2.1
		BG	2,000		435.4	2.3
		BH	2,993		435.6	2.3
		Mean	2,619	6,548	427.4	2.3
		Yield from 2 rows		2,611		

3. The degree to which the crop in the lysimeter represents the field crop in ontogeny, behaviour and constraints.

The first factor is discussed by Forsgate, Hosegood and McCulloch (1965) for the lysimeters used in this experiment. The balancing column could usually be read easily to 0.5 mm, but fluctuations due to wind sometimes increased this to 1 mm. This can be serious in daily readings but less so in 5-day or 10-day totals. There was little change in sensitivity and error from this source was reduced by using monthly calibrations in the conversion of column readings to water use.

A much more serious source of error was the zero drift, i.e. systematic changes in column height unrelated to changes in the weight of the tank. This could be checked easily before planting by covering the lysimeter with tarpaulin and observing any movement in the balancing water column. This check was carried out in 1967 but the period was cut short by planting date for the maize crop, and no conclusion can be drawn from data obtained. The only check that could be applied with a crop on the lysimeter was by assuming that the tank and contents would return to the same weight each time the soil was wetted to field capacity. The main difficulty was to decide when this condition was achieved and the start and end of drainage were chosen as the most reliable criteria in this experiment. These checks facilitated critical evaluation of lysimeter data as shown in Table 12 below:

TABLE 12

Column height (cm) corresponding to approximate field capacity conditions in the lysimeters

Date	Lysimeter A	Date	Lysimeter B
5.9.67	33.2	14.9.67	79.1
1.10.67	24.5*	22.9.67	75.0
9.11.67	26.6	28.10.67	75.2
1.12.67	26.5	10.11.67	71.2
		30.11.67	52.5

*possibly underestimated

The data in Table 12 show a fall in column in lysimeter A in September, but the lysimeter was stable from

1st October to the end of the season. Lysimeter B was less satisfactory, starting off with a rapid drop in column. The lysimeter data are reasonable between 22nd September and 28th October, doubtful between 28th October and 24th November, and reliable from November 26th to the end of the season. A sudden column drop of 21.6 cm occurred on 25th November in spite of 39.4 mm of rain on this day. The five-day period following this day has been removed from Et/Eo calculations. The calibration factor changed from 0.88 to 0.98 mm on lysimeter/mm change in column. This reduction in sensitivity implies an increase in the bearing area on the bolsters possibly caused by a slight shift of the lysimeter.

Both lysimeters were covered with tarpaulin after harvesting the crop in January 1968. The data obtained over a period of 38 days are plotted in Fig. 11 together with mean and maximum air temperatures. These data show fall in column equivalent to about 0.5 mm/day in lysimeter A. It is possible that this much evaporation managed to escape through imperfections in the tarpaulin cover. Data from lysimeter B show large variations apparently correlated with temperature. Although an attempt

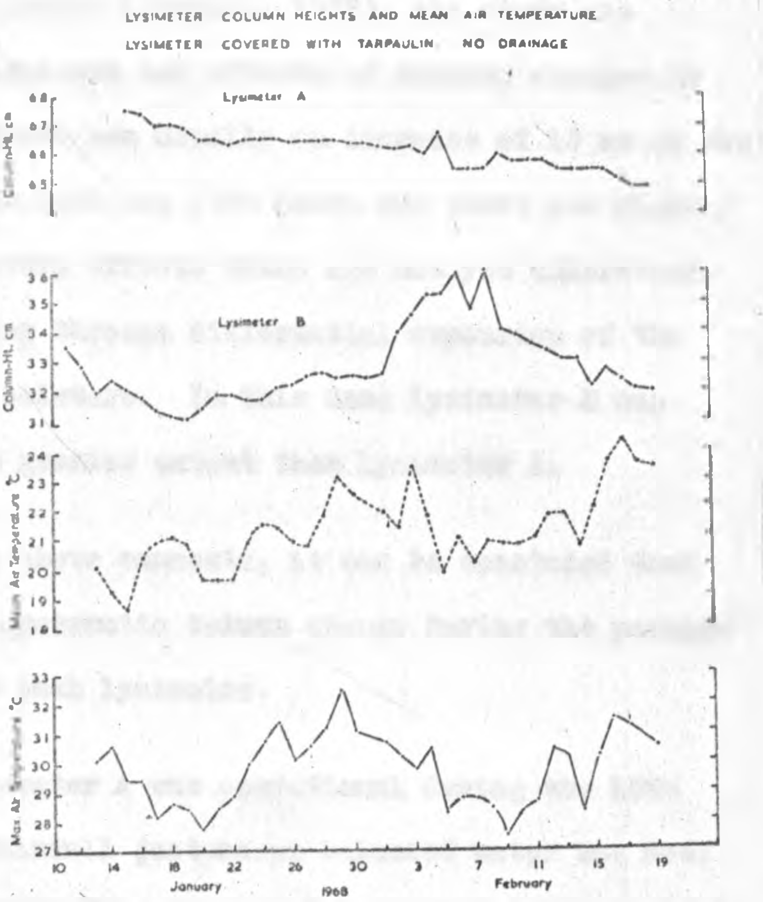


Fig. 11. Lysimeter column height and mean air temperature. Lysimeter covered with tarpaulin and no drainage recorded.

has been made to study temperature response of the hydraulic lysimeter (Wangati, 1965), the study was limited to magnitude and effects of density changes in the water. There was usually an increase of 10 mm on the column between 0900 and 1500 hours but there are clearly other temperature effects which are not yet understood, possibly acting through differential expansion of the tank and the bolsters. In this case lysimeter B was affected to a greater extent than lysimeter A.

From the above comments, it can be concluded that there was no systematic column change during the periods specified for each lysimeter.

Only lysimeter A was operational during the 1968 bean crop. Rainfall just about balanced water use most of the time during the crop, and lysimeter column height at field capacity (82.0 cm on 28th April and 80.0 cm on 14th May) was sufficiently consistent. Column height with the lysimeter under tarpaulin cover at the end of the season showed satisfactory stability (72.8 cm on 11th June, 73.3 cm on 25th June).

Although the check with tarpaulin cover after the bean crop had been harvested did not show any drift in the lysimeter column, column height at estimated field capacity conditions during the 1968 maize crop showed a decrease from 76.0 cm on 26th July to 70.0 cm on 21st November. This means a possible error of 0.5 mm/day in the lysimeter estimate of crop water use.

Another source of error occurred after heavy irrigation. The column took a long and variable time to reach maximum height and then fell suddenly. The data recorded on days of irrigation have therefore had to be discarded and the average for the five-day period used.

The degree to which the lysimeter crop is represented raises problems of a more fundamental nature. When functioning properly, the lysimeter gives an accurate pattern of water use for the crop in the lysimeter. The extent to which this pattern represents the behaviour of a real field crop depends entirely on the differences in soil profile and energy balance between the field and the lysimeter. The results from growth measurements in this experiment (Figs. 12 and 13) are a good demonstration of the difficulty in establishing a representative crop in the lysimeter. It was impossible to pack the soil in the lysimeter to the same density as in the field and the water holding capacity of the lysimeter soil was higher. This might have encouraged faster growth in the lysimeter crop and although the difference was not noticeable in the short bean crop, large differences were recorded with the maize crop.

The difference in height between lysimeter and field crops can affect estimates of crop water use in the lysimeter in two ways:

(a) Increased turbulence is likely to occur within the projecting lysimeter crop. This would tend to decrease boundary layer resistance to evaporation, particularly at high wind speeds, and could increase evaporation from the lysimeter considerably in advective conditions. This effect is considered unimportant because of the low wind speed and non-advective conditions at the experimental site.

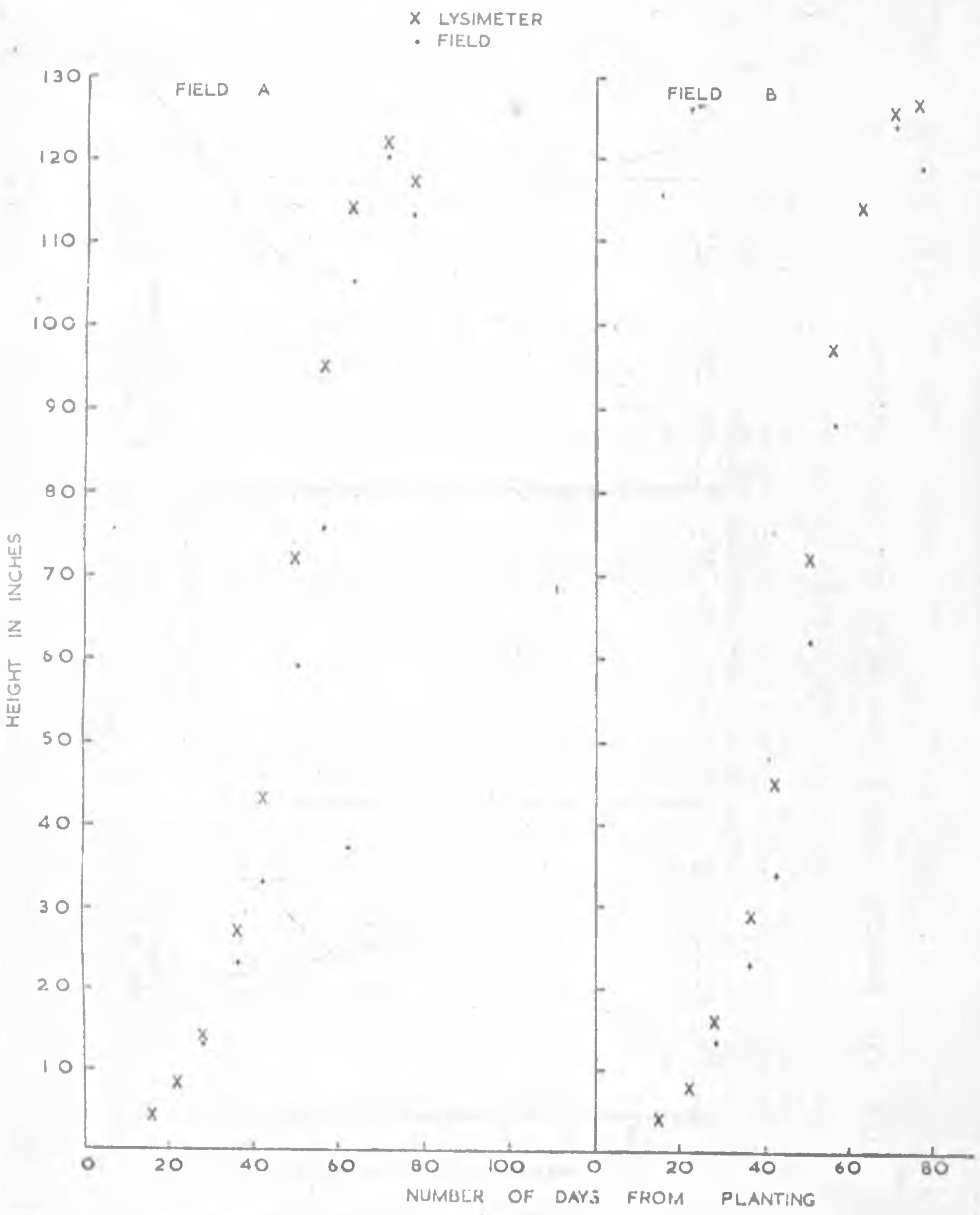


Fig. 12. Average height of maize in the 1967 experiment

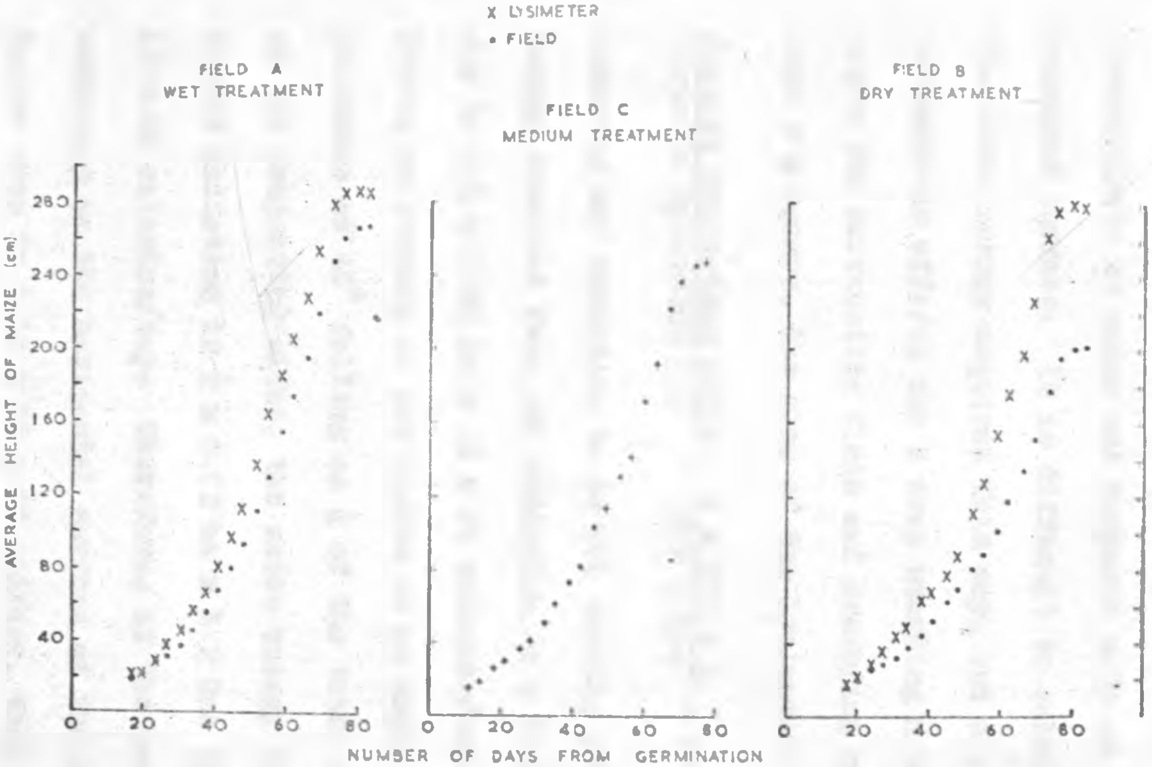


Fig. 13. Average height of maize in the 1968 experiment

(b) The radiation absorbed by the projecting sides of the lysimeter crop can give rise to overestimate of water use compared with an extended surface. It is difficult to calculate the extra energy acquired this way, but a rough estimate is offered for a crop standing h cm above the surrounding field and occupying an area 2 m square, the size of the lysimeter.

$$\frac{\text{Area of projecting sides}}{\text{Area of lysimeter (A)}} = \frac{4 \times 200 \times h}{200 \times 200} = 0.02\ h$$

Assuming sky radiation to be 0.1 Ly/min, extra energy absorbed from sky radiation in a 12 hour day is $0.1 \times 0.02\ hA \times 12 \times 60$ calories/day. Taking an average of 1.2 Ly/min at an angle of incidence of 45° falling on ¼ of the total area of the projecting sides, the extra energy from direct radiation is $\frac{1}{4} \times 0.02\ hA \times 1.2 \cos 45^\circ \times 12 \times 60$ calories/day. Therefore, if the total radiation on the horizontal surface of the lysimeter crop is $1.1A \times 12 \times 60$ cal/day, then the extra energy absorbed by the crop is given by

$$\frac{0.0042\ hA \times 12 \times 60}{1.1A \times 12 \times 60} = 0.38h\%.$$

TABLE 13

Summary presentation of errors due to zero drift in manometer and differences between the height of lysimeter and field crops

Crop:	1967 maize crop						1968 maize crop				
Lysimeter:	A	B	A	B	A	B	A				
Month:	Oct.	Oct.	Oct.	Oct.	Oct.	Oct.	October		November		
10-day period:	I	I	II	II	III	III	II	III	I	II	III
% error in Et due to:											
*a. zero drift	0	0	0	0	0	0	7	6	10	8	22
**b. projecting lysimeter crop	4	7	13	10	19	7	8	8	8	8	8
Total	4	7	13	10	19	7	15	14	18	16	30
Average Et/Eo	0.80	0.80	1.30	1.40	1.40	1.60	1.20	1.20	1.10	1.10	0.80
Corrected Et/Eo	0.77	0.74	1.13	1.39	1.14	1.49	1.02	1.03	0.90	0.92	0.56

*Assuming that zero drift was constant with time

**Assuming that all the extra energy was converted to latent heat

From the above calculation, the extra energy absorbed by the 1967 maize crop (h = 35 cm) was 13%, and for the 1968 maize crop (h = 30 cm), 8% in the wet treatment and 30% in the dry treatment (h = 80 cm).

The above analysis shows that the differences between the height of lysimeter and field crop could have resulted in considerable extra energy falling on the lysimeter crop. The partition of this extra energy into sensible and latent heat is however uncertain, and the actual increase in evaporation is likely to be less than the increases in energy shown above. The effects of these sources of error on Et/Eo are summarised in Table 13.

Evaporation from wet and dry leaves

The high Et/Eo values obtained in these experiments cannot therefore be explained entirely in terms of lysimeter performance, advection and differences in the height of the lysimeter and field crops. One factor which has not been considered so far is the evaporation of intercepted water. Peak Et/Eo occurred in periods of heavy rain which, for the 1967 maize crop, coincided with tasselling, silking and maximum ground cover. For the 1968 maize crop, this peak was absent at the tasselling-silking stage of development, but occurred with the onset of heavy rain when the leaves were drying off, i.e. when the expected transpiration rate would be very low and decreasing. This observation calls for a discussion of the role of aerodynamic and internal resistances in crop water use.

The process of evaporation is the same whether this takes place at an open water surface or the surface of a leaf of a transpiring plant. The rate of evaporation is in all cases governed by the rate of energy input and the resistance to flow of water vapour from the evaporating surface to the surrounding air.

For a surface where the vapour pressure is equal to the saturation vapour pressure at surface temperature, it can be shown (Monteith, 1965b) that

$$\lambda E_w = \frac{\Delta H_w + \rho c\{es(T) - e\}/r_a}{\Delta + \gamma} \qquad \ldots\ldots(2{:}1)$$

where E_w = evaporation rate (gm.cm^{-2}sec^{-1})

λ = latent heat of evaporation (cal.gm^{-1})

Δ = slope of saturation vapour pressure/temperature curve (mb.^{o}C^{-1}) at the mean of wet bulb temp. of the air and the surface temp.

H_w = net radiation (cal.cm^{-2}sec^{-1})

ρ = density of air (gm.cm^{-3})

c = specific heat of air at constant pressure (cal.gm^{-1} ^{o}C^{-1})

es(T) = saturation vapour pressure (mb) at temp. T

e = vapour pressure of the atmosphere (mb)

γ = psychrometric constant (mb.^{o}C^{-1}) given by $\frac{CpP}{\epsilon\lambda}$ where Cp = specific heat of dry air (per unit volume) at constant pressure, P = atmospheric pressure, and ϵ is ratio of density of water vapour to that of dry air at the same temperature and pressure (0.662).

r_a = aerodynamic resistance (sec.cm^{-1}). $\frac{1}{r_a}$ is defined as the rate in which 1 cm^3 of air exchanges heat, vapour or momentum with 1 cm^2 of the evaporating surface.

The subscript w indicates free water on the evaporating surface.

For a dry leaf surface, Monteith (1965b) also showed that

$$\lambda E_d = \frac{\Delta H_d + \rho c\{es(T) - e\}/r_a}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad .....(2:2)$$

where the subscript d indicates a surface where vapour pressure is less than saturation vapour pressure at surface temperature and r_s is resistance to diffusion of water vapour through the stomata, to be known simply as internal resistance.

If the reflection coefficients for the two surfaces arethe same, the only significant difference between H_d and H_w would be due to differences in surface radiative temperature, the wet surface being cooler than the dry. However, as long as there is adequate soil moisture, the "dry" leaf surfaces are unlikely to attain a temperature sufficiently higher than the "wet" leaf surfaces for this factor to be significant.

Monteith (1965b) argued that since the degree of wetness on the leaf during most of the day had very little effect on their reflection coefficient for solar radiation, H_d could be equated with H_o and hence

$$\frac{E_w}{E_d} = \frac{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}{\Delta + \gamma} \qquad \text{......(2:3a)}$$

The values of $\frac{E_w}{E_d}$ would therefore depend on mean air temperature (for Δ), mean air temperature and altitude (for γ), and $\frac{r_s}{r_a}$.

Monteith's method can be extended to give $\frac{E_d}{Eo}$ where Eo is the open water evaporation, provided aerodynamic resistance for open water surface (r_{a_1}) is known. It is, however, now necessary to maintain the identity of H_d and H_o, since the albedo for the two surfaces may be quite different.

Following from equations (2:1) and (2:2) above,

$$\lambda Eo = \frac{\Delta H_o + \rho c\{es(T) - e\}/r_{a_1}}{\Delta + \gamma} \qquad \text{.....(2:3b)}$$

and combining (2:2) and (2:3b), we have

$$\frac{E_d}{Eo} = \left\{\frac{\Delta H_d + \{es(T) - e\}\rho c/r_a}{\Delta H_o + \{es(T) - e\}\rho c/r_{a_1}}\right\}\left\{\frac{\Delta + \gamma}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}\right\}$$

$$\text{.....(2:4)}$$

The components of total net radiation H are given by

$$H = (1 - \alpha)R + L_D - L_U \qquad \text{.....(2:5)}$$

where D and U represent downward and upward fluxes of long wave radiation.

Monteith and Szeicz (1961) obtained the equation

$$L_D - L_U = \frac{b}{a} - H\left(\frac{1 - a}{a}\right) \qquad \text{.....(2:6)}$$

or $$L_D - L_U = L = \frac{b}{a} - \beta H \qquad \text{.....(2:7)}$$

where the constant β could be regarded as a heating coefficient, and if $L = L_o$ when $R = 0$, then

$$H_d = \left(\frac{1 - \alpha}{1 + \beta}\right)R + L_o \qquad \text{.....(2:8)}$$

The factor $L_o = L_D - L_U$ at mean air temperature T_a may be calculated from

$$L_o = (1 - C)L_D + C\sigma(T_a - 2)^4 - \sigma T_a^{\ 4} \qquad \text{.....(2:9)}$$

On cloudy days ($C \rightarrow 1$), $\frac{L_o}{R}$ becomes very much smaller than $\frac{1 - \alpha}{1 + \beta}$ and can be neglected.

A comparison of published values of β by Idso, Baker and Blad (1969) suggests an average value of β close to

0.096 for several crops. Therefore, for $\alpha = 0.20$, the coefficient of R in equation (2:8) becomes 0.73.

In the case of an open water surface, the ratio of daily back radiation component to the net short wave radiation in the Penman formula was approximately 0.12 at Mwea; hence

$$H_o \bumpeq (1 - \alpha_o)R - 0.12R \qquad \ldots\ldots(2{:}10)$$

and for $\alpha_o = 0.05$, $H_o \bumpeq 0.83R$.

If, however, the assumption is made that the main difference between H_d and H_o is in the albedo ($\alpha_d = 0.20$, $\alpha_o = 0.05$), equation (2:4) becomes:

$$\frac{E_d}{E_o} = \left\{\frac{0.80\,\Delta R + \rho c\{es(T) - e\}/r_a}{0.95\,\Delta R + \rho c\{es(T) - e\}/r_{a_1}}\right\}\left\{\frac{\Delta + \gamma}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}\right\} \qquad \ldots\ldots(2{:}11)$$

where R is now the incoming radiation ($\mathrm{cal.cm^{-2}sec^{-1}}$), and

$$\frac{E_w}{E_o} = \frac{E_w}{E_d}\,\frac{E_d}{E_o} = \left\{\frac{0.80\,\Delta R + \rho c\{es(T) - e\}/r_a}{0.95\,\Delta R + \rho c\{es(T) - e\}/r_{a_1}}\right\} \qquad \ldots\ldots(2{:}12)$$

The corrections contained in (2:8) and (2:10), if applied to (2:11) and (2:12) would result in 10-15%

increase in $\frac{E_w}{Eo}$ and $\frac{E_d}{Eo}$, but because of the uncertainties in almost all the long wave radiation factors, these corrections are omitted in the following treatment.

Values of r_a, r_{a_1} and r_s

Representative values of r_a, r_{a_1} and r_s are required before proceeding with (2:11) and (2:12). These measurements are rare and an attempt was made in this experiment to derive r_a from wind profiles, assuming neutral stability, above a mature maize crop. The details of these measurements can be found in Appendix 9. The result was that during the four days of investigation, the value of r_a changed with diurnal variation in windspeed. r_a was highest (0.12 - 0.15) in the morning before 1100 hrs. and decreased to 0.03 in the afternoon. These values can only be approximate and an average of 0.10 would presumably be valid for a large part of the day. No measurements are available for the bean crop (30 cm high) but a value near 0.15 may be representative.

Similar windspeed profile measurements over open water were not possible and it is necessary to estimate value of r_{a_1} from the Penman equation.

The expression used by McCulloch (1965) for the computation of Penman Eo (open water evaporation) is

$$
\begin{aligned}
Eo = \frac{\Delta}{\Delta + \gamma} & \left\{ R_a(1 - r)(0.29 \cos \phi + 0.52 \frac{n}{N} \right\} \\
& - \frac{\Delta}{\Delta + \gamma} \left\{ \sigma T_a{}^4 (0.10 - 0.90 \frac{n}{N})(0.56 - 0.08\sqrt{e}) \right\} \\
& + \frac{\gamma}{\Delta + \gamma} \left\{ 0.26(1 + \frac{h}{20,000})(1 + \frac{u}{100})(es(T) - e) \right\}
\end{aligned}
\qquad .....(2:13)
$$

h = altitude (metres)

u = windspeed (miles per day).

Comparing (2:13) with (2:3b), and recognising that the term $\frac{e_c}{\Delta + \gamma}$ has to be modified to take account of altitude,

$$
\begin{aligned}
& (1 + \frac{h}{20,000}) \frac{\gamma}{\Delta + \gamma} \left\{ 0.26(1 + \frac{u}{100})(es(T) - e) \right\} \text{ mm/day} \\
& = \frac{e_c}{\Delta + \gamma}(1 + \frac{h}{20,000}) \frac{(es(T) - e)}{\lambda r_{a_1}} \text{ cm/sec.} \qquad .....(2:14)
\end{aligned}
$$

But $\gamma = \frac{C_pP}{\epsilon\lambda}$;

the term $\frac{\rho c}{\lambda(\Delta + \gamma)}$ can therefore be replaced by $\frac{\rho \gamma \epsilon}{(\Delta + \gamma)P}$

giving $0.26(1 + \frac{u}{100})(es(T) - e)$ mm/day

$$= \frac{\rho \epsilon}{Pr_{a_1}} (es(T) - e) \text{ cm/sec.} \qquad \ldots\ldots(2{:}15)$$

$$\text{and } r_{a_1} = \frac{\rho\epsilon \times 3{,}600 \times 24 \times 10}{P \times 0.26(1 + \frac{u}{100})} (\text{sec.cm}^{-1}) \qquad \ldots\ldots(2{:}16)$$

Equation (2:16) can now be used to determine values of r_{a_1} in terms of windspeed for a given location, the only other variables being air density ρ and atmospheric pressure P.

Values of r_{a_1} for various windspeeds have been calculated for a few stations (see Appendix 10). The sensitivity of r_{a_1} to the "Dalton" factor $(1 + \frac{u}{100})$ is highest (>2.0) at windspeeds below 60 miles per day, and decreases rapidly to less than 0.3 at windspeeds above 160 m.p.d.

At Mwea, the average windspeed during the 1967 maize crop and 1968 bean crop was 68 miles per day; r_{a_1} was therefore 1.45. Average windspeed during the 1968 maize crop was 64 m.p.d., and r_{a_1} had the value 1.48.

There are relatively few measurements of r_s reported in literature and the data compiled by Monteith (1965b) show wide variations in r_s. Monteith showed, however, that the empirical relationship

$$\frac{\lambda E}{N - S} = \log\left(\frac{25}{r_s}\right)^{\frac{1}{2}} \qquad \text{.....(2:17)}$$

gave very good fit for the data for $0.25 \leqslant r_s < 10$, and suggested that although the constants in the equation may show some variation for different crops, the equation could be used to estimate internal resistance of closed crop canopies.

By rearranging (2:17), Szeicz and Endrődi (1969) used the equation

$$\log_{10} r_s = 1.40 - \frac{22\lambda E}{N - S} \qquad \text{.....(2:18)}$$

to calculate values of r_s for different vegetation. They found a marked seasonal variation in r_s, but values of the order of 0.9 - 1.5 for pine forest, 0.5 - 1.3 for potatoes and 0.3 - 0.7 for lucerne were similar for south-east England and California.

TABLE 14

Values of internal resistance r_s calculated from hourly energy balance (Bowen's Ratio) measurements over maize and bean crops

Local time	Values of r_s (sec.cm^{-1})						
	1967 maize crop		1968 maize crop			1968 bean crop	
	20.12.67	21.12.67	12.10.68	13.10.68	14.10.68	6.5.68	7.5.68
0700-0800	-	-	-	0.35	1.38	-	-
0800-0900	-	0.25	0.07	2.40	0.44	-	-
0900-1000	0.35	0.22	1.10	1.10	2.51	0.32	0.38
1000-1100	0.21	0.19	0.01	0.72	0.18	0.24	0.26
1100-1200	0.19	0.19	1.10	0.35	0.21	0.25	0.23
1200-1300	0.17	0.21	0.74	0.01	0.22	0.35	0.23
1300-1400	0.17	0.29	0.10	0.01	0.36	0.36	0.17
1400-1500	0.24	0.23	1.00	0.42	0.32	0.48	0.36
1500-1600	0.24	0.29	1.32	0.83	0.35	0.22	0.35
1600-1700	0.23	0.30	0.42	0.17	0.42	0.29	0.52
1700-1800	0.32	0.38	0.33	0.24	0.60	0.33	0.38
1800-1900	-	-	-	-	-	-	0.35
Mean days from germination	0.24	0.26	0.62	0.60	0.64	0.32	0.32

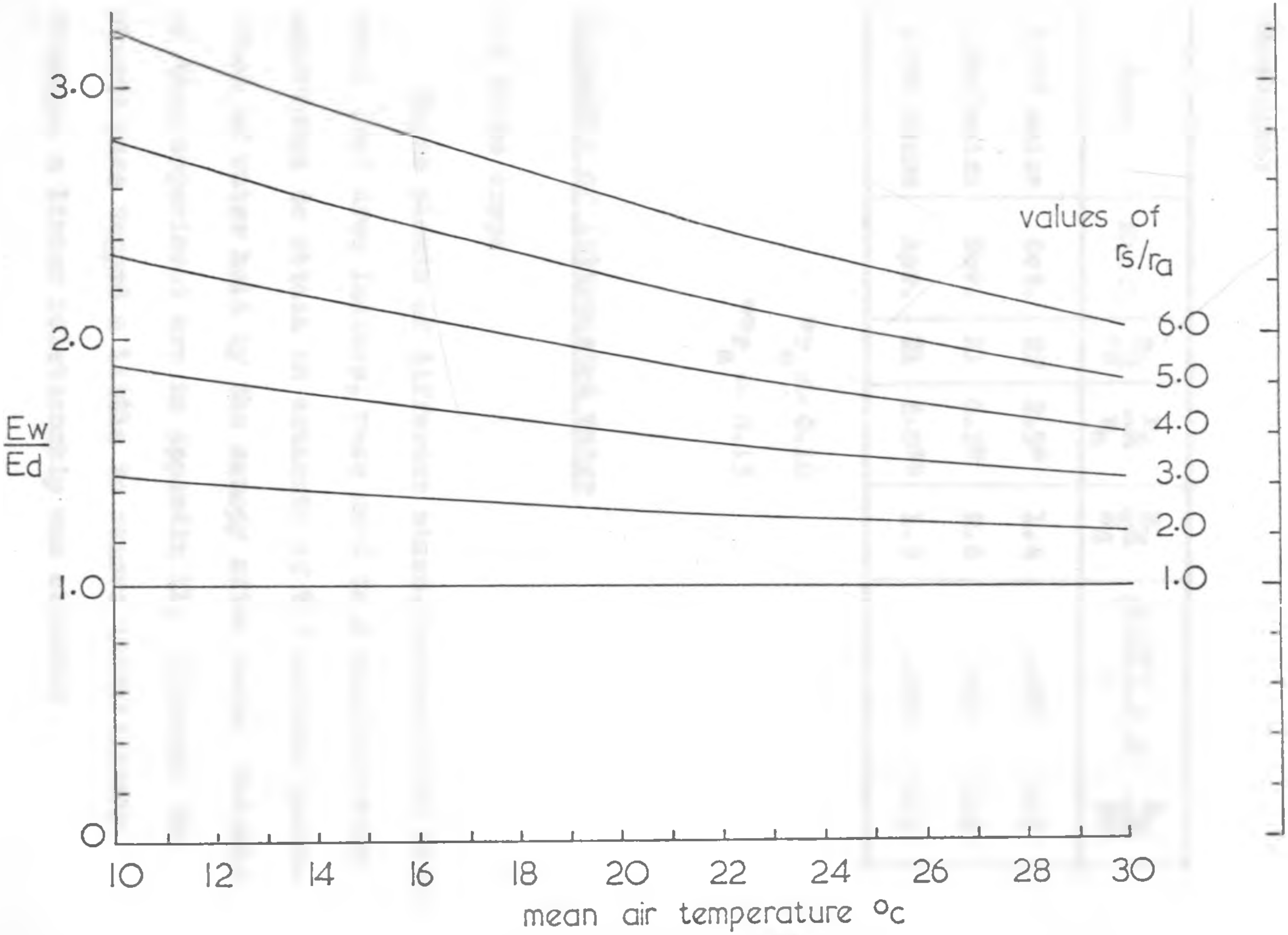
Values of r_s in Table 14 have been calculated from energy balance measurements (see Chapter IV) over mature crops of maize and beans at Mwea. Ground cover was complete in the bean crop but was at most 80% in the maize crops.

Average values of r_s for the 1968 maize crop (0.6) are higher than the values for the 1967 maize crop (0.25). The average value of r_s for the bean crop was 0.32.

Calculation of $\frac{E_w}{E_d}$ and $\frac{E_w}{Ho}$

Values of r_a, r_{a_i} and r_s derived above can now be used in equations (2:3), (2:11) and (2:12), to obtain theoretical or the expected values of the above ratios.

Fig. 12 shows values of $\frac{E_w}{E_d}$ for different values of $\frac{r_s}{r_a}$ and for different mean air temperatures (altitude 1,500 metres). The altitude dependence of these values is higher for the lower temperatures and higher values of $\frac{r_s}{r_a}$. The correction for altitude is, however, at most $\pm 5\%$ at $\frac{r_s}{r_a} = 6.0$, $T_a = 10^\circ C$, for the altitude range 0–2,000 metres.



<u>Fig 14</u>: Changes in computed values of $\frac{E_w}{E_d}$ with mean air temperature for different values of r_s/r_a

The expected values of $\frac{E_W}{E_d}$ and $\frac{E_W}{Eo}$ (Figs. 14 and 15) for the three crops at Mwea during peak Et/Eo are therefore:

Crop	Month	T_a °C	$\frac{r_s}{r_a}$	$\frac{E_W}{E_d}$	$(\frac{es(T) - e}{E})$	$\frac{E_W}{Eo}$
1967 maize	Oct.	22	2.5^{*}	1.4	.015	1.7
1968 maize	Nov.	21	6.2^{*}	2.6	.012	1.5
1968 beans	Apr.	21	2.0^{**}	1.3	.008	1.3

$^{*}r_a \bumpeq 0.10$

$^{**}r_a \bumpeq 0.15$

Estimates of intercepted water

(a) Maize crop:

Maize plants of different sizes, representing different Leaf Area Indices, were used in a supplementary experiment to obtain an estimate of the maximum quantities of water held by the canopy after rain. Details of this experiment are in Appendix 11. Although the plants were tapped a little to remove transitionary storage, a linear relationship was obtained

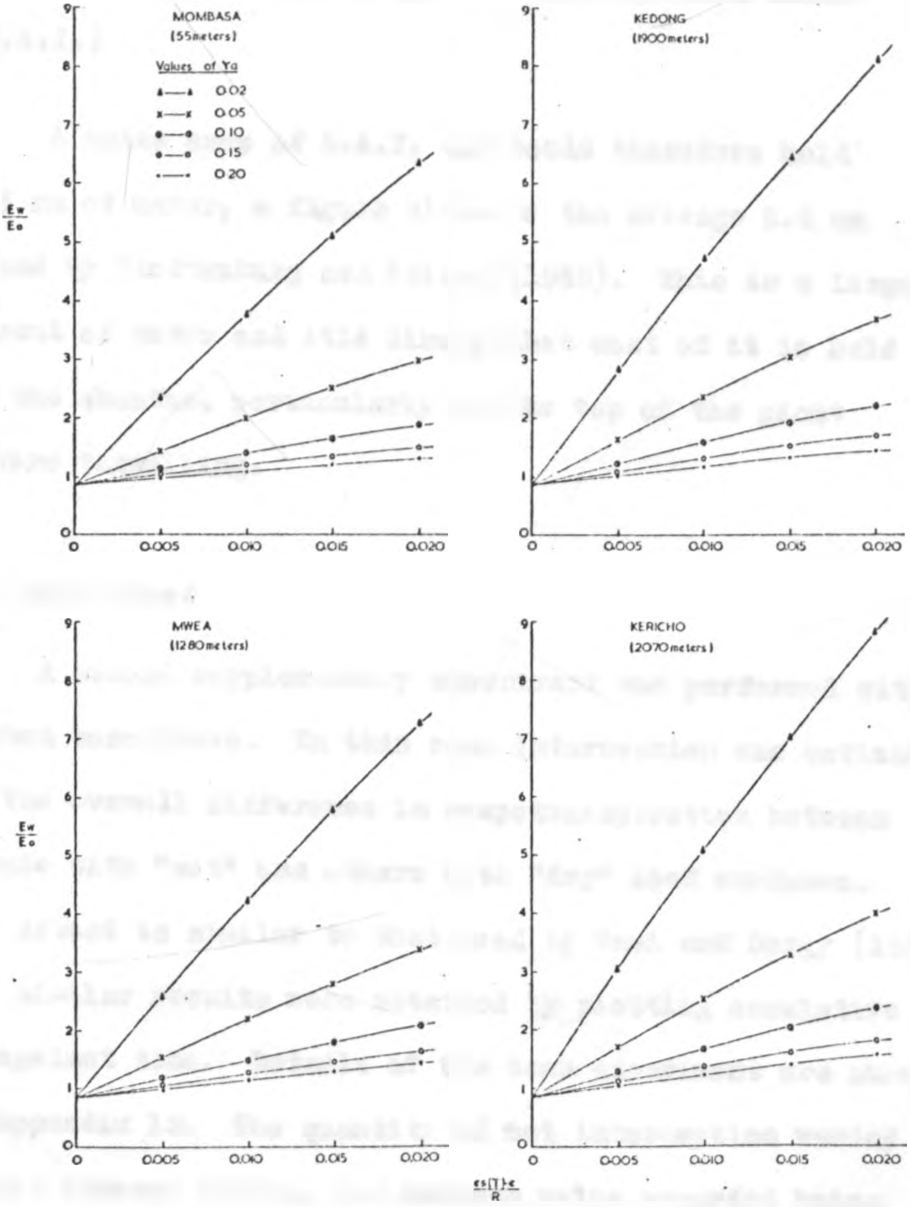


Fig. 15: The response of calculated values of $\frac{E_w}{E_o}$ to aerodynamic resistance r_a at different altitudes

$I = 0.12\ L.A.I. + 0.07,\ r^2 = 0.89$

between net interception (I) and the Leaf Area Index (L.A.I.)

A maize crop of L.A.I. 4.0 could therefore hold 5.5 mm of water, a figure close to the average 5.8 mm found by Stottenburg and Wilson (1950). This is a large amount of water and itis likely that most of it is held in the sheaths, particularly at the top of the plant before tasselling.

(b) Bean crop:

A second supplementary experiment was performed with potted bean plants. In this case interception was estimated as the overall difference in evapotranspiration between plants with "wet" and others with "dry" leaf surfaces. The method is similar to that used by Paul and Burgy (1961) and similar results were obtained by plotting cumulative Et against time. Details of the bean experiment are shown in Appendix 12. The quantity of net interception varied widely between plants, the maximum value recorded being about 50 gm. Taking as average 25 gm per plant, net interception in the lysimeter crop for row spacing 50 cm, seed spacing 15 cm within the row, would be approximately 0.4 mm.

The net interception by the bean plant is therefore small and does not explain the high Et/Eo figures unless:

(i) the intercepted water was evaporated within 1-1½ hours under field conditions (compare Appendix 11 for isolated bean plants),

(ii) there were frequent periods of rain during the day, and

(iii) the Eo for the day was low, so that net interception constituted a large percentage of daily Et.

It is, however, more likely that the field bean crop, at full ground cover and with overlapping leaves, retained much more water than the above calculations indicate.

Results from other workers

The effect of intercepted water on crop water use has been investigated by several workers, but in most cases the experimental conditions were far from representative of a field crop; the experimental plants usually stood in isolation. Burgy and Pomeroy (1958) in nutrient solution studies found that in vigorously growing grass, the evaporation of intercepted water caused an equal reduction in transpiration from the plants, hence total moisture loss was approximately the same in plots with "wet" and "dry" leaf surfaces. Similar results were obtained by McMillan and Burgy (1960) and McIlroy and Angus (1964) for grass under field conditions. Monteith (1965) suggested that such results with well watered grass are due to low r_s, the relatively high r_a making $\frac{r_s}{r_a}$ close to unity, and $\frac{E_w}{E_d}$ close to 1.0 (see Fig. 14).

Summary of discussion on Et/Eo ratios

The validity of crop water use data obtained with lysimeters has been established. Errors associated with these measurements have failed to account for all the apparent excess crop water use which caused high Et/Eo ratio under wet conditions. The theory relating excessive Et to aerodynamic resistance factors for the two crops has been discussed and advanced as a likely explanation. It has also been shown, at least for the maize crop, that the extra water would be available on the plant. The source of energy for the extra evaporation will be discussed in Chapter IV which deals with partition of energy in the crop.

Validity of estimating crop water use with neutron moisture meters

One of the main objectives of this experiment was to evaluate the chances of obtaining a fairly good estimate of actual evaporation under well-defined conditions through soil moisture measurements with a neutron moisture meter, supplemented by gravimetric soil moisture measurements in the top soil layer. With E.A.L. 104 moisture meter, agreement with lysimeter estimates was good during the bean crop, and the 100 mm difference during the 1968 maize crop (see Table 9) is accounted for by the possible error due to systematic zero drift in the lysimeter.

It is now necessary to specify the "well-defined conditions" referred to in the preceding paragraph. Any attempt to deduce crop water use from differences in soil moisture input through irrigation, rainfall or upward flow from deeper layers in the soil profile and loss through drainage. The poor distribution of water during irrigation at once sets a limit to the reliability of this method in irrigated crops, but evenif this source of error could be eliminated, the drainage component is difficult to determine accurately. Suggestions have been made that it may be possible to calculate drainage correction from records of soil moisture tension at a suitable level in the soil profile. This correction depends on obtaining representative unsaturated conductivity data but, as demonstrated by van Bavel, Stirk and Brust (1968), the variability of such measurements is such that they are unreliable for calculating such corrections. A more serious objection to this procedure arises from the presence of roots. Unless the water potential gradient is measured truly below the root range, any attempts to calculate drainage correction would be invalid. The root system of maize is capable of penetrating and drawing water from more than 200 cm depth. Although observations indicate that the average maximum soil depth in the experimental plot was about 200 cm, the underlying layer of tuff rock was usually saturated with seepage water from irrigation canals and could be a source of water for any roots reaching it.

CHAPTER III

DRY MATTER PRODUCTION IN MAIZE AND BEANS

The successful application of any photosynthesis model in predicting potential agricultural crop production in a given area depends on the ability of the model to follow increase in total dry matter in all stages of growth. Since grain is the most important end product of maize, several attempts have been made to relate dry matter production and grain yield.

Hanway (1962) found that dry weight of the whole plant and of the grain were directly related to and highly correlated with the weight of leaves on the plants. Thus at maturity, the weight of grain constituted about one half of the total dry weight of the plant. According to Dale and Shaw (1965), the number of days in the period from six weeks before to three weeks after silking, on which maize was under no moisture stress, were highly related to grain yield. The effect of plant density on the relationship was only apparent when there were more than 40 days of moisture stress in this period. Ragland *et al*. (1965), however, showed that the rate of dry matter accumulation by maize was roughly linear in the period between three and four weeks after emergence to the onset of senescence.

Kalju Eik and Hanway (1966) have found that Leaf Area Index at silking time and Leaf Area Index days over grain formation period are linearly related to grain yield. The maximum Leaf Area Index for this linearity was four.

Maximum or potential yield of maize has therefore proved difficult to define, and Earley (1965) suggested the use of "relative maximum yield" of maize expressed as

$$\frac{\text{Weight of maize per unit leaf area}}{\text{Maximum weight of maize per unit leaf area of the top three leaves.}}$$

This definition was based on the observation that the top three leaves were the most efficient photosynthetically during grain formation. To complicate the situation even further, Ragland *et al*. (1965) found that the rate of growth of maize was also correlated with air temperature at 150 cm and soil temperature at 5 cm depth.

The usefulness of the transpiration ratio has already been discussed in Chapter I, and it has been shown that only in very special conditions could such a relationship be reproduced (de Wit, 1958; Monteith, 1965; Lemon, 1966). The methods cited above suffer from one defect: they are all empirical and therefore strongly influenced by the behaviour of a given crop growing under particular environmental conditions.

However, potential photosynthesis, like potential evaporation, is governed by meteorological and plant factors. A more logical approach to estimating potential crop productivity could therefore be the measurement and integration of these factors assuming that soil fertility is not limiting. There are three basic steps in this process:

(a) Determination of the light photosynthesis function - that is the rate of photosynthesis for different temperatures, light intensities and carbon dioxide concentrations. This is usually done with single leaves or whole plants in controlled environment chambers.

(b) Determination of light intensity and carbon dioxide concentrations within the canopy of the field crop;

(c) Calculation of potential dry matter production by combining (a) and (b).

The work described in this chapter was not designed to produce either original information on the above parameters, or a new photosynthesis formula, but to test the usefulness of existing photosynthesis formulae in predicting yields of field crops.

Theoretical background to photosynthesis formulae

The photosynthesis function

Between the lowest (completely limiting) and highest (completely saturating) light intensities, there is a wide range of values in which photosynthesis of leaves in normal air is affected by variation of both light intensity and carbon dioxide concentration (Gaastra, 1959; Chapman and Loomis, 1953).

The light and carbon dioxide response curves are usually characteristic of plant species, but actual values on these curves depend also on the health and age of the leaf being studied. Two of the more recent forms of the photosynthesis functions are considered here.

1. $P = (a + \frac{b}{I})^{-1}$ .....(3:1)

At a given atmospheric concentration of CO_2, where P is the gross photosynthesis, a and b are constants which may be regarded as proportional to resistances in the diffusion of carbon dioxide, and in photochemical reactions respectively. I is the light intensity at leaf surface.

2. $A = H(H + HH)^{-1}Amax.$ .....(3:2)

at a given concentration of CO_2. A is the gross photosynthesis, H is the absorbed light intensity, and HH is the light intensity at which half of the maximum photosynthesis (Amax) occurs.

Light distribution functions

In using (3:1) or (3:2) tocalculate photosynthesis of a field crop, it is necessary to know the pattern of light interception at various levels within the canopy. The photosynthesis function of a plant in the middle of a field crop will depend on such functions for individual leaves which may vary widely because of differences in leaf age and position within the canopy. The situation is complicated further by the fact that the effect of reduced light intensity due to shading of lower leaves is also partially compensated for by a higher efficiency of energy conversion.

Monteith (1965) examined earlier attempts to describe the mean intensity of solar radiation, I_L, below a canopy of Leaf Area Index, L. He found that the assumptions of a constant light extinction factor following Beer's Law,

$$I_L = I_o e^{-kL} \qquad \text{.....(3:3)}$$

and the neglect of the changes in spectral composition of radiation as it filters into the canopy, led to serious errors. Monteith therefore suggested a new formula for radiation extinction:

$$I_L = I_o \left\{ S + (1 + S)\tau \right\}^L \qquad \text{.....(3:4)}$$

where I_L is the radiation intensity after L layers of unit Leaf Area Index have been penetrated;

S is the fraction of incident radiation passing through unit layer of leaf without interception;

τ is a mean light transmission coefficient for leaves of the given plants;

I_o is the incident radiation at the top of the canopy.

Since τ is small, the effective radiation for photosynthesis is that intercepted by the leaves which are directly sunlit, and that intercepted by "once shaded" leaves, i.e. the light reaching a lower leaf after only one transmission through an upper leaf.

The area of sunlit leaves can therefore be shown to be

$$A_o = \frac{1 - S^L}{1 - S} \qquad .....(3:5)$$

and that of "once shaded" leaves

$$A_1 = \frac{1 - S^L - (1 - S)LS^{L-1}}{1 - S} \qquad .....(3:6)$$

Monteith used equation (3:1) to derive instantaneous photosynthesis of sunlit leaves:

$$P_o = (1 - S)A_o\left\{a(1 - S) + \frac{b}{I_o}\right\}^{-1} \qquad \text{.....(3:7)}$$

and for "once shaded" leaves

$$P_1 = (1 - S)A_1\left\{a(1 - S) + \frac{b}{I_o\tau}\right\}^{-1} \qquad \text{.....(3:8)}$$

so that the total P is given by

$$P_m = P_o + P_1 \qquad \text{.....(3:9)}$$

Daily totals may be found by integrating (3:9) over the daylight hours. Assuming that solar radiation varies sinusoidally between sunrise and sunset, the daily total of solar radiation S is then given by

$$R = \int_o^h I_o dt = 2\ I^* \frac{h}{\pi} \qquad \text{.....(3:10)}$$

where R is the total solar radiation measured by

a solarimeter;

h is the daylength (min)

and I* is the apparent midday intensity

(cal.$cm^{-2}min^{-1}$).

Therefore the final equation derived by Monteith takes the form

$$P_m = \frac{h}{a}\left[A_o\left\{1 - f(n_o)\right\} + A_1\left\{1 - f(n_1)\right\}\right] \qquad \text{.....(3:11)}$$

where $\{1 - f(n)\}$ is a function of I^* and may be regarded here as a saturation efficiency.

The above derivation of (3:11) is only meant to highlight the major steps; the reader is referred to the original paper by Monteith for the detailed analysis and, more important, for the assumptions and conditions implied at each stage.

Methods and Procedure

The measurements described in this chapter were made on the same site and crops described in Chapter II.

Measurement of Leaf Area Index

Destructive sampling was necessary for the determination of Leaf Area Index. The same samples were, however, used for estimating total dry matter production and because of the large plant population no significant gaps were caused by these samplings.

Measurement of total leaf area was a very laborious task and only two maize and four bean samples were taken at random from each plot on each sampling date. Samples consisted of all plants in an area of 1 square metre for maize (i.e. 5 plants), or ¾ square metre for beans. It was not possible for measurements to be made on the day of sampling. The plants were therefore preserved by dipping the roots in water overnight and all measurements were carried out on the following day. There was therefore a gap of 24 hours between field sampling and actual measurements.

There were three components for the maize L.A.I.: complete leaves, half leaves and stalks. A good ~~calibration~~ Correlation was obtained between leaf area (measured by planimeter) and the products of maximum length of the mid-rib and maximum width (Appendix 13). Leaf area was therefore calculated from the linear measurements which were simpler to make. The half-leaves were treated simply as triangles. It was assumed that only half the maize stem area contributed to interception of direct light at any time, the contribution being virtually nil at midday when the sun was overhead. Stem area for beans was considered insignificant. The sampling interval was 1-2 weeks and covered all stages of growth.

Light interception in the crop: determination of the factor S in (3:4)

Two simple solarimeters (Monteith, 1959) were used to measure the fraction of short wave radiation reaching various levels in the canopy. One solarimeter was mounted above the crop while the second solarimeter was placed on horizontal rails (Fig. 16) at the required height in the crop. Both instruments were connected, via a changeover switch, to a millivolt meter. By reading the top and bottom solarimeters alternately, the fraction of radiation intercepted by the crop could be calculated. Spatial averaging within the crop was achieved by placing the bottom solarimeter at twenty-one different positions on the rails at each setting.

The Leaf Area Index associated with each light interception was obtained by sampling the crop in layers and measuring L.A.I. for each layer. This method was successful with the maize crop, but only one setting was possible in the bean crop and the measurements may not be representative.

Fig. 16: Solarimeter on rails as used to estimate radiation interception in the maize crop

The transmission coefficient τ in (3:4) was taken as 5.5% (Yocum and Lemon, 1964) for maize. The same value of τ was assumed for beans in the absence of published data. Daily totals of solar radiation were obtained from a Gunn-Bellani radiation integrator (see Chapter II).

Following Monteith's (1965) calculations based on published photosynthesis data, values of a = 0.25, b = 0.05 were assumed for maize and a = 1.0, b = 0.05 for beans.

A sample calculation of P_m is shown in Appendix 14. Daily values of L.A.I. were obtained by interpolation on the L.A.I. curves.

Measurement of total dry matter

The dry weight of above-ground parts of the crop was obtained by cutting up and drying separately the leaves, stems, cobs, tassels, pods and grain in a ventilated oven at 70°C to constant weight. The optimum drying time was found to be 36 hours for leaves and 48 hours for stalks,

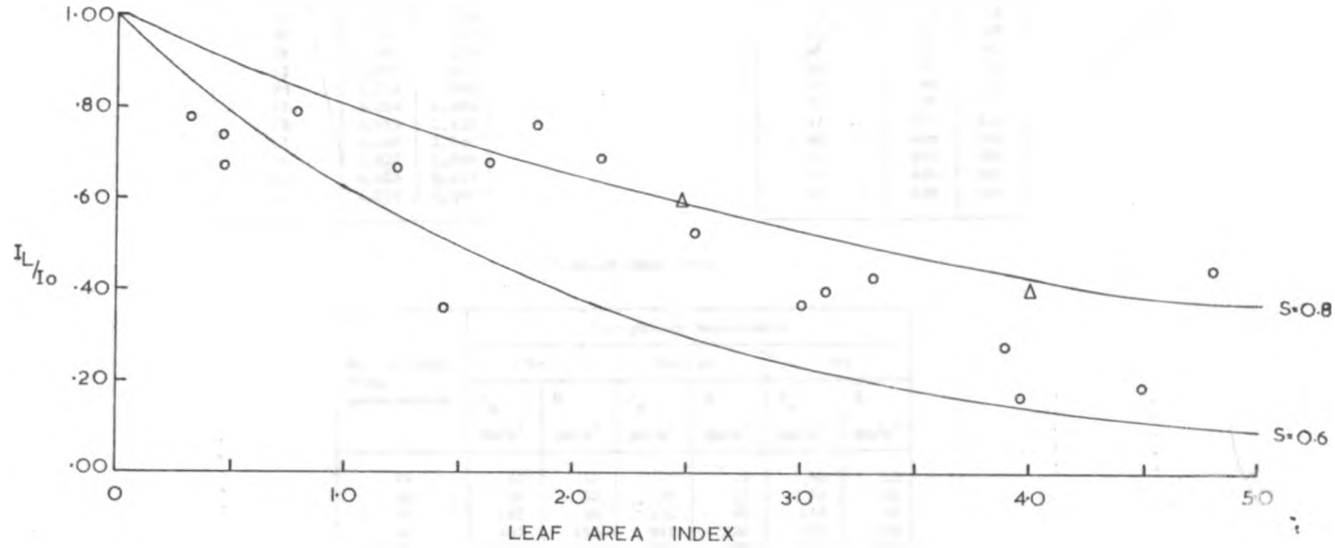


Fig. 17: Fraction of solar radiation I_L/I_o penetrating the canopy of a maize crop at different Leaf Area Indices.

TABLE 15

Comparison between measured (M) and calculated (P_m) total dry matter production from planting to maturity

(a) MAIZE CROP 1967

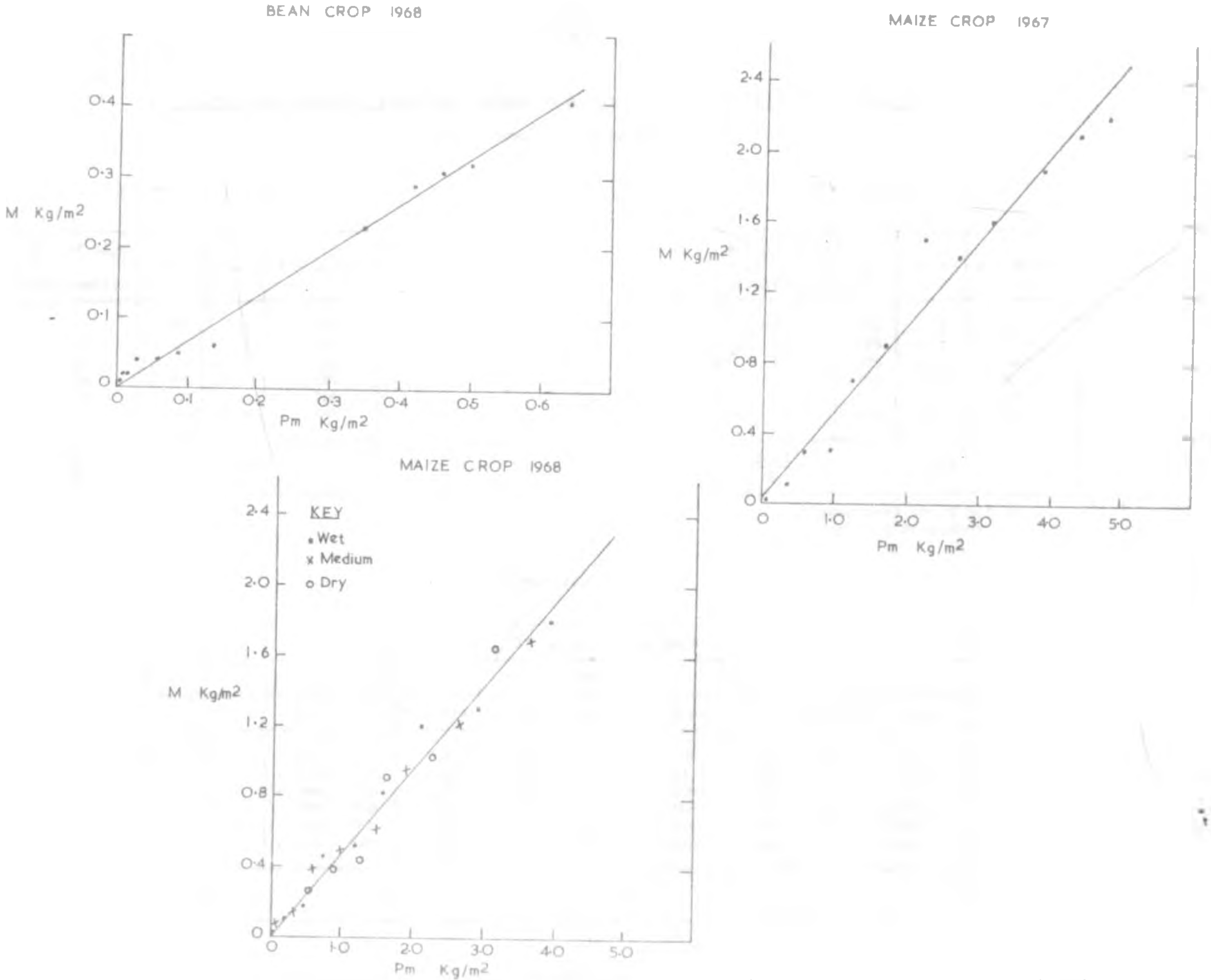
No. of days from germination	P_m gm/m^2	M gm/m^2
17	38	15
32	324	106
38	560	323
46	965	336
52	1,271	657
59	1,714	889
67	2,254	1,484
73	2,677	1,426
81	3,200	1,560
94	3,917	1,896
102	4,414	2,112
111	4,759	2,248

(b) BEAN CROP 1968

No. of days from germination	P_m gm/m^2	M gm/m^2
5	2	11
9	7	15
12	14	18
16	31	41
20	57	43
23	86	49
27	137	63
43	351	225
48	419	285
54	459	305
58	496	321
65	638	406

(c) MAIZE CROP 1968

No. of days from germination	Irrigation treatments					
	Wet		Medium		Dry	
	P_m gm/m^2	M gm/m^2	P_m gm/m^2	M gm/m^2	P_m gm/m^2	M gm/m^2
24	60	12	17	6	50	12
29	92	32	35	13	74	20
36	183	98	111	65	144	40
44	467	165	361	126	350	129
50	718	453	604	382	548	261
58	1,152	512	1,035	491	902	376
65	1,585	818	1,454	605	1,258	425
72	2,060	1,198	1,906	947	1,649	900
84	2,856	1,290	2,664	1,219	2,271	1,020
100	3,876	1,786	3,642	1,684	3,154	1,636



<u>Fig. 18</u>: Relationships between measured (M) and calculated (P_m) dry matter in the Mwea experiments

TABLE 16

Yield of grain (saleable product) compared with total dry matter (M) in maize and beans

All figures are in gm/m².

(a) Maize Crop 1967

No. of days from germination	M	Grain	M - Grain
67	1,484	0	1,484
73	1,426	0	1,426
81	1,560	148	1,412
94	1,896	314	1,582
102	2,112	406	1,706
111	2,248	583	1,665
$\frac{\text{Grain}}{\text{M}}$:		0.26	

(b) Bean Crop 1968

No. of days from germination	M	Seed	M - Seed
27	63	0	63
43	225	*	225*
48	285	69	216
54	305	109	196
58	321	137	184
65	406	200	206
$\frac{\text{Seed}}{\text{M}}$:		0.49	

*Young seed could not be separated from pods.

(c) Maize Crop 1968

No. of days from germination	Irrigation treatments								
	Wet			Medium			Dry		
	M	Grain	M - Grain	M	Grain	M - Grain	M	Grain	M - Grain
65	818	0	818	605	0	605	425	0	425
72	1,198	0	1,198	947	0	947	900	0	900
84	1,290	26	1,264	1,219	11	1,208	1,020	31	989
100	1,786	248	1,538	1,684	196	1,488	1,636	268	1,368
119	2,459	757	1,702	2,005	589	1,416	1,837	662	1,175
130	2,426	798	1,637	2,310	784	1,526	2,191	781	1,410
$\frac{\text{Grain}}{\text{M}}$:		0.33			0.34			0.36	

cobs and grain. The root component could not be measured but for maize a correction was applied to the above measurement by assuming that the root component was 20% for young plants up to tasselling and 16% after tasselling. These are approximate values from root/top ratios obtained at Muguga with closely related varieties of maize (Gwynne, 1968).

Results

Results of light interception studies in the maize crop are shown in Fig. 17. Most values of S were between 0.6 and 0.8, and $S = 0.7$ was used in all calculations of P_m for the maize crop. Measurements in the bean crop indicated a value of S close to 0.8. The calculated values (P_m) are compared with measured dry matter (M) in Table 15. The relationship between the predicted and measured total dry matter production (Fig. 18) can be expressed closely by linear equations:

For the beans the equation is

$$M = (0.64 \pm 0.02)P_m + (5.7 \pm 5.2),\ r^2 = 0.99,\ n = 12.$$

For the 1968 maize crop the equation is

$$M = (0.48 \pm 0.01)P_m - (5 \pm 21),\ r^2 = 0.98,\ n = 30,$$

which is very similar to that for the 1967 maize crop:

$$M = (0.48 \pm 0.03)P + (34 \pm 68),\ r^2 = 0.97,\ n = 12.$$

The difference between the slope for maize and that for beans may be due either to the values assigned to the factor 'a' (proportional to carbon dioxide assimilation) for which there are few field data, or to differences in the fraction used in respiration.

Assuming the only difference between P_m and M is the respiration loss R, and that R is a constant fraction K of P_m,

$$\frac{R}{P_m} = \frac{P_m - M}{P_m} = K, \text{ and } M = (1 - K)P_m \qquad .....(3:12)$$

The value of K in this experiment was therefore 0.52 ± 0.03 for maize and 0.36 ± 0.02 for beans. The magnitude of the respiration loss is not known with certainty except that it increases from about 25% in cold to 50% in hot climates (Gaastra, 1963). The values of K obtained above are therefore of the right order and could probably be improved by adjustments based on experimental determination of a number of factors, especially the factor 'a'.

Ratio of saleable product to total dry matter

Although total dry matter is economically important where the whole crop is turned into silage, the most important part of maize or beans in East Africa is the grain, and increase in grain yield is a major aim in the cereals breeding programme. It would therefore be of interest to look into the ratio of grain to total dry matter for the varieties of maize and beans used in these experiments.

The data in Table 16 show that during the last 30 days for maize and 20 days for beans, almost all net photosynthesis was channelled into grain formation.

The final grain yields constituted approximately 25-36% total dry matter in maize and about 50% for beans.

Discussion of Results

In spite of the numerous assumptions made in calculations, the estimates of potential photosynthesis (equation (3:11)) were very closely correlated with the actual dry matter production in the field crops of maize ($r^2 = 0.97, 0.98$) and beans ($r^2 = 0.99$) in all stages of growth. The success of this approach in the warm climate of the Mwea experiments may be partly due to removal of temperature as a major variable in growth and this result needs to be tested in the cooler climates of the East African highlands. The correlation of dry matter production and Leaf Area Index in these experiments was also quite high ($r^2 \sim 0.80$) and it may be argued that it is not necessary to perform the laborious task of following equation (3:11) to account for an additional 17% of variance. The L.A.I. approach is however empirical and can only be expected to yield comparable results where light intensity is not limiting.

de Wit's method

C. T. de Wit (1965) published another method of calculating light distribution functions for different leaf distribution functions (canopy structures). The incident light intensity on a leaf due to direct light is proportional to the sine of the angle (LS) between the leaf and the ray of the sun. In this method, the light distribution function is expressed in terms of sine (LS) for 10° increments of the sun and leaf angles in all combinations. The leaf distribution function, i.e. the frequency distribution of leaf angles in the canopy, is first calculated from direct measurements, and then used to calculate light distribution functions.

In calculating photosynthesis, equation (3:2) is used and instead of using typical values for various factors to minimise laborious calculations, the method assumes a computer is freely available and the best fitting values are found empirically. de Wit does, however, give a table of light and photosynthesis values for a canopy under standardised conditions, from which photosynthesis at any place and time of year can be calculated. The chosen standard conditions are:

Leaves:

Scattering coefficient	0.30
EH	0.56 $cal.cm^{-2}min^{-1}$
Amax	20 $KgCH_2O\ ha^{-1}hr^{-1}$

Canopy:

Spherical leaf distribution	
Canopy density	0.1
Leaf Area Index	5.0

Light:

Clear sky	
Inclination of the sun	45°
Direct light	0.484 $cal.cm^{-2}min^{-1}$
Diffuse light	0.092 $cal.cm^{-2}min^{-1}$

CO_2:

Aerodynamic diffusive
resistance r_a 0.5 $sec.cm^{-1}$

de Wit suggested that likely variations from most of the above values would have little effect on the calculated photosynthesis, but the choice of L.A.I. of 5.0 implies complete canopy. The application of this table of standard values has already been discussed in the introductory chapter.

An attempt was made to determine the light distribution function in the maize crop by the system of two spheres suggested by de Wit (1965, loc. cit.). Results were inconclusive and failed to confirm whether the maize canopy was "spherical" as suggested by Nichiporovich (1961) or plagiophile, as found by de Wit (1965 loc. cit.). It is therefore not surprising that photosynthesis calculated on the basis of the table of standard values did not yield values comparable to observed dry matter production at the beginning and towards the end of the growing season. The method should, however, be applicable to canopies of perennial crops like tea and coffee provided all the relevant parameters can be determined *in situ*.

CHAPTER IV

THE PARTITION OF SOLAR ENERGY
IN FIELD CROPS OF MAIZE AND BEANS

Evaporation and photosynthesis are both dependent on energy, the principal source of which is the incoming solar radiation. The partition of solar energy in the field crop is therefore an important factor in studies of crop water use efficiency. The experiments described in this section had two main aims:

1. To obtain some indication of the hourly distribution of the major energy components in field crops of maize and beans;

2. To compare the latent heat component on a daily basis with lysimeter observations of crop water use.

Methods and Procedure - 1: Derivation of Bowen's Ratio from gradients of temperature and humidity above the evaporating surface

The basic equations for the transfer of heat, water vapour and momentum are:

Sensible heat: $Q = - \rho C_p K_h \frac{dT}{dz}$ .....(4:1)

Water vapour: $E = - \rho K_v \frac{dq}{dz}$ .....(4:2)

Momentum: $M = - \rho K_m \frac{du}{dz}$ .....(4:3)

where q = specific humidity (gm. water vapour/gm. moist air)

K_m, K_v, K_h = eddy transfer coefficients (cm^{2}sec.$^{-1}$),

and all other terms retain their meaning in Chapter 3.

Bowen's ratio is defined as

$$\beta = \frac{Q}{\lambda E} = \frac{C_p}{\lambda} \frac{K_h}{K_v} \frac{\frac{dT}{dz}}{\frac{dq}{dz}} \qquad .....(4:4)$$

If q is expressed in terms of dry air, it becomes the mixing ratio x where

$$x = \frac{\epsilon e}{P - e} \qquad .....(4:5)$$

e = vapour pressure (mb)

P = atmospheric pressure (mb)

and for $e \ll P$

$$x \doteq \frac{\epsilon e}{P} \qquad \text{.....(4:6)}$$

and $$\beta = \gamma \frac{K_h}{K_v} \frac{\frac{dT}{dz}}{\frac{de}{dz}} \qquad \text{.....(4:7)}$$

The values of K_h and K_v have been shown to be identical under stable and neutral conditions (Pasquill, 1949; Swinbank, 1955; Taylor, 1960; Crawford, 1965). Under unstable conditions, variations in the ratio $\frac{K_h}{K_v}$ are not significant (Rider and Robinson, 1951; Suomi and Tanner, 1958), and there is evidence to show that the ratio is close to unity. Equality of K_h and K_v is therefore assumed in the analysis of data from the following measurements.

The two quantities $\frac{dT}{dz}$ and $\frac{de}{dz}$ should be measured at the same point above the evaporating surface.

<u>Apparatus</u>

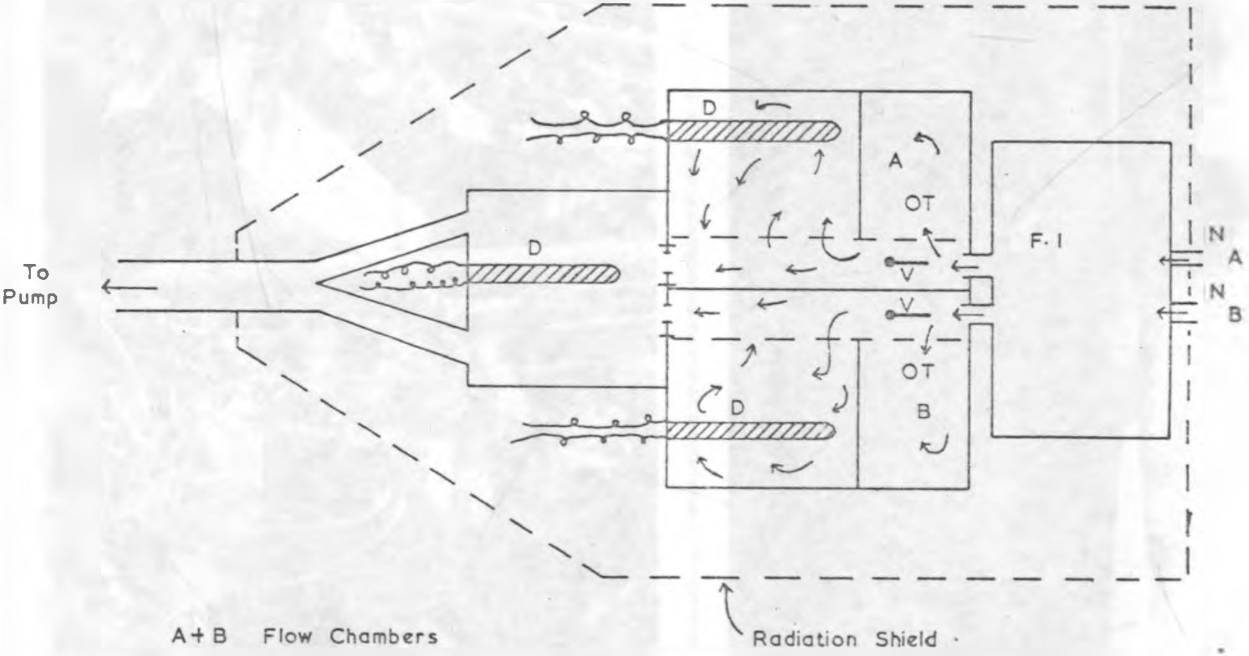
The system used was similar to that of Fritschen (1965), and the equipment was designed and constructed by

B. A. Ripley at Muguga. Figs. 19 and 20 show the components, construction and operation of this equipment. To improve spatial averaging of the measurements, a hydraulic system was used to swing the entire apparatus to and fro horizontally over an angle of 160 degrees. The period of each swing was sometimes affected by the wind but was on the average two minutes. This system of spatial averaging was only possible over the low bean crop and could not be operated 3 m above the ground over the tall maize crop.

Air was sucked into the equipment continuously from the two nozzles with a vacuum pump. The two air streams were kept separate as they passed through chambers A and B for measurements of humidity and temperature differences. The difference in dewpoint was measured by a differential thermocouple system attached to lithium chloride dewcels (Tanner and Suomi, 1956). Two thermocouples, soldered on to copper tubes to increase time constant, were used to measure the temperature difference, dT. The two air streams were then mixed in a final chamber containing the third dewcel for the determination of mean dewpoint,

FIG. 19

Diagram Of Bowens Ratio Equipment — not to scale



A + B	Flow Chambers
N	Intake Nozzles
T	Thermocouples
D	Dewcels
V	Adjustable Flow Regulators
F I	Flow Interchanger

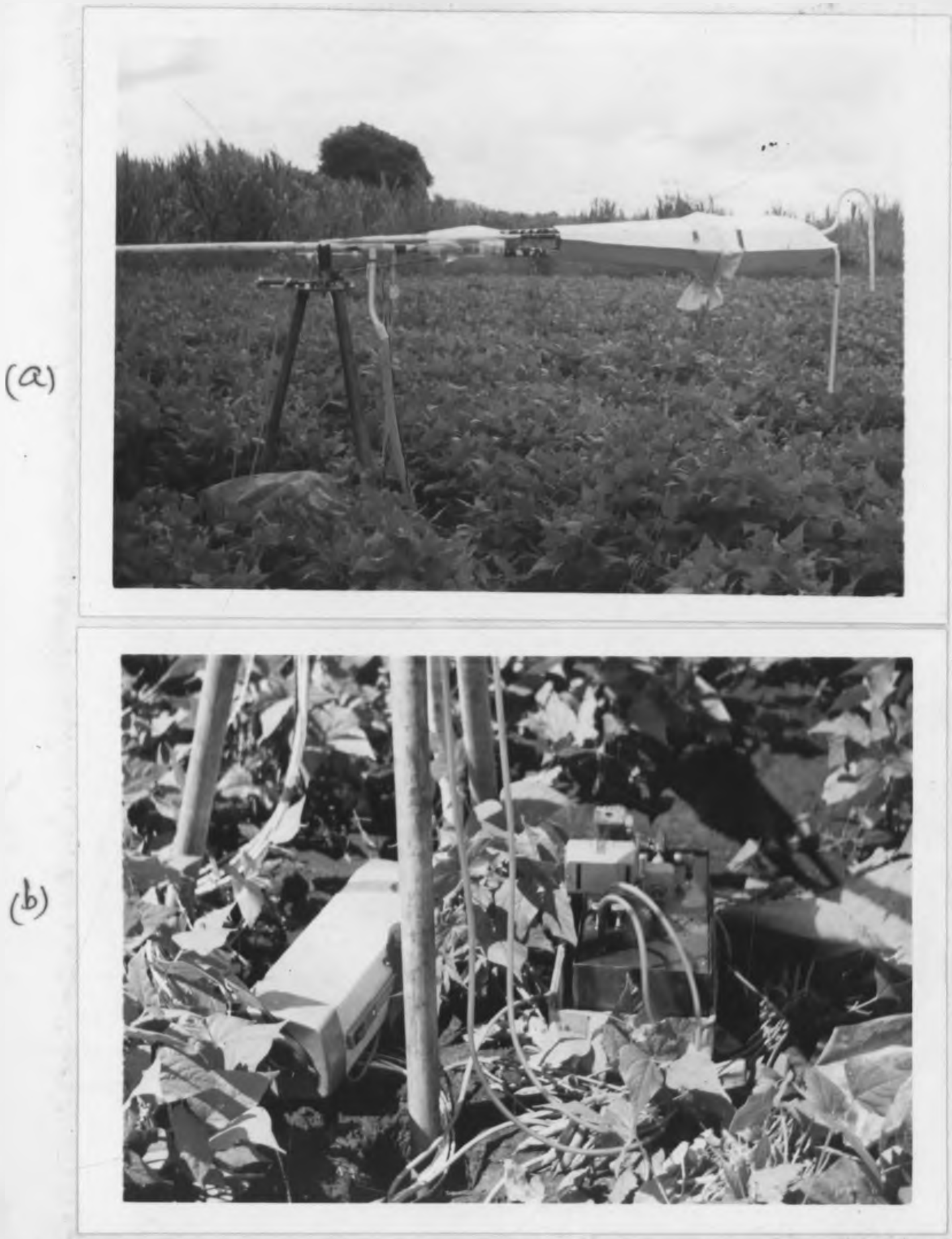


Fig. 20: Operation of Bowen's Ratio equipment. (a) rotating boom above bean crop, (b) details of tripod support, vacuum cleaner for sucking air, and hydraulic system for rotating boom.

Td. The vapour pressure difference, de, was obtained from Td and the difference in dewcel element temperatures, D.E.T. (see Appendix 15). The response times for the dewcels and thermocouples were 4 and 1-1½ minutes respectively.

Continuous recording

Because of the rather long time taken by the dewcels to reach equilibrium, the time interval between flow changes was fixed at 10 minutes. The differential thermocouple outputs were first passed through a D.C. amplifier which changed the range of a 12 channel Leeds and Northrup centre zero recorder to ± 50, 100, 200, 500 and 1,000 μV as required. Unfortunately there was no provision in the amplifier for separate amplifications for different inputs. The maximum amplification chosen was therefore dictated by the rather large absolute temperature differences between the two dewcels.

Fig. 21 shows a typical record of these parameters for a chart speed of 6 inches/hour. The output from each sensor was recorded once every minute. There were therefore 10 readings of each parameter for each 10 minute period. Avoiding the first four readings, corresponding with equilibration period, and the last reading before air interchange, the average reading for each 10 minute period was calculated from the remaining five readings.

Mean dewpoint Td was recorded directly on a separate calibrated Leeds and Northrup 16 channel recorder. All recorders, timer and power stabiliser were located in a mobile meteorological laboratory. Power supply was from a portable 1.5 KW generator.

Elimination of errors by interchanging airstreams

The vapour pressure and temperature differences over 50 cm are quite small (~ 0.01 mb and 0.05°C respectively), and errors introduced by differences between sensors can therefore be very important. To overcome this source of error, one can either interchange the sensors regularly or interchange the airflow between fixed sensors. The

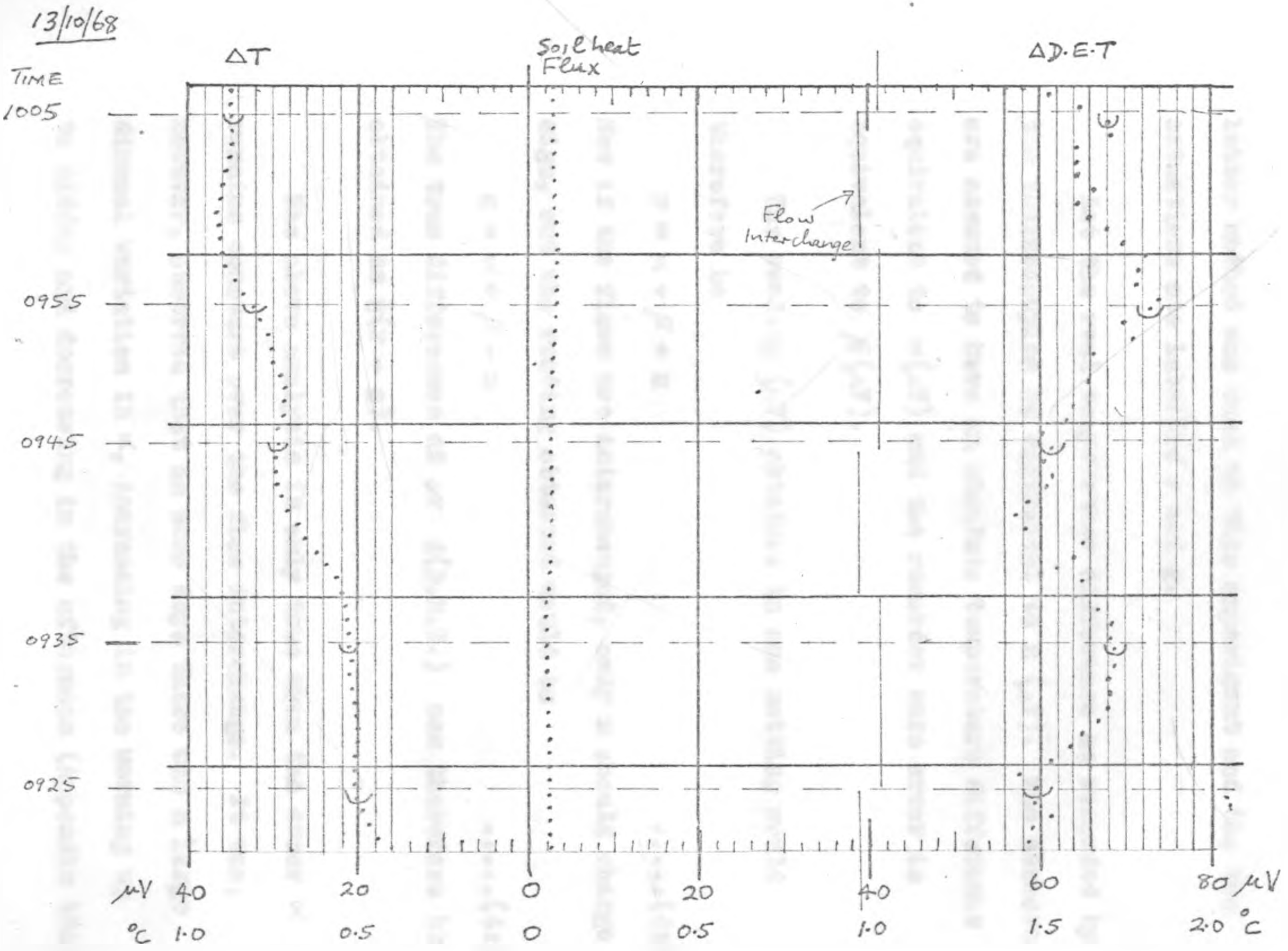


Fig. 21 A part of chart record (actual size) of measurements with Bowen's Ratio equipment above maize crop on 13/10/68.

latter method was used in this experiment and the two situations are labelled r and g.

Let the real temperature difference as recorded by the thermocouples be equivalent to x (μV). The sensors are assumed to have an absolute temperature difference equivalent to α(μV) and the recorder zero error is equivalent to β(μV).

The reading (μV) obtained in one setting would therefore be

$$r = \alpha + \beta + x \qquad \text{.....(4:8)}$$

Now if the flows are interchanged, only x should change sign, and the reading obtained would be

$$g = \alpha + \beta - x \qquad \text{.....(4:9)}$$

The true differences dT or d(D.B.T.) can therefore be obtained as $\frac{1}{2}(r - g)$.

The above analysis is only true when the error α remains constant over the flow interchange. It was, however, observed that on some days there was a large diurnal variation in α, increasing in the morning up to midday and decreasing in the afternoon (Appendix 16a).

This could have been due to solar radiation affecting one chamber more than the other, in spite of the radiation shield. The analysis in Appendix 16b shows how this error has been reduced by averaging readings over two rather than one stream interchange.

Methods and Procedure - 2: Measurements of solar radiation, net radiation and soil heat flux

Total short wave solar radiation and net radiation were measured with an Eppley pyrheliometer and Funk net radiometers respectively. Calibrations of these instruments were obtained by comparing the vertical component of direct radiation with the Eppley model of the Ångström electrical compensation pyrheliometer. The sensitivity of the Eppley pyrheliometer No. 4284 varied slightly with solar angle, being lowest in the morning before 9 a.m. and in the evening after 5 p.m. but relatively constant for the hours in between. The average for the day was 6.62 mv.min.Ly^{-1}. Calibration of the Funk net radiometer No. 470 was 8.85 Mv.min.Ly^{-1}.

Solar radiation and net radiation were recorded separately on two Kent Millivolt recorders with a range -5 to +15 mv. The recorders were fitted with mechanical integrators and the total radiation for a given period could be read off the totalising counter or on the automatic hourly printout on EWM counters. Radiation values obtained this way agreed well with planimeter integration of chart records.

Soil heat flux was recorded by three glass soil heat flux plates (Deacon, 1950) buried horizontally 1 cm below the soil surface and arranged so that one plate was halfway between the rows, the second plate was ¼ of the distance between 2 rows, and the third plate was between plants in the row. The plates were installed one week before measurements commenced and they were connected in series to improve spatial averaging. The average sensitivity of the plates in series was 11.5 mv.min.Ly^{-1}. The output was continuously recorded on the same chart as the temperature and humidity gradients discussed in the previous section, but without amplification. Soil heat flux was calculated from the average chart reading for each 10 minute period.

Methods and Procedure - 3:

Energy storage in photosynthesis

The energy used in photosynthesis is only a small fraction of daily radiation; the fraction of energy stored in dry matter is even smaller, and though almost insignificant in comparison with other components of surface energy balance, it is the basis of crop production. An estimate of stored energy can be made by converting dry matter increments to energy equivalent per unit land area. In accurate work, it would be necessary to split up the total dry matter into the major chemical components, i.e. carbohydrates, fibre, protein and fat, and then calculate energy equivalent from the data reported by Maynard (1947) as follows:

Fibre and carbohydrates	4.15 K cal/gm
Fats	9.40 K cal/gm
Protein	5.65 K cal/gm.

The maize data in Table 17, compiled from Morrisson (1956), show that about 77% of dry matter comprises fibre and carbohydrates. The figures for beans were obtained at Muguga. The energy equivalent of dry matter for the beans was found to be 4.25 K cal/gm. In view of the rather large variability in field samples and the attendant errors in the measured dry matter, the value 4.2 K cal/gm was used for both maize and beans in the conversion of dry matter to energy equivalent.

TABLE 17

Chemical composition of maize and beans

% D.M.

Maize	Carbohydrates	Crude Fibre	Crude Protein	Fat
Stover (stem + leaves)	46.5	30.8	5.9	1.6
Grain	69.2	2.0	8.7	4.0
Cobs	54.0	32.1	2.3	0.4
Complete ears (grain + husks + cobs)	65.3	10.5	7.8	3.0
Beans	49.1	19.3	14.5	19.3

TABLE 18a

Energy balance (cal.cm^{-2}) over bean crop at Mwea

6.5.68

Period (local time)	Solar	Net N	Soil heat flux S	N - S	$\beta = \frac{Q}{\lambda E}$	$1 + \beta$	λE	Q	Net / Solar	Albedo r
0700-0800	10.1	7.1	-0.7	7.8	-	-	-	-	0.70	0.30
0800-0900	17.8	12.7	0.6	12.1	-	-	-	-	0.71	0.29
0900-1000	31.4	23.5	1.3	22.2	0.05	1.05	21.1	1.1	0.75	0.25
1000-1100	65.5	48.5	2.3	46.2	-0.01	0.99	46.6	-0.4	0.74	0.26
1100-1200	77.0	67.8	3.7	64.1	0.00	1.00	64.1	0.0	0.88	0.12
1200-1300	82.9	72.0	5.1	66.9	0.07	1.07	62.5	4.4	0.87	0.13
1300-1400	86.4	74.9	4.0	70.9	0.09	1.09	65.1	5.8	0.87	0.13
1400-1500	74.8	66.7	2.5	64.2	0.16	1.16	55.3	8.9	0.89	0.11
1500-1600	35.6	30.5	-0.2	30.7	-0.03	0.97	31.7	-1.0	0.86	0.14
1600-1700	39.3	32.8	-0.1	32.9	0.03	1.03	31.9	1.0	0.83	0.17
1700-1800	3.0	0.7	-1.2	1.9	0.06	1.06	1.8	0.1	0.23	0.77*
Total	523.8	437.2	17.3	419.9			380.2	19.9		
						Equiv. (mm):	6.5		Mean:	0.19

*excluded from the mean

TABLE 18b

Energy balance (cal.cm^{-2}) over bean crop at Mwea

7.5.68

Period (local time)	Solar	Net N	Soil heat flux S	N - S	$\beta = \frac{Q}{\lambda E}$	$1 + \beta$	λE	Q	Net / Solar	Albedo r
0900-1000	27.8	17.3	0.7	16.6	0.10	1.10	15.1	1.5	0.62	0.38
1000-1100	37.6	26.9	1.2	25.7	0.01	1.01	25.5	0.2	0.72	0.28
1100-1200	65.7	51.6	2.4	49.2	-0.02	0.98	50.2	-1.0	0.79	0.21
1200-1300	73.7	60.5	4.3	56.2	-0.02	0.98	57.3	-1.1	0.82	0.18
1300-1400	81.1	67.0	4.3	62.7	-0.08	0.92	68.1	-5.4	0.83	0.17
1400-1500	70.5	52.9	3.0	49.9	0.09	1.09	45.8	4.1	0.75	0.25
1500-1600	57.1	45.5	1.4	44.1	0.08	1.08	40.8	3.3	0.80	0.20
1600-1700	33.4	25.3	0.0	25.3	0.19	1.19	21.3	4.0	0.76	0.24
1700-1800	16.9	4.3	-1.0	5.3	0.10	1.10	4.8	0.5	0.25	0.75*
1800-1900	0.6	-3.5	-1.2	-2.3	0.07	1.07	-2.1	-0.2	-	-
Total:	464.4	347.8	15.1	332.7			326.8	5.9		
						Equiv. (mm):	5.6		Mean:	0.21

*excluded from the mean

TABLE 19a

Energy balance (cal.cm^{-2}) over maize crop at Mwea

20.12.67

Period (local time)	Solar	Net R	Soil heat flux S	R - S	$\beta = \frac{Q}{\lambda E}$	$1 + \beta$	λE	Q	Net/Solar	Albedo r
0900-1000	67.9	49.1	0.8	48.3	0.07	1.07	45.2	3.1	0.72	0.28
1000-1100	76.6	63.2	1.1	62.1	-0.04	0.96	64.7	-2.6	0.82	0.18
1100-1200	87.9	72.3	1.2	71.1	-0.06	0.94	75.6	-4.5	0.82	0.18
1200-1300	87.0	74.4	1.2	73.2	-0.07	0.93	78.8	-5.6	0.86	0.14
1300-1400	83.4	71.2	2.0	69.2	-0.07	0.93	74.5	-5.3	0.85	0.15
1400-1500	66.4	58.3	1.1	57.2	-0.01	0.99	57.7	-0.5	0.88	0.12
1500-1600	47.8	40.9	0.5	40.4	-0.01	0.99	40.8	-0.4	0.86	0.14
1600-1700	29.8	22.0	0.2	21.8	-0.02	0.98	22.2	-0.4	0.74	0.26
1700-1800	9.2	-2.2	-0.1	-2.1	0.05	1.05	-1.9	-0.2	0.23	0.77*
Total:	556.0	449.2	8.0	441.2			457.6	-16.4	Mean:	0.18
						Equiv. (mm):	7.8			

*excluded from the mean

TABLE 19b

Energy balance (cal.cm^{-2}) over maize crop at Muea

21.12.67

Period (local time)	Solar	Net N	Soil heat flux S	N - S	$\beta = \frac{Q}{\lambda E}$	$1 + \beta$	λE	Q	$\frac{\text{Net}}{\text{Solar}}$	Albedo r
0830-0930	52.5	44.5	0.6	43.9	0.00	1.00	43.9	0.0	0.85	0.15
0930-1030	69.4	60.1	1.0	59.1	-0.03	0.97	60.9	-1.8	0.87	0.13
1030-1130	75.4	66.8	1.3	65.5	-0.06	0.94	69.6	-4.1	0.89	0.11
1130-1230	96.5	87.8	1.2	86.6	-0.06	0.94	92.2	-5.6	0.91	0.09*
1230-1330	82.0	76.9	1.7	75.2	-0.04	0.96	78.3	-3.1	0.94	0.06*
1330-1430	63.0	61.8	1.7	60.1	0.03	1.03	58.3	1.8	0.98	0.02*
1430-1530	56.7	45.5	0.7	44.8	-0.02	0.98	45.7	-0.9	0.80	0.20
1530-1630	39.1	31.1	0.4	30.7	0.03	1.03	29.8	0.9	0.80	0.20
1630-1730	18.1	9.3	0.1	9.2	0.04	1.04	8.9	0.3	0.51	0.49
1730-1800	-	-2.3	-0.1	-2.2	0.10	1.10	-2.0	-0.2	-	-
Total:	552.7	481.5	8.6	472.9			485.6	-12.7		
						Equiv. (mm):	8.3		Mean:	0.21

*excluded from the mean

TABLE 20a

Energy balance (cal.cm^{-2}) over maize crop at Mwea

11.10.68

No record of soil heat flux. λE therefore overestimated by at least 2%.

Period (local time)	Solar	Net N	$\beta = \frac{Q}{\lambda E}$	$1 + \beta$	λE	Q	Net / Solar	Albedo r
0730–0800	16.5	11.1	–	–	–	–	0.67	0.32
0800–0900	26.1	20.4	0.10	1.00	20.4	0.0	0.78	0.22
0900–1000	56.2	43.8	–0.16	0.84	52.1	–8.3	0.78	0.22
1000–1100	84.3	72.5	0.06	1.06	68.4	4.1	0.86	0.14
1100–1200	89.8	78.1	0.42	1.42	55.0	3.1	0.87	0.13
1200–1300	88.9	77.3	–0.22	0.78	99.1	–21.8	0.87	0.13
1300–1400	87.9	76.5	0.31	1.31	58.4	18.1	0.87	0.13
1400–1500	62.2	53.5	0.87	1.87	28.6	24.9	0.86	0.14
1500–1600	46.4	37.1	1.80	2.80	13.3	23.8	0.80	0.20
1600–1700	21.6	16.2	–0.20	0.80	20.3	–4.1	0.75	0.25
1700–1800	26.1	5.5	0.30	1.30	4.2	1.3	0.21	0.79*
Total:	606.0	492.0			419.8	41.1		
				Equiv. (mm):	7.2		Mean:	0.18

*excluded from the mean

TABLE 20b

Energy balance (cal.cm^{-2}) over maize crop at Mwea - 12.10.68

Period (local time)	Solar	Net N	Soil heat flux S	N - S	$\beta = \frac{Q}{\lambda E}$	$1 + \beta$	λE	Q	Net / Solar	Albedo r
0800-0900	-	19.5	0.9	18.6	-0.22	0.78	23.8	-5.2	-	-
0900-1000	69.0	53.8	2.0	51.8	0.47	1.47	35.2	16.6	0.78	0.22
1000-1100	69.8	60.0	2.1	57.9	-0.42	0.58	99.8	-41.9	0.86	0.14
1100-1200	82.9	72.1	2.5	69.6	0.46	1.46	47.7	21.9	0.87	0.13
1200-1300	91.8	79.9	4.1	75.8	0.32	1.32	57.4	18.4	0.87	0.13
1300-1400	86.2	75.0	5.0	70.0	-0.17	0.83	84.3	-14.3	0.87	0.13
1400-1500	60.1	51.7	2.0	49.7	0.43	1.43	34.8	14.9	0.86	0.14
1500-1600	38.7	31.0	1.4	29.6	0.57	1.57	18.9	10.7	0.80	0.20
1600-1700	21.9	16.4	1.1	15.3	0.13	1.13	13.5	1.8	0.75	0.25
1700-1800	7.1	1.5	0.7	0.8	0.06	1.06	0.8	0.0	0.21	0.79*
Total:	527.5	460.9	21.8	439.1			416.2	22.9		
						Equiv. (mm):	7.1		Mean:	0.17

*excluded from the mean

TABLE 20c

Energy balance (cal.cm^{-2}) over maize crop at [illegible]

13.10.68

Period (local time)	Solar	Net R	Soil heat flux S	R - S	$\beta = \frac{Q}{\lambda E}$	$1 + \beta$	λE	Q	Net/Solar	Albedo r
0700-0800	6.3	4.2	0.1	4.1	0.08	1.08	3.8	0.3	0.67	0.33
0800-0900	27.2	21.9	0.9	21.0	0.98	1.98	10.6	10.4	0.81	0.19
0900-1000	50.7	38.6	1.3	37.3	0.46	1.46	25.5	11.8	0.76	0.24
1000-1100	74.6	61.6	1.8	59.8	0.30	1.30	46.0	13.8	0.83	0.17
1100-1200	98.6	81.4	2.4	79.0	0.08	1.08	73.1	5.9	0.83	0.17
1200-1300	96.0	80.7	4.1	76.6	-0.40	0.60	127.7	-51.1	0.84	0.16
1300-1400	71.4	68.0	4.1	63.9	-0.42	0.58	110.1	-46.2	0.86	0.14
1400-1500	72.5	61.9	2.3	59.6	0.13	1.13	52.7	6.9	0.85	0.15
1500-1600	50.0	39.1	1.7	37.4	0.35	1.35	27.7	9.7	0.78	0.22
1600-1700	36.7	27.1	1.1	26.0	-0.07	0.93	28.0	-2.0	0.74	0.26
1700-1800	13.9	2.7	0.7	2.0	-0.01	0.99	2.0	0.0	0.19	0.81*
Total:	605.9	487.2	20.5	466.7			507.2	-40.5		
						Equiv. (mm):	8.7		Mean:	0.18

*excluded from the mean

TABLE 20d

Energy balance (cal.cm^{-2}) over maize crop at Mwea

14.10.68

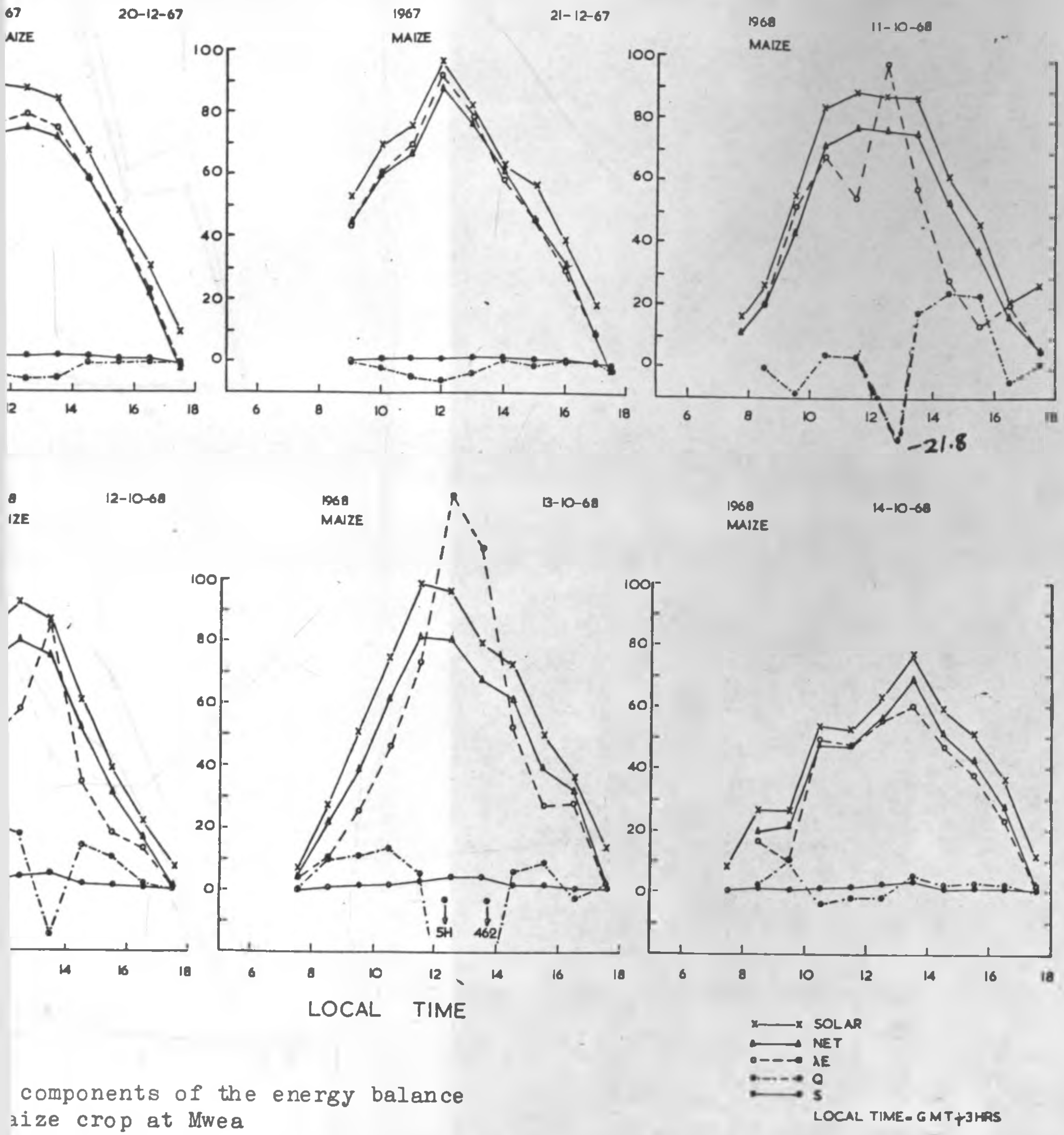
Period (local time)	Solar	Net N	Soil heat flux S	N − S	$\beta = \frac{Q}{\lambda E}$	$1 + \beta$	λE	Q	Net / Solar	Albedo r
0700–0800	8.9	–	0.4	–	0.58	1.58	–	–	–	–
0800–0900	26.7	20.0	1.0	19.0	0.14	1.14	16.7	2.3	0.75	0.25
0900–1000	26.6	21.6	0.8	20.8	1.01	2.01	10.3	10.5	0.81	0.19
1000–1100	53.8	47.8	1.6	46.2	−0.07	0.93	49.6	−3.4	0.89	0.11
1100–1200	52.4	47.6	1.8	45.8	−0.04	0.96	47.7	−1.9	0.91	0.09
1200–1300	63.0	56.2	2.4	53.8	−0.03	0.97	55.5	−1.7	0.89	0.11
1300–1400	77.3	69.2	3.3	65.9	0.09	1.09	60.5	5.4	0.90	0.10
1400–1500	59.0	51.2	1.8	49.4	0.05	1.05	47.0	2.4	0.87	0.13
1500–1600	51.2	42.6	1.6	41.0	0.07	1.07	38.3	2.7	0.83	0.17
1600–1700	36.2	27.3	1.2	26.1	0.12	1.12	23.3	2.8	0.75	0.25
1700–1800	11.8	2.7	0.7	2.0	0.24	1.24	1.6	0.4	0.23	0.77*
Total:	466.9	386.2	16.6	370.0			350.5	19.5		
						Equiv. (mm):	6.0		Mean:	0.16

*excluded from the mean

TABLE 21

Comparison between evaporation derived from energy balance measurements in field A and lysimeter A estimate of crop water use

Date	Crop	Et Lysimeter A mm.	Et	
			Energy balance mm.	Period
6.5.68 7.5.68	Beans	5.4 4.3	6.5 5.6	0900-1800 0900-1500
Total		9.7	12.1	
11.10.68 12.10.68 13.10.68 14.10.68	Maize	6.9 7.5 8.0 8.9	7.2 7.1 8.7 6.0	0800-1800 0800-1800 0700-1800 0800-1800
Total		31.3	29.0	
20.12.67 21.12.67	Maize	7.5 9.7	7.8 8.3	0900-1800 0830-1800
Total		17.2	16.1	



components of the energy balance
aize crop at Mwea

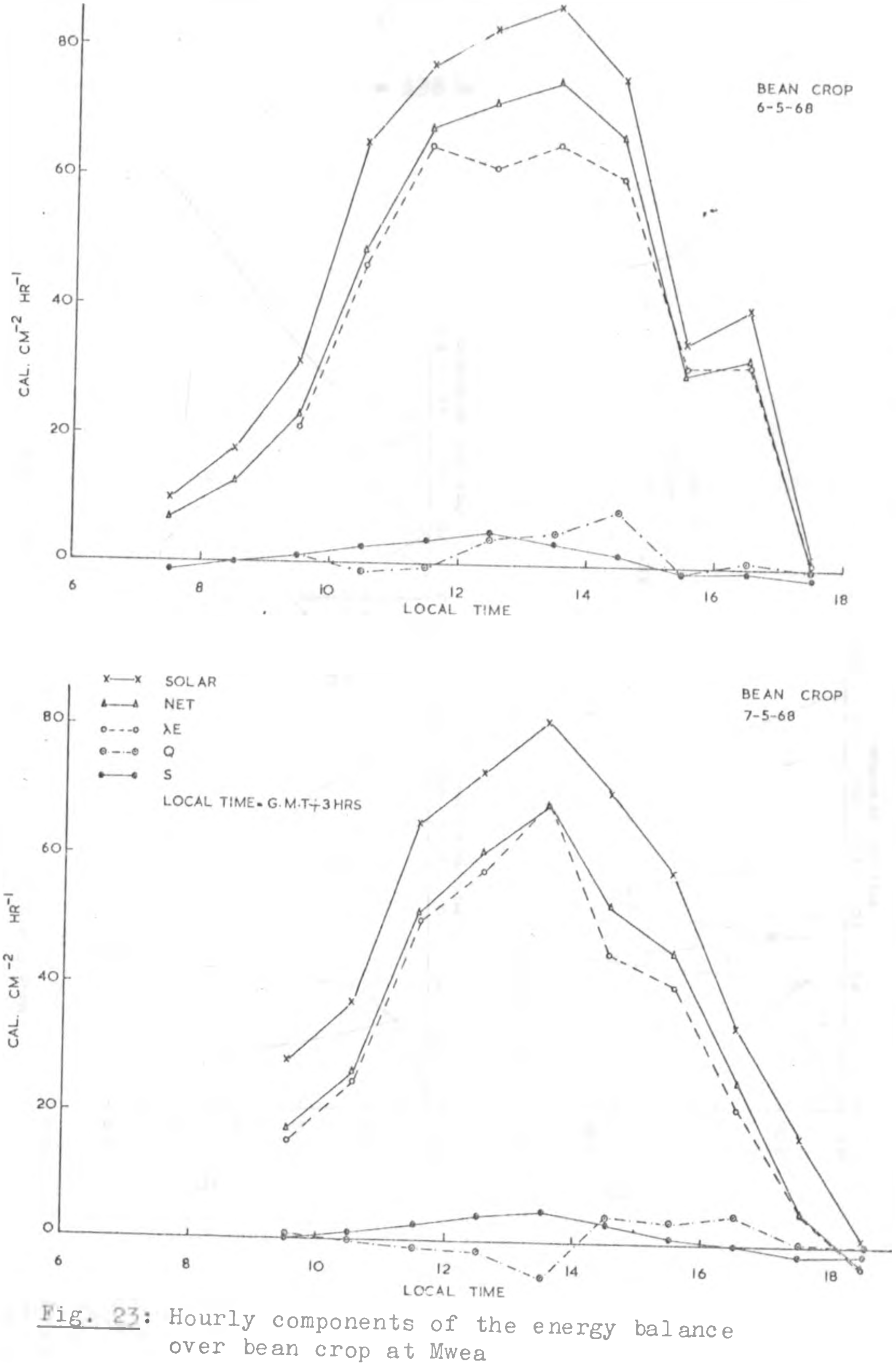


Fig. 23: Hourly components of the energy balance over bean crop at Mwea

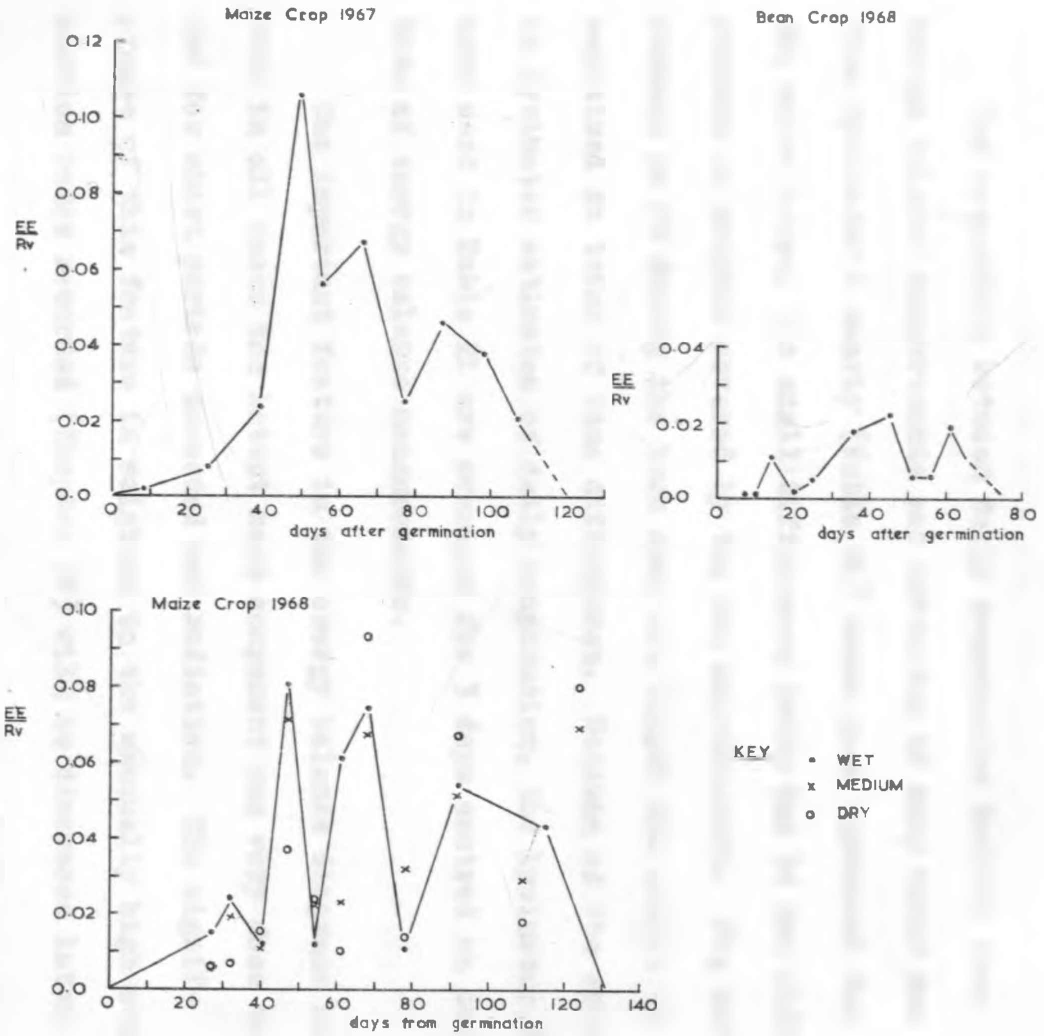


FIG. 24: Fraction of solar radiation (0.4 - 0.7) stored in dry matter at various stages of crop growth

Results

A sample calculation of Bowen's ratio from the data recorded is shown in Appendix 17. The components of the hourly energy balance are plotted in Figs. 22 and 23 and the actual values are presented in Tables 18, 19 and 20.

The comparison between daily evaporation derived from energy balance measurements and estimates of crop water use from Lysimeter A nearby (Table 21) shows good agreement for the maize crops, the small differences being due to the differences in periods covered by the two measurements. The differences in Et during the bean crop are bigger and cannot be explained in terms of time differences. Because of the errors in lysimeter estimates of daily evaporation, the lysimeter figures used in Table 21 are averages for 3 days centred on the date of energy balance measurements.

One important feature in the energy balance diagrams is that in all cases the latent heat component was very close to and for short periods exceeded net radiation. The significance of this feature in relation to the unusually high evaporation rates recorded (Chapter II) will be discussed later.

Conversion of total dry matter increments (ΔM) into the equivalent energy, and the comparison of these values with the fraction of total short wave radiation in the photosynthetic (0.4 - 0.7μ) wavelength (approximately 0.47), are shown in Appendix 18. The results (Fig. 24) show that the fraction of light energy stored in dry matter per unit area was higher in maize (0 - 8%, seasonal average ≃ 4%) than in beans (0 - 2%, seasonal average ≃ 1%). The corresponding fractions of total short wave radiation are 1.9% and 0.5% for maize and beans respectively.

Discussion of results

The maximum error in the measurement of solar and net radiation was 3%, all of which was in the calibration and integration. Soil heat flux measurements were less precise and although errors in calibration and integration were no more than 5%, the representativeness of the measurements could not be assessed and the spatial averaging by the use of three flux plates in series may not have been sufficiently effective in smoothing out effects of differential shading by plants and by surface clods. It has been shown (Tanner, Peterson and Love, 1960) that for short periods during the day soil heat flux can be a large proportion of net radiation. The values of soil heat flux recorded in these measurements (highest 5 - 8% of net radiation) are therefore no more than rough estimates, but it is considered that with evapotranspiration rates near potential, the errors in λE from this source were less than 10%.

The major source of error in the calculation of λE was in the Bowen's Ratio where even without considering errors due to inadequate spatial averaging, the temperature and humidity differences were so small that it was necessary to use a rather elaborate system of flow interchanges. Differences of more than 100% between successive 10-minute estimates of β were common, but probably genuine variations.

The agreement obtained between energy balance and lysimeter estimates of crop water use in these experiments is therefore remarkably good and consistent, increasing confidence in the working of the lysimeter and the high Et/Eo values recorded (Chapter II).

Fig. 24 shows two large drops in photosynthetic efficiency of the two maize crops. The dips are less in the 1967 crop but occur at the same stages of crop growth, 55 and 75 days after germination, in both crops irrespective of water treatments. In the absence of adverse soil conditions there are at least two possible causes:

(a) that these changes are entirely due to experimental error in dry matter determination; in which case the occurrence at similar stages of growth was purely a coincidence.

(b) that these drops represent genuine reduction of photosynthetic efficiency due to crop physiological factors.

Since all plant samples were randomly selected and treated in a similar manner, it is unlikely that the experimental error exceeded 20%. This is much less than the 50-90% drops in Fig. 24, but could serve to explain the rather high peaks of energy recovery which approach the theoretical limit of 8% (Monteith, 1965c). The seasonal averages are however larger than the usual 1-2% quoted for agricultural production (Monteith, 1965d; Huxley, 1965). Alternative (b) above is therefore a possibility. The two periods coincide with tasselling and the start of the grain filling respectively, but apart from possible reduction of light penetration by the inflorescence, the cause of this phenomenon, which is not reflected in the linear growth curves (Figs. 12 and 13), is not immediately obvious.

In the case of the bean crop, the drop between 50 and 60 days after germination (Fig. 24) coincides with 212 mm of rain in 10 days and 60 mm in the following 5 days. Since maximum available water in the depth 0-150 cm is 250 mm (Table 1) the addition of the 212 mm to an already wet profile could have led to soil saturation; anaerobic conditions, however temporary, could have resulted in reduced rate of dry matter formation. The canopy was already fully developed for this effect to show on the leaf area index curve.

CHAPTER V

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

1. Crop Water Use

The hydraulic weighing lysimeter of the type described by Forsgate, Hosegood and McCulloch (1965), if properly sited and operated, can provide reliable estimates of crop water use in all stages of crop growth. The accuracy of these estimates, however, diminishes rapidly as the time interval is reduced below 5 days. The main cause of this seems to be a variable response time apparently dependent on both the magnitude and spatial distribution of the change in load on the lysimeter. The exact mechanism resulting in erratic movement of the water level in the balancing column remains to be investigated. Sensitivity of the weighing system can be increased but the benefit would be minimal unless the drift in column height can be eliminated.

The patterns of crop water use presented in Chapter II, and the subsequent discussion, have however revealed two major considerations much more important than the proper operation and reliability of lysimeters:

(a) the difficulty in growing, in a lysimeter, a crop truly representative of the surrounding field crop, and the proper corrections to be applied if this condition is not satisfied;

and (b) the importance of the frequency of rainfall or irrigation, for a valid extension of crop water use data to environmental and agronomic conditions different from those obtaining at the experimental plot where the measurements were originally made.

No proven answer has been found for (a), but for (b) comparison between the patterns of crop water use for the 1967 and 1968 maize crops suggests strongly that the occurrence of high Et/Eo values when rainfall is frequent is due to direct evaporation of water intercepted by the crop. The magnitude of this effect is governed mainly by the ratio of crop surface resistance r_s to aerodynamic resistance r_a. There are very few published values of these resistances and more work is required to determine representative values of these factors. Various methods of determining r_s are discussed by Szeicz and Long (1969) whose prediction of large seasonal changes in r_s for the forest canopy in Kericho, Kenya, appears to be well supported by the bimodal rainfall pattern. Until these factors can be determined with certainty, extrapolation of crop water use measurements between different environments should be carried out with caution and with full realisation that in the absence of supporting meteorological data, the predictions of Et/Eo may be entirely unrealistic.

Fortunately, agriculture and land use planning do not have to wait until the above corrections can be applied rigorously in every case. Results of this work suggest strongly that in irrigated crops substantial water use efficiency can be achieved by applying fewer but reasonably heavy irrigations direct to the soil surface, notwithstanding the difficulties of uniformity of water application, and the water storage capacity of the soil profile within root range.

A simpler but interim application of these results is is the incorporation of the number of rain days in the prediction of crop water use. Promising results of this approach have been obtained by Dagg (1970) in the case of tea where an equation of the form

$$\frac{Et}{Eo} = a_1 f + a_2 n(1 - f),$$

where $a_1 = a_2 = 0.90$

f = fraction of area shaded by the ~~ground~~ tea,

and n = fractional number of rain days per month,

has given values of Et/Eo closely correlated with measurements of Et/Eo with a lysimeter. The main response to rain days in the case of young tea is in evaporation from bare soil, suggesting that $\frac{r_s}{r_a}$ for tea has a value close to unity. This may not be the case with other crops and the presence of empirical factors like a_1 and a_2 is still unsatisfactory. The general usefulness of this formula should however be checked where accurate measurements of crop water use and percentage ground cover are available.

2. The use of Neutron Moisture Meters

Of the two makes of neutron moisture meter tested, the N.A.L. and the NIV-I, the former has proved more accurate and better suited to detection of small changes in moisture content in soil with large water holding capacity. Under the right conditions, these changes in moisture content can readily be used to calculate a reasonable estimate of crop water use in the field, but in irrigated fields, uniformity of water application is an important source of error. Another limiting factor is the lack of reliable methods of estimating the upward and downward flux of soil water. This is more serious in annual crops where the maximum root depth at a given time is variable and often unknown, and where sub-surface cracks in the soil profile may be dominant in downward drainage.

The effect of moisture content on the sphere of influence of neutron moisture meters becomes critical near the soil surface and this can result in serious errors in water use measurements when most of the water for evaporation comes from this layer. It is possible to apply a separate calibration for the first 30 cm (van Bavel and Stirk, 1967) where a relatively small area such as a lysimeter is concerned, but the applicability of this procedure in the open field is limited by the spatial variability of soil density and organic matter content in this layer. The use of standardised neutron reflectors for attachment to normal depth probes has been tried elsewhere without much success, partly because of the effect of such reflectors on the spherical symmetry of the slow neutron cloud around the detector. The alternative method of soil sampling in this layer was tried in the Mwea experiments. The results and subsequent examination of the method suggest that it is unsatisfactory since many samples are required in order to achieve spatial average moisture content. This procedure could also change soil conditions near the neutron probe access pipe to the extent that the entire soil profile water content may not be representative. Development of a simple but reliable and rapid method of soil moisture determination in the top layer of soil is therefore called for.

3. Estimating Potential Dry Matter Production

A high degree of correlation (98% of variance accounted for) has been obtained between measured dry matter production in all stages of growth and theoretical estimates of gross photosynthesis based on the method of Monteith (1965a). The only measurements required are daily totals of solar radiation, leaf area index, and the relationship between light extinction in the canopy and leaf area index. The fraction of gross photosynthesis used in respiration under field conditions will be difficult to measure but results of Mwea experiments indicate that this fraction is relatively constant in a given climate and values of 0.5 for maize and 0.4 for beans would be applicable in a warm climate similar to that of Mwea.

These findings should be tested over a wide range of environments. The possibility of predicting maximum yields, not only of stover but also of grain, in crops of maize and beans will be a valuable aid not only in land use planning, but also to plant breeders who would welcome the possibility of assessing the potentialities of genetic material before final yields are obtained. It is evident that a good variety of maize will be one which develops full leaf area quickly, maintains this condition for the larger fraction of the growing season, and in which all net photosynthesis after silking is stored in the grain.

4. Partition of energy in crops of maize and beans

Results from the Mwea experiments have shown that if soil moisture is available, almost all net radiation in maize and bean crops may be converted into latent heat and that for short periods latent heat in the maize crop can exceed net radiation with consequential cooling of the air. The method of Fritschen (1965) for the determination of hourly values of Bowen's Ratio, β, has yielded consistent results. Analysis of chart records proved cumbersome and development of a simple data handling system is very desirable. The main obstacle will be the subjective quality control found necessary before integration of chart records. The fraction of total radiation stored in the form of total dry matter is very small compared with the latent and sensible heat components. This component does not appear to be correlated with the three soil moisture treatments in the 1968 maize crop and does not therefore seem to be a suitable parameter for defining water use efficiency of maize.

The drop in rate of dry matter formation at certain stages of growth in both maize and beans could, however, be a valuable indicator of the effects of physiological (in the case of maize) and /or excessive soil moisture (in the case of beans) conditions on the efficiency of solar energy utilisation for photosynthesis in field crops. These aspects are described in greater detail in Chapter IV, but further detailed experiments are required to check the reproducibility of such effects and, if confirmed, to work out the mechanism of these phenomena.

5. Water Use Efficiency

The experiments carried out at Mwea have therefore shown that water use efficiency of maize and beans cannot be defined in quantitative terms without reference to the environment. Crop management is a significant factor which cannot be quantified, but optimum plant populations and direct application of irrigation water to the soil beneath the vegetation should result in increased water use efficiency. Provided soil moisture storage capacity is good, heavy doses of irrigation applied less frequently would be more economical than frequent applications of small amounts of water.

REFERENCES

Alberda, T. and Sibma, L. (1962). Inst. Biol. Scheik. Onderz. Landb. Gewas., 47-58.

Allen, L. H., Yocum, C. S. and Lemon, E. R. (1964). Agron. J. 56, 253-259.

Bell, J. P. and Eeles, C. W. O. (1967). Soil Sci. 103, 1-3.

__________ and McCulloch, J. S. G. (1966). J. Hydrol. 4, 254-263.

Black, J. N. (1963). Aust. J. agric. Res. 14, 20-38.

Blackie, J. R. (1964). E. Afr. geogr. Rev. 2, 17-22.

Blackman, F. F. (1895). Phil. Trans. R. Soc. B 186, 503-562.

Blaney, H. F. and Criddle, W. D. (1950). U.S. Dep. Agric. S.C.S. Tech. Pubn. 96.

Briggs, L. J. and Shantz, H. L. (1914-1917). J. agric. Res. 3, 1; 5, 117; 5, 583; 7, 155; 9, 277.

Brougham, R. W. (1956). Aust. J. agric. Res. 7, 377-387.

Brown, H. T. and Escombe, F. (1905). Proc. R. Soc. B 76, 61.

Burgy, R. H. and Pomeroy, C. R. (1958). Trans. am. geophys. Un. 39, 1095-1100.

Cackett, K. E. and Metelerkamp, H. R. R. (1963). Rhod. J. agric. Res. 1, 18-21.

______________ and ____________________ (1964). Rhod. J. agric. Res. 2, 35-44.

Calson, C. W., Alessi, J. and Mickelson, R. H. (1959). Proc. Soil Sci. Soc. Am. 23, 242-245.

Cowan, I. R. (1965). J. appl. Ecol. 2, 221.

Crawford, T. V. (1965). Q. Jl. R. met. Soc. 91, 18-27.

Dagg, M. (1965). E. Afr. agric. For. J. 30, 296-300.

_______ (1970). To be published in Agric. Met.

_______ and Blackie, J. R. (1965). Bull. int. Ass. scient. Hydrol. 4, 63-75.

Dagg, M., Woodhead, T., and Rijks, D. A. (1970). Bull. int. Ass. scient. Hydrol. 15, 1-7.

Dale, R. F. and Shaw, R. H. (1965). Agron. J. 57, 475.

Dalton, J. (1834). Meteorological Observations and Essays (2nd Edition).

Davidson, J. L. and Philip, J. R. (1958). In Arid Zone Research XI Proc. Canberra Symp., 181. UNESCO, Paris.

______________ and Donald, C. M. (1958). Aust. J. agric. Res. 9, 53-72.

Deacon, E. L. (1950). Q. Jl R. met. Soc. 76, 479-483.

Denmead, O. T. and Shaw, R. H. (1959). Agron. J. 51, 725-726.

______________ and ____________ (1962). Agron. J. 57, 475.

de Wit, C. T. (1958). Versl. landbouwk. Onderz., 64-66.

____________ (1959). Neth. J. agric. Sci. 7, 141-149.

de Wit, C. T. (1965). Agric. Res. Report No. 663, Wageningen.

England, C. B. (1963). Agron. J. 55, 239-242.

Earley, E. B. (1965). Agron. J. 57, 514.

Forsgate, J., Hosegood, P. H. and McCulloch, J. S. G. (1965). Agric. Met. 2, 43.

Fritschen, L. J. (1965). Bull. int. Ass. scient. Hydrol. 10(2), 38-48.

________________ and Shaw, R. H. (1961). Agron. J. 53, 71-74.

________________ and van Bavel, C. H. M. (1964). Agron. J. 56, 201-204.

Fuehring, H. D., Mazaheri, A., Bybordi, M., and Khan, A. K. S. (1966). Agron. J. 58, 195.

Gaastra, P. (1959). Meded. LandbHogesch. Wageningen, 59, 1.

Gaastra, P. (1963). In "Environmental Control of Plant Growth", 113. (Ed.) Evans, L. New York: Academic Press.

Garber, J. F. and Decker, W. L. (1961). Agron. J. <u>53</u>, 259-261.

Gardner, W. and Kirkham, D. (1952). Soil Sci. <u>73</u>, 391-401.

Haise, H. R. and Viets, F. G. (1957). Proc. int. Comm. Irrig. Drain. 3rd Congr. R.25, Question 8: 8.497-8.508.

Hanway, J. J. (1962). Agron. J. <u>54</u>, 145.

Harrold, L. L., Peters, D. B., Dreibelbis, F. R. and McGuinness, J. L. (1959). Proc. Soil Sci. Soc. Am. <u>23</u>, 174-178.

Haynes, J. L. (1948). Agron. J. <u>40</u>, 385.

Heath, O. V. S. (1951). Symp. Soc. exp. Biol. <u>5</u>, 94-114.

Hesketh, J. D. and Moss, D. N. (1963). Crop Sci. 3, 107.

________ and Musgrave, R. B. (1962). Crop Sci. 2, 311.

Holmes, J. W. (1953). Aust. Conf. Soil Sci., Adelaide, 2, 4.1, p. 3.

Honert, T. H. van den (1948). Disc. Faraday Soc. 3, 146.

Hutchinson, Sir J., Manning, H. L. and Farbrother, H. G. (1958). J. agric. Sci. 51, 177-188.

Huxley, P. A. (1965). Expl Agric. 1, 81-97.

Huxley, P. A., Turk, A. and Mitchell, H. W. (1969). Kenya Coffee - Monthly Bulletin for February.

Idso, S. B., Baker, D. G. and Blad, B. L. (1969). Q. Jl R. met. Soc. 95, 244-257.

Kalju Eik and Hanway, J. J. (1966). Agron. J. 58, 16.

Lemon, E.R. (1966). Energy conversion and water use efficiency in plants, in "Plant Environment and Efficient Water Use", Ed. Pierre et al., published by Am. Soc. Agron. and Soil Sci. Soc. Am.

Letey, J. and Peters, D. B. (1957). Agron. J. 49, 362.

Manning, H. L. (1956). Proc. R. Soc. B 144, 460–480.

Maskell, E. J. (1928). Proc. R. Soc. B 102, 467–532.

Mather, J. R. (1954). Johns Hopkins Univ. Publ. Climat. 7, 177–199.

Maynard, L. A. and Loosli, J. K. (1962). In "Animal Nutrition". McGraw-Hill Co., New York. 325.

McCloud, D. E. and Dunavin, L. S. (1954). Johns Hopkins Univ. Publ. Climat. 7, 55–68.

McCulloch, J. S. G. (1965). E. Afr. agric. For. J. 30, 286–295.

McIlroy, I. C. and Angus, D. E. (1964). Agric. Met. 1, 201–224.

McMillan, W. D. and Burgy, R. H. (1960). J. geophys. Res. 65, 2389–2394.

Mitchell, H. W. (1965). Tanganyika Coffee News, July/Sept.

Monteith, J. L. (1959). J. scient. Instrum. 36. 341-345.

_______________ (1963). Gas exchange in plant communities in environmental control of plant growth, Academic Press, New York, 95-110.

_______________ (1965a). Ann. Bot. N.S.29. 17-37.

_______________ (1965b). Symp. Soc. expl Biol. 19, 205-234.

_______________ (1965c). Expl Agric. 1, 241-251.

_______________ (1965d). Field crops Abstracts 18, 213-219.

_______________ and Szeicz, G. (1961). Q. Jl R. met. Soc. 87, 159-170.

Morrison, F. B. (1947). In "Feeds and Feeding". Morrison Publ. Co., New York.

Munn, R. E. (1966). Descriptive Micrometeorology. Academic Press, New York, 59-61.

Nichiporovich, A. A. (1961). Soviet Pl. Physiol. 8, 428-435.

Olivier, H. (1961). Irrigation and Climate. Publ. Edward Ltd., London.

Pasquill, F. (1949). Proc. R. Soc. A 198. 116-140.

Paul, H. A. and Burgy, R. H. (1961). Interception losses from small trees. Dept. of Irrig., Univ. of California.

Penman, H. L. (1941). J. agric. Sci., Camb. 31, 454.

______________ (1948). Proc. R. Soc. A 193. 120-145.

______________ (1956). Neth. J. agric. Sci. 4, 9-29.

______________ and Long, I. F. (1960). Q. Jl R. met. Soc. 86, 16.

______________ and Schofield, R. K. (1951). Symp. Soc. expl Biol. 5, 129.

Pereira, H. C. (1957). E. Afr. agric. For. J. 22, 188-193.

Peters, D. B. and Russell, M. B. (1959). Proc. Soil Sci. Soc. Am. 23, 170.

Philip, J. R. (1956). Arid Zone Research XI.

Prescott, J. A. (1938). J. Aust. Inst. agric. Sci. 4, 33-40.

Ragland, J. L., Hatfield, A. L., and Benoit, G. R. (1965). Agron. J. 57, 217.

Rider, W. E. and Robinson, G. D. (1951). Q. Jl R. met. Soc. 77, 375-401.

Rijks, D. A. and Owen, W. G. (1965). Hydrometeorological records from areas of potential agricultural development in Uganda. Water Development Department, Ministry of Mineral and Water Resources, Uganda.

Rohwer, C. (1931). U.S. Dep. Agric. Tech. Bull. 271.

Saeki, T. (1960). Bot. Mag., Tokyo 73, 55

Sibbons, J. L. H. (1962). Geogr. Annlr 44. 279-292.

Slatyer, R. O. and McIlroy, I. C. (1961). Practical Microclimatology. UNESCO, Paris.

Stanhill, G. (1958). Nature 182, 125.

__________ (1962). Neth. J. agric. Sci. 10, 247.

Stoller, J. and Lemon, E. R. (1963). The Energy Budget at the earth's Surface, II. Production & Research Dept., U.S. Dept. Agric.

Stoltenburg, N. L., and Wilson, T. V. (1950). Trans. Am. geophys. Un. 31, 443-448.

Suomi, V. E. and Tanner, C. B. (1958). Trans. Am. geophys. Un. 39, 298-304.

Sutton, O. G. (1953). Micrometeorology. McGraw-Hill Book Co., New York.

Swinbank, W. C. (1955). C.S.I.R.O. Div. Met. Phys. Tech. Paper 2.

Szeicz, G., Endrődi, G. and Tajchman, S. (1969). Wat. Resour. Res. 5, 380-394.

__________ and Long, I. F. (1969). Wat. Resour. Res. 5, 622-633.

Takeda, T. (1961). Jap. J. Bot. 17, 403-457.

Tanner, C. B., Peterson, A. E. and Love, J. R. (1960). Agron. J. **52**, 373-379.

______________ and Suomi, V. E. (1956). Trans. Am. geophys. Un. **37**, 413-420.

Taylor, R. J. (1952). Q. Jl R. met. Soc. **78**, 179-185.

______________ (1960). Q. Jl R. met. Soc. **86**, 67-78.

Thornthwaite, C. W. (1948). Geogrl Rev. **38**, 55-94.

van Bavel, C. H. M. Hood, E. E., and Underwood, N. (1954). Trans. Am. geophys. Un. **35**, 595-600.

___________________ and Stirk, G. B. (1967). J. Hydrol. **5**, 40-46.

___________________, Stirk, G. B. and Brust, K. G. (1968). Proc. Soil Sci. Soc. Am. **32**, 310.

Veihmeyer, F. J. and Brooks, F. A. (1954). Trans. Am. geophys. Un. **35**, 601.

Waggoner, P. E. (1966). In "Plant environment and efficient water use". Ed. Pierre *et al*. Publ. by Am. Soc. Agron. and Soil Sci. Soc. Am., 49-72.

Walker, J. T. G. and Rijks, D. A. (1967). Expl Agric. 3, 337-341.

Wallis, J. A. N. (1963). J. agric. Sci. Camb. 60, 381.

Wangati, F. J. (1965). Agric. Met. 2, 53.

______________ (1966). M.Sc. Thesis, Univ. of London.

Watson, D. J. (1947). Ann. Bot. N.S.11, 41-76.

______________ (1958). Ann. Bot. N.S.22, 37-55.

______________ and Witts, K. J. (1959). Ann. Bot. N.S.23, 431-439.

Williams, W. A., Loomis, R. S. and Lepley, C. R. (1965). Crop Sci. 5, 211-219.

Woodhead, T. (1968a). Studies of potential evaporation in Kenya. Publ. by Water Development Division, Min. of Agric., Kenya.

Woodhead, T. (1968b). Studies of potential evaporation in Tanzania. Publ. by Water Development & Irrigation Division, Min. of Lands, Settlement and Water Development, Tanzania.

Yao, A. Y. M. and Shaw, R. H. (1964a). Agron. J. 56, 147-152.

____________________ (1964b). Agron. J. 56, 165-169.

Yocum, C. S., Allen, L. H. and Lemon, E. R. (1964). Agron. J. 56, 249-259.

APPENDIX 1

Chemical Analysis of Soils from the Experimental Fields

Field	Depth cm	pH (soil paste)	Organic matter (% ODS)	Exchangeable Cations (m. eq. % ODS)				Conductivity $EC_1 \times 10^3$ mhos at 25° C (1:1 suspension)	Sodium adsorption ratio SAR	Exchangeable sodium percentage ESP	Mechanical analysis (pipette method) (% ODS)		
				K	Ca	Mg	Mn				Sand	Clay	Silt
A	0-15	6.1	3.58	2.95	10.34	7.1	0.194	0.113	Less than 1-2	Less than 1-2	25.6	36.6	34.2
	15-30	6.2	3.58	2.67	10.33	7.0	0.167	0.072			29.0	36.6	30.8
	30-45	5.9	3.08	2.46	8.19	5.9	0.452	0.110			25.6	42.0	29.3
	45-75	5.5	2.04	0.84	5.93	4.9	0.647	0.130			21.2	54.0	22.8
	75-105	5.6	1.36	0.36	4.50	4.2	0.139	0.082			19.7	57.8	21.1
	105-135	5.8	1.50	0.17	3.36	4.2	0.141	0.180			20.1	58.6	19.1
	135-150	5.9	1.26	0.17	2.58	4.2	0.086	0.140			20.4	55.9	22.4
B	0-15	5.6	3.44	1.95	8.56	5.0	0.482	0.180	Less than 1-2	Less than 1-2	28.3	38.5	29.8
	15-30	5.6	2.46	1.29	7.50	4.8	0.450	0.300			26.0	44.0	27.5
	30-45	5.6	1.88	0.76	6.49	4.2	0.551	0.172			23.3	49.7	25.1
	45-75	5.6	1.60	0.45	5.08	4.1	0.227	0.144			24.4	54.0	20.0
	75-105	5.7	1.26	0.30	4.30	4.1	0.140	0.164			21.7	55.8	21.2
	105-135	5.7	1.10	0.17	3.67	4.8	0.108	0.170			20.0	57.2	21.6
	135-150	5.6	1.04	0.22	3.35	4.5	0.108	0.258			23.3	55.1	20.6

APPENDIX 2

Summary of Meteorological Observations at Mwea Irrigation Scheme

Period	Rainfall	Air temperature			Air humidity			Wind speed	Radiation	Sunshine	Open water evaporation
	Monthly totals	Monthly means of daily values			Dewpoint mean of 0900 and 1500 hrs	Saturation deficit mean of 0900 and 1500 hrs	Relative humidity at 1500 hrs	Mean wind speed at 6 ft above ground	Gunn Bellani	Mean daily sunshine hours	Raised pan with grid cover
	mm	Max °C	Min °C	Mean °C	°C	mm of mercury	%	mph	Ly/day	hrs	mm
1967											
Jul.	21.1	24.8	15.0	19.9	14.4	5.12	53	2.1	420	4.3	121.7
Aug.	20.6	25.5	14.2	19.9	13.3	5.97	48	2.6	462	5.0	141.5
Sep.	15.5	28.2	14.3	21.3	13.4	7.47	40	3.3	568	7.2	182.1
Oct.	236.5	28.0	15.8	21.9	15.6	6.42	48	3.4	556	6.7	183.1
Nov.	206.0	26.3	15.4	20.9	17.9	3.15	66	2.5	515	6.7	138.2
Dec.	0	27.2	12.5	19.9	16.2	3.61	56	3.1	630	10.1	178.8
1968											
Jan.	0	29.2	11.1	20.2	13.1	6.45	39	3.8	695	11.1	225.0
Feb.	149.6	28.6	14.7	21.7	15.3	6.43	43	3.5	574	7.1	176.3
Mar.	123.2	27.6	15.4	21.5	17.2	4.52	59	3.1	544	6.7	160.8
Apr.	305.6	26.6	15.4	21.0	17.6	3.56	62	2.6	491	5.8	136.9
May	92.5	26.0	16.3	21.1	16.8	4.42	61	2.3	491	6.0	128.8
Jun.	17.0	25.2	15.0	20.1	15.1	4.77	58	1.8	435	4.6	112.0
Jul.	19.8	23.4	15.0	19.2	13.9	4.77	59	1.8	341	2.4	87.6
Aug.	8.9	23.5	14.7	19.1	13.4	5.06	55	1.9	353	2.4	102.4
Sep.	2.5	28.5	14.7	21.6	13.1	8.04	39	3.2	603	7.1	189.7
Oct.	168.4	28.6	17.1	22.8	15.3	7.78	45	3.2	562	6.4	179.6
Nov.	334.5	25.8	16.9	21.4	16.9	4.68	62	3.0	468	5.7	126.7
Dec.	136.1	26.7	14.0	20.4	16.3	4.05	58	2.8	591	9.4	153.9

APPENDIX 3a

Lysimeter A and B readings and calculation of Et for the 1967 maize crop

SEPTEMBER 1967												
	Lysimeter A						Lysimeter B					
Date	Column height cm.	Column change x 1.03 mm.	Drainage mm.	Rainfall mm.	Et mm.	5-day total mm.	Column height cm.	Column change x 0.88 mm.	Drainage mm.	Rainfall mm.	Et mm.	5-day total mm.
1	34.1	5.2	2.1	0	3.1							
2	33.6	-1.0	2.1	0	-3.1							
3	33.7	5.2	1.1	0	4.1							
4	33.2	0	0.7	0	-0.7							
5	33.2	17.5	0.6	2.0	18.9	22.3						
6	31.5	-23.7	0.3	8.1	-15.9							
7	33.8	25.8	0.2	5.1	30.7							
8	31.3	4.1	0	0	4.1							
9	30.9	5.2	0	0.3	5.5							
10	30.4	-4.1	0	0	-4.1	20.3						
11	30.8	6.2	0	0	6.2							
12	30.2	-	0	0	4.4*							
13	✱ 31.7	-	3.9	0	4.4*							
14	32.9	17.5	3.8	0	13.7		79.1	9.7	1.2	0	8.5	
15	31.2	0	6.8	0	-6.8	21.9	78.0	2.6	2.8	0	-0.2	
16	31.2	5.2	4.0	0	1.2		77.7	4.4	2.8	0	1.6	
17	30.7	-2.1	2.8	0	-4.9		77.2	0.9	1.9	0	-1.0	
18	30.9	9.3	1.7	0	7.6		77.1	5.3	1.2	0	4.1	
19	30.0	14.4	1.4	0	13.0		76.5	4.4	1.0	0	3.4	
20	28.6	8.2	0.6	0	7.6	24.5	76.0	5.3	0.6	0	4.7	12.8
21	27.8	5.2	0.5	0	4.7		75.4	3.5	0.4	0	3.1	
22	27.3	11.3	0.4	0	10.9		75.0	3.5	0.2	0	3.3	
23	26.2	-3.1	0.2	0	-3.3		74.6	2.6	0.1	0	2.5	
24	26.5	-2.1	0.1	0	-2.2		74.3	0.9	0	0	0.9	
25	26.7	-	0	0	2.5*	12.6	74.2	-	0	0	2.5*	12.3
26	✱ 26.5	-	3.2	0	8.4*		✱ 73.7	-	0.1	0	6.4*	
27	28.2	10.3	1.8	0	8.5		75.4	4.4	0	0	4.4	
28	27.2	16.5	2.9	0	13.6		74.9	7.9	0	0	7.9	
29	25.6	9.3	1.2	0	8.1		74.0	6.2	0	0	6.2	
30	24.7	4.1	0.9	0	3.2	41.8	73.3	7.0	0	0	7.0	31.9

* 5-day average

✱ Days with irrigation

APPENDIX 3b

Lysimeter A and B readings and calculation of Et for the 1967 maize crop

OCTOBER 1967												
	Lysimeter A						Lysimeter B					
Date	Column height cm.	Column change x 1.03 mm.	Drainage mm.	Rainfall mm.	Et mm.	5-day total mm.	Column height cm.	Column change x 0.88 mm.	Drainage mm.	Rainfall mm.	Et mm.	5-day total mm.
1	24.3	1.0	0.2	0	0.8		72.5	1.8	0	0	1.8	
2	24.2	0	0.5	0	-0.5		72.3	2.6	0	0	2.6	
3	24.2	0	0.3	0	-0.3		72.0	4.4	0	0	4.4	
4	24.2	2.1	0.2	0	1.9		71.5	2.6	0	0	2.6	
5	24.0	5.2	0.1	0	5.1	7.0	71.2	5.3	0	0	5.3	16.7
6	23.5	2.1	0.1	0	2.0		70.6	4.4	0	0	4.4	
7	23.3	1.0	0	0.3	1.3		70.1	3.5	0	0.3	3.8	
8	23.2	0	0	19.1	19.1		69.7	-10.6	0	19.1	8.5	
9	23.2	7.2	0	0	7.2		70.9	10.6	0	0	10.6	
10	22.5	-	0	0	7.4*	37.0	69.7	-	0	0	6.8*	34.1
11	✱ 23.7	-	0	0	9.2*		✱ 69.5	-	0	0	8.1*	
12	26.0	5.2	0	0	5.2		72.0	12.3	0	0	12.3	
13	25.5	15.5	0	1.5	17.0		70.6	7.9	0	1.5	9.4	
14	24.0	11.3	0	0	11.3		69.7	7.0	0	0	7.0	
.15	22.9	3.1	0	0	3.1	45.8	68.9	3.5	0	0	3.5	40.3
16	22.6	-21.6	0	44.2	22.6		68.5	-22.9	0	44.2	21.3	
17	24.7	1.0	0	0	1.0		71.1	16.7	0	0	16.7	
18	24.6	4.1	0	0	4.1		69.2	-6.2	0	0	-6.2	
19	24.2	4.1	0	6.4	10.5		69.9	16.7	0	6.4	23.1	
20	23.8	4.1	0	4.3	8.4	46.6	68.0	2.6	0	4.3	6.9	61.8
21	23.4	7.2	0	1.3	8.5		67.7	-7.0	0	1.3	-5.7	
22	22.7	-3.1	0	8.9	5.8		68.5	7.0	0	8.9	15.9	
23	23.0	-8.2	0	16.5	8.3		67.7	-12.3	0	16.5	4.2	
24	23.8	-10.3	0	11.9	1.6		69.1	-7.0	0	11.9	4.9	
25	24.8	6.2	0	0.5	6.7	30.9	69.9	6.2	0	0.5	6.7	26.0
26	24.2	1.0	0	5.6	6.6		69.2	0.9	0	5.6	6.5	
27	24.1	-51.5	0	70.1	18.6		69.1	-53.7	0	70.1	16.4	
28	29.1	7.2	13.6	3.8	-2.6		75.2	9.7	0	3.8	13.5	
29	28.4	17.5	7.0	9.7	20.2		74.1	4.4	3.5	9.7	10.6	
30	26.7	-14.4	6.8	26.2	5.0		73.6	-12.3	7.4	26.2	6.5	
31	28.1	6.2	13.6	6.4	-1.0	46.8	75.0	6.2	7.5	6.4	5.1	58.6

* 5-day average

✱ Days with irrigation

APPENDIX 3

Lysimeter A and B readings and calculation of Et for the 1967 [illegible] crop

	NOVEMBER 1967											
	Lysimeter A						Lysimeter B					
Date	Column height cm.	Column change x 1.03 mm.	Drainage mm.	Rainfall mm.	Et mm.	5-day total mm.	Column height cm.	Column change x 0.88 mm.	Drainage mm.	Rainfall mm.	Et mm.	5-day total mm.
1	27.5	22.7	10.4	1.8	14.1		74.3	17.6	6.4	1.8	13.0	
2	25.3	-38.1	2.5	41.7	1.1		72.3	-29.0	6.3	41.7	6.4	
3	29.0	10.3	13.6	4.8	1.5		75.6	11.4	6.3	4.8	9.9	
4	28.0	13.4	11.3	4.1	6.2		74.3	11.4	6.3	4.1	9.2	
5	26.7	4.1	5.8	5.3	3.6	26.5	73.0	5.3	6.3	5.3	4.3	42.8
6	26.3	-15.5	3.7	24.1	4.9		72.4	-16.7	5.1	24.1	2.3	
7	27.8	7.2	6.3	2.0	2.9		74.3	7.9	6.1	2.0	3.8	
8	27.1	5.2	4.7	4.3	4.8		73.4	7.9	5.6	4.3	6.6	
9	26.6	9.3	3.3	0	6.0		72.5	11.4	3.5	0	7.9	
10	25.7	4.1	1.2	0	2.9	21.5	71.2	5.3	1.9	0	3.4	24.0
11	25.3	9.3	0.4	0	8.9		70.6	7.9	0.7	0	7.2	
12	24.4	0	0	6.6	6.6		69.7	1.8	0.1	6.6	8.3	
13	24.4	0	0	1.8	1.8		69.5	4.4	0	1.8	6.2	
14	24.4	1.0	0	0	1.0		69.0	1.8	0	0	1.8	
15	24.3	-6.2	0	16.5	10.3	28.6	68.8	-0.9	0	16.5	15.6	39.1
16	24.9	-6.2	0	11.9	5.7		68.9	0.9	0	11.9	12.8	
17	25.5	-2.1	0	3.8	1.7		68.8	0	0	3.8	3.8	
18	25.7	-3.1	0	1.3	-1.8		68.8	-3.5	0	1.3	-2.2	
19	26.0	4.1	0	0	4.1		69.2	3.5	0	0	3.5	
20	25.6	4.1	0	0	4.1	13.8	68.8	3.5	0	0	3.5	21.4
21	25.2	-12.4	0	12.7	0.3		68.4	-12.3	0	12.7	0.4	
22	+ 26.4	1.1	0	0.8	1.9		‡ 69.8	2.0	0	0.8	2.8	
23	26.3	5.4	0	0	5.4		69.6	8.8	0	0	8.8	
24	25.8	-1.1	0	5.6	4.5		68.7	1.0	0	5.6	6.6	
25	25.9	-35.3	0	39.4	4.1	16.2	68.6	211.7	0	39.4	4.7*	23.3
26	29.2	-10.7	0	9.7	-1.0		47.0	-36.3	0	9.7	-	
27	30.2	11.8	7.2	7.9	12.5		50.4	-5.9	0	7.9	-	
28	29.1	12.8	6.4	0	6.4		51.0	-11.8	0.7	0	-	
29	27.9	10.7	4.5	0	6.2		52.2	-2.9	3.5	0	-	
30	26.9	4.3	2.0	0	2.3	26.4	52.5	-9.8	2.3	0	-	

* 5-day average

\+ Calibration factor changed to 1.07

‡ Calibration factor changed to 0.98

APPENDIX 31

Lysimeter A and B readings and calculation of Et for the 1967 maize crop

DECEMBER 1967										
	Lysimeter A					Lysimeter B				
Date	Column height cm.	Column change x 1.03 mm.	Drainage mm.	Et mm.	5-day total mm.	Column height cm.	Column change x 0.98 mm.	Drainage mm.	Et mm.	5-day total mm.
1	26.5	1.1	1.1	0		53.5	4.9	1.3	3.6	
2	25.4	8.6	0	8.6		53.0	8.8	0	8.8	
3	24.6	8.6	0	8.6		52.1	2.9	0	2.9	
4	23.8	3.2	0	3.2		51.8	10.8	0	10.8	
5	23.5	7.5	0	7.5	27.9	50.7	14.7	0	14.7	40.8
6	22.8	-4.3	0	-4.3		49.2	-4.9	0	-4.9	
7	23.2	-7.5	0	-7.5		49.7	-4.9	0	-4.9	
8	23.9	-6.4	0	-6.4		50.2	-1.0	0	-1.0	
9	24.5	8.6	0	8.6		50.3	14.7	0	14.7	
10	23.7	-1.1	0	-1.1	-10.7	48.8	-2.0	0	-2.0	1.9
11	23.8	-1.1	0	-1.1		49.0	2.0	0	2.0	
12	23.9	3.2	0	3.2		48.8	3.9	0	3.9	
13	23.6	13.9	0	13.9		48.4	13.7	0	13.7	
14	22.3	-3.2	0	-3.2		47.0	-4.9	0	-4.9	
15	22.6	5.4	0	5.4	18.2	47.5	4.9	0	4.9	19.6
16	22.1	10.7	0	10.7		47.0	3.9	0	3.9	
17	21.1	4.3	0	4.3		46.6	7.8	0	7.8	
18	20.7	-4.3	0	-4.3		45.8	-2.9	0	-2.9	
19	21.1	-1.1	0	-1.1		46.1	-1.0	0	-1.0	
20	21.2	4.3	0	4.3	13.9	46.2	3.9	0	3.9	11.7
21	20.8	19.3	0	19.3		45.8	15.7	0	15.7	
22	19.0	5.4	0	5.4		44.2	3.9	0	3.9	
23	18.5	7.5	0	7.5		43.8	5.9	0	5.9	
24	17.8	-1.1	0	-1.1		43.2	0	0	0	
25	17.9	5.4	0	5.4	36.5	43.2	4.9	0	4.9	30.4
26	17.4	5.4	0	5.4		42.7	5.9	0	5.9	
27	16.9	13.9	0	13.9		42.1	2.0	0	2.0	
28	15.6	6.4	0	6.4		40.9	6.9	0	6.9	
29	15.0	-4.3	0	-4.3		40.2	-1.0	0	-1.0	
30	15.4	8.6	0	8.6		40.3	5.9	0	5.9	
31	14.6	-5.4	0	-5.4	24.6	39.7	2.9	0	2.9	22.6

There was no rainfall in December.

APPENDIX 3e

Crop water use, Et, from lysimeter compared with pan evaporation, E_p, and Penman estimate Eo 1967 maize crop

Period		Et mm		Eo mm	E_p mm
		Lys. A	Lys. B		
Sep.	1-5	22.3	-	26.4	29.0
	6-10	20.3	-	26.3	19.6
	11-15	21.9	-	27.1	24.4
	16-20	24.5	12.8	33.8	36.0
	21-25	12.6	12.3	34.3	31.5
	26-30	41.8	31.9	34.3	35.5
Oct.	1-5	7.0	16.7	35.8	38.0
	6-10	37.0	34.1	35.9	32.5
	11-15	45.8	40.3	33.3	32.0
	16-20	46.6	61.8	33.4	30.0
	21-25	30.9	26.0	25.3	19.8
	26-31	46.8	58.6	30.4	30.7
Nov.	1-5	26.5	42.8	27.0	24.6
	6-10	21.5	24.0	27.0	25.5
	11-15	28.6	39.1	29.2	26.0
	16-20	13.7	21.4	29.1	25.5
	21-25	16.2	23.3	21.9	20.9
	26-30	26.4	-	21.9	17.0
Dec.	1-5	27.9	40.8	28.4	27.0
	6-10	-10.7	1.9	28.3	27.0
	11-15	18.2	19.6	30.3	24.0
	16-20	13.9	11.7	30.4	29.0
	21-25	36.5	30.4	30.4	30.5
	26-31	24.6	22.6	36.5	36.1

APPENDIX 4a

Lysimeter A readings and calculation of Et for the 1966 bean crop

Date	MARCH Column height cm.	Column change x 0.88 mm.	Rainfall mm.	Et mm.	5-day total mm.
1	78.3	0	4.3	4.3	
2	78.3	1.8	4.1	5.9	
3	78.1	4.4	0	4.4	
4	77.6	-6.2	9.4	3.2	
5	78.3	-1.8	7.6	5.8	23.6
6	78.5	-4.4	9.4	5.0	
7	79.0	-0.9	1.0	0.1	
8	79.1	2.6	3.3	5.9	
9	78.8	5.3	1.0	6.3	
10	78.2	2.6	0	2.6	19.9
11	77.9	3.5	1.3	4.8	
12	77.5	-3.5	6.9	3.4	
13	77.9	4.4	0	4.4	
14	77.4	3.5	0	3.5	
15	77.0	2.6	0	2.6	18.7
16	76.7	5.3	0	5.3	
17	76.1	0.9	0	0.9	
18	76.0	-21.2	30.2	9.0	
19	78.4	-15.8	21.8	6.0	
20	80.2	3.5	1.0	4.5	25.7
21	79.8	-11.4	13.7	2.3	
22	81.1	2.6	0	2.6	
23	80.8	7.0	0	7.0	
24	80.0	4.4	0.5	4.9	
25	79.5	-5.3	7.6	2.3	19.1
26	80.1	5.3	0	5.3	
27	79.5	6.2	0	6.2	
28	78.8	10.6	0	10.6	
29	77.6	7.9	0	7.9	
30	76.7	9.7	0	9.7	
31	75.6	6.2	0	6.2	45.9

Date	APRIL Column height cm.	Column change x 0.88 mm.	Drainage mm.	Rainfall mm.	Et mm.	5-day total mm.
1	74.9	-11.4	0	19.0	7.6	
2	76.2	-10.6	0	18.8	8.2	
3	77.4	2.6	0	7.1	9.7	
4	77.1	2.6	0	1.8	4.4	
5	76.8	5.3	0	0	5.3	35.2
6	76.2	7.0	0	0.5	7.5	
7	75.4	-0.9	0	8.4	7.5	
8	75.5	5.3	0	0	5.3	
9	74.9	8.8	0	0	8.8	
10	73.9	1.8	0	4.1	5.9	35.0
11	73.7	0	0	7.6	7.6	
12	73.7	0	0	4.3	4.3	
13	73.7	10.6	0	2.5	13.1	
14	72.5	0.9	0	1.0	1.9	
15	72.4	-17.6	0	20.8	3.2	30.1
16	74.4	-16.7	0	18.0	1.3	
17	76.3	7.0	0	0	7.0	
18	75.5	4.4	0	1.8	6.2	
19	75.0	7.9	0	0	7.9	
20	74.1	2.6	0	5.3	7.9	30.3
21	73.8	4.4	0	0.5	4.9	
22	73.3	-51.9	0	57.0	5.1	
23	79.2	-19.4	0	23.8	4.4	
24	81.4	7.0	0	0.5	7.5	
25	80.6	0	0	4.3	4.3	26.2
26	80.6	-7.8	0	11.7	3.9	
27	81.6	4.7	0	0	4.7	
28	81.0	-27.3	0	40.5	13.2	
29	84.5	3.9	0	1.1	5.0	
30	84.0	-23.4	7.0	44.7	14.3	41.1

Date	MAY Column height cm.	Column change x 0.78 mm.	Drainage mm.	Rainfall mm.	Et mm.	5-day total mm.
1	87.0	16.4	12.8	6.9	10.5	
2	84.9	-9.4	10.8	27.2	7.0	
3	86.1	17.9	12.8	0	5.1	
4	83.8	-7.0	8.4	20.5	5.1	
5	84.7	11.7	8.4	3.1	6.4	34.1
6	83.2	10.9	6.4	0	4.5	
7	81.8	6.2	4.0	3.1	5.3	
8	81.0	5.5	2.4	0	3.1	
9	80.3	6.2	1.5	0.8	5.5	
10	79.5	6.2	0.9	0.5	5.8	24.2
11	78.7	1.6	0.6	4.3	5.3	
12	78.5	3.9	0.6	0	3.3	
13	78.0	3.9	0.7	0	3.2	
14	77.5	4.7	0.4	0	4.3	
15	76.9	2.3	0.4	0.5	2.4	18.5
16	76.6	4.7	0.3	0	4.4	
17	76.0	3.1	0.2	0.8	3.7	
18	75.6	2.3	0.2	0.8	2.9	
19	75.3	3.1	0.1	0	3.0	
20	74.9	1.6	0.1	0.8	2.3	16.3
21	74.7	3.1	0.1	0.3	3.3	
22	74.3	3.9	0	0.3	4.2	
23	73.8	-0.8	0	0	-0.8	
24	73.9	0.8	0	2.3	3.1	
25	73.8	-12.5	0	16.8	4.3	14.1
26	75.4	3.1	0	0.3	3.4	
27	75.0	3.9	0	0	3.9	
28	74.5	-0.8	0	3.3	2.5	
29	74.6	2.3	0	0.3	2.6	
30	74.3	2.3	0	0	2.3	
31	74.0	3.1	0	0	3.1	17.8

N.B. No drainage was recorded in March.

APPENDIX 4b

Water use of beans (Canadian Wonder). Mwea Experiment 1968

Month	5-day periods	Lys.A Et mm	Lys.B Et mm	E.Pan mm	Eo mm	Et/Eo Lys.A	Et/Eo Lys.A 10 day averages	Rainfall mm	L.A.I.
March	I	23.6	26.0	25.4	25.7	0.92		25.4	0.0
	II	19.9	18.6	22.8	25.8	0.77	0.85	14.7	0.02
	III	18.7	8.3	32.0	31.8	0.59	0.68	8.2	0.10
	IV	25.7	LEAK	29.3	29.0	0.89	0.74	42.0	0.36
	V	19.1	EXCA-	15.8	23.5	0.81	0.85	21.8	0.80
	VI	45.9	VATED	35.3	37.0	1.24	1.02	0.0	1.75
April	I	35.2		24.9	27.8	1.27	1.25	46.7	3.00
	II	35.0		21.6	25.4	1.38	1.33	13.0	3.70
	III	30.1		22.6	24.8	1.21	1.30	36.2	4.1
	IV	30.3		19.1	21.9	1.43	1.32	25.1	4.25
	V	26.2		18.5	22.2	1.18	1.31	105.1	4.0
	VI	41.1		17.3	24.8	1.66	1.42	106.9	3.1
May	I	34.1		21.6	30.3	1.13	1.40	57.7	2.0
	II	24.2		23.6	27.8	0.87	1.00	4.4	1.0
	III	18.5		22.1	27.4	0.68	0.78	4.8	0.0
	IV	26.3		22.1	25.6	0.64	0.66	2.4	0.0
	V	14.1	18	18.0	22.6	0.63	0.63	19.7	0.0
	VI	17.8		20.5	28.2	0.63	0.63	3.9	0.0

Germination in both lysimeters on 6th March. Harvest in 'A' 23rd May. Leaves dried off from 13th May.

APPENDIX 5a

Lysimeter A readings and calculation of Et for the 1968 maize crop

Date	JULY						AUGUST					
	Column height cm.	Column change x 0.89 mm.	Drainage mm.	Rainfall mm.	Et mm.	5-day total mm.	Column height cm.	Column change x 0.89 mm.	Drainage mm.	Rainfall mm.	Et mm.	5-day total mm.
1	72.6	0.9	0	0	0.9		73.3	-0.9	0.2	0	-1.1	
2	72.5	0.9	0	0	0.9		73.4	0.9	0.3	0	0.6	
3	72.4	0	0	0	0		73.3	2.7	0.2	0	2.5	
4	72.4	0.9	0	3.6	4.5		73.0	1.8	0.2	0	1.6	
5	72.3	1.8	0	0	1.8	8.1	72.8	1.8	0.1	0.3	2.0	5.6
6	72.1	0.9	0	1.3	2.2		72.6	0	0.1	2.5	2.4	
7	72.0	0.9	0	0.5	1.4		72.6	-1.8	0	0.5	-1.3	
8	71.9	0	0	0	0		72.8	1.8	0	1.3	3.1	
9	71.9	2.7	0	0	2.7		72.6	-	0	0	1.4*	
10	71.6	-0.9	0	0	-0.9	5.4	‡ 74.5	-	0	0	1.4*	7.0
11	71.7	2.7	0	0	2.7		74.2	1.8	0	0	1.6	
12	71.4	0.9	0	2.5	3.4		74.0	2.7	0.2	0	2.5	
13	71.3	0.9	0	0	0.9		73.7	2.7	0.5	0	2.2	
14	71.2	0	0	0	0		73.4	3.6	0.4	0	3.2	
15	‡ 71.2	-	0	0	1.8*	8.6	73.0	0	0.6	0	-0.6	9.1
16	‡ 75.3	-	0	0	7.5*		73.0	3.6	0.2	2.5	5.9	
17	87.9	-	6.8	0	7.5*		72.6	2.7	0.1	0.8	3.4	
18	85.2	22.3	13.2	0.8	9.9		72.3	0.9	0	0	0.9	
19	80.7	14.2	9.0	0	5.2		72.2	0	0.1	0.2	0.1	
20	79.1	12.4	5.1	0	7.3	37.4	72.2	1.8	0	0	1.8	12.1
21	77.7	6.2	3.5	0	2.7		72.0	2.7	0	0	2.7	
22	77.0	8.0	2.1	0	5.9		71.7	1.8	0	0	1.8	
23	76.1	3.6	1.7	0	1.9		71.5	0.9	0	0	0.9	
24	75.7	4.5	1.3	1.5	4.7		71.4	5.3	0	0.5*	5.8	
25	75.2	5.3	1.0	0	4.3	19.5	70.8	-	0	0	2.6*	14.0
26	74.6	2.7	0.7	1.8	3.8		‡ 70.7	-	0	0	3.2*	
27	74.3	4.5	0.7	2.6	6.6		73.3	1.8	0	0	1.8	
28	73.8	-2.7	0.5	2.3	-0.9		73.1	0.9	0	0	0.9	
29	74.1	2.7	0.5	0	2.2		73.0	6.2	0	0	6.2	
30	73.8	2.7	0.4	0	2.3		72.3	3.6	0	0	3.6	
31	73.5	1.8	0.4	0	1.4	15.4	71.9	3.6	0	0	3.6	19.3

* 5-day average

‡ Days with irrigation

APPENDIX 5a (continued)

Lysimeter A readings and calculation of Et for the 19[illegible] maize crop

Date	SEPTEMBER					OCTOBER					NOVEMBER					
	Column height cm.	Column change x 0.89 mm.	Rainfall mm.	Et mm.	5-day total mm.	Column height cm.	Column change x 0.89 mm.	Rainfall mm.	Et mm.	5-day total mm.	Column height cm.	Column change x 0.89 mm.	Drainage mm.	Rainfall mm.	Et mm.	5-day total mm.
1	71.5	4.5	0	4.5		62.1	6.2	2.2	8.4		56.7	-17.9	0	20.0	2.1	
2	71.0	1.8	0	1.8		61.4	5.3	1.2	6.5		58.7	1.8	0	7.9	9.7	
3	70.8	3.6	0	3.6		60.8	6.2	0	6.2		58.5	6.2	0	1.5	7.7	
4	70.4	6.2	0	6.2		60.1	6.2	0	6.2		57.8	5.3	0	1.0	6.3	
5	69.7	4.5	0	4.5		59.4	3.6	0	3.6		57.2	-4.5	0	9.6	5.1	
					20.6					30.9						30.9
6	69.2	6.2	0	6.2		59.0	7.1	0	7.1		57.7	1.8	0	0	1.8	
7	‡ 68.5	-	0	5.3*		58.2	6.2	0	6.2		57.5	3.6	0	1.3	4.9	
8	71.6	-	0	5.3*		57.5	7.1	0	7.1		57.1	-2.7	0	6.9	4.2	
9	71.1	3.6	0	3.6		56.7	7.1	0	7.1		57.4	-3.6	0	3.3	-0.3	
10	70.7	6.2	0	6.2		55.9	4.5	0	4.5		57.8	8.9	0	2.3	11.2	
					26.6					32.0						21.8
11	70.0	7.1	0	7.1		55.4	8.0	1.2	9.2		56.8	3.6	0	0	3.6	
12	69.2	1.8	0	1.8		54.5	7.1	0	7.1		56.4	-0.9	0	13.5	12.6	
13	69.0	5.3	0	5.3		53.7	6.2	0	6.2		56.5	-7.1	0	5.3	-1.8	
14	68.4	8.0	0	8.0		53.0	-18.7	29.5	10.8		57.3	5.3	0	0	5.3	
15	67.5	4.5	0	4.5		55.1	8.9	0.8	9.7		56.7	6.2	0	0.5	6.7	
					26.7					43.0						26.4
16	67.0	3.6	0	3.6		54.1	-17.8	28.0	10.2		56.0	4.5	0	0.8	5.3	
17	66.6	6.2	0	6.2		56.1	0	7.1	7.1		55.5	-10.7	0	16.7	6.0	
18	65.9	3.6	0	3.6		56.1	-5.3	7.1	1.8		56.7	-4.5	0	14.2	9.7	
19	65.5	-	0	4.5*		56.7	3.6	0	3.6		57.2	-24.9	0	27.8	2.9	
20	‡ 65.0	-	0	4.5*		56.3	7.1	0	7.1		60.0	-44.5	0	56.0	11.5	
					22.4					29.8						35.4
21	70.9	8.0	0	8.0		55.5	9.8	0	9.8		65.0	-41.0	0	47.5	6.5	
22	70.0	10.7	0.3	11.0		54.4	6.2	0	6.2		69.6	-2.7	6.9	18.3	8.7	
23	[illegible]	7.1	0	7.1		53.7	1.8	0	1.8		69.9	-6.2	14.1	19.6	-0.7	
24	68.0	7.1	0	7.1		53.5	8.9	0.8	9.7		70.6	-3.6	15.6	27.0	7.6	
25	67.2	8.0	0	8.0		52.5	7.1	1.2	8.3		71.0	-7.1	19.0	17.0	-9.1	
					41.2					35.8						13.0
26	66.3	4.5	0	4.5		51.7	-71.2	80.0	8.8		70.2	16.9	18.2	4.3	3.0	
27	65.8	8.0	0	8.0		59.7	9.8	0	9.8		68.3	10.7	10.9	3.1	2.9	
28	64.9	3.6	0	3.6		58.6	10.7	0	10.7		67.1	8.9	6.3	1.5	4.1	
29	64.5	13.4	0	13.4		57.4	8.0	0.5	8.5		66.1	7.1	3.9	2.3	5.5	
30	63.0	8.0	0	8.0		56.5	-3.6	9.1	5.5		65.3	1.8	2.5	5.6	4.9	
31						56.9	1.8	0	1.8							
					37.5					45.1						20.4

*5-day average

‡ Days with irrigation

No drainage recorded in September and October.

APPENDIX 5b

Water use (Et) for the 1968 Maize Crop (Wet Treatment)

Month	5-day periods	Et(mm) Lys. A	Penman Eo (mm)	Et/Eo	Rainfall (mm)	Irrigation (mm)	Pan Eo (mm)
Jul.	I	8.1	26.2	0.31	3.6		20.3
	II	5.4	16.7	0.32	1.8		11.9
	III	8.8	19.4	0.45	2.5		15.2
	IV	-	22.7	-	0.8	152	18.0
	V	19.5	17.4	1.12	1.5		11.2
	VI	15.4	19.9	0.77	6.9		13.0
Aug.	I	5.6	22.0	0.25	0.3		20.1
	II	7.0	13.0	0.54	4.6	25	8.6
	III	9.1	22.1	0.41	0.0		18.3
	IV	12.1	15.2	0.80	3.5		10.2
	V	14.0	22.9	0.61	0.5		16.8
	VI	19.3	33.8	0.57	0.0	36	28.4
Sep.	I	20.6	36.7	0.56	0.0		34.5
	II	26.6	27.4	0.97	0.0	42	26.0
	III	26.7	33.9	0.79	0.0		30.5
	IV	22.4	32.8	0.68	0.0	71	31.0
	V	41.2	35.6	1.16	0.3		31.0
	VI	37.5	39.5	0.95	0.0		34.0
Oct.	I	30.9	37.5	0.82	3.4		30.0
	II	32.0	36.6	0.87	0.0		31.7
	III	43.0	34.3	1.25	31.5		32.8
	IV	29.8	27.4	1.09	42.2		24.9
	V	35.8	31.7	1.13	2.0		27.8
	VI	45.1	37.0	1.22	89.6		30.6
Nov.	I	30.9	30.2	1.02	40.0		22.4
	II	21.8	24.7	0.88	13.8		19.3
	III	26.4	29.5	0.89	19.3		24.9
	IV	35.4	26.5	1.34	115.5		24.9
	V	13.0	19.1	0.68	129.4		15.5
	VI	20.4	24.5	0.83	8.9		11.4

APPENDIX 6

Comparison between Et estimated from soil sampling and from lysimeters A.& B

1967 maize crop

Depth in ft.	Period 1967													
	12/9 - 16/9		26/9 - 10/10		10/10 - 24/10		24/10 - 8/11		8/11 - 22/11		22/11 - 5/12		5/12 - 21/12	
	A ins	B ins	A ins	B ins	A ins	B ins	A ins	B ins	A ins	B ins	A ins	B ins	A ins	B ins
½	.07	.31	.04	.10	-.53	-.84	.06	.00	-.12	.09	.50	.16	.33	.63
1	-.01	.19	.11	.21	-.24	-.28	-.13	-.27	.14	.06	.08	.08	.56	.59
2	-.08	.17	.31	.22	-.05	-.26	-.25	-.72	.52	.48	-.10	.09	.58	.59
3	-.21	-.16	.00	.30	.01	-.26	-.49	-.40	.56	.01	-.27	.43	.51	.25
4	.06	.00	-.21	.10	.06	-.15	-.21	-.37	.49	.30	-.54	.36	.43	.13
5	-.13	.16	-.06	.14	.03	-.14	-.43	-.42	.26	.50	.02	-.01	.68	.25
6	-	-	-.14	-.03	.06	-.15	-.46	-.12	.49	.55	-.20	-.39	.47	.17
Total water removed (ins)	-.30	.73	.05	1.04	-1.11	-2.08	-1.[illegible]	[illegible]	2.34	1.99	-.51	.74	3.31	2.51
Total water removed (mm)	-7.6	18.5	1.3	26.4	-28.2	-52.8	[illegible].5	-58.4	59.4	50.5	-13.0	18.8	84.1	63.8
Irrigation (mm)	68.8	43.8	57.6	27.5	79.9	51.7	0	0	0	0	0	0	0	0
Rainfall (mm)	0	0	19.4	19.4	83.1	83.1	218.0	218.0	58.9	58.9	63.4	63.4	0	0
Et (mm)	61.2	62.3	78.3	73.3	134.8	82.0	189.8	159.6	118.3	109.4	50.4	82.2	84.1	63.8
Et (lysimeter) (mm)	57.1	43.6	79.0	71.3	109.5	117.7	92.6	125.7	53.4	75.0	68.3	85.9*	40.7	48.9

Estimate
* 60.9 + 5 days @ 5 mm/day

APPENDIX 7a

Estimates of soil moisture with IAL 104 moisture meter

Bean crop 1968

23.2.68

Depth cm.	Water content (mm.)									
	Field A					Field B				
	AA	AB	AC	AD	Lys.A	BE	BF	BG	BH	Lys.B
30	48.0	51.0	60.0	48.0	55.5	55.5	60.0	66.0	66.0	66.0
60	66.0	78.0	90.0	78.0	106.5	78.0	75.0	79.5	81.0	75.0
90	90.0	93.0	93.0	93.0	99.0	96.0	96.0	99.0	99.0	78.0
120	93.0	96.0	93.0	96.0	111.0	99.0	106.5	102.0	106.5	81.0
150	106.5	106.5	93.0	90.0	136.5	106.5	106.5	102.0	111.0	93.0
180	106.5	106.5	106.5	90.0		121.5	118.5	117.0	117.0	
Total	510.0	531.0	535.5	495.0	508.5	556.5	562.5	565.5	580.5	393.0
Mean		518					566			
	6.3.68									
30	114.0	118.5	118.5	103.5	96.0	116.5	126.0	129.0	129.0	129.0
60	114.0	126.0	129.0	118.5	139.5	111.5	126.0	129.0	126.0	103.5
90	103.5	106.5	111.0	106.5	118.5	99.0	111.0	121.5	114.0	96.0
120	96.0	93.0	100.5	99.0	126.0	99.0	103.5	103.5	106.5	85.5
150	103.5	103.5	90.0	90.0	159.0	106.5	103.5	103.5	111.0	88.5
180	103.5	100.0	111.0	85.5		121.5	114.0	121.5	118.5	
Total	634.5	647.5	660.0	603.0	639.0	654.0	684.0	708.0	705.0	502.5
Mean		636					688			
	17.4.68									
30	139	137	138	121	115	128	152	154	154	
60	98	114	110	102	113	121	115	133	121	
90	102	105	109	113	107	117	116	125	121	
120	100	104	104	107	130	113	117	119	122	
150	111	113	99	99	161	120	117	118	122	
180	112	107	113	97		133	127	133	130	
Total	662	680	673	639	626	732	744	782	770	
Mean		664					757			

APPENDIX 7a (continued)

Depth cm.	Water content (mm.)								
	Field A					Field B			
	AA	AB	AC	AD	Lys.A	BE	BF	BG	BH
					2.5.68				
30	130	130	136	121	110	114	136	146	143
60	127	140	139	133	153	141	135	146	143
90	127	138	140	140	128	143	143	145	142
120	119	137	125	126	146	131	137	139	141
150	128	142	119	115	178	140	134	136	143
180	127	125	134	113		152	139	155	147
Total	758	812	793	748	715	821	824	867	859
Mean		778					843		
					8.5.68				
30	112	117	119	107	99	107	125	129	132
60	114	134	134	121	145	129	131	138	132
90	124	130	132	132	121	131	135	139	131
120	119	129	122	126	145	131	133	134	137
150	129	114	120	113	181	137	135	133	142
180	136	131	139	119		152	141	152	146
Total	734	755	766	718	691	787	800	825	820
Mean		743					808		
					29.5.68				
30	84	93	101	87	83	80	104	109	109
60	100	104	119	108	130	113	114	117	117
90	110	124	120	119	119	121	122	125	122
120	110	122	113	117	144	120	123	123	124
150	125	127	116	105	179	129	125	123	131
180	126	125	136	112		148	134	144	141
Total	655	695	705	648	655	711	722	741	744
Mean		676					730		

APPENDIX 7b

Estimates of soil moisture with KTV 90 moisture meter
Bean crop 1968

Depth cm.	Water content (mm.)									
	Field A					Field B				
	AA	AB	AC	AD	Lys. A	BE	BF	BG	BH	Lys. B
					1.3.68					
30	45	108	125	45	32	113	128	113	125	119
60	53	111	119	45	48	96	117	114	117	122
90	45	96	105	30	45	96	96	99	99	117
120	42	105	105	35	48	96	99	105	105	90
150	53	105	99	38	53	105	102	105	108	108
180	71	108	108	35		110	105	113	113	
Total	309	633	661	228	226	616	647	649	667	556
Mean	647 excluding AA & AD							644		
					9.3.68					
30	93	93	107	96	90	99	107	113	116	107
60	116	99	105	107	111	102	102	113	113	116
90	90	122	105	102	107	90	111	107	102	96
120	99	102	102	87	111	99	99	105	99	82
150	102	90	96	90	111	99	87	107	105	105
180	102	93	87	90		105	102	107	113	
Total	602	599	602	572	530	594	608	652	648	506
Mean		594						626		
					13.3.68					
30	105	107	107	107	85	77	96	93	96	102
60	111	102	111	107	113	93	93	105	87	107
90	99	93	99	99	105	87	85	96	93	96
120	96	111	99	96	119	85	82	99	90	82
150	93	111	105	90	153	82	79	96	102	82
180	99	102	105	102		93	96	99	96	
Total	603	626	626	601	575	517	531	588	564	469
Mean		614						550		

APPENDIX 7b (continued)

Depth cm.	Water content (mm.)									
	Field A					Field B				
	AA	AB	AC	AD	Lys. A	BE	BF	BG	BH	Lys. B
	16.3.68									
30	90	96	105	87	73	93	96	107	105	102
60	90	107	111	102	102	105	122	107	105	113
90	96	105	102	105	116	96	105	105	99	105
120	96	105	102	96	122	99	93	105	99	87
150	96	96	105	96	145	93	99	102	113	102
180	99	104	102	111		102	99	102	113	
Total	567	613	627	597	558	588	614	628	634	509
Mean		601					616			
	20.3.68									
30	90	102	113	96	87	96	102	116	113	102
60	90	96	107	99	107	102	99	105	99	99
90	90	87	105	102	102	102	99	105	96	99
120	96	93	90	96	119	96	96	107	107	96
150	93	90	93	96	136	99	99	111	105	99
180	96	96	96	96		102	102	107	107	
Total	555	564	604	585	551	597	597	651	627	495
Mean		577					618			
	27.3.68									
30	85	96	102	87	79	87	102	105	113	
60	90	102	105	99	107	107	105	105	105	
90	87	102	93	96	99	111	105	105	96	
120	85	93	99	93	107	99	102	111	96	
150	85	105	99	93	148	105	99	130	111	
180	85	92	102	90		113	99	116	105	
Total	517	590	600	558	540	622	612	672	626	
Mean		566					633			

APPENDIX 7c

SUMMARY OF SOIL MOISTURE CHANGES (mm) AT DIFFERENT DEPTHS IN THE SOIL PROFILE, MEASUREMENTS WITH E.A.L. NEUTRON MOISTURE METER

Negative figures indicate increase in soil moisture.

23.7.68 - 31.7.68

Soil depth (cm.)	Field A				Field B				Field C			
	AA	AB	AC	AD	BE	BF	BG	BH	CI	CJ	CK	CL
5	0.6	-1.0	-0.5	-3.7	-0.3	-1.2	-1.2	0.6	4.6	0.6	3.7	4.2
15	-0.3	1.6	0.2	-2.6	-1.2	3.8	-0.6	-1.1	1.1	6.6	2.6	-0.7
30	3.6	4.8	2.0	1.2	2.4	3.4	2.0	2.6	4.0	1.8	8.2	3.6
50	3.0	8.6	3.4	1.4	5.6	3.6	3.0	3.0	13.8	3.4	4.6	6.0
70	3.0	2.6	2.6	2.2	2.0	3.4	3.4	3.0	6.0	3.0	4.0	5.0
90	0.8	2.4	3.4	0.0	1.0	2.0	3.4	3.8	4.4	3.6	3.2	15.2
110	2.6	2.8	2.0	26.0	2.6	3.0	3.8	1.6	3.4	-15.0	4.0	4.0
130	1.6	6.0	1.2	26.8	3.2	4.2	1.0	2.0	3.2	2.0	5.8	1.2
150	-0.2	1.6	2.0	-3.8	2.6	0.6	4.4	0.6	2.4	0.0	0.0	-2.2
170	0.6	-5.4	-1.6	-5.2	2.4	1.0	2.6	0.8	0.0	1.8	-1.6	-4.0
Total	15.3	18.0	14.7	42.3	20.3	23.8	21.8	[illegible]	42.9	7.8	34.5	32.3
Rain	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4
Irrigation	-	-	-	-	-	-	-	-	-	-	-	-
Et	23.7	26.4	23.1	50.7	28.7	32.2	30.2	25.3	51.3	16.2	42.9	40.7
Mean Et				31.0				29.1				37.8
					31.7.68 - 7.8.68							
5	1.2	1.3	5.6	4.0	-0.2	3.3	3.3	3.5	4.2	8.5	2.6	6.1
15	-0.3	2.5	-4.1	-2.6	1.2	-3.0	1.5	0.5	6.0	6.9	4.7	7.5
30	2.0	2.4	2.4	3.6	2.6	4.0	3.0	2.6	-0.6	2.8	3.4	1.6
50	2.0	-1.0	2.0	5.0	-0.2	1.0	2.4	4.0	-4.8	2.0	1.4	2.2
70	1.4	12.4	2.4	-1.8	2.0	3.0	0.4	3.0	4.4	2.0	4.0	1.8
90	3.2	1.4	3.0	5.6	5.0	3.6	2.4	2.6	2.4	3.0	3.2	-6.8
110	3.0	0.6	4.0	4.0	10.4	2.2	2.6	2.6	3.4	2.6	2.4	2.4
130	1.2	-0.6	0.8	1.4	0.8	1.8	3.0	3.2	1.2	0.8	1.6	2.8
150	3.6	2.4	1.6	8.0	0.4	0.4	4.4	1.4	1.2	3.2	2.2	4.0
170	2.4	2.0	4.0	8.6	1.6	2.0	2.6	1.6	3.4	2.2	2.2	1.2
Total	19.7	23.4	21.7	35.8	23.6	18.3	25.6	25.0	20.8	34.0	27.7	22.8
Rain	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Irrigation	-	-	-	-	-	-	-	-	-	-	-	-
Et	22.5	26.2	24.5	38.6	26.4	21.1	28.4	27.8	23.6	36.8	30.5	25.6
Mean Et				28.0				25.9				29.1

APPENDIX 7c (continued)

7.8.68 - 21.8.68

Soil Depth (cm.)	Field A				Field B				Field C			
	AA	AB	AC	AD	BE	BF	BG	BH	CI	CJ	CK	CL
5	-3.3	-3.0	-4.6	-4.1	0.3	2.6	4.5	-7.3	-3.6	-5.3	-3.6	-2.1
15	-2.0	-5.8	-0.8	2.8	-1.3	0.8	1.2	1.1	-1.1	-5.2	-3.4	-4.6
30	0.4	-0.8	-1.4	-0.8	0.4	-0.2	2.2	1.8	5.4	0.2	0.4	1.2
50	0.6	0.2	-1.0	-3.8	2.0	1.2	1.4	-0.8	-1.2	1.4	1.4	-0.2
70	-0.8	-11.6	0.2	3.2	0.6	0.6	1.0	-0.2	-1.4	1.8	-1.8	1.8
90	-1.2	-0.4	-0.8	-0.2	-0.6	0.8	0.6	0.6	0.4	-1.0	0.2	0.4
110	-0.2	-0.8	-1.8	-0.8	-7.6	1.4	0.6	1.0	0.0	0.6	2.6	3.0
130	-1.6	2.2	1.4	0.0	1.2	-0.2	0.2	-0.8	3.2	2.0	0.4	1.6
150	-3.2	-0.4	-0.6	-0.6	0.2	3.0	-1.4	2.0	1.8	1.6	-0.6	-0.2
170	-0.8	-0.2	-0.8	0.2	-0.6	0.4	0.2	2.2	0.8	3.2	-0.2	3.6
Total	-12.1	-20.6	-10.2	-4.1	-5.4	10.4	10.5	-0.4	4.3	-0.7	-4.6	4.5
Rain	5.3	5.3	5.3	5.3	1.8	1.8	1.8	1.8	5.3	5.3	5.3	5.3
Irrigation	25.0	25.0	25.0	25.0	12.5	12.5	12.5	12.5	18.8	18.8	18.8	18.8
Et	18.2	9.7	20.1	26.2	8.9	24.7	24.8	13.9	28.4	23.4	19.5	28.6
Mean Et				18.6				18.1				25.0
21.8.68 - 28.8.68												
5	1.4	-4.5	-9.9	-5.6	0.3	-7.5	8.6	0.5	-8.6	-6.9	-5.1	-7.9
15	-1.8	-4.2	-3.2	-1.4	3.5	-0.7	1.5	1.8	-5.1	-7.2	-1.6	3.3
30	-3.2	-1.4	-8.6	0.0	20.2	24.2	0.8	0.8	1.8	0.0	-0.2	-2.2
50	-1.2	2.4	-8.2	1.4	30.0	4.8	0.6	0.2	2.4	0.6	-2.0	1.2
70	2.0	2.2	-8.0	1.8	7.8	2.0	1.2	0.4	0.6	-0.6	0.0	-1.0
90	2.2	0.0	-9.0	-0.8	0.0	0.8	0.4	0.2	0.2	2.0	0.4	1.2
110	2.0	3.2	-7.4	0.4	0.2	1.2	-0.8	-0.2	0.4	-1.0	0.4	1.0
130	3.8	1.8	-6.6	-1.2	2.2	0.2	0.0	1.0	-0.4	0.6	1.2	1.2
150	3.8	0.8	-1.8	1.0	2.0	0.6	0.6	0.2	0.0	0.0	0.6	1.6
170	1.2	5.1	-3.4	-0.8	3.8	2.8	0.2	-0.6	-0.4	-1.0	-0.4	-0.6
Total	10.2	5.4	-66.1	-5.2	70.0	28.4	13.1	4.3	-9.1	-13.5	-6.7	-2.2
Rain	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Irrigation	36.0	36.0	36.0	36.0	18.0	18.0	18.0	18.0	27.0	27.0	27.0	27.0
Et	46.7	41.9	-29.6	31.3	88.5	46.9	31.6	22.8	18.4	14.0	20.8	25.3
Mean Et				22.6				47.5				19.6

APPENDIX 7c (continued)

28.6.68 - 11.9.68

Soil depth (cm)	Field A				Field B				Field C			
	AA	AB	AC	AD	BE	BF	BG	BH	CI	CJ	CK	CL
5	-0.5	4.8	7.7	5.1	7.7	8.2	6.8	7.6	5.2	3.3	6.8	4.8
15	3.1	7.3	4.9	-0.9	3.4	4.0	-1.7	1.7	-0.9	6.0	4.7	1.7
30	7.2	7.0	18.8	-6.2	-11.8	-11.6	10.4	5.6	-14.2	-39.8	-22.4	-28.8
50	3.0	2.6	17.4	-9.2	-6.4	2.2	6.6	4.4	9.0	-16.6	-5.8	-6.8
70	0.6	0.0	11.0	-7.2	-5.4	3.2	3.2	2.6	13.6	-3.6	-0.6	0.4
90	0.4	2.2	8.4	-1.6	1.8	2.6	2.8	2.2	10.4	-6.4	7.4	5.8
110	-0.8	-1.2	5.4	1.0	1.0	1.8	3.0	1.6	10.8	5.2	14.6	6.8
130	-1.2	0.4	7.0	-1.2	-0.2	3.8	1.4	1.8	12.4	11.4	14.8	13.6
150	-1.4	0.8	6.6	-6.2	-0.2	1.8	3.0	1.4	21.8	12.4	21.6	19.6
170	-0.6	-5.3	10.6	-7.6	-2.0	-1.0	2.0	0.8	26.8	23.4	30.4	27.8
Total	9.8	18.6	97.8	-34.0	-12.1	15.0	37.5	29.7	94.7	-4.7	71.5	44.9
Rain	51.8	60.6	139.8	-8.0	-	-	-	-	-	-	-	-
Irrigation	42.0	42.0	42.0	42.0	20.0	20.0	20.0	20.0	31.0	31.0	31.0	31.0
Et					7.9	35.0	57.5	49.7	125.9	26.3	102.5	75.9
Mean Et				61.1				37.5				82.7
	21.8.68 - 11.9.68				96.4	81.9	89.1	72.5				
					11.9.68 - 19.9.68							
5	9.4	9.8	8.7	8.6	7.0	5.9	6.8	8.2	13.7	13.2	11.6	11.0
15	5.5	4.4	6.8	10.4	3.2	5.5	9.6	7.3	12.6	4.8	6.7	6.3
30	6.4	6.8	-2.2	18.2	3.8	1.8	1.4	2.6	26.0	51.2	35.6	42.6
50	5.2	5.6	-5.2	16.4	4.8	4.6	3.6	2.2	-1.2	24.6	18.2	14.6
70	2.0	5.4	-2.4	10.2	1.8	0.6	-0.4	4.4	-10.2	8.4	5.6	3.2
90	1.0	1.8	1.4	3.8	-2.0	0.4	-1.0	-0.2	-6.8	6.6	-7.0	-5.2
110	1.6	2.0	1.8	-1.2	0.4	0.0	-1.6	1.0	-9.4	-3.0	-15.4	-7.2
130	0.8	0.8	-0.8	2.0	-0.2	-1.6	-0.4	-0.6	-14.2	-12.4	-15.4	-13.6
150	1.2	0.6	-2.0	4.4	-0.6	0.0	-2.0	-2.4	-22.0	-12.2	-21.6	-21.4
170	1.6	2.2	-7.2	8.2	-1.2	-1.0	0.0	-1.2	-28.4	-23.4	-29.2	-31.0
Total	34.7	39.4	-1.1	81.0	17.0	14.2	16.0	21.3	-39.9	57.8	-10.9	-0.7
Rain	-	-	-	-	-	-	-	-	-	-	-	-
Irrigation	-	-	-	-	-	-	-	-	-	-	-	-
Et	34.7	39.4	-1.1	81.0	-	-	-	-	-	-	-	-
Mean Et				38.5				17.1	-	-	-	-
								Total	55.6	53.1	60.6	44.6
								Irrigation	31.0	31.0	31.0	31.0
								Et	86.6	84.1	91.6	75.6
								Mean Et				84.5

APPENDIX 7c (continued)

19.9.68 - 26.9.68

Soil depth (cm)	Field A				Field B				Field C			
	AA	AB	AC	AD	BE	BF	BG	BH	CI	CJ	CK	CL
5	-4.2	-5.7	-12.1	-11.2	-10.5	-1.2	-4.8	-8.2	-11.2	-8.7	-9.6	-11.8
15	-6.7	-6.9	-8.5	-9.6	-7.7	-3.4	-3.9	-4.4	-7.7	-6.7	-5.3	-3.3
30	-9.6	-5.6	-11.8	-13.4	1.4	-0.8	0.6	-4.0	-16.4	1.0	0.2	1.0
50	-0.8	-0.2	-7.4	-8.8	4.0	1.8	2.4	-5.0	-9.8	1.6	0.2	3.6
70	3.4	1.0	-4.2	-1.4	4.8	5.4	2.6	-6.8	-2.2	2.6	2.6	3.0
90	0.6	2.2	-6.2	0.8	4.0	2.8	1.2	-1.8	-2.6	2.0	1.8	0.8
110	1.8	0.2	-2.4	1.0	0.6	0.4	0.6	-2.6	-0.8	1.4	1.2	2.6
130	1.4	0.6	-2.8	0.2	1.0	1.0	0.2	-5.4	0.2	3.6	0.4	2.2
150	1.0	1.8	-5.6	1.4	0.4	-1.0	-0.2	-2.2	-1.6	-0.6	1.0	7.0
170	0.2	0.0	-4.2	0.4	1.0	0.6	-0.2	-6.2	0.4	2.2	0.4	8.4
Total	-12.9	-12.6	-65.2	-40.6	-1.0	5.6	-1.5	-46.6	-51.7	-1.6	-7.1	13.5
Rain	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Irrigation	57.2	36.6	120.7	48.8	27.9	25.7	15.7	23.9	30.2	36.8	30.5	39.4
Et	44.6	24.3	55.8	8.5	27.2	31.6	14.5	-22.4	-21.2	35.5	23.7	53.2
Mean Et				33.3	excluding BH			24.4	excluding CI			37.5
					26.9.68 - 3.10.68							
5	4.0	5.3	9.1	9.7	1.8	1.4	2.6	7.1	7.4	9.4	8.8	12.0
15	5.8	5.8	4.5	6.2	9.8	2.2	2.4	2.1	6.6	8.0	5.3	0.0
30	6.2	6.0	8.6	8.2	2.2	2.2	2.4	9.0	8.8	2.0	1.2	2.0
50	4.0	2.8	6.6	8.6	3.2	2.8	2.8	11.6	7.4	2.0	2.2	4.4
70	3.8	2.8	4.8	3.0	7.2	4.6	5.0	10.4	3.4	3.4	4.4	7.0
90	4.2	2.6	6.2	1.2	4.4	6.8	3.6	7.4	2.4	4.0	3.2	6.0
110	1.4	3.0	3.0	2.2	3.4	6.4	2.8	5.4	1.4	3.6	0.0	2.0
130	0.4	0.6	2.8	2.4	2.4	3.2	2.6	9.0	1.0	9.8	2.2	0.6
150	-0.6	0.4	3.6	1.0	1.2	2.6	1.4	6.2	0.8	3.6	0.6	-3.6
170	0.6	4.4	1.4	1.6	3.4	2.8	1.6	8.2	0.2	0.8	0.6	-5.0
Total	29.8	33.7	50.6	44.1	39:0	35.0	27.2	76.4	39.4	46.6	28.5	25.4
Rain	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Irrigation	-	-	-	-	-	-	-	-	-	-	-	-
Et	33.2	37.1	54.0	47.5	42.4	38.4	30.6	79.8	42.8	50.0	31.9	28.8
Mean Et				43.0				47.8				38.4

APPENDIX 7c (continued)

3.10.68 - 15.10.68

Soil depth (cm)	Field A				Field B				Field C			
	AA	AB	AC	AD	BE	BF	BG	BH	CI	CJ	CK	CL
5	-14.5	-16.1	-13.8	-14.2	-15.9	-18.0	-18.8	-20.3	-14.5	-17.1	-19.4	-16.0
15	-2.5	-4.1	-3.7	-2.6	-9.4	-3.0	-7.6	-0.7	-0.4	-5.2	-0.9	2.2
30	5.4	4.2	5.2	5.8	-2.4	-0.8	-0.4	0.8	5.2	-1.0	-0.4	0.6
50	1.2	4.2	15.2	5.0	0.6	0.0	1.8	3.0	5.8	-0.8	-2.0	1.2
70	3.6	5.0	5.4	6.6	2.0	0.6	4.2	5.2	6.0	2.0	1.4	3.4
90	4.8	5.2	4.0	6.6	8.0	2.0	4.6	3.4	7.4	6.2	7.6	8.6
110	7.2	9.6	4.8	3.4	5.8	4.4	2.8	4.6	5.2	9.6	2.8	10.2
130	5.6	9.0	3.4	1.0	4.2	6.6	1.8	0.8	3.4	1.0	-0.4	5.2
150	3.8	6.8	3.0	1.2	3.8	3.6	2.8	2.0	4.6	6.6	0.0	5.6
170	1.2	3.6	4.0	0.0	1.0	2.2	0.2	0.8	3.[illegible]	5.6	-0.6	5.8
Total	15.8	27.4	27.5	12.8	-2.3	-2.4	-8.6	-0.4	26.5	6.9	-11.9	26.8
Rain	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7
Irrigation	-	-	-	-	-	-	-	-	-	-	-	-
Et	46.5	58.1	58.2	43.5	28.4	28.3	22.1	30.3	57.2	37.6	18.8	57.5
Mean Et				51.6				7.3				42.8
					15.10.68 - 31.10.68							
5	-1.8	0.2	0.0	-0.9	0.5	-0.5	1.4	-1.4	-2.0	-0.5	0.7	-2.9
15	-10.9	-9.1	-5.0	-7.8	-9.5	-11.0	-6.5	-12.1	-12.1	-7.7	-12.6	-13.2
30	-17.4	-20.6	-13.0	-15.8	-17.0	-19.4	-21.6	-20.2	-21.2	-16.4	-21.0	-23.4
50	-15.8	-19.4	-22.2	-15.6	-20.6	-20.4	-22.8	-20.4	-17.8	-17.4	-16.8	-20.0
70	-18.4	-17.0	-10.0	-11.0	-18.4	-15.6	-19.2	-18.6	-14.4	-11.8	-13.8	-14.2
90	-8.6	-1.6	-6.8	-1.8	-15.8	-4.0	-11.6	-9.6	-8.6	-2.2	-4.2	-2.8
110	-3.0	3.4	-4.2	1.4	-3.6	2.0	-2.8	-5.4	-0.4	-1.6	1.2	-0.4
130	2.4	4.0	0.0	3.4	-0.8	-0.8	1.0	-0.6	3.6	-0.8	1.8	1.6
150	2.4	6.8	3.0	3.8	4.4	2.4	1.6	2.0	2.0	0.0	1.6	2.2
170	5.6	9.8	5.0	4.6	4.6	3.6	2.4	3.8	3.4	0.8	2.4	2.6
Total	-65.5	-43.5	-53.2	-39.7	-76.2	-63.7	-78.1	-82.5	-67.5	-57.6	-60.7	-70.5
Rain	134.6	134.6	134.6	134.6	134.6	134.6	134.6	134.6	134.6	134.6	134.6	134.6
Irrigation	-	-	-	-	-	-	-	-	-	-	-	-
Et	69.1	91.1	81.4	94.9	58.4	70.9	56.5	52.1	67.1	77.0	73.9	64.1
Mean Et				84.1				59.5				70.6

APPENDIX 7c (continued)

31.10.68 - 19.11.68

Soil depth (cm.)	Field A				Field B				Field C			
	AA	AB	AC	AD	BE	BF	BG	BH	CI	CJ	CK	CL
5	-3.5	-2.9	-2.9	-2.6	-4.4	-5.1	-5.6	-2.1	-1.4	-2.8	-7.5	-2.7
15	-2.4	-3.1	-2.8	-6.4	-6.4	-4.8	-4.4	-3.9	-4.4	-4.0	-5.2	-3.0
30	-12.6	-8.6	-9.2	-12.6	-15.4	-15.6	-12.8	-13.8	-6.6	-5.4	-7.0	-0.4
50	-3.2	0.0	0.4	-1.4	-5.0	-1.2	-6.4	-5.6	-0.2	1.6	0.6	-1.6
70	0.6	2.6	-1.2	-2.2	0.2	-1.2	0.8	-0.8	1.8	-2.2	-0.6	-0.8
90	-3.4	-7.8	0.2	-5.6	0.4	-8.8	-1.4	-1.8	-0.4	-8.4	-7.8	-10.6
110	-6.0	-8.4	1.2	-3.8	-2.4	-8.8	-3.6	-0.6	-3.6	-3.8	-3.4	-7.4
130	-4.8	-2.4	0.6	-0.8	-0.6	-2.0	-2.2	-1.4	-3.2	0.8	1.4	0.4
150	-1.0	-1.8	-1.2	-2.0	-4.0	-2.0	-0.8	-2.8	0.6	2.2	1.4	-0.8
170	-1.4	-6.4	-2.8	-1.2	-0.2	-0.2	1.6	-2.0	1.2	1.4	1.2	2.0
Total	-37.7	-38.8	-17.7	-38.5	-37.8	-49.7	-34.8	-34.8	-16.2	-20.6	-26.9	-24.9
Rain	104.8	104.8	104.8	104.8	104.8	104.8	104.8	104.8	104.8	104.8	104.8	104.8
Irrigation	-	-	-	-	-	-	-	-	-	-	-	-
Et	67.1	66.0	87.1	66.0	67.0	55.1	70.0	70.0	88.6	84.2	77.9	79.9
Mean Et				71.6				75.5				82.7
					19.11.68 - 29.11.68							
5	3.4	2.0	2.1	1.1	2.4	3.4	4.1	1.1	1.0	1.6	4.7	1.5
15	2.1	1.5	4.1	5.1	5.9	2.4	4.2	3.1	3.3	1.1	2.2	2.5
30	5.6	5.6	5.4	6.0	10.8	10.2	9.8	9.6	7.8	2.8	5.4	7.4
50	-2.0	-4.2	-3.6	-3.6	0.8	-5.2	3.6	2.4	-0.6	-2.6	-1.8	-2.8
70	-4.4	-9.2	-3.2	-6.8	-6.4	-8.4	-4.6	-3.0	-4.2	-4.6	-3.4	-7.8
90	24.8	-13.0	-9.4	-11.0	-9.2	-12.6	-5.4	-7.0	-6.0	-8.4	-6.0	-10.0
110	-11.6	-16.2	-9.6	-11.0	-13.6	-15.6	-8.6	-11.4	-9.4	-14.4	-8.6	-13.8
130	-13.8	-14.0	-12.0	-14.0	-15.6	-17.0	-11.2	-12.4	-10.4	-19.6	-10.0	-16.6
150	-14.8	-24.4	-10.0	-11.0	-13.6	-17.2	-12.0	-12.4	-14.8	-19.2	-13.0	-16.4
170	-14.0	-19.8	-8.2	-11.6	-16.8	-3.8	-13.2	-11.6	-13.6	-24.2	-11.4	-19.2
Total	-24.7	-91.7	-44.4	-56.8	-55.3	-63.8	-33.3	-41.6	-46.9	-87.5	-41.9	-75.2
Rain	220.3	220.3	220.3	220.3	220.3	220.3	220.3	220.3	220.3	220.3	220.3	220.3
Irrigation	-	-	-	-	-	-	-	-	-	-	-	-
Et	195.6	128.6	175.9	163.5	165.0	156.5	187.0	178.7	173.4	132.8	178.4	145.1
Mean Et				165.9				171.8				157.4

APPENDIX 7d

Soil moisture changes in Lysimeters A and B

EAL 104 Neutron Moisture Meter

Depth (cm)	23/7 - 31/7		31/7 - 7/8		7/8 - 1/8	
	Lys. A	Lys. B	Lys. A	Lys. B	Lys. A	Lys. B
15	1.0)	-0.4	2.0)	2.4	0.2)	2.8
30	1.0)		2.0)		0.2)	
50	1.6	4.0	2.4	0.0	1.0	2.4
70	1.6	0.4	3.0	3.0	-1.2	-7.8
90	0.8	0.8	0.4	3.8	-0.8	-1.4
110	-0.2	0.0	-2.0	2.0	1.0	0.2
130	-2.6	-0.2	0.0	0.8	0.4	-3.2
150	-3.0	0.0	-2.0	0.6	1.0	-0.4
Total	0.2	4.6	5.8	11.4	1.8	-7.4
Rain	8.4	8.4	2.8	2.8	1.8	1.8
Irrigation	-	-	-	-	25.0	12.5
Drainage	6.8	12.7	1.5	14.2	2.1	4.5
Et	1.8	0.3	7.1	3.8	26.5	2.4
Et column	25.3		9.4		28.6	

	21/8 - 28/8		28/8 - 11/9		11/9 - 19/9	
15	-4.0)	3.2	-1.3)	21.8	13.9)	-7.4
30	-4.0)		7.8)		4.8)	
50	-1.6	1.4	4.6	4.4	4.8	2.6
70	-0.6	6.8	1.2	4.8	6.2	0.8
90	1.6	1.4	-0.6	2.6	0.8	-2.4
110	0.0	-0.2	1.0	2.6	1.2	-0.8
130	1.8	0.6	0.8	4.8	-3.0	-0.4
150	4.0	0.2	0.2	4.2	-2.6	-4.2
Total	-2.8	13.4	13.7	45.2	26.1	-11.8
Rain	0.5	0.5	-	-	-	-
Irrigation	36.0	18.0	42.0	20.0	-	-
Drainage	-	0.5	-	-	-	-
Et	33.7	31.4	55.7	65.2	26.1	-11.8
Et column	17.1	44.0	60.4	41.6	40.1	34.4

APPENDIX 7d (continued)

EAL 104 Neutron Moisture Meter

Depth (cm)	19/9 - 26/9		26/9 - 3/10		3/10 - 15/10	
	Lys. A	Lys. B	Lys. A	Lys. B	Lys. A	Lys. B
15	-7.8)	4.4	6.6)	5.0	4.2)	1.0
30	-7.8)		6.6)		4.2)	
50	-1.6	4.2	1.6	5.6	3.4	1.8
70	0.2	4.0	2.2	5.8	4.0	2.2
90	1.8	3.6	2.4	7.6	3.8	3.8
110	1.0	2.4	1.8	4.8	4.0	14.2
130	3.4	-0.6	2.6	4.0	7.4	21.2
150	2.2	3.2	0.6	-2.2	12.0	14.6
Total	-8.6	21.2	24.4	30.6	43.0	58.8
Rain	0.3	0.3	3.4	3.4	30.7	30.7
Irrigation	71.0	22.4	-	-	-	-
Drainage	-	-	-	-	-	-
Et	62.7	43.9	27.8	34.0	73.7	89.5
Et column	50.2		52.4		81.3	

	15/10 - 31/10		31/10 - 19/11		
15	-16.2)	-32.0	-7.8)	-24.8	
30	-16.2)		-7.8)		
50	-17.0	-17.8	-1.0	-7.0	
70	-15.4	-11.6	-0.6	-1.0	
90	-7.0	0.6	0.2	-7.8	
110	1.8	-0.2	-0.6	-3.8	
130	6.2	3.8	-4.4	-2.2	
150	9.6	12.4	-3.4	0.2	
Total	-54.2	-44.8	-25.4	-46.4	
Rain	134.6	134.6	104.8	104.8	
Irrigation	-	-	-	-	
Drainage	-	-	-	-	
Et	80.4	89.8	79.4	58.4	
Et column	118.6		101.9		

APPENDIX 7e

Summary of soil moisture changes (mm) at different depths in the soil profile

NIV 96 Neutron Moisture Meter

7.8.68 - 21.8.68

Soil depth (cm)	Field A				Field B				Field C			
	AA	AB	AC	AD	BE	BF	BG	BH	CI	CJ	CK	CL
5	-3.3	-3.0	-4.6	-4.1	0.3	2.6	4.5	-7.3				
15	-2.0	-5.8	-0.8	2.8	-1.3	0.8	1.2	1.1				
30	18.6	24.4	27.0	22.8	-10.2	-15.6	-13.0	3.8				
50	14.6	25.8	13.0	25.0	-2.6	-8.2	-7.8	-2.0				
70	16.4	19.0	15.2	16.8	-0.8	-4.6	-10.2	-7.4				
90	20.6	25.0	16.2	24.8	-1.8	-20.6	-0.8	-5.8				
110	30.2	23.2	14.4	28.2	-14.4	-5.2	-8.2	-6.2				
130	24.0	17.8	19.0	25.4	-0.2	-7.4	-6.2	-11.2				
150	34.0	3.0	38.2	26.8	-1.8	-5.2	2.8	-0.6				
170	26.2	28.4	25.6	13.2	-3.8	-1.6	5.2	1.4				
Total	179.3	157.8	163.2	181.7	-36.6	-65.0	-32.5	-34.2				
Rain	5.3	5.3	5.3	5.3	1.8	1.8	1.8	1.8				
Irrigation	25.0	25.0	25.0	25.0	12.5	12.5	12.5	12.5				
Et	209.6	188.1	193.5	212.0	-22.3	-50.7	-18.2	-19.9				
Mean Et				200.8				-27.6				
					21.8.68 - 28.8.68							
5	1.4	-4.5	-9.9	-5.6	0.3	-7.5	-8.6	0.5	-8.6	-6.9	-5.1	-7.9
15	-1.8	-4.2	-3.2	-1.4	3.5	-0.7	1.5	1.8	-5.1	-7.2	-1.6	3.3
30	-4.6	-4.6	-19.2	-11.0	8.4	17.4	-6.8	-1.8	7.0	-6.0	6.0	-8.6
50	-0.6	-6.0	-1.2	-1.0	0.6	8.2	5.8	0.2	2.0	13.4	3.8	1.2
70	9.4	3.0	-3.2	-3.0	-7.0	-3.4	8.4	5.4	16.4	13.8	13.0	2.0
90	-10.6	-1.2	-12.4	-2.8	0.0	18.6	-1.0	-0.2	3.0	8.2	14.8	-2.0
110	3.8	10.8	5.4	-0.2	10.6	-0.6	4.2	2.4	8.0	-4.4	9.2	-7.6
130	0.0	0.4	1.0	-5.6	4.2	5.4	4.4	1.2	5.8	12.2	11.6	0.0
150	-2.2	15.0	-8.4	-6.8	-12.2	1.2	-2.8	0.6	1.0	-4.8	1.4	8.0
170	1.6	-8.6	-6.0	4.6	1.6	3.8	-5.2	-3.4	9.8	5.8	4.8	4.2
Total	-3.6	0.1	-57.1	-32.8	10.0	42.4	-0.1	6.7	39.3	24.1	57.9	-7.4
Rain	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Irrigation	36.0	36.0	36.0	36.0	18.0	18.0	18.0	18.0	27.0	27.0	27.0	27.0
Et	32.9	36.6	-20.6	3.7	28.5	60.9	18.4	25.2	66.8	51.6	85.4	20.1
Mean Et				13.2				33.3				56.0

APPENDIX 7e (continued)

NIV 96 Neutron Moisture Meter

28.8.68 - 5.9.68

Soil depth (cm.)	Field A				Field b				Field C			
	AA	AB	AC	AD	BE	BF	BG	BH	CI	CJ	CK	CL
5	2.2	14.9	16.4	6.4	8.2	10.5	9.6	4.0	16.6	9.0	15.1	17.2
15	6.7	13.6	16.9	9.1	0.0	3.9	8.4	5.8	16.3	10.5	9.3	3.9
30	20.0	16.0	28.0	18.0	0.0	-8.0	9.8	-6.0	4.0	8.0	2.2	7.8
50	12.2	12.0	8.0	-2.2	-14.0	0.0	-7.8	-10.2	0.2	-4.0	2.2	-4.0
70	0.2	5.8	14.0	2.0	0.0	6.0	-12.2	-15.8	-18.0	-5.8	-6.2	-8.0
90	14.0	12.0	22.0	0.0	-2.0	-12.0	-8.2	-12.0	2.2	6.0	-1.8	4.0
110	3.8	2.0	8.0	-4.2	-12.2	-12.2	-10.0	-12.2	-2.2	-8.0	-8.2	-2.2
130	11.8	-0.2	8.0	-2.0	-7.8	-14.0	-12.2	-8.0	-2.0	-10.0	-12.2	-1.0
150	10.2	-2.0	2.0	12.0	4.0	-15.8	-10.0	-6.0	-8.2	-1.8	-2.0	-14.0
170	8.0	8.0	6.0	2.2	-11.8	-12.2	-4.0	-4.0	-8.0	-12.0	2.2	-9.8
Total	89.1	82.1	131.3	41.3	-35.6	-53.8	-36.6	-64.4	0.9	-14.1	0.6	-6.1
Rain	-	-	-	-	-	-	-	-	-	-	-	-
Irrigation	-	-	-	-	-	-	-	-	-	-	-	-
Et	89.1	82.1	131.3	41.3	-35.6	-53.8	-36.6	-64.4	0.9	-14.1	0.6	-6.1
Mean Et				86.0				-7.6				-4.7
	5.9.68 - 11.9.68											
5	-2.7	-10.1	-10.7	-1.3	-0.5	-2.3	-2.8	3.6	-11.4	-5.7	-8.3	-12.4
15	-3.6	-6.3	-12.0	4.0	3.4	0.1	-10.1	-4.1	-17.2	-4.5	4.6	-2.2
30	-6.0	4.0	-11.8	-4.0	3.8	8.0	6.0	10.0	6.0	18.0	15.8	6.0
50	-6.2	2.0	6.0	6.0	18.0	18.0	21.8	16.0	14.0	6.0	-4.0	13.8
70	-0.2	-1.8	-4.0	12.0	13.8	4.0	18.0	19.8	15.8	7.8	4.0	8.0
90	0.0	-7.8	-5.8	10.0	6.0	16.0	8.2	16.0	14.0	4.0	-6.2	3.8
110	-2.0	-9.8	0.0	6.0	12.2	18.0	8.2	16.0	2.2	6.2	10.0	8.0
130	-2.0	-4.0	-1.8	14.0	6.0	14.0	16.2	10.2	10.2	10.0	6.0	7.2
150	-2.2	3.8	0.0	-1.8	12.0	10.0	14.0	12.0	10.6	11.8	0.0	15.8
170	-4.0	-5.8	6.2	3.8	14.0	18.0	12.2	12.2	4.0	14.0	0.0	14.0
Total	-28.9	-35.8	-33.9	48.7	88.7	103.8	91.7	111.7	48.2	67.6	12.7	62.0
Rain	-	-	-	-	-	-	-	-	-	-	-	-
Irrigation	42.0	42.0	42.0	42.0	20.0	20.0	20.0	20.0	31.0	31.0	31.0	31.0
Et	13.1	6.2	8.1	90.7	108.7	123.8	111.7	131.7	79.2	98.6	43.7	93.0
Mean Et				29.5				119.0				78.6

APPENDIX 8

Record of tensiometer readings at 0900 hrs. September - December, 1967

*Negative values, i.e. tensiometer reading less than the contribution from the hanging column of water as measured from mercury reservoir to the depth of tensiometer cup.

L = additional lower tensiometer in lysimeter A: 180 cm.
L = Lower tensiometer: 170 cm in field
150 cm in lysimeter
U = Upper tensiometer: 120 cm in field
100 cm in lysimeter
IRR = fields irrigated.

Date 1967	Field A			Lysimeter A			Field B			Lysimeter B		
	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm
Sep. 1	119.7	149.6	.40	24.5	129.2	-1.09	194.5	246.2	-.03	43.5	144.2	-1.01
2	115.6	145.5	.40	36.7	125.1	-.76	180.9	190.4	.81	42.2	127.8	-.71
3	112.9	149.6	.26	21.8	81.6	-.19	168.6	159.1	1.19	35.4	95.2	-.19
4	114.2	152.3	.23	27.2	88.4	-.22	161.8	151.0	1.21	38.1	95.2	-.14
5	117.0	157.8	.18	34.0	107.4	-.46	161.8	146.9	1.29	59.8	129.2	-.36
6	114.2	155.0	.18	23.1	81.6	-.17	153.7	131.9	1.03	35.4	89.8	-.08
7	117.0	159.1	.15	29.9	100.6	-.41	153.7	144.2	1.19	39.4	107.4	-.36
8	122.4	164.6	.15	32.6	85.7	-.06	163.2	176.2	.70	38.1	107.4	-.38
9	122.4	163.2	.18	16.3	78.9	-.05	161.8	179.5	.64	32.6	100.6	-.36
10	122.4	161.8	.21	20.4	73.4	-.06	153.7	175.4	.56	17.7	81.6	-.27
11	129.2	161.8	.34	23.1	81.6	-.17	163.2	175.4	.75	27.2	119.7	-.85
12	129.2	163.2	.32	20.4	77.5	-.14	160.5	179.5	.62	29.9	106.1	-.52
IRR 13	129.2	172.7	.13	25.8	80.2	-.08	155.0	174.1	.61	35.4	107.4	-.44
14	129.2	167.3	.23	16.3	73.4	-.14	156.4	182.2	.48	32.6	97.9	-.30
15	126.5	155.0	.43	24.5	70.7	+.07	159.1	184.9	.48	36.7	107.4	-.41
16	121.0	138.7	.64	32.6	80.2	+.04	152.3	175.4	.53	31.3	111.5	-.60
17	118.3	141.4	.53	29.9	84.3	-.08	152.3	174.1	.56	31.3	111.5	-.60
18	122.4	149.6	.45	27.2	88.4	-.22	149.6	-	-	27.2	116.9	-.79
19	115.6	151.0	.29	28.6	84.3	-.11	149.6	-	-	27.2	103.4	-.52
20	119.7	137.4	.64	24.5	133.3	-1.17	164.6	167.3	.94	53.0	141.4	-1.16

APPENDIX 8 (continued)

Date 1967	Field A			Lysimeter A			Field B			Lysimeter B		
	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm
Sep. 21	118.3	151.0	.34	27.2	111.5	-.66	167.3	179.5	.75	46.2	123.8	-.55
22	119.7	156.4	.26	27.2	107.4	-.60	185.9	183.6	.04	40.8	117.0	-.52
23	113.3	155.0	.26	24.5	110.2	-.71	168.6	161.8	1.13	36.7	110.2	-.47
24	117.0	146.9	.40	21.8	100.6	-.57	167.3	160.5	1.13	35.4	107.4	-.44
25	121.0	157.8	.26	21.8	122.4	-1.01	159.1	118.3	1.81	40.8	123.8	-.66
IRR 26	115.6	155.0	.47	19.0	108.6	-.59	156.4	121.0	1.70	43.5	118.3	-.49
27	123.5	161.8	.24	20.4	119.7	-.98	175.8	115.6	2.22	50.3	117.0	-.33
28	127.6	164.6	.26	20.4	118.3	-.95	193.1	191.8	1.02	57.1	117.0	-.19
29	123.8	160.5	.26	23.1	111.5	-.76	176.8	155.0	1.43	53.0	107.4	-.08
30	125.1	163.2	.23	21.7	97.9	--.52	167.3	157.8	1.19	55.8	106.1	.00
Oct. 1	121.0	160.5	.21	19.0	100.6	-.63	161.8	141.4	1.40	42.3	102.0	-.19
2	125.1	161.8	.26	19.0	100.6	-.63	160.5	133.3	1.54	47.6	96.6	+.02
3	125.1	161.8	.26	19.0	112.9	-.87	159.1	125.1	1.68	47.6	100.6	-.06
4	125.1	170.0	.10	19.0	97.9	-.57	159.1	131.9	1.54	44.9	96.6	-.03
5	125.1	164.6	.21	16.3	114.2	-.95	148.2	174.1	.48	50.3	100.6	.00
6	125.1	165.9	.18	10.9	99.3	-.76	141.4	131.9	1.19	46.2	97.9	-.03
7	125.1	163.2	.23	10.9	103.4	-.85	142.8	131.9	1.21	50.3	102.0	-.03
8	126.5	163.2	.25	8.2	99.3	-.82	138.7	118.3	1.40	47.6	99.3	-.03
9	122.1	160.5	.23	4.1	95.2	-.82	133.3	93.8	1.79	47.6	95.2	+.04
10	126.5	172.7	.07	5.4	92.5	-.74	142.8	118.3	1.49	46.2	97.9	-.03
IRR 11	146.9	195.8	.02	8.2	96.6	-.76	167.3	103.4	2.27	59.8	151.0	-.82
12	144.2	198.6	-.08	8.2	96.6	-.76	174.1	99.3	2.49	62.6	136.0	-.46
13	142.8	183.6	.18	2.7	91.1	-.76	163.2	69.8	2.46	57.1	134.6	-.55
14	141.4	185.0	.12	2.7	95.2	-.85	163.2	85.7	2.55	40.8	117.0	-.51
15	141.4	186.3	.10	5.4	97.9	-.85	163.2	42.2	3.42	57.1	121.0	-.27
16	141.4	186.3	.10	4.1	92.5	-.76	170.0	104.7	2.30	58.5	114.2	-.11
17	141.4	187.7	.07	4.1	102.0	-.95	160.5	36.1	3.44	59.8	119.6	-.19
18	152.3	179.5	.45	5.4	93.8	-.76	153.7	16.3	3.74	59.8	118.3	-.17
19	146.9	176.8	.40	5,4	104.7	-.98	163.2	20.4	3.85	63.9	119.7	-.11
20	150.9	175.4	.51	1.4	107.4	-1.12	165.9	17.7	3.96	63.9	117.0	-.06

APPENDIX 8 (continued)

Date 1967	Field A			Lysimeter A					Field B			Lysimeter B		
	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	L cm water	L' cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	$\left(\frac{L'-L}{30}\right)$ cm/cm	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm
Oct. 21	150.9	179.5	.42	4.1	16.3	100.6	-.93	1.40	165.9	35.4	3.61	58.5	117.0	-.17
22	149.6	174.1	.51	1.4	15.0	115.6	-1.28	1.45	163.2	46.2	3.34	61.2	121.0	-.19
23	146.9	179.5	.34	1.4	16.3	107.4	-1.12	1.49	171.4	55.8	3.31	65.3	123.8	-.17
24	149.6	162.2	.34	1.4	19.0	104.7	-1.06	1.56	166.6	72.1	2.93	63.9	122.4	-.17
25	150.9	183.6	.34	2.7	16.3	114.2	-1.23	1.45	168.6	46.2	3.44	65.3	122.4	-.14
26	145.5	172.7	.45	1.4	16.3	93.8	-.84	1.49	166.6	29.9	3.77	65.3	119.7	-.08
27	146.9	170.0	.53	0	0	95.2	-.90	1.00	170.0	69.4	3.01	63.9	117.0	-.06
28	145.5	166.6	.53	*	15.0	89.8	-	-	175.4	57.1	3.36	59.8	114.2	-.08
29	119.7	125.1	.89	*	2.7	57.1	-	-	126.5	63.9	2.25	32.6	70.7	+.23
30	117.0	108.8	1.16	*	4.1	68.0	-	-	122.4	42.2	2.60	23.1	69.4	+.07
31	115.6	112.9	1.05	*	4.1	73.4	-	-	118.3	46.2	2.44	23.1	73.4	.00
Nov. 1	88.4	99.3	.78		4.1	62.6	-	-	104.7	74.8	1.59	19.0	65.3	.07
2	89.8	103.4	.73		4.1	70.7	-	-	104.7	47.6	2.14	20.4	69.4	.02
3	87.0	110.2	.53		4.1	57.1	-	-	106.1	65.3	1.81	23.1	74.8	.03
4	74.8	95.2	.59	35.4	1.4	57.8	.55	-.13	93.8	54.4	1.78	17.7	62.6	.10
5	80.2	102.0	.56	40.8	5.4	72.1	.37	-.18	91.1	58.5	1.65	19.0	68.0	.02
6	80.2	102.0	.56	40.8	1.4	72.1	.37	-.31	95.2	59.8	1.70	20.4	72.1	-.03
7	87.0	112.9	.48	36.7	2.7	73.5	.26	-.13	97.9	49.0	1.97	21.7	74.8	-.06
8	87.0	110.2	.53	34.0	9.5	49.0	.70	+.18	96.7	76.2	1.41	20.4	73.4	-.06
9	89.8	125.1	.29	40.8	8.2	77.5	.26	-.08	106.1	6.8	2.98	21.7	74.8	-.06
10	93.8	123.8	.40	40.8	5.4	76.9	.23	-.18	107.4	8.2	2.98	21.7	76.2	-.09
11	95.2	130.6	.29	35.4	5.4	80.2	.10	0	106.8	58.5	2.00	21.7	77.5	-.11
12	100.6	138.7	.23	39.4	8.2	84.3	.10	-.04	111.5	53.0	2.17	23.1	80.2	-.14
13	100.6	142.8	.15	39.4	5.4	84.3	.10	-.13	118.3	57.1	2.22	23.1	84.3	-.22
14	106.1	146.9	.18	36.7	5.4	83.0	.07	-.04	121.0	55.6	2.30	23.1	83.0	-.19
15	112.8	160.5	.04	-	16.3	121.0	-	-	140.1	9.5	3.61	58.5	117.0	-.17
16	121.0	160.5	.21	39.4	9.5	107.4	-.36	0	138.7	83.0	2.11	44.9	104.7	-.19
17	121.0	165.9	.10	32.6	10.9	93.6	-.22	+.27	137.4	81.6	2.11	40.8	99.3	-.17
18	125.1	172.7	.04	39.4	10.9	100.6	-.22	+.05	145.5	35.4	3.18	47.6	106.1	-.17
19	125.1	174.1	.02	34.0	9.5	97.9	-.27	+.18	149.6	15.0	3.69	48.9	110.2	-.22
20	127.8	172.7	.10	35.4	9.5	107.4	-.44	+.13	152.3	16.3	3.52	51.7	112.9	-.22

APPENDIX 8 (continued)

Date 1967	Field A			Lysimeter A					Field B			Lysimeter B		
	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	L cm water	L' cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	$\left(\frac{L'-L}{30}\right)$ cm/cm	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm	L cm water	U cm water	$\left(\frac{L-U}{50}+1\right)$ cm/cm
Nov.														
21	129.2	176.8	.04	34.0	10.9	104.7	-.41	.23	152.3	36.7	3.31	51.7	114.2	-.25
22	129.2	178.2	.02	4.0	9.5	103.4	-.38	.18	155.0	84.3	2.41	53.1	115.6	-.25
23	131.9	183.6	-.01	35.4	9.5	104.8	-.38	.13	152.3	70.7	2.63	50.3	110.2	-.19
24	130.6	179.5	.02	34.0	9.5	95.2	-.22	.16	151.0	27.2	3.47	47.6	106.1	-.17
25	130.6	179.5	.02	32.6	9.5	91.1	-.17	.23	151.0	29.9	3.42	48.9	104.7	-.11
26	129.2	179.5	-.00	34.0	9.5	89.8	-.11	.18	151.0	15.0	3.72	47.6	104.7	-.14
27	1[illegible].6	172.7	-.15	28.6	6.8	65.3	+.26	.27	153.7	16.3	3.74	44.9	93.8	+.02
28	129.2	151.0	56	27.2	5.4	69.4	+.15	.27	144.2	10.9	3.66	32.6	81.6	+.02
29	114.2	140.1	.48	24.5	5.4	72.1	+.04	.36	125.1	10.9	3.28	29.9	80.2	0
30	107.4	133.3	.48	25.9	5.4	76.2	0	.31	129.2	88.4	1.81	29.9	81.6	-.03
Dec.														
1	126.5	137.4	.78	31.3	9.5	91.1	-.19	.27	127.8	77.5	2.00	38.1	91.1	-.06
2	107.4	141.4	.32	28.6	12.2	91.1	-.25	.45	129.2	12.2	3.34	39.4	85.7	+.07
3	106.1	145.5	.21	25.8	9.5	95.2	-.38	.45	130.6	0	3.60	38.1	97.9	-.19
4	111.5	143.7	.15	25.8	6.8	100.6	-.49	.36	131.9	17.7	3.28	38.1	91.1	-.06
5	112.9	155.0	.15	28.6	13.6	89.8	-.22	.50	131.9	66.6	2.30	40.8	96.6	-.11
6	115.6	161.8	.07	28.6	8.2	89.8	-.22	.32	137.4	42.2	2.90	36.7	92.5	-.11
	118.3	165.9	.04	29.9	15.0	92.5	-.25	.50	138.7	49.0	2.79	44.9	99.3	-.08
	122.4	174.[illegible]	-.03	32.6	16.3	96.6	-.28	.45	141.4	16.3	3.50	48.9	102.0	-1.06
	125.1	176.8	-.03	34.0	24.5	100.6	-.33	.68	144.2	15.0	3.58	54.4	10[illegible].4	-.06
	126.1	178.2	-.03	34.0	23.1	100.6	-.33	.83	145.5	9.5	3.72	53.0	107.4	-.08
	127.8	183.6	-.11	35.4	23.1	102.0	-.33	.59	148.2	76.2	2.44	55.8	110.2	-.08
12	130.6	186.3	-.11	35.4	24.5	103.4	-.36	.63	149.6	10.9	3.77	59.8	114.2	-.08
13	134.6	191.8	-.14	36.7	25.8	104.7	-.36	.63	152.3	5.4	3.93	62.6	117.0	-.08
14	131.9	194.5	-.25	36.7	27.2	102.0	-.26	.68	153.7	9.5	3.88	65.3	118.3	-.06
15	137.4	193.1	-.11	39.4	29.9	107.4	-.36	.68	157.8	27.2	3.61	72.1	123.8	-.03
16	140.1	201.3	-.17	42.2	32.6	110.2	-.36	.68	160.5	8.2	4.04	74.8	127.8	-.06
17	142.8	209.4	-.33	43.5	34.0	112.9	-.38	.68	160.5	43.5	3.34	80.2	133.3	-.06
18	144.4	213.5	-.44	43.5	32.6	114.2	-.41	.63	160.5	19.0	3.83	84.3	136.7	-.08
19	144.2	223.0	-.57	47.6	39.4	118.3	-.41	.72	163.2	23.1	3.80	91.1	145.5	-.08
20	151.0	228.5	-.55	50.3	42.2	121.0	-.41	.73	164.6	28.6	3.72	96.6	152.3	-.11

APPENDIX 8 (continued)

SOIL MOISTURE TENSION (CM. WATER) RECORDED WITH TENSIOMETERS PLACED AT DIFFERENT DEPTHS IN THE SOIL PROFILE

Date	Field A			Lysimeter A		Field B			Lysimeter B		Field C		
	170cm.	150cm.	70cm.	170cm.	150cm.	170cm.	150cm.	70cm.	170cm.	150cm.	120cm.	100cm.	50cm.
AUG. 1968													
1	137	140	203	22		146	170	212		47	286		286
2	145	157	240			134	163	195		34	264		264
3	141	155	226			134	169	217		45			264
4	137	149	206			127	166	219		48	297		198
5	137	169	226			136	169	226		44	286		220
6	140	154	217			132	166	229		42	297	165	242
7	140	154	212			137	168	235		47	308	242	264
8	149	161	226	40	60	139	171	235		44	308	253	264
9	149	160	224	39		132	164	239		43	308	253	286
10	150	163	235	40	64	132	163	237		43	308	264	286
11	151	163	235	56	-	129	144	239		40	297	253	264
12	150	156	224	56		115	131	220		26	266	242	253
13	150	161	221	46	88	124		237		48	308	264	297
14	151	160	219	47		120		239		48	320	264	297
15	153	160	217	39	60	137	184	253		50	331	264	308
16	153	160	221	39	66	132	189	249		45	308		297
17	153	150	220	35	55	137	184	253		50	331	132	331
18	153	159	225	37	60	136	193	249		44	320	275	331
19	154	159	229	42	64	136	190	244		47	331	275	308
20	154	160	229	40	58	141	189	243		49	331	286	331
21	155	160	230	37	55	143	192	235		52	331	286	331
22	154	157	229	39	58	121	190	216		49	331	286	331
23	155	157	229	44	62	137	188	202		50	331	308	331
24	154	157	227	42	63	141	188	197		49	331		331
25	156	157	229		62	140	188	197		47	331		308
26	168	157	230		62	140	185	200		52	331	220	253
27	146	160	235		58	146	189	211		58	353	286	209
28	158	159	235		52	146	189	215		52	331	286	264
29	146	164	231		63	129	179	182			297	253	242
30	159	155	221		57	77	183	216		-	331	264	320
31	153	152	219		59	73	183	215		52	331	198	331

APPENDIX 8 (continued)

Date	Field A			Lysimeter A		Field B			Lysimeter B		Field C		
	170cm.	150cm.	70cm.	170cm.	150cm.	170cm.	150cm.	70cm.	170cm.	150cm.	120cm.	100cm.	50cm.
SEP. 1968													
1	154	155	217			20	183	216	54		308		331
2	154	155	221				186	235	52		331	275	342
3	148	151	216				180	207	53		331	220	320
4	149	155	217				185	212	58		342	242	331
5	151	154	229				168	215	54		342	220	342
6	164	169	240	49		165	231	237	56		342	253	331
7	161	174	254	39		61	219	270	51		353	286	364
8	161	17[illegible]	246	38		39	204	264	49		364	320	375
9	165	174	249	47		33	210	260	54		353	331	386
10	169	175	241	61		11	215	226	62		331	286	331
11	166	171	239	48		30	205	248	56		353	320	375
12	163	166	236	46		59	202	260	56		353	264	397
13	161	165	229	54		35	197	251	59		331	286	364
14	161	165	241	51		28	197	251	61		342	275	364
15	164	164	256	47		25	199	280	32		364	286	397
16	161	161	260	44		32	199	297	56		364	353	408
17	160	163	268	47		49	199	312	58		364	353	408
18	159	160	274	47		59	199	331	57		264	264	408
19	160	159	274	49		61	198	347			353	353	375
20	165	163	287	62		18	204	380	73		375	331	441
21	161	175	283	59			205	345	76		386	463	441
22	161	161	255	53		18	200	319	71		353	463	430
23	160	161	255	49		6	199	375	67		386	474	452
24	161	157	243	54		37	198	403	72		375	441	463
25	160	159	246	53		29	198	434	72		397	463	463
26	161	160	253	80		66	195	459	74		386	452	441
27	164	163	263	61		57	171	482	78		397	441	397
28	165	159	274	59		74	195	517	81		397	496	386
29	161	157	277	61		73	200	534	83		375	518	375
30	166	160	308	63		148	200	554	88		397	331	364

APPENDIX 8 (continued)

Date	Field A			Lysimeter A		Field B			Lysimeter B		Field C		
	170cm.	150cm.	70cm.	170cm.	150cm.	170cm.	150cm.	70cm.	170cm.	150cm.	120cm.	100cm.	50cm.
OCT. 1968													
1	166	159	333	64	64	106	203	588	92	286	408	275	507
2	166	160	369	66	82	27	204	502	96	300	419	551	529
3	169	166	392	68	86	46	205	540	103	318	419	353	529
4	172	161	429	72	92	42	205	561	111	331	419	485	540
5	173	155	474	77	96	72	210	575	122	349	441	375	502
6	168	155	502	77	93	40	210	583	129	352	397	573	573
7	175	156	505	82	100	47	209	568	143	357	452	386	584
8	177	161	484	86	103	87	209	598	155	360	463	672	419
9	178	168	500	88	106	77	209	437	170	359	463	397	364
10	182	170	566	92		66	212	552	189	244	496	573	496
11	180	161	565	97		111	205	564	198	194	485	683	551
12	185	169	618	103		111	206	575		242	485	397	573
13	189	163	628	110	145	69	212	588		330	507	639	617
14	190	155	629	119	152	90	210	590		364	518	397	617
15	194	160	559	124	155	59	215	596		388	551	661	650
16	198	155	588	130	160	155	213	598	140	397	529	617	661
17	199	149	595	135	163	187	209	598	172	407	551	650	650
18	203	142	599	140	168	200	204	598	185	408	529	716	661
19	204	154	529	144	173	208	203	598	195	409	465	606	485
20	197	146	594	146	170	206	193	598	200	398	485	639	507
21	207	146	595	153	179	212	189	598	208	407	474	663	485
22	211	147	590	160	184	213	185	596	211	402	551	738	485
23	212	147	487	169	189	182	183	463	214	403	551	573	672
24	209	142	522	169	190	217	178	527	217	399	551	661	661
25	216	156	544	180	199	224	174	550	218	399	573	705	683
26	218	161	554	187	204	231	170	556	221	398	573	551	683
27	206	169	474	208	163	235	160	459	223	394	573	331	617
28	217	165	512	197	205	233	165	510	226	396	573	683	639
29	206	169	474	208	163	235	160	459	223	394	573	331	617
30	187	165	437	208	126	237	159	419	102	328	562	353	595
31	178	161	403	200	117	233	154	382	150	374	551	364	573

APPENDIX 8 (continued)

Date	Field A			Lysimeter A		Field B			Lysimeter B		Field C		
	170cm.	150cm.	70cm.	170cm.	150cm.	170cm.	150cm.	70cm.	170cm.	150cm.	120cm.	100cm.	50cm.
NOV. 1968													
1	169	155	376	130	117	233	154	356	180	382	551	364	661
2	172	146	356	182	120	227	147	331	199	375	551	375	529
3	168	141	338	173	118	226	146	312	207	370	551	375	507
4	168	136	318	168	108	221	139	285	223	358	562	364	485
5	168	132	300	164	101	217	136	265	233	348	573	353	463
6	163	132	288	153	96	218	137	253	245	344	584	331	452
7		126	275	140	93	213	130	234	247	333	463	331	441
8			266	134	93	208	125	222	243	325	551	308	419
9			166	125	91	207	126	214	120	313	562	308	419
10		161	205	112	83	199	122	200	168	305	551	286	397
11		160	240	114	86	195	117	197	192	296	551	286	397
12		170	244		82	197	120	198	211	296	551	286	397
13		188	259	146	88	193	117	200	221	291	551	286	397
14		180	245	143	87	188	115	198	232	287	529	286	375
15		165	245	144	88	188	112	196	240	283	518	275	364
16		160	254	146	91	185	112	198	240	281	518	264	353
17		159	260	148	91	182	108	202	242	278	518	253	353
18		156	261	146	88	180	108	206	246	277	507	253	342
19		155	265	146	92	184	110	217	252	278	518	242	353
20		166	146	156	154	145	127	135	342	425	507	220	331
21		161	94	146	97	136	136	71	384	262	507		331
22		160	61	44	45	140	126	85	387	10	375	44	320
23		156	108	33	45	111	118	105	367	24	242	77	320
24		146	35	35	48	116	130	111	67	25	242	88	286
25		142	72	39	55	122	136	111	51	28	242	88	266
26		140	108	34	47	112	123	101	42	23	242	88	286
27		135	125	34	50	117	131	117	40	30	264	88	264
28		132	139	34	52	117	132	132	34	34	220	99	275
29													
30													

APPENDIX 8 (continued)

Date	Field A			Lysimeter A		Field B			Lysimeter B		Field C		
	170cm.	150cm.	70cm.	170cm.	150cm.	170cm.	150cm.	70cm.	170cm.	150cm.	120cm.	100cm.	50cm.
Dec. 1968													
1		120	180	38	52	135	149	163	44	50	286	110	264
2		117	183	35	50	139	150	172	44	49	286	110	242
3		113	143	32	42	141	155	74	37	6	297	110	242
4		108	77	33	38	107	112	74	25	8	220	55	264
5		106	166	34	44	103	112	101	34	25	220	55	242
6		102	130	37	49	111	123	22	35	35	253	66	242
7		100	158	40	50	117	131	142	37	49	242	88	242
8		93	168	39	44	116	132	142	34	53	220	110	209
9		92	180	36	48	125	137	163	39	52	286	132	242
10		87	196	38	[illegible]	126	140	167	38	62	286	110	242
11			201	37	48	134	146	183	40	60	297	132	242
12		60	210	38	48	137	151	187	39	66	308	132	264
13		58	212	35	44	134	151	176	39	66	286	154	242
14		55	230	38	49	143	156	196	39	76	308	154	264
15		54	226	37	44	144	157	205	38	66	308	165	264
16		50	229	37	43	144	159	209	35	67	320	165	264
17		49	237	37	44	143	163	217	37	74	320	176	264
18													
19													
20													
21													
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31													

APPENDIX 9

MEASUREMENTS OF WIND PROFILES ABOVE MATURING MAIZE CROP AT MWEA AND THE DETERMINATION OF AERODYNAMIC RESISTANCE r_a

Theory

(a) Characteristics of wind profile

Since the atmosphere is viscous, the mean windspeed $\bar{U}$ is not constant, but increases with height as a result of the surface shearing stress τ_0 dynes/cm^2, which is the force of retardation per unit surface area.

The magnitude of τ_0 depends on geostrophic windspeed, surface roughness and buoyancy; and for laminar flow in which shearing stresses are due entirely to molecular vibrations, the relationship between shearing stress and windspeed gradient is linear (Sutton, 1953).

In the absence of buoyancy,

$$\tau = \mu \frac{\partial \overline{U}}{\partial z} \qquad \text{.....(1)}$$

where μ is the dynamic viscosity (gm.cm^{-1}sec^{-1}) and is related to kinematic viscosity ν (cm^{-2}sec^{-1}) by

$$\nu = \frac{\mu}{\rho} \qquad \text{.....(2)}$$

the frictional velocity U_* is hence defined by

$$U_*^2 = \frac{\tau}{\rho} = \nu \frac{\partial \overline{U}}{\partial z} \qquad \text{.....(3)}$$

and introducing momentum eddy diffusivity K_m,

$$U_*^2 = (K_m + \nu)\frac{\partial \overline{U}}{\partial z} \simeq K_m \frac{\partial \overline{U}}{\partial z} \qquad \text{.....(4)}$$

This applies strictly in the surface boundary layer defined as the region where τ does not vary by more than 5%. If we now define the rate of viscous dissipation per unit mass of air (cm^{2}sec^{-3}),

$$k\epsilon = \frac{U_*^3}{z} \qquad \text{.....(5)}$$

where k is von Karman's constant.

Taylor (1952) observed that the shear-flow energy production P is related to $\overline{U}$ by

$$P = \frac{\partial}{\partial z}(\bar{U}\ U_*^2) \qquad \text{.....(6)}$$

and balancing production (6) with dissipation (5) gives

$$U^* = z \frac{\bar{U}}{z} \qquad \text{.....(7)}$$

If we now make $\bar{U} = 0$ at $z = z_o$, the windspeed profile over a uniform and extensive surface may be represented by a logarithmic function of the form

$$\bar{U} = \frac{U^*}{k} \ln \frac{z}{z_o} \qquad \text{.....(8)}$$

where z_o is roughness length, a characteristic of the surface.

Over tall vegetation, a similar equation is applicable but in a modified form:

$$\bar{U} = \frac{U^*}{k} \ln \frac{z - d}{z_o} \qquad \text{.....(9)}$$

where d is zero plane displacement.

(b) Derivation of aerodynamic resistance from the logarithmic wind profile

The aerodynamic resistance r_a is defined as the time in which 1 cm^3 of air exchanges heat or water vapour with 1 cm^2 of surface. It can therefore be shown (Monteith, 1965) that if E is the evaporation rate, γ the psychrometric constant, ρc specific heat of air and e and e_o are vapour pressures at height z and at the evaporating surface,

$$\frac{E\gamma\lambda}{\rho c} = \frac{e_o - e}{r_a} \qquad \text{.....(10)}$$

If also the profiles of e and U are the same shape above a uniform crop, the graph of e plotted against U is a straight line intercepting the axis U = 0 at e = e_o. Penman and Long (1960) showed that under these conditions the latent heat of evaporation is given by

$$\lambda E = \frac{k^2 \rho c (e_o - e) U}{\gamma \left\{ \ln \frac{(z - d)}{z_o} \right\}^2} \qquad \text{.....(11)}$$

Equations (10) and (11) then give

$$r_a = \frac{\left\{\ln\frac{(z - d)}{z_o}\right\}^2}{k^2 U} \qquad .....(12)$$

Site of measurements and apparatus

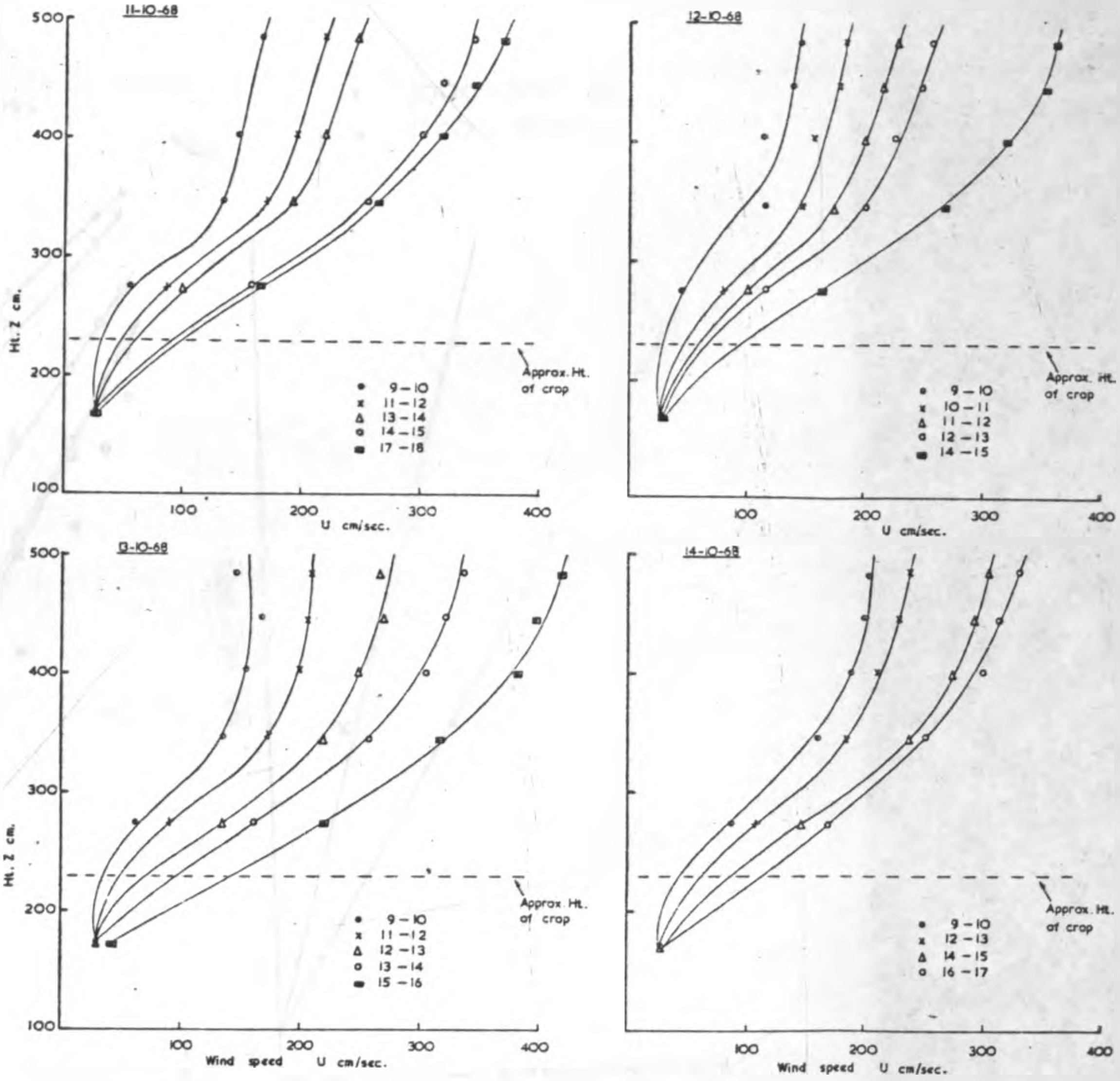
The measurements were made over a maize crop at Mwea Irrigation Scheme, altitude 1,280 metres, two weeks after silking. Six small sensitive cup anemometers (C. F. Cassella & Co.) mounted at 173, 275, 347, 402 and 487 cm above the ground were set up on a mast at a point 20 m from the downwind edge of the field.

The maize was planted 20 cm apart on north-south rows 100 cm apart. The direction of the wind was E to SE, i.e. mostly at right angles to the maize rows. Anemometer cup rotations were recorded as electrical pulses from which hourly averages of windspeeds were obtained, using calibration curves supplied by the manufacturers. After the experiment, all the anemometers were mounted on a horizontal bar and compared against one another. They all yielded the same windspeed ± 2% and this was taken into account when construsting the actual wind profiles.

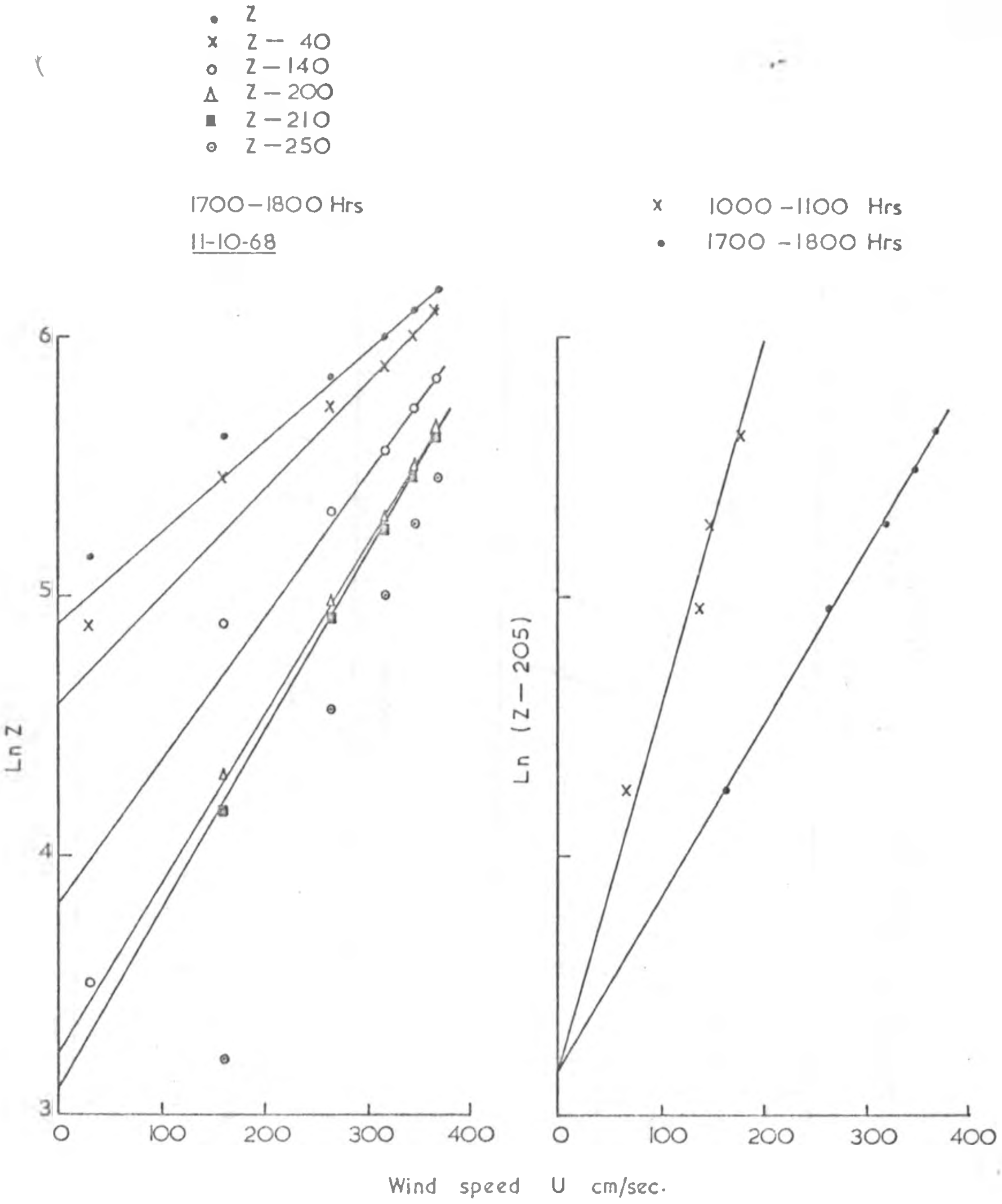
Results

The representative hourly wind profiles, some of which are shown in Fig. 9:1 for clarity, resemble those obtained by Stoller and Lemon (1963), above and within a maize crop, but as in the wheat crop (Penman and Long, 1960) there is no evidence of increase in windspeed above the crop, and the canopy tends to seal up. This explains the large value of zero plane displacement (205 cm) found necessary in adjusting the windspeed profiles to fit the logarithmic function of equation (9)(Fig. 9:2). The roughness length z_0 was determined from the adjusted logarithmic windspeed profiles above the crop in Fig. 9:3; z_0 was virtually constant at 24.0 ± 0.5 cm on 11th and 12th October, but decreased occasionally on 13th and 14th October, to a minimum of 15.7 cm. The maximum value of z_0 is close to 10% of average crop height (Slatyer and McIlroy, 1961; Munn, 1966).

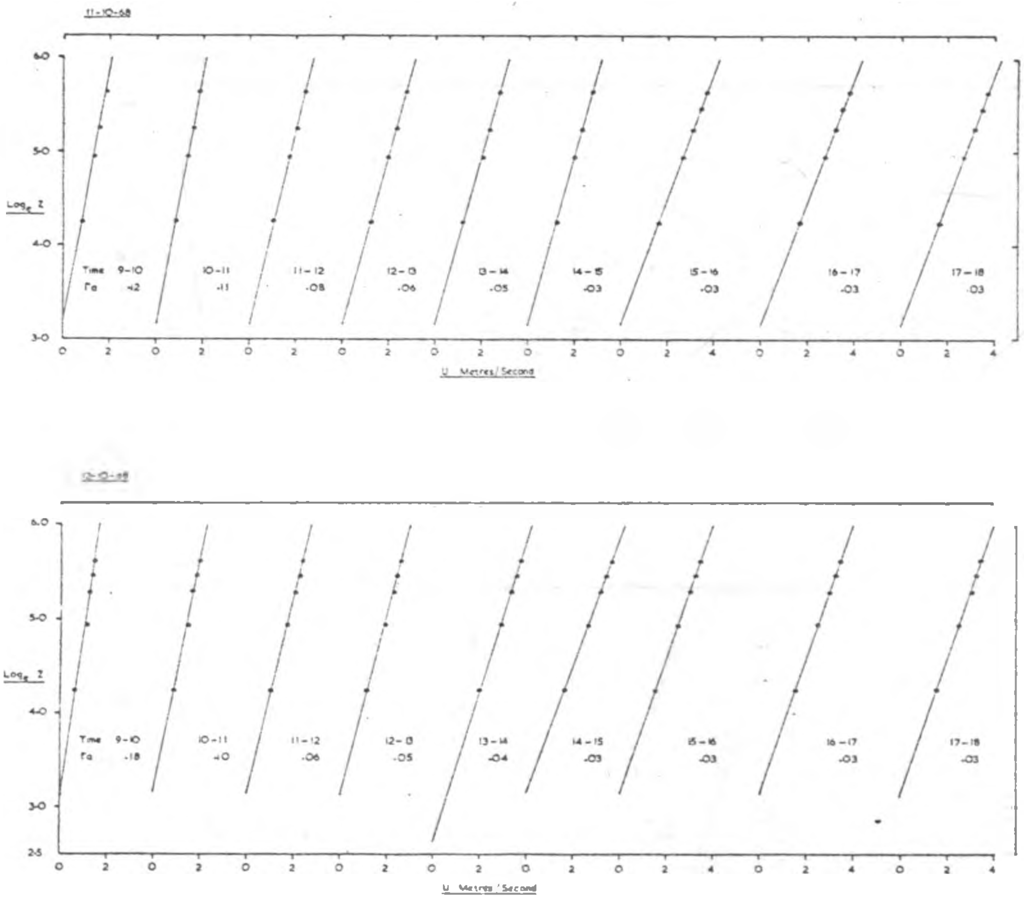
Hourly values of r_a showed a similar trend each day, decreasing gradually from 0.12 - 0.18 at 0900-1000 hours to 0.03 - 0.05 at 1700-1800 hours. These values of r_a are however much smaller than the minimum values 0.2 - 0.5 quoted by Monteith (1965), and approach 0.03 for a pine forest (Szeicz, Endrödi and Tajchman, 1969).



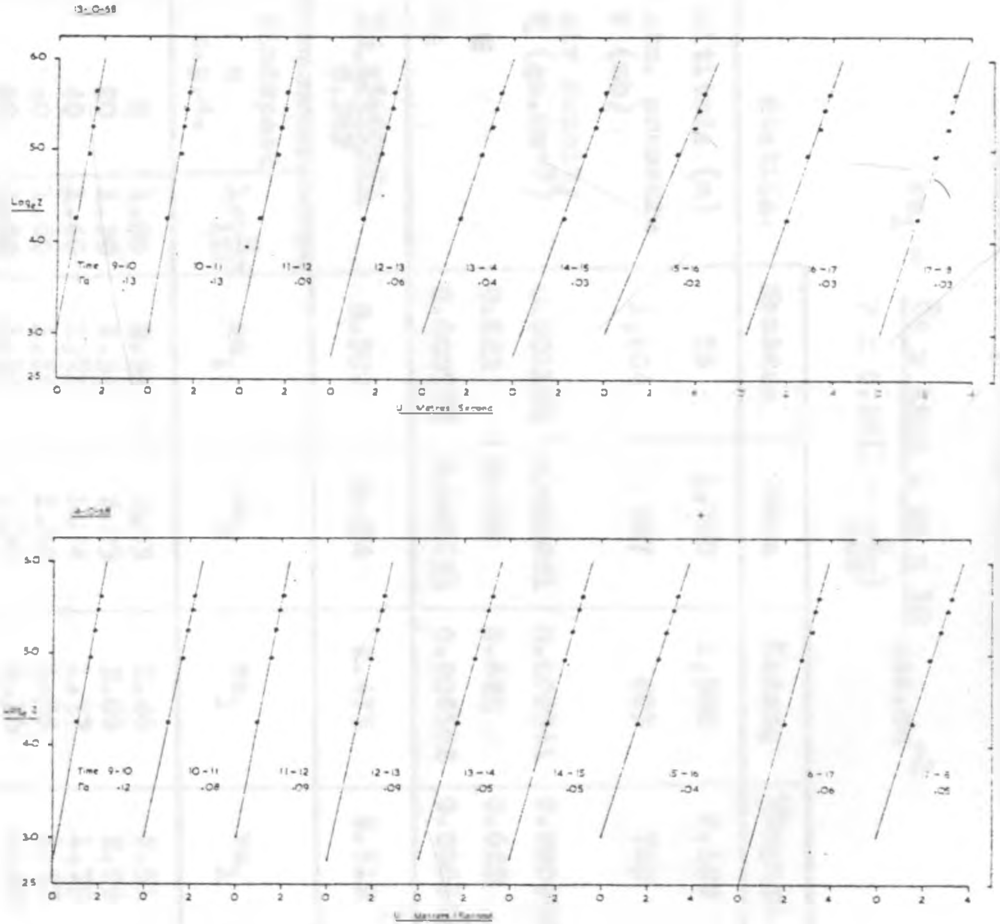
APPENDIX 9 - Fig. 9:1 Windspeed profiles above maize crop at Mwea



APPENDIX 9 - Fig. 9:2 Fitting logarithmic function on windspeed profiles above maize crop at Mwea



APPENDIX 9 - Fig. 9:3 Logarithmic windspeed profiles and determination of r_a above maize crop at Mwea



APPENDIX 9 - Fig. 9:3 (continued)

APPENDIX 10

Values of ra_1 for different wind speeds

$$ra_1 = \frac{\rho\epsilon \times 3600 \times 24 \times 10}{P \times 0.26(1 + \frac{u}{100})} \; sec.cm^{-1}$$

Station:	Mombasa	Mwea	Kedong	Muguga
Altitude (m)	55	1,280	1,900	2,100
Atm. pressure P (mb)	1,004	867	803	783
Air density ρ ($gm.cm^{-3}$)	0.001163	0.001021	0.000961	0.000952
ϵ	0.622	0.622	0.622	0.622
$\rho\epsilon$	0.000723	0.000635	0.000598	0.000592
$\frac{\rho\epsilon \times 3600 \times 24}{0.26P}$	2.392	2.434	2.475	2.512

Windspeed u m.p.d.	$1+\frac{u}{100}$	ra_1	ra_1	ra_1	ra_1
0	1.00	2.39	2.43	2.48	2.51
20	1.20	1.99	2.03	2.06	2.09
40	1.40	1.71	1.74	1.77	1.79
60	1.60	1.50	1.52	1.55	1.57
80	1.80	1.33	1.35	1.38	1.40
100	2.00	1.20	1.22	1.24	1.26
120	2.20	1.09	1.11	1.12	1.14
140	2.40	1.00	1.01	1.03	1.05
160	2.60	0.92	0.94	0.95	0.97
180	2.80	0.85	0.87	0.88	0.90

APPENDIX 11

ESTIMATE OF QUANTITY OF WATER INTERCEPTED BY MAIZE PLANTS

Method

Seventeen maize plants of different sizes were uprooted from a field crop and quickly transferred to the laboratory. The roots and first 15 cm of the stem for each plant were then inserted in a flat bottomed container and dry soil added to keep the plants upright. An open ended plastic tube was slipped over the container and tied tightly around the stem to prevent water entry into the container.

Each plant was then weighed, sprayed thoroughly with water, and shaken to remove excess water before being reweighed. This procedure was repeated until a constant maximum weight was achieved.

Results

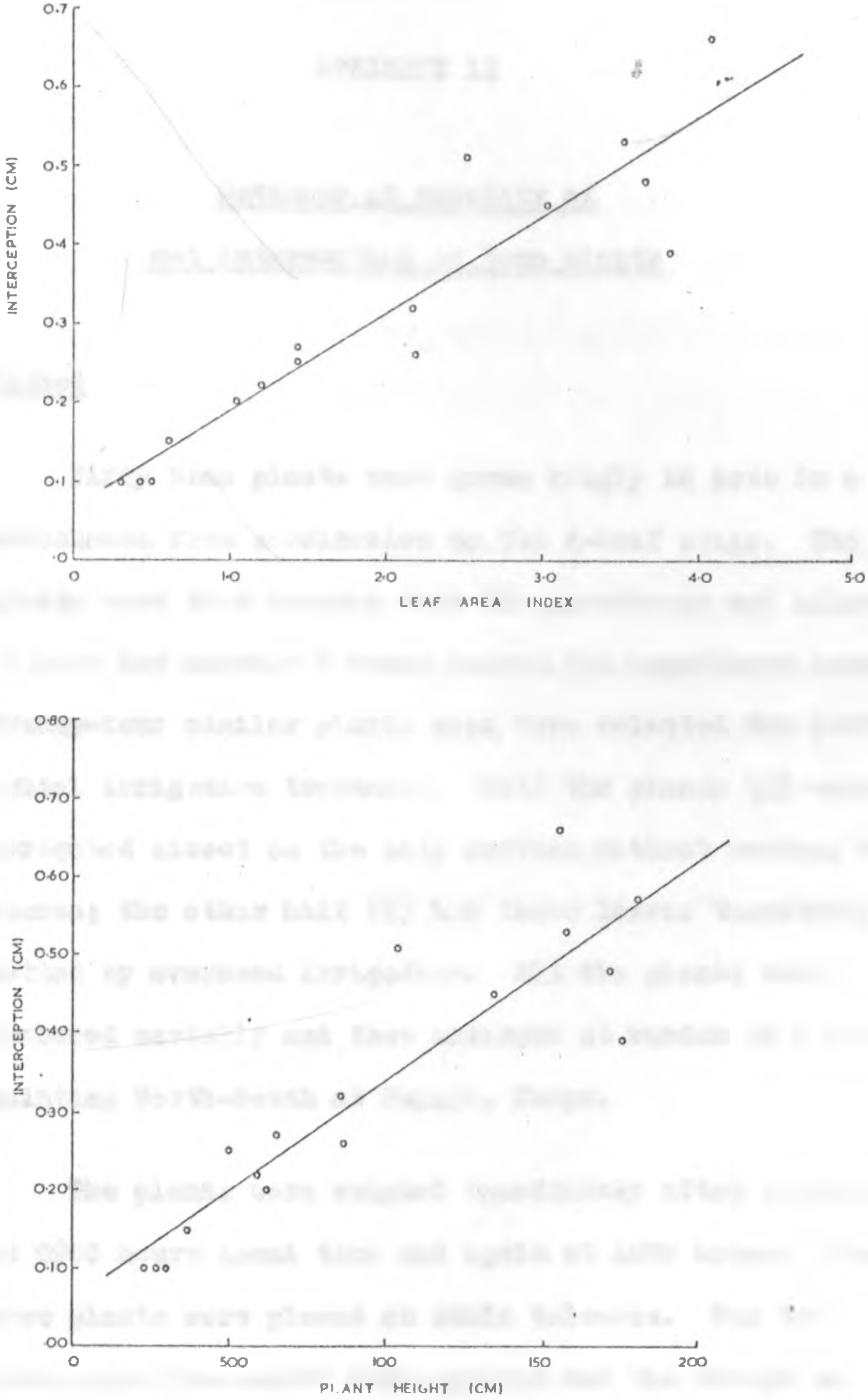
The results are plotted in Fig. 11:1 which also features the straight lines of best fit calculated from linear regression of interception on either leaf area index or height (H) of the plants. The two equations obtained are

1. Interception (cm) = 0.12 L.A.I. + 0.07, r^2 = 0.89

2. Interception (cm) = 0.003H (cm) + 0.06, r^2 = 0.82.

Comment

The y-intercepts shown in the above equations have no meaning other than that L.A.I. and H were underestimated.



APPENDIX 11 - Fig. 11:1 Net interception of water by maize plants of different sizes as functions of leaf area index and plant height

APPENDIX 12

Estimate of quantity of net interception by bean plants

Method

Fifty bean plants were grown singly in pots in a greenhouse from germination to the 4-leaf stage. The plants were then removed from the greenhouse and allowed to grow for another 2 weeks before the experiment started. Twenty-four similar plants were then selected for differential irrigation treatment. Half the plants (X) were irrigated direct on the soil surface without wetting the leaves; the other half (Y) had their leaves thoroughly wetted by overhead irrigation. All the plants were numbered serially and then arranged at random in a row pointing North-South at Muguga, Kenya.

The plants were weighed immediately after irrigation at 0900 hours local time and again at 1800 hours. Two more plants were placed on scale balances. The two irrigation treatments were applied and the change in weight of each plant was recorded once every hour.

Results

Results of these experiments are shown in Appendices 12a and 12b. The experiment with two bean plants was repeated several times, interchanging the plants between the two irrigation treatments, but the results were similar.

Evaporation from the plants with wetted leaves was significantly higher than water loss from plants irrigated direct on the soil surface, but the difference was not significant when total water loss exceeded 50 gm/plant/day.

Almost all the differences in water loss occurred in the first 1-2 hours.

APPENDIX 12a

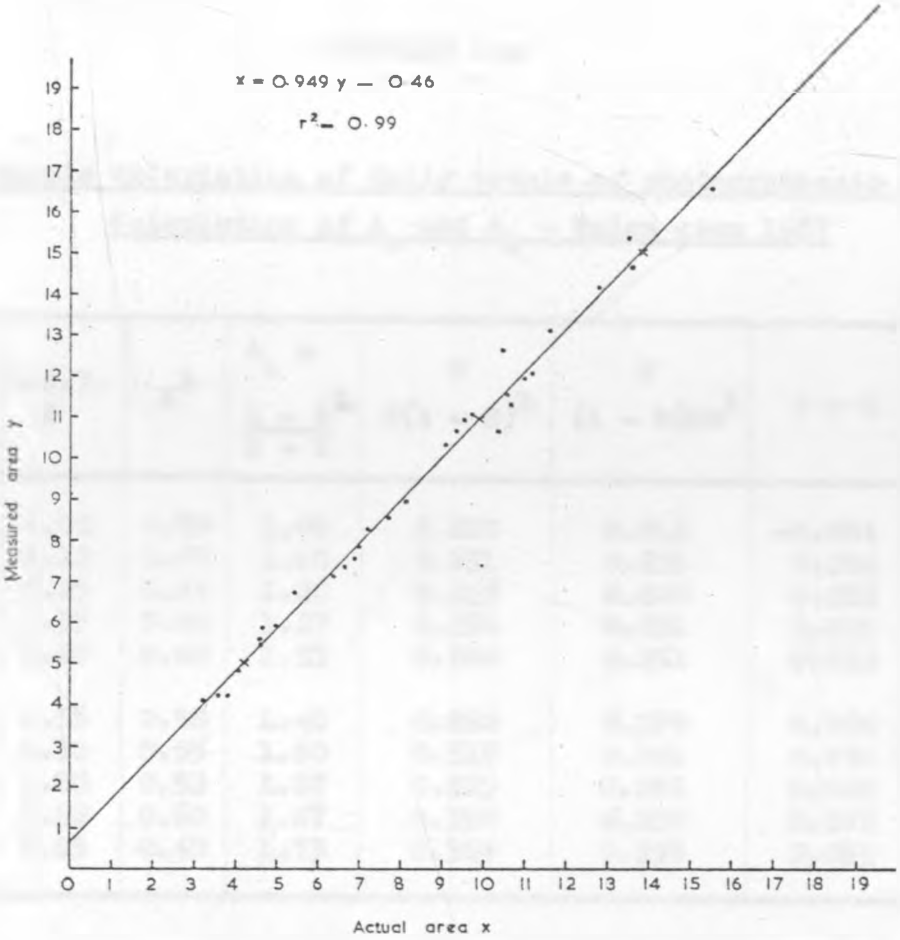
Evaporation (gm/day) from potted bean plants irrigated on soil (X) and on leaves (Y)

Plant No.	26/8/68		28/8/68		29/8/68		30/8/68		2/9/68		3/9/68	
	X	Y	X	Y	X	Y	X	Y	Y	X	Y	X
1	33.3		34.5		68.9		76.6		91.6		86.8	
2		31.2		33.4		55.2		57.8		82.9		78.3
3		42.5		33.6		51.2		43.8		65.0		58.6
4	32.6		22.9		61.1		46.1		91.8		85.2	
5	43.4		26.7		50.2		48.1		91.1		89.4	
6		46.8		35.8		72.2		59.6		82.7		89.7
7	37.0		23.0		55.6		48.5		79.5		79.5	
8	32.1		23.5		60.6		48.6		62.1		92.6	
10		43.3		35.5		55.5		59.3		58.2		78.0
11		56.6		40.8		66.8		69.0		78.8		80.9
12	36.5		29.1		53.8		51.6		91.5		90.8	
13	35.1		26.9		46.2		51.6		84.2		84.1	
14		45.0		32.2		51.2		55.4		57.1		79.5
15		30.5		25.9		42.0		46.9		84.6		80.9
16		28.7		26.7		58.8		40.8		63.6		78.3
17		39.7		33.0		50.5		45.2		82.5		77.8
18		33.5		26.2		54.2		42.4		70.0		80.7
19		40.4		28.9		64.0		46.4		84.1		78.5
20	29.2		24.0		70.8		45.0		85.9		64.0	
21	35.1		24.6		49.6		48.6		70.3		51.1	
22	42.8		22.5		76.7		48.9		69.4		86.6	
23		43.9		25.5		49.8		40.2		68.6		77.3
24		32.3		34.7		82.5		49.9		66.0		86.0
Mean of 1st 6	32.7	44.2	25.2	35.2	57.0	58.7	52.4	57.5	81.8	70.8	84.9	77.5
" " 2nd 6	34.6	36.7	25.6	29.0	59.3	57.2	47.8	45.2	77.5	74.3	75.8	80.2
Mean Y-X												
1st 6	11.5		10.0		1.7		5.1		11.0		7.4	
2nd 6	2.1		3.4		-2.1		-2.6		3.2		4.4	
	13.6		13.4		-0.4		2.5		14.2		3.0	
Significance	S		S		N.S.		N.S.		S at 2%		N.S.	

APPENDIX 12b

Evaporation from two bean plants: watered on the soil (X) and on the leaves (Y) on 3/9/68

Time hrs	Evaporation gm/hr	
	X	Y
6 - 9	14.5	63.8
9 - 10	15.7	25.2
10 - 11	5.8	12.3
11 - 12	5.0	7.7
12 - 13	11.2	8.7
13 - 14	9.5	12.6
14 - 15	12.4	10.4
15 - 16	11.9	12.5
16 - 17	9.3	11.4
17 - 18	5.1	4.5
Total	100.4	169.1



Appendix 13: calibration of the products of maximum length and width against actual leaf area for beans. All units are sq. ins.

APPENDIX 14a

Sample calculation of daily totals of photosynthesis (P_m)

Calculation of A_0 and A_1 - Maize crop 1967

Date	L.A.I. L	s^L	$A_0 = \frac{1 - s^L}{1 - s}$	B $s(1 - s)^L$	C $(1 - s)Ls^L$	B - C	$A_1 = \frac{B - C}{B}$
Oct. 1	1.02	0.70	1.00	0.210	0.214	-0.004	-0.019
" 2	1.12	0.67	1.10	0.231	0.225	0.006	0.029
" 3	1.25	0.64	1.20	0.252	0.240	0.012	0.057
" 4	1.35	0.62	1.27	0.266	0.251	0.015	0.071
" 5	1.45	0.60	1.33	0.280	0.261	0.019	0.090
" 6	1.55	0.58	1.40	0.294	0.270	0.024	0.114
" 7	1.70	0.55	1.50	0.315	0.281	0.034	0.162
" 8	1.80	0.53	1.57	0.329	0.286	0.043	0.205
" 9	1.92	0.50	1.67	0.350	0.288	0.062	0.295
" 10	2.05	0.48	1.73	0.364	0.295	0.069	0.329

APPENDIX 14 (i)

Sample calculation of daily photosynthesis (P_m)

Calculation of P_o, P_1 and hence P_m for Maize Crop 1967

$I^* = \frac{\pi R}{2h}$ cal cm^{-2}min^{-1}

$a = 0.25$

$\tau = 0.055$

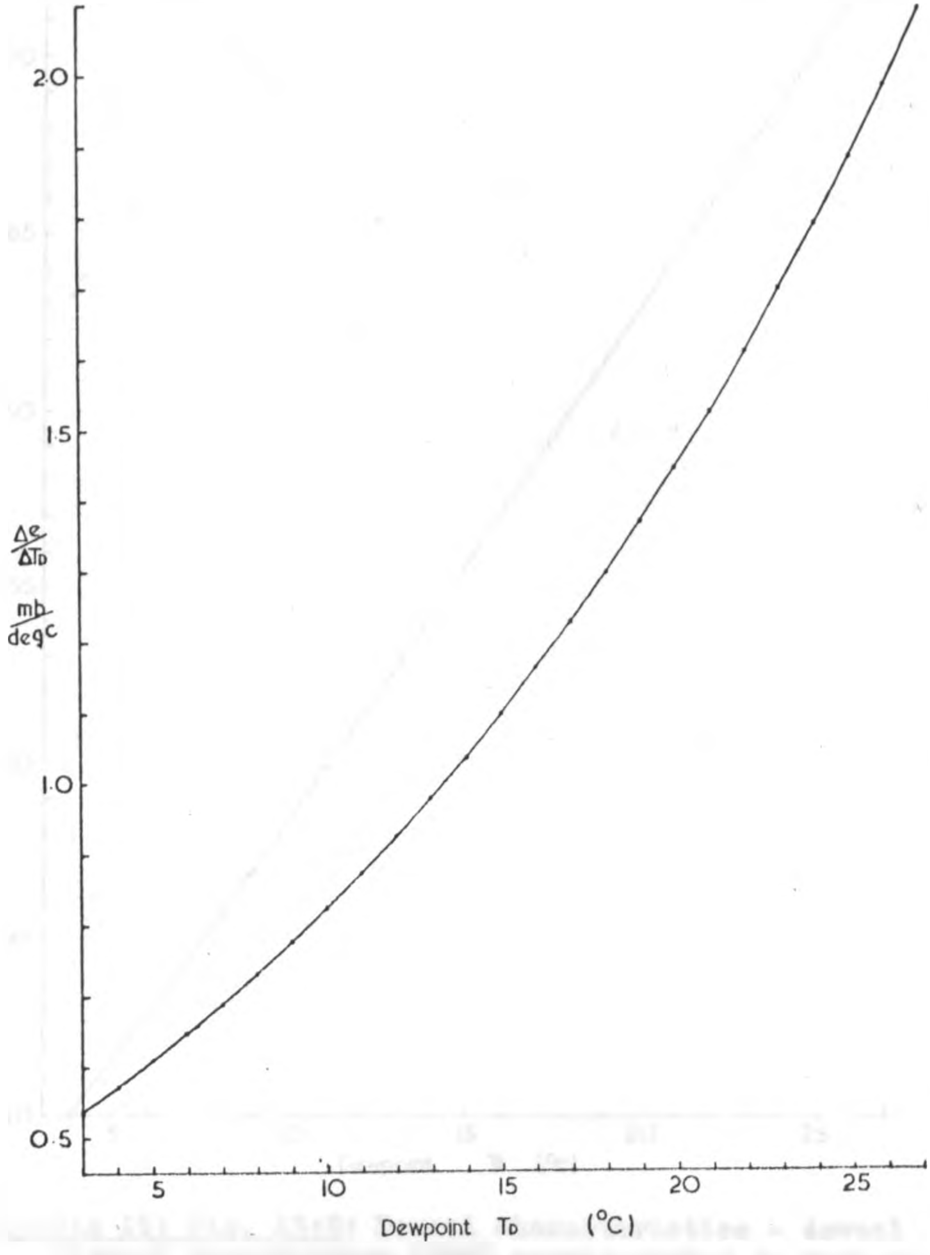
$$P_m = P_o + P_1 = \frac{h}{a}\left\{A_o\left[1 - f(\eta_o)\right] + A_1\left[1 - f(\eta_1)\right]\right\} \quad \text{gm.m}^{-2}\text{day}^{-1}$$

Date	h min.	R Ly/day	I* Ly/min.	η_o	$1 - f(\eta_o)$	A_o	$A_o[1 - f(\eta_o)]$	$\frac{h}{a \times 60}$	P_o gm.m^{-2}day^{-1}	$I^*\tau$	η_1	$1 - f(\eta_1)$	A_1	$A_1[1 - f(\eta_1)]$	P_1	$P_m = P_o + P_1$
OCTOBER																
1	726	573.8	1.24	0.32	0.51	1.00	0.510	48.4	24.68	0.07	-0.80	0.07	-0.019	-0.001	-0.06	24.62
2	726	680.0	1.47	0.37	0.54	1.10	0.594	48.4	28.75	0.08	-0.78	0.08	0.029	0.002	0.11	28.86
3	[illegible]	656.4	1.42	0.36	0.53	1.20	0.636	48.4	30.78	0.08	-0.78	0.08	0.057	0.005	0.22	31.00
4	726	591.5	1.28	0.32	0.51	1.27	0.648	48.4	31.35	0.07	-0.80	0.07	0.071	0.005	0.24	31.59
5	727	[illegible]	1.49	0.39	0.54	1.33	0.718	48.5	34.76	0.08	-0.78	0.08	0.090	0.007	0.35	35.11
6	727	508.9	1.10	0.27	0.48	1.40	0.672	48.5	32.52	0.06	-0.83	0.06	0.114	0.007	0.33	32.85
7	727	612.1	1.32	0.34	0.52	1.50	0.780	48.5	37.75	0.07	-0.80	0.07	0.162	0.011	0.55	38.30
8	727	668.2	1.44	0.36	0.53	1.57	0.832	48.5	40.27	0.08	-0.78	0.08	0.205	0.016	0.79	41.06
9	727	615.1	1.33	0.34	0.52	1.67	0.868	48.5	42.03	0.07	-0.80	0.07	0.295	0.021	1.00	43.03
10	727	638.7	1.38	0.36	0.53	1.73	0.917	48.5	44.38	0.08	-0.78	0.08	0.329	0.026	1.27	45.65

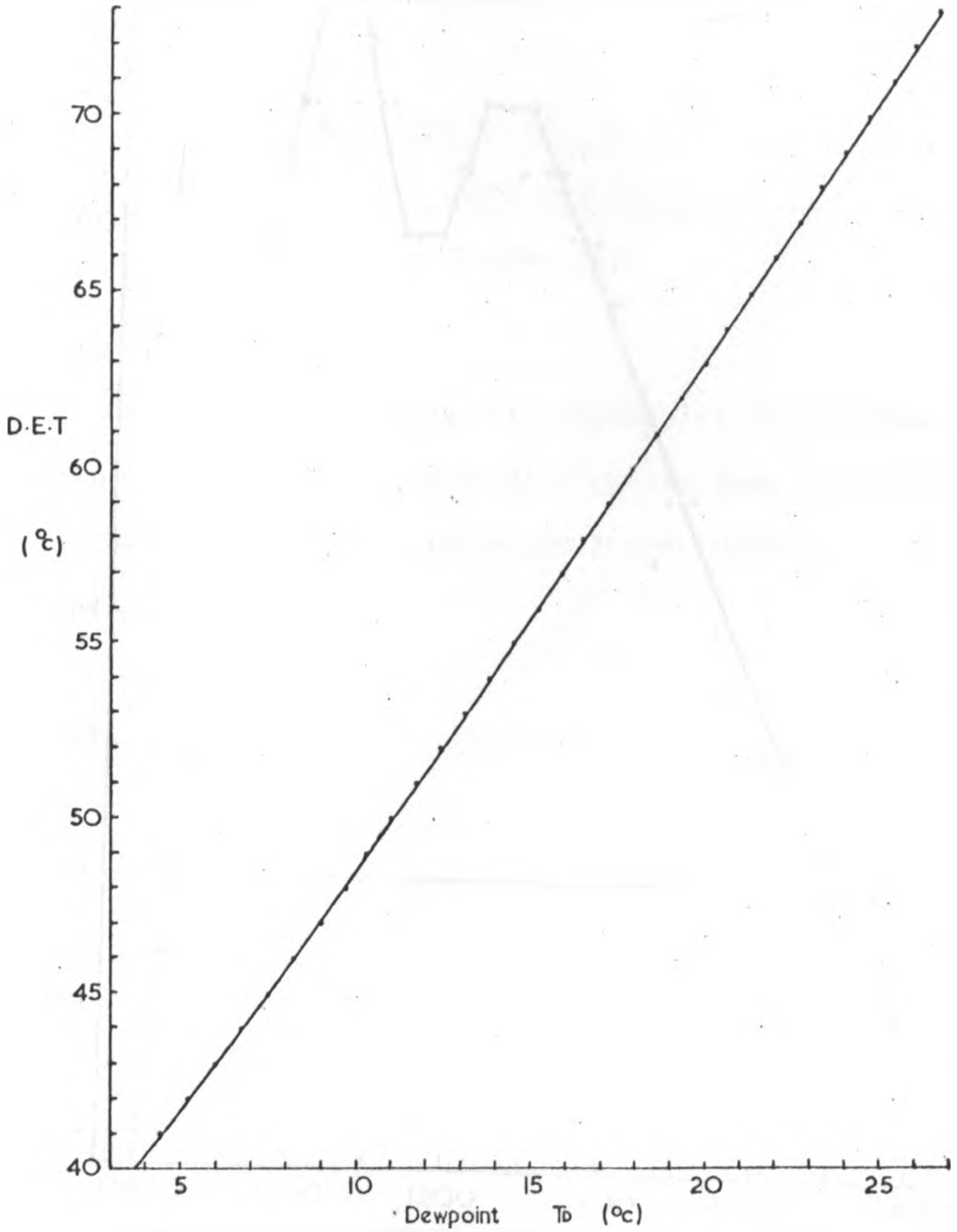
APPENDIX 15

Computation of vapour pressure gradient (de), from mean dewpoint (T_D) and the differences in dewcel element temperatures (DET):

By entering Figs. 15:1 and 15:2 with the mean dewpoing temp. T_D, values of $\frac{\Delta e}{\Delta T_D}$ and $\frac{\Delta DET}{\Delta T_D}$ were obtained. A table of values of $\frac{\Delta e}{\Delta DET}$ for different values of T_D was then constructed.

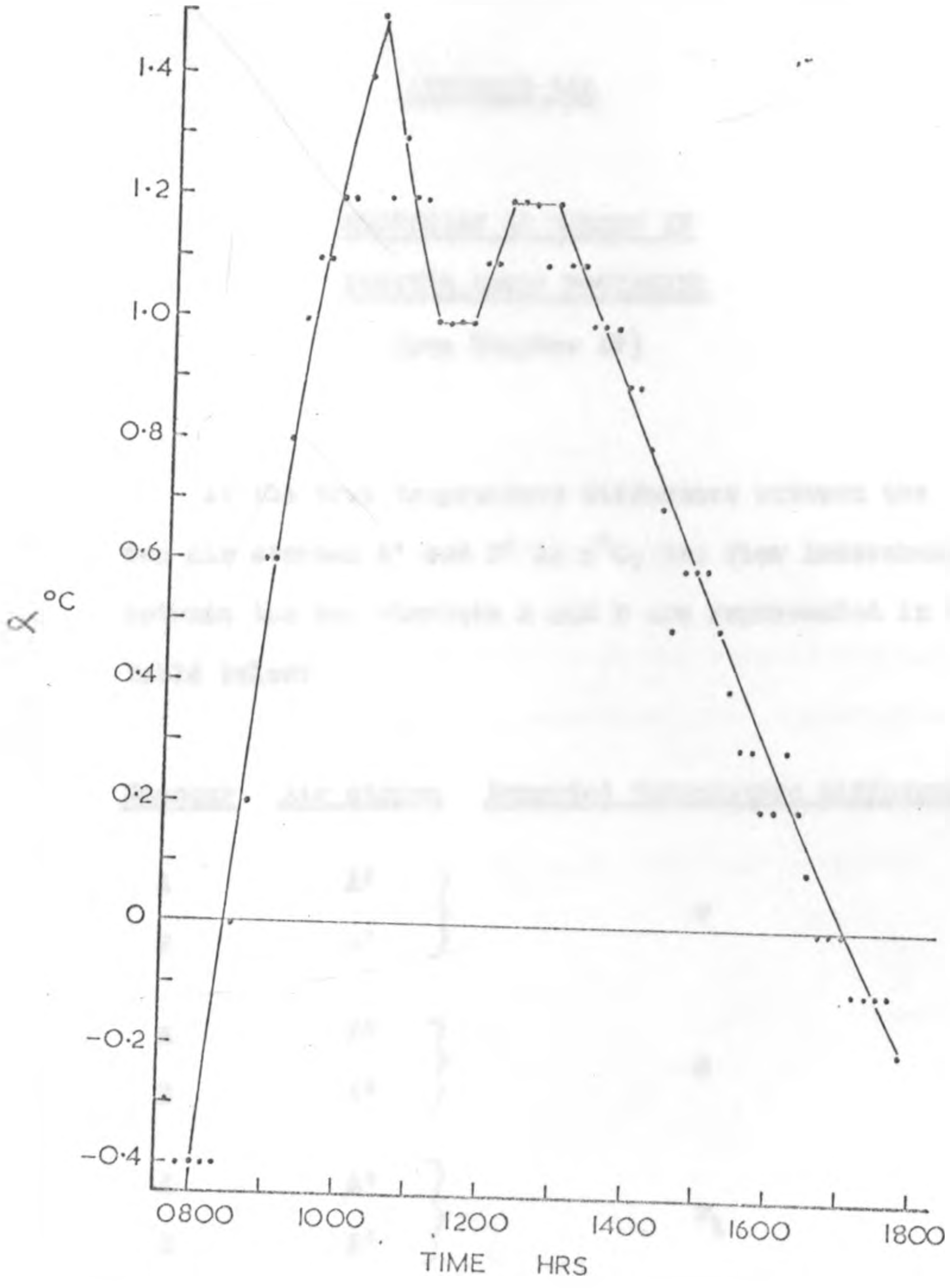


Appendix 15: Fig. 15:1 The ratio of vapour pressure to dewpoint gradients $\frac{\Delta e}{\Delta T_D}$ at different dewpoint temperatures.



Appendix 15: Fig. 15:2: Dewcel characteristics - dewcel element temperatures (DET) corresponding to various despoint temperatures (T_D).

APPENDIX 16a



APPENDIX 16a: Variation of absolute temperature difference α between the two thermocouple champers in Bowen's Ratio equipment

APPENDIX 16b

REDUCTION OF ERRORS IN BOWEN'S RATIO EQUIPMENT

(see Chapter IV)

If the true temperature difference between the two air streams A' and B' is x°C, two flow interchanges between the two chambers A and B are represented in the table below:

Chamber	Air stream	Recorded temperature difference
A	A'	r
B	B'	
A	B'	s
B	A'	
A	A'	r_1
B	B'	

For the three situations,

$$r = \beta + \alpha_r + x \qquad \text{.....(1)}$$

$$g = \beta + \alpha_g + x \qquad \text{.....(2)}$$

$$r_1 = \beta + \alpha_{r_1} + x \qquad \text{.....(3)}$$

from which it can be shown that

$$\tfrac{1}{2}\left\{\frac{r - g}{2} + \frac{r_1 - g}{2}\right\} = x + \tfrac{1}{2}\left\{(\alpha_r + \alpha_{r_1}) - 2\alpha_g\right\} \qquad \text{.....(4)}$$

and the same argument applies in the case of humidity measured as difference in dewcel element temperature (D.E.T.).

If α changes linearly with time (see Appendix 16a),

$$\alpha_r - \alpha_{r_1} = \alpha_{r_1} - \alpha_g \qquad \text{.....(5)}$$

giving

$$\tfrac{1}{2}(\alpha_r + \alpha_{r_1}) = 2\alpha_g \qquad \text{.....(6)}$$

and therefore

$$\varkappa = \frac{1}{t}\left\{\frac{r - g}{2} + \frac{r_1 - g}{2}\right\} \qquad \text{.....(7)}$$

This procedure does therefore considerably reduce the error in the determination of , the error increasing slowly as the increase in with time departs from linearity.

APPENDIX 17

Sample calculation of Bowen's Ratio β

STATION: Mwea
SURFACE: Bean crop
SURFACE CONDITION: Pods filling, complete ground cover

DATE: 7th May, 1968
NOZZLE HEIGHT ABOVE CROP: Upper: 70 cm.
Lower: 20 cm.

$$A = \tfrac{1}{2}\left\{\frac{(g-r)}{2} + \frac{g_1-r}{2}\right\} \qquad A_1 = \tfrac{1}{2}\left\{\frac{(r-g)}{2} + \left(\frac{r_1-g}{2}\right)\right\} \qquad r = 0.60$$

Flow setting	10-minute period starting hrs.	d(D.E.T.) °C.			$\frac{de}{d(D.E.T.)}$	de mb.	dT °C.			$\frac{dT}{de}$	$\beta = \gamma \frac{dT}{de}$	$1+\beta$
		chart reading	$\frac{1}{2}(g-r)$	A			chart reading	$\frac{1}{2}(r-g)$	$A_1=dT$			
g	0900	4.35	-0.01	0.13	0.892	0.12	-0.15	0.01	0.03	0.25	0.15	1.15
r	0910	4.37	0.28	0.27	0.892	0.24	-0.14	0.04	0.05	0.21	0.13	1.13
g	0920	4.92	0.27	0.32	0.902	0.29	-0.21	0.05	0.06	0.21	0.13	1.13
r	0930	4.38	0.36	0.29	0.888	0.26	-0.12	0.07	0.04	0.15	0.09	1.09
g	0940	5.09	0.21	0.25	0.888	0.22	-0.25	0.01	0.02	0.09	0.05	1.05
r	0950	4.67	0.28	0.29	0.888	0.26	-0.24	0.02	0.02	0.08	0.05	1.05
										hourly mean:		1.10
g	1000	5.22	0.29	0.31	0.888	0.28	-0.27	0.02	0.02	0.07	0.04	1.04
r	1010	4.65	0.32	0.29	0.897	0.26	-0.24	0.02	0.01	0.04	0.02	1.02
g	1020	5.28	0.25	0.27	0.892	0.24	-0.24	0.00	0.01	0.04	0.02	1.02
r	1030	4.78	0.29	0.30	0.892	0.27	-0.23	0.01	0.02	0.07	0.04	1.04
g	1040	5.35	0.30	0.29	0.902	0.26	-0.20	0.02	-0.01	-0.04	-0.02	0.98
r	1050	4.75	0.27	0.28	0.892	0.25	-0.16	-0.03	-0.01	-0.04	-0.02	0.98
										hourly mean:		1.01
g	1100	5.28	0.29				-0.10	0.01				
r	1110	4.70					-0.08					

APPENDIX 18

Energy storage in photosynthesis

(a) Maize crop 1967

Period (days from germination)	Increase in dry matter ΔM gm/m^2	A Energy equivalent K.cal./m^2	Total shortwave radiation K.cal./m^2	B Total radiation 0.4 - 0.7μ K.cal./m^2	$\frac{A}{B}$
0-17	15	62	90,080	42,338	0.002
17-32	91	374	92,820	43,625	0.008
32-46	230	955	83,830	39,400	0.024
46-52	321	1,332	26,700	12,549	0.106
52-59	232	963	36,650	17,226	0.056
59-73	537	2,229	71,320	33,520	0.067
73-81	134	556	47,780	22,457	0.025
81-94	336	1,394	64,310	30,226	0.046
94-102	216	896	50,490	23,730	0.038
102-111	136	564	56,800	26,696	0.021

(b) Bean crop 1968

Period (days from germination)	Increase in dry matter ΔM gm/m^2	A Energy equivalent K.cal./m^2	Total shortwave radiation K.cal./m^2	B Total radiation 0.4 - 0.7μ K.cal./m^2	$\frac{A}{B}$
5-9	4	17	24,370	11,454	0.001
9-12	3	12	20,130	9,461	0.001
12-16	23	95	18,780	8,827	0.011
16-23	8	33	34,640	16,281	0.002
23-27	14	58	24,930	11,717	0.005
27-43	162	672	77,410	36,383	0.018
43-48	60	249	24,430	11,482	0.022
48-54	20	83	27,320	12,840	0.006
54-58	16	66	21,860	10,274	0.006
58-65	85	353	39,170	18,410	0.019

APPENDIX 18 (continued)

(c) Maize crop 1968

Period (days from germination)	Increase in dry matter Δ W gm/m²			Energy equivalent (A) K.cal./m²			Total shortwave radiation K.cal./m²	B Total radiation 0.4 - 0.7μ K.cal./m²	A/B		
	Wet	Medium	Dry	Wet	Medium	Dry			Wet	Medium	Dry
24-29	20	7	8	83	29	33	11,990	5,635	0.015	0.005	0.006
29-36	66	52	20	274	216	83	24,710	11,614	0.024	0.019	0.007
36-44	67	61	89	278	253	369	51,200	24,064	0.012	0.011	0.015
44-50	288	256	132	1,195	1,062	548	31,740	14,918	0.080	0.071	0.037
50-58	59	109	115	245	452	477	43,750	20.563	0.012	0.022	0.023
58-65	306	114	49	1,270	473	203	44,660	20,990	0.061	0.023	0.010
65-72	380	342	475	1,577	1,419	1,971	45,310	21,296	0.074	0.067	0.093
72-84	92	272	120	382	1,129	498	75,450	35,462	0.011	0.032	0.014
84-100	496	465	616	2,058	1,930	2,556	81,180	38,155	0.054	0.051	0.067
100-119	640	321	201	2,656	1,332	834	97,270	45,717	0.043	0.029	0.018
119-130		305	354		1,266	1,469	38,880	18,274		0.069	0.080