MEASUREMENT OF SOIL WATER EVAPORATION USING MICROLYSIMETERS OF DIFFERENT SIZES: EFFECT OF SHADE AND SOIL TEXTURE

BY

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A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN SOIL SCIENCE AND LAND MANAGEMENT OF SOKOINE UNIVERSITY OF AGRICULTURE

1996

ABSTRACT

The effect of soil texture and shade on soil water evaporation using microlysimeters of different sizes was investigated. The rate of evaporation from the different sized microlysimeters was studied to see which evaporates the most. The days after irrigation were monitored to see if evaporation would increase or decrease. The effect of the depth of the microlysimeters was also studied to find out which depth evaporates more between the shallow depth microlysimeters (SDM) (10 cm), and the deeper depth microlysimeters (DDM) (20 cm). Two periods of the day, morning period (MP) and afternoon period (AP) were also studied to determine which one had more evaporation.

The study, which was conducted from October to December 1994, was carried out in two sites with contrasting soils viz; (a) Ismani, in Iringa region selected for its clayey soils, and (b) Hombolo, in Dodoma region which had sandy soils.

For the experiment, two plots were used, one shaded and the other unshaded. Shading was obtained by using a shade screen (a black net) which provided a shade of about 50 per cent. Sixty mm of irrigation water was applied on both plots at the same time.

Results show that sandy soils evaporated significantly ($P<0.05$) more water, up to about 20 per cent, than clayey soils. Shading significantly ($P<0.05$) reduced evaporation by 5 to 10 per cent.

The 10 cm diameter microlysimeters lost more water than the 5 cm diameter ones. This was prominent in clayey soils ($P<0.05$) than in the sandy soils, at the initiation of the experiment. However, towards the end of the study the difference was reduced.

It was also observed that evaporation significantly decreased as the soil progressively dried after irrigation. The second day's evaporation was reduced by almost 50 per cent. The rest of the days' evaporation was steady at about 10 to 20 per cent of the first day. There was no significant difference between the SDM and DDM. It seems depth (10-20 cm) does not significantly affect evaporation. The periods of the day showed some significant difference. In clayey soils significantly ($P<0.05$) more water was lost in the MP than in the AP. However, the reverse was true for the sandy soils.

DECLARATION

I, STEPHEN PHUZ'UKUVELA MASEKO, do hereby declare to the Senate of the Sokoine University of Agriculture that this dissertation is my original work and has never been submitted for a degree in any other University.

Date...13/11/96.......   Signature..........................

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ACKNOWLEDGEMENTS

I would like to thank the following organizations and people:

The Norwegian Agency for Development Cooperation (NORAD), through the Department of Soil Science (Sokoine University of Agriculture), for their financial support.

The Seedbed Physical Properties and Crop Establishment project (NRI project EMC X0237) coordinated by the University of Aberdeen, UK in collaboration with Sokoine University of Agriculture, Tanzania and the University of Reading, UK for their support with equipment during data collection.

The government of the Kingdom of Swaziland (Ministry of Education) for granting me a study leave.

The Department of Soil Science and the entire SUA community for being supportive during my stay in Tanzania.

The post graduate studentry, particularly my classmates, who kept me going in the 24 months of my stay in SUA. Dr. Wambura (MVM student) for his assistance during data analysis.

Alice Ambrose Ottaru for assisting during the plot establishment in Ismani.

Hamidou Idrissa for his everlasting support and encouragement during my entire period of stay in Tanzania, not to mention Bongani Magongo for his ever present comments during the final write up as well as Noah Dlamini.

Bukhosi, my son, for the bravery he showed in my 24 months of absence, my daughter, Mbali for suffering the effort without complaint, if not entirely in silence.

My parents and the rest of the family who are my source of inspiration.

Lastly, I am deeply indebted to Dr. Peter W. Mtakwa, my supervisor. He undertook the unenviable task of guiding me from the initiation of the study, to the final write up of the thesis. His constructive criticisms and suggestions motivated me to work harder. I am sure without his support, encouragement, understanding and care I would not have made it. He, really, is a father to me and I say *Mzee* Mtakwa, *asante sana* (thank you very much).

DEDICATION

In memory of my late wife (Thembayena), whose silent presence guided my efforts.

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LIST OF ABBREVIATIONS

MP	Morning period
AP	Afternoon period
LAM	Large area microlysimeter (10 cm diameter)
SAM	Small area microlysimeter (5 cm diameter)
SDM	Shallow depth microlysimeter (10 cm)
DDM	Deep depth microlysimeter (20 cm)

CHAPTER 1

INTRODUCTION

1.1 Introductory information

Evaporation of water from bare soils is the process by which moisture stored in the upper layer of the soil (i.e. near the soil surface) due to precipitation, irrigation, or uplift by capillary action is returned to the atmosphere (Sadeghi *et al.*, 1984).

Evaporation in the field usually takes place from plant canopies and from the soil surface. Evaporation from plants, called *transpiration,* is the principal mechanism of soil water transfer to the atmosphere when the soil surface is covered with vegetation (Hillel, 1980). In the absence of vegetation, evaporation occurs directly and entirely from the soil. Generally, transpiration and evaporation occur concurrently and are commonly referred to as *evapotranspiration* (Hillel, 1971).

Loss of water by direct evaporation from the soil surface is a serious problem in arid regions. This is because arid regions receive little precipitation. Sadeghi *et al.* (1984) reported that in moisture deficient (arid) regions of the world the loss of water through evaporation has been estimated to be 60% of the total amount received by soil.

Evapotranspiration measurements are useful in predicting the frequency and severity of drought. They are also used in models in order to predict production in arid and semi-arid regions. There are many methods used to measure evaporation ranging from hydraulic to meteorological methods (Taylor and Ashcroft, 1972; Peterschmitt and Perrier, 1991). The methods include the evaporimeter technique (Walker, 1984), aerodynamic method, the Bowen ratio method (Vogt and Jaeger, 1990), and the atmometer method (Giambelluca *et al.*, 1992). Recently, the use of lysimeters to measure evaporation has gained importance (Reicosky *et al.*,1983; Bernhofer, 1992).

This study compared evaporation rates measured by small lysimeters (microlysimeters) of four different sizes. The intention was to evaluate the possibility of adopting the smaller diameter microlysimeters since they are less destructive to soil because they disturb a smaller area of study.

1.2 Importance of evaporation

The rate of evaporation or the amount of water turned to aqueous vapour in a day, month or season by natural meteorological processes is important in many branches of research. The hydrologist is interested in the loss of water from streams, lakes, canals and reservoirs. Such information is necessary in order that storage capacities, amount of available water, and size of distribution systems can be designed efficiently.

The irrigation engineer, besides having the same interest in evaporation as the hydrologist, is also interested in the rate at which water is used by crops and lost from the land surface. This is necessary so that irrigation canals and channels can be properly designed and water applied to the land in the correct amount at the right time. The forester is interested in evaporation from the standpoint of drying of fuel (wood, tuff and grass) for estimating potential forest fire hazards (Robertson, 1970). The plant pathologist is interested from the point of view of drying plant surfaces to check the spread of certain diseases which incubate and multiply in liquid water. The agronomist is interested in water loss from land as affected by different cultural practices. The plant physiologist and the botanist are interested in transpiration rates, i.e. loss of moisture from plants through their stomata, in relation to plant growth. Other branches of science interested in evaporation data include medicine, geography, climatology and certain branches of engineering. Each has a specific problem in evaporation, but all are interested in one thing: the rate at which water leaves its container, whether it be a lake, a plant cell, or a soil pore, and is carried off in the form of vapour (Robertson, 1970).

1.3 Hypothesis

The extent to which ground cover (shading) reduces evaporation depends strongly on the soil texture and type of cover. On sandy soils, shading is expected to have much less effect than on finer textured soils because of the tendency of sandy soils to form a "mulching" layer at the soil surface.

The effect of shading and soil hydrological properties can be predicted using water evaporation data from microlysimeters. Standard microlysimeters (10 cm diameter by 10 cm depth) (Daamen *et al.*, 1993) would be expected to have different evaporation rates from smaller microlysimeters of, say, 5 cm diameter by 10 cm depth.

So the hypotheses are as follows:

1) Shade and soil texture have an effect on evaporation

2) There is a significant difference in evaporation between 10 cm diameter and 5 cm diameter microlysimeters.

1.4 Justification

Direct evaporation of water from the soil is an important process in crop production and can be a major component of the water budget on a farm and in areas of rainfed agriculture (Hanks and Ashcroft, 1980; Verma and Deo, 1993). It is, therefore, important to measure it.

Crop management might have an important impact on evaporation through altering the extent to which the soil surface is shaded by the crop canopy or crop residues. Shading is a practice done in nurseries to reduce excess water loss. However, the extent to which ground cover (shading) reduces evaporation depends strongly on soil texture, rainfall distribution and the type of cover. Yet data on the effect of soil texture on evaporation is still inconclusive as shown by many authors (Gupta and Ranade, 1987; Parton *et al.*, 1981; Nath and Singh, 1984 and Vossen, 1990).

Another important aspect of evaporation is the measuring devices. In many instances the measuring of the effects of shade and soil texture on evaporation has been done using expensive devices e.g. large lysimeters. Little sustained attention has been given to economical devices for measuring the effects of shade and texture. Such devices should, additionally, cause minimal disturbance to the soil during the study. It was against this background that the study is undertaken. The study used a simple microlysimeter method for monitoring evaporation from bare soils, using a shade screen (a net) to vary the radiation regime. Microlysimeters can generate a large amount of data within a small area and within a short period of time which is essential for modelling. It is essential, therefore, to find the smallest convenient and yet reliable microlysimeters.

1.5 Objectives

The study was undertaken:

1. To study the impact of soil texture on evaporation.

2. To study the effect of shade on evaporation.

3. To compare evaporation rates of microlysimeters of different sizes as influenced by soil texture and shade.

4. To monitor evaporation for periods of 8 consecutive days following rain or irrigation in order to determine whether evaporation rate differences persist.

CHAPTER 2

LITERATURE REVIEW

In computing water balances, whether for large or small areas, a major component in the water balance equation is evaporation. In recent years there has been an increasing interest in water balance in both planning studies and in the practical problems of making the best use of available water (Hounam, 1971).

The term "evaporation" is used in a wide sense to describe the movement of water vapour from a surface into the atmosphere (Robertson, 1970; Weisner, 1979). In this definition the term "surface" can include the surface of an evaporation pan, lake, a leaf or soil (Robertson, 1970). The physical process of evaporation is similar in each case, the difference being in the availability of water and the diffusive resistance in the pathway from the water surface to the atmosphere. In soils, the latter is controlled by the movement of water from other regions of the soil to where active evaporation is taking place (Weisner, 1979).

For most practical uses evaporation implies a rate. Thus measurements of evaporation are expressed as centimetres, cubic centimetres, or inches of water per hour, day, month or year. The rate of evaporation influences the time of seeding, scheduling of irrigation, herbicide and pesticide application and tillage practices (Sadeghi *et al.*, 1984).

2.1 Phases of evaporation

There are three distinct phases of evaporation from the soil surface. The phases occur because of the three conditions necessary for evaporation to persist. The first stage is the loss of water from the soil surface at a rate equal to the atmospheric demand. In this stage, there must be a continuous supply of energy to meet the latent heat requirement. During the second stage a rapid decline in evaporation rate occurs due to drying of the surface. In this stage, the intrinsic soil factors such as surface soil mosture, formation of surface hard cap, govern the rate of the moisture movement to the soil surface. There must also be a vapour pressure gradient between the surface and the atmosphere. In the third stage of evaporation, the rate of water loss is slow. This stage predominates after the moisture content in the soil has become relatively low (Sadeghi *et al.*, 1984).

2.2 Factors affecting soil evaporation

The nature of the local climate and soil conditions characterizes the amount of water loss in any given area. Hence, the rate of evaporation varies with soil texture, soil cover, soil wetness, relative humidity, wind velocity, temperature and radiation.

2.2.1 Influence of soil texture on evaporation

The available data on the effect of soil texture on evaporation are inconclusive. Weisner (1979) observed that soils which drain freely (e.g. sandy soils) reduce the amount of water available for evaporation at the surface and show less moisture losses due to less capillary action because of larger pores. He suggested that finer grained soils, such as silts, exhibit more water evaporation because they allow water to move more easily by capillary action. In the heavy clay soils, cracking facilitates evaporation along the cracked surfaces. Fine grained soils generally have more water available per centimetre depth and so can be expected to lose more by evaporation (Parton *et al.*, 1981). Gupta and Ranade (1987) found that clayey soils (primarily vertisols) lost more water than sandy soils (by 28 to 55%) through evaporation. The rate of drying and the degree of volume changes in soil significantly depended on the content and type of clay and cations present. Yet, in Botswana, bare sandy soils showed significantly higher evaporation rates when compared with fine textured soils (Vossen, 1990). Also Nath and Singh (1984) found that sand, sandy loam and sandy clay loam soils evaporated more water than their clay and silt counterparts. This was attributed to sand's inability to easily form a crust which reduces surface evaporation. So it is important to do more studies on the effect of soil texture on evaporation.

2.2.2 Influence of soil cover (shade) on evaporation

Shade reduces evaporation although shade provided by plants may increase water loss through transpiration (Weisner, 1979). However, transpiration is essential for dry matter production. Shelter (shade) in the form of windbreaks is reported to have improved the microclimate in a protected area by decreasing water evaporation from soil (Ramachandran Nait, 1993). Smika (1983) demonstrated that shade in the form of standing wheat was more effective than flattened residue for reducing evaporation from the soil surface.

Allen (1990) suggested that the enhanced early growth of well fertilized plants restricts evaporative loss from the soil surface. This improves the water-use efficiency by decreasing the ratio of evaporation from the soil to transpiration.

Hanson and Rauzi (1977) observed that class A pan evaporation was reduced by 14% when the pan was placed under the shade. Judd and McAneney (1984) had the same observation on tamarillos, *Cyphomandra betacea*. Strong evidence of evaporation reduction due to reduced radiation under kiwi fruit plants was also recorded by McAneney *et al.* (1992). Hence, shade seems to reduce evaporation. It will be interesting to see whether there is a soil texture-shade interaction on evaporation.

2.2.3 Influence of soil wetness on evaporation

In saturated soils (e.g. on irrigated areas) evaporation takes place at nearly the same rate as in a free water surface (e.g. a pond, lake) (Hounam, 1971). With a saturated soil surface, the solar energy is available for evaporation instead of warming the soil (Robertson, 1970). Some workers have observed that evaporation rate at the period immediately after rainfall or irrigation occurs at a rate close to the potential rate i.e. evaporation occurs at the rate of an open reservoir e.g. lake, dam or sea (Stewart, 1984). But Paruelo *et al.* (1991) reported that the amount of water lost by evaporation increases with dry weather and in arid zones, it can account for up to 50% or more of total precipitation. For Sahelian grasslands, evaporation accounts for more than 80% of the water lost by evapotranspiration.

2.2.4 Turbidity of water and evaporation

The rate of evaporation of water is also influenced by the turbidity of water. The suspended particles of silt reflect back heat rays, resulting in less temperature rise of water. This results in less evaporation. Thus the greater the turbidity of water the less the evaporation (Jackson, 1989). Linacre *et al.*(1970) found that a swamp evaporated less water compared to a lake. The lower evaporation in the swamp was attributed to the lower albedo of the clear water surface of the lake, compared to the shelter given by the reeds in the swamp to the water surface and the internal resistance to water movement of the reeds themselves (Linacre *et al.*, 1970).

2.2.5 Effect of relative humidity on evaporation

The rate of evaporation is inversely proportional to the relative humidity. The greater the relative humidity in the atmosphere, the less will be the evaporation (Stewart, 1984; Seymour and Hsiao, 1984). The humidity of the air and the other atmospheric factors influencing the vapour pressure gradient are equally important. If there is no air movement, air contacting the evaporating surface would soon become saturated. This reduces evaporation (Luxmore *et al.*, 1981; Jackson, 1989).

2.2.6 Wind speed and evaporation

Wind results in the movement of fresh air bringing it into contact with the moist surface. Within one mm of the soil surface, upward movement of individual water molecules (molecular diffusion) is important. Above this, turbulent air movement (eddy diffusion) takes over. Turbulence varies with the vertical windspeed gradient. Spatial variations in these meteorological factors, particularly in areas of rugged relief and cloud cover, their influence on solar radiation may create considerable differences in evaporation (Jackson, 1989).

The rate of evaporation is directly proportional to wind velocity. If the velocity of air contacting the water surface is high, the saturated film of air containing water vapour will be removed rapidly causing increased rates of diffusion and dispersion of vapour. This causes greater evaporation (Stewart, 1984).

Reduced evaporation was observed in a field under stubble (standing stalk) compared to the bare soil of another field without stubble (Enz *et al.*, 1988). This was attributed to reduced windspeed and associated turbulent exchange with the standing stubble (Capro *et al.*, 1985; Heilman *et al.*, 1992). Frequently, shelterbelts and windbreaks are used primarily to reduce evaporation by reducing windspeed (Sidmore and Hager, 1970). Evaporation percentages are reduced less than wind speed percentages by shelterbelts. In fact, evaporation occasionally increases in sheltered areas. Sidmore and Hager (1970) reported that evaporation was less in the open wind than on the leeside of a solid barrier, which they ascribed to greater turbulence behind the barrier. Wind velocity can also affect the evaporation rate because wind is generally associated with movement of fresh, unsaturated air which will absorb the available moisture, a process called *advection* (Barry and Chorley, 1982). Advection of energy by air from outside the wet area may greatly increase evaporative demand. In arid and semi-arid regions, considerable energy may be advected from surrounding dry areas over irrigated zones or evaporation pans. Evaporation from the latter will be much less if they are surrounded by moist conditions (Jackson, 1989).

2.2.7 Effect of temperature on evaporation

Evaporation occurs wherever energy is transferred to an evaporating surface if the vapour pressure of the air is below the saturation value. Since saturation vapour pressure increases with temperature (Barry and Chorley, 1982), the surface temperature of water governs the vapour pressure at the surface, hence influencing the vapour pressure gradient (Jackson, 1989). Evaporation is directly proportional to the temperature of the atmosphere (Luxmore *et al.*, 1981; Stewart, 1984; Buchan,1984).

2.2.8 Effect of radiation on evaporation

Radiation is the emission of energy in the form of electromagnetic waves from all bodies above 0 K (Barry and Chorley, 1982). Solar radiation is the dominant source of energy and sets the broad limits of evaporation. It is, however, the net (incoming - outgoing) radiation which matters most (Jackson, 1989).

As evaporation energy requirement rises, the high net radiation leads to higher rates of evaporation. But once the surface dries, it acts as a barrier between thermal energy and the water at deeper layers (Satterlund, 1972). But Walker (1984) argued that evaporation from the soil surface often exceeded the radiant energy supply, indicating a downward flux of sensible heat.

2.3 Modelling of evaporation

2.3.1 SWEAT - Model

In recent years, mathematical modelling and simulation techniques relying on the use of computers, have been developed for the purpose of providing a comprehensive quantitative description of the behaviour of dynamic systems (Hillel, 1977). Evaporation from soil is a flux that is important to both the energy balance at the soil surface and the water balance of the soil profile. In order to study these processes in detail the model **Soil Water, Energy And Transpiration (SWEAT)** (University of Reading, 1992) simulates both water and heat fluxes in the soil and in the atmosphere above it. The effect of a crop on soil evaporation is also simulated by SWEAT; the canopy energy balance is also calculated. Evaporation predicted by SWEAT can be validated by comparing predicted evaporation to actual evaporation as measured by microlysimeters which can generate a lot of data within a short time.

2.3.2 PARCH - Model

PARCH is a model for predicting the growth of crops in response to meteorological data:

- temperature
- solar radiation
- rainfall
- humidity

and from soil information, management factors and a series of crop cultivar parameters. The model is intended as a tool to examine the many factors important in determining the effectiveness of semi-arid agriculture.

In essence PARCH is a soil profile divided into a series of layers, linked to a crop growth module. Water balance and flux are simulated within the soil, as well as inputs and losses through rainfall, runoff and drainage (Bradley and Crout, 1994). The calculation of soil water available for plant uptake is a vital component of PARCH, and a full water balance is incorporated within the program. At the surface, a driving force for evaporation can be estimated from pan evaporation, vegetation cover and a surface dryness reduction factor. As PARCH can simulate areas of bare ground between expanding circles of crop, total soil potential evaporation is found by dividing the soil area into shaded and unshaded zones, then summing up these. Predicted evaporation can be validated using microlysimeter data (Bradley and Crout, 1994).

2.4 Measurement of evaporation

Several methods have been developed over the years to calculate evaporation rates. Each method, however, has certain limitations. Firstly, they are dependent on many climatological parameters and soil surface characteristics that vary significantly from location to location. Secondly, many have been developed to calculate the potential rate of evaporation, i.e. the evaporation rate under a condition of non-limiting water supply at the surface (Sadeghi *et al.*, 1984). The methods for calculating evaporation rates include evaporation pan, atmometer method, lysimetry and microlysimetry, aerodynamic methods, energy budget methods, empirical formulae, moisture/water budget methods and remote sensing.

2.4.1 Evaporation pan method

The evaporation pan method is a very useful method. It is relatively inexpensive and easy to handle. The measurement is done by reading the level of the water in a calibrated pan. The reduced difference between last reading and the present reading is assumed to be the amount evaporated. After that the water should be refilled to the maximum mark. The amount of evaporation from the pan must be adjusted to take any rainfall into account. Pans come in different depths, sizes, material, colours and exposure. Even the brand of paint used has some effect on evaporation. Many types of pans are in use but the US Weather Bureau Class A pan is perhaps the most widely adopted. Advection effects can result in the pan seriously overestimating evaporation from a large water surface or a large irrigated area. It has been shown that use of the Class A pan to estimate atmospheric evaporation demand induces marked errors, particularly on a daily basis. Pan results must, therefore, be treated with considerable caution (Jackson, 1989).

2.4.2 Atmometric method

Atmometers measure water evaporated from surfaces such as porous filter papers (Piche type), porous porcelain spheres (Livingstone type) or plates (Bellani type) (Jackson, 1989). One example of a Bellani plate is the black and white Bellani plate evaporimeter. These can be useful as tools to evaluate potential evapotranspiration (PET) at large numbers of sites in complex terrain (Feldhake and Boyer, 1988). A number of workers (e.g. Holmes and Robertson, 1958; Carder, 1960) concluded that "no instrument of like simplicity so closely approximates the integration of the influences of the plant". But Mukammal (1961) cautions that while the Bellani plate evaporimeter is very responsive to weather parameters, atmometer observations have been found difficult to interpret, and it is therefore not advisable to rely on their results until there is a greater understanding of conditions created by this instrument. All types of atmometers are sensitive to windspeed. They do not indicate evaporation from an open water surface and are generally only of value in relative comparisons between identical instruments exposed similarly. They can be mounted in pairs (unshaded/shaded) or mounted at different heights in assessing net radiation and evaporation (Jackson, 1989).

2.4.3 Aerodynamic methods

These consider the factors influencing removal of water vapour from the evaporating surface, the vertical gradient of humidity and the turbulence of the airflow. Turbulence can be assessed by measuring the vertical gradient in windspeed at two different heights of say, 9.6 m: 9.85 m., 10.7 m: 15.32 m, and 13.57 m: 18.95 m as used by Vogt and Jaeger (1990). Care and frequency are important in taking readings at the two heights. The bulk aerodynamic approach uses windspeed at only one height to estimate evaporation from lakes.

The aerodynamic method has been extensively used to measure the sensible heat flux over flat and homogenous soil or vegetation (Cellier and Brunet, 1992; Ottoni *et al.*, 1992; Zhang and Lemeur, 1992).

Another aerodynamic method is the eddy correlation technique. It is the most elegant and attractive micrometeorological method of measuring surface energy fluxes since it provides a direct measurement with few theoretical assumptions (Stewart, 1983; Lloyd *et al.*, 1984; Nicholas, 1992). The eddy correlation technique needs very detailed simultaneous measurements of fluctuations in vertical wind velocity, air density and specific humidity. Theoretically the technique is very sound but there are considerable instrumentation problems. A micro-processor-controlled data acquisition and processing system is available, which calculates fluxes of heat, water vapour and momentum using the eddy correlation approach (James. 1988; Jackson, 1989).

Kaizer and Elliot (1991) proposed the use of a portable eddy correlation system to make direct, real time measurement of evaporation over irrigated fields. The surface energy balance equation was used to evaluate the system. The closure ratio was defined as the ratio of the sum of latent heat flux and sensible heat flux to the sum of net radiation and soil heat flux.

The Bowen ratio method has become a standard technique for measuring latent and sensible heat fluxes from the surface energy balance. Unlike other flux profile techniques, the Bowen ratio method does not require information on windspeed and aerodynamic properties of the surface, and the calculation of the fluxes is independent of atmospheric stability if equality of eddy diffusivities of heat and vapour transport is assumed (Heilman *et al.*, 1989). The method assumes similarity of temperature and humidity profiles. If different sources or sinks of heat and water vapour exist, dissimilar profiles may develop above the canopy. However, profile differences may disappear at some elevation above the surface. Data from Garratt (1978) indicate that the minimum elevation for measurements is three to five times the height of the roughness elements.

The main requirement for the Bowen ratio method is that temperature and humidity gradients be measured within the internal boundary layer and preferably in the portion of the boundary layer that is in equilibrium with the surface (Heilman *et al.*, 1989). As air moves downward after a change in surface roughness, it adjusts to the new surface conditions and forms an internal boundary layer whose thickness increases with the fetch (Heilman *et al.*, 1989). Model calculations indicate that the lowest 10% of the boundary layer is in equilibrium with the surface for an aerodynamically smooth-to-rough transition, and the lowest 5%, for a rough-to-smooth transition (Brutsaert, 1982). The equilibrium sublayer is defined as the region where the momentum flux density within 10% of the value is at the surface. This has led to formulations of minimum fetch-to-height ratios to ensure that measurements are made in the equilibrium layer. Ratios ranging from 10:1 to 200:1 have been recommended with 100:1 considered adequate for most measurements (Rosenberg *et al.*, 1983).

Dugas *et al.* (1991) compared Bowen ratios and calculated latent heat flux and sensible heat flux from four Bowen ratio systems (BR1 to BR4) of different designs with each other and with fluxes measured by three sets of eddy correlation instrumentation and a portable chamber. They found that (1) Bowen ratios from instrumentation of different designs are similar (2) eddy correlations from the three systems were similar to each other and were slightly less than the Bowen ratios (3) eddy correlation latent heat flux was consistently and significantly less than the Bowen ratio latent heat flux and (4) measurements of portable chamber latent heat flux on the edge of a field were affected by surrounding conditions. The Bowen ratios and calculated latent heat flux from the four Bowen ratio systems were similar.

2.4.4 The energy budget approach

The underlying assumption behind the energy budget approach is that if the energy available for evaporation can be determined, then the value of evaporation can be calculated. For a given area, the following equation can be written:

$R_n + H = S + A + E + C^* + P^*$ (2.1) where

R_n - net radiation (W m^{-2})

H - horizontal advection of sensible and latent heat (W m^{-2})

S - heat flux (flow) into the soil (W m^{-2})

A - heat flux into the air (W m^{-2})

E - evaporation energy (W m^{-2})

P^* - Photosynthesis (W m^{-2})

C^* - heat storage in the crop (W m^{-2})

* small compared to the other terms and are ignored.

Heat flux into the soil is commonly measured for land surfaces or for a water body evaluated from changes in water heat content. However, over a twenty four hour period, the totals of the soil heat flux, S, and the storage of energy within the vegetation, C^*, become insignificant (Stewart, 1983). Also the net absorption of energy by photosynthesis, P^*, is only a few percent of the total net radiation, R_n. Advected energy can be considerable in arid/semi arid areas but since it is difficult to evaluate, most methods ignore this factor. Therefore, the original equation reduces to:

$$R_n = A + E \qquad (2.2)$$

Despite this simplification, measurement problems exist and certain assumptions must be made in order to evaluate the proportion of R_n used for evaporation (Jackson, 1989).

The measurement of above canopy sensible and latent heat fluxes includes the fluxes from both the canopy and the bare soil. Much of the time in semi arid and arid rangelands, all or most of the latent heat flux comes from the canopy, while all or most of the sensible heat flux is from the bare soil. Many researchers have done energy budget studies (Oliver and Sene, 1992; Nicholas, 1992; Yao and Goue, 1992). To explore and evaluate more fully the sources of fluxes of latent and sensible heat, it is necessary to determine the energy budget for each source: one for the soil surface and one for the canopy (Nicholas, 1992). Lafleur (1992) observed that only 20% of the total evaporation flux comes from tree canopy.

2.4.5 Empirical formulae methods

There are many of these, using various meteorological parameters. They are based on physical principles on observed relationships between evaporation (e.g. from an evaporation pan) and one or more meteorological variables. Since these relationships have often been derived in one location, they may be unsatisfactory elsewhere. Examples of such are the Thornthwaite and the Blaney-Criddle formulae.

There are also numerous models which have been developed (Table 1) to estimate actual evaporation. The Thornthwaite method utilises only mean monthly temperature together with an adjustment for the day lengths of the months. While it appears to work well in temperate continental North America where it was derived, it seems to be less satisfactory in some other areas (e.g. in Nigeria), (Jackson, 1989).

The Blaney-Criddle formula is

$$\mu = k.p(0.46t_c + 8.13) \qquad (2.3)$$

where

μ - monthly consumptive water use by the crop (mm)

k - a crop coefficient (determined for each crop)

t_c - mean monthly temperature (^{0}C)

p - monthly percentage of day time hours in the year

By including a crop coefficient, the significance of the crop type is recognized. The crop coeffient K increases with height of crop and completeness of ground cover. The dependence of the Blaney-Criddle equation on temperature is a disadvantage in some countries where this factor is constant. This necessitates a humidity factor incorporation. Constants for the equation are derived using Class A pan values.

Table 1. The main forms of the combination equation for estimating evaporation with their assumptions and data requirements

Estimation	Type of model	Assumption	Data requirements			Author
			Variables	Average	No. of Levels	
Actual, hourly	Analytical	Extensive uniform surface, steady state conditions	R_n,S,G,T e,r_{STO}, r^H,r^v,R^{HA}, R^{VA}	Hour	Many	Shuttleworth(1976)
Actual hourly	One-level	Extensive uniform surface, steady state conditions, mean sources and sinks of sensible heat and water vapour at same height as sink of momentum	R_n, S,G,T e, r_s, r_a	hour	one	Monteith (1965)
Actual or annually	One-level	Extensive uniform surface same height for both source and sink, empirical relationships for r_{ab}, r_s and r_a	R_n G, e, m, n	Day, month, year	one	Thom and Oliver (1977)
Potential weekly or monthly	One-level	Extensive uniform, same height for both sources sinks, aerodynamically smooth, zero surface resistance, empirical relationships for R_n and r_a	n, T_{max} T_{min}, e_{09}, V	Day, month	one	Penman (1948)
Potential weekly or monthly	One-level	Extensive uniform surface, same height for both sources and sink, zero surface resistance constant relationship between vapour pressure deficit	R_n, G, T	day month	one	Priestly and Taylor (1972)

Adopted from Stewart (1983) for symbols see Appendix 1

2.4.6 Moisture/Water budget methods

According to Jackson (1989), the water balance of a stream catchment or lake can be examined using equation 2.4

$$E_t = R - Q + \Delta S + \Delta G + L \qquad (2.4)$$

where

E_t - evapotranspiration from the catchment (mm)

R - rainfall (mm)

Q - streamflow (m^3)

ΔS - water storage change within root range (mm)

ΔG - water storage change beyond root range (mm)

L - outflow/inflow other than past streamflow (M^3) measurement points.

The approach is also used to examine the impact of land use changes on the hydrologic cycle. Accurate assessments of R and Q are necessary. Because of problems in the assessment of ΔS and ΔG it is desirable to adopt a yearly period such that they are negligible. The end of the dry season is a suitable start and finish time for the assessment. In its simplest form, where ΔS,ΔG and L are assumed to be zero, then,

$$E_t = R - Q. \qquad (2.5)$$

There is a range of meteorological water budget approaches to estimate evapotranspiration before deriving a model to estimate water loss in fallow and cropped situations.

Lake evaporation estimation can be done using a **water-vapour-budget approach.** With this approach upwind and downwind horizontal water vapour flux in the atmosphere for air moving over the lake water is measured, the difference equalling surface evaporation (Jackson, 1989).

2.4.7 Remote sensing method

This method is based on the use of models simulating the interactions between the soil, the vegetation and the atmosphere, which are able to assimilate infrared surface temperatures from satellites and the surface moisture from microwave radar or radiometers.

Surface energy fluxes can be evaluated from remotely sensed data using models describing the transfers between soil and atmosphere. In order to be applied over bare soils and over partial canopies for which the soil evaporation is comparable to that from foliage, these models need three key soil parameters: thermal inertia, hydraulic diffusivity, and limit evaporation which strongly depend on the soil type and its moisture content (Ben Mehrez *et al.*, 1992).

Parameters of thermal and hydraulic properties are tested by comparing the simulated fluxes using a two-reservoir model with the fluxes observed. None of these parameters are able to reproduce the observed fluxes. To overcome this problem, evaluation of these soil parameters is done in the field by minimizing the difference between observed and simulated surface fluxes. It is based on the adjustment of the soil parameters using measurements of the surface water content and of surface fluxes. This approach may be easily applied to remote sensing observations. It requires measurements in the thermal infrared (to deduce the thermal inertia), and in the microwave region (to deduce the hydraulic diffusivity), and micrometeorological networks, able to deliver atmospheric fluxes from representative regional sites (to deduce the limit evaporation) (Ben Mehrez *et al.*, 1992).

2.4.8 Other approaches

The above discussion indicates the wide range of approaches available for evaporation measurement. Some techniques do not readily fall into any classification. For example, tritiated water has been used as a tracer in the measurement of transpiration and biomass in a tropical pine plantation (Jackson, 1989). Porometers can be used to measure stomatal opening resistance in millet, together with measurement of other crop and environmental variables to assess water use. One advantage of the method is that evaporation can be estimated over periods of a day or less.

2.4.9 Lysimetric methods

The term "lysimeter" was derived from the Greek words "lysis" and "metron" meaning dissolving and measuring, respectively. The term is thus applicable to any device utilized for studying the rate, amount and composition of percolating water through a porous medium (FAO, 1982).

A lysimeter is a device in which a volume of soil, which may be planted with vegetation, is located in a container to isolate it hydrologically from the surrounding soil for a specific study (Tanner, 1968).

Although lysimetry had its historical beginning during the seventeenth century, significant and rapid progress has been made during the last four decades. Advances in fields such as electronic engineering, irrigation science, soil physics and micro-meteorology have resulted in additional inputs which have contributed to lysimeter research and worldwide use. These rapid developments continue especially in the areas of evapotranspiration studies and water management (FAO, 1982).

Lysimeters can be conveniently divided into two types according to their size: (1) big lysimeters (vol. > 1 m^3) (FAO, 1982) and (2) microlysimeters (normally vol. < 0.010 m^3, e.g. those used by Villalobos and Fereres, 1990 as quoted by Daamen *et al.*, 1993). Lysimeters can be of a weighing or non-weighing type. The weighing lysimeters are weighed manually or provided with weighing devices which include an electronic system, a floating liquid, and a hydraulic system for the big lysimeters (FAO, 1982), and load cells for the microlysimeters (Daamen *et al.*, 1993).

The principle of the microlysimeter method is that a core of soil is isolated from the soil adjacent and the soil below, such that any subsequent change in weight can be attributed to infiltration or direct evaporation from the lysimeter. Also, there is no drainage of water from the microlysimeter. Water is added by irrigation or rain. Water lost represents evaporation or evapotranspiration (Weisner, 1979).

Lysimetry is an established method that permits the direct measurement of evaporation or evapotranspiration from the ground surface. It is the most accurate amongst the evapotranspiration measuring methods (Grimmonds and Belding, 1992). Lysimeters have been compared against other evaporation measuring devices (e.g. open pan) and showed more accuracy (van Zyl and de Jager, 1987).

Lysimetry in its various forms is the only hydrological method in which the experimenter has complete knowledge of all the terms in the equation below

$E^* = W - (Q_r + Q_l + Q_i + \Delta Q_w + \Delta Q_s)/A$ (Tanner,1968) (2.6)

where

E^* - Evaporation (cm or mm)

W - Precipitation (cm or mm)

Q_r - volume of surface runoff from catchment (cm^3)

Q_l - volume of leakage from catchment (cm^3)

Q_i - volume of intercepted water (cm^3)

ΔQ_w - volume change in ground water storage (cm^3)

ΔQ_s - volume change in water stored above water table (cm^3)

A - Area (cm^2).

Lysimetry is important not only for gathering evaporation information but also as an independent check on the suitability of micrometeorological methods and for calibrating empirical formulae used in estimating evaporation (Tanner, 1968). In the past, the focus was on big lysimeters, used mostly in forest evaporation and transpiration studies. However, there is increasing evidence that microlysimeters are now in use (see Table 2).

The lack of adequate replication in lysimeter installations precludes their use for statistically valid, within-season comparisons between treatments (Dugas and Bland, 1989). Giambelluca *et al.* (1992) argued that, using big lysimeters is expensive and cumbersome. Smaller lysimeters (vol. <1 m^3), weighed periodically with a common device, are one means of combining the direct fundamental nature of lysimetric measurements with the numerous experimental units required for statistical tests (Dugas and Bland, 1989). The microlysimeter method is arguably the simplest, most direct and independent method of soil evaporation measurement (Daamen *et al.*, 1993). Solov'ev and Bolysheva (1982) observed that when properly used, microlysimetry provides a technique for seasonal evaporation measurements. Microlysimeters of 21.4 cm, 15.2 cm and 5.1 cm diameters with 10 and 20 cm for depth were used on sandy soils in Niger (Daamen *et al.*, 1993) and no statistical difference was found in their evaporation rates. Shawcroft and Gardner (1983) used microlysimeters with two depths of 10 cm and 20 cm and the same diameter of 20.3 cm to measure evaporation and came up with results showing no significant difference in evaporation rates between the two depths. Microlysimetry is an attractive method because evaporation can be estimated over periods of less than a day.

Table 2. **Dimensions and usable lifetime of microlysimeters used in field studies**

Diameter (cm)	Depth (cm)	Life (days)	Source
7.6	14.6	-	Boast and Robertson (1982)[a]
	10.6	-	
	7.0	1 to 2	
20.3	20.0	Crop season	
	10.0	(water added)	
	5.0		
7.6	12.0	8 to 10	Walker (1983)
15.0	20.0	Crop season (water added)	Martin *et al* (1985)
7.6	12.0	8 to 10	Boast (1986)
20.3	20.0	Crop season	Boast (1986)
	10.0	(water added)	
7.4	13.0	1 to 2	Lascano and Van Bavel (1986)
7.6	15.0	6	Matthias *et al.* (1986)
20.0	30.0	1	Villalobos and Fereres (1990)
10.0	15.0	2	Alle (1990)
15.0	30.0	1	Wallace *et al.* (1992)

a Laboratory experiment.
- no data available.
Adopted from Daamen *et al.* (1993).

CHAPTER 3

MATERIALS AND METHODS

3.1 Description of the study areas

3.1.1 Locations

The study was carried out between October and December 1994. The experiment was conducted in two locations with soils of different texture. The locations belong to different regions of Tanzania namely Iringa and Dodoma (Fig 1).

These sites were:

i) Ismani

The experimental site was located at the Ismani substation of Uyole Agricultural station in Iringa region (Fig 1). The substation was started in 1960 by the Ministry of Agriculture as an outstation to Seatondale (Iringa) experimental station. It was later upgraded to a full substation by Uyole Agricultural Centre in 1976 (Min. of Agric., 1983). The site lies on 6°51'S, 35°29'E at an altitude of 1370 m above sea level (Mtakwa, 1993). It is 30 km north of Iringa town, along the Iringa - Dodoma main road (Figure 2). The site is near the bottom of a long gentle slope with fresh rock (basic gneiss) on an erosion surface well below the plateau at Iringa. The soils are classified as Eutric Nitosol (FAO) and Paleustalf (US taxonomy). Ismani has dark red clay loam soils. The soils are moderately deep (Agrar und Hydrotechnik, 1987). The soils are notable for hardsetting (Mtakwa, 1993). The topography is fairly flat with a slope of 2 - 8% (Agrar und Hydrotechnik,1987).

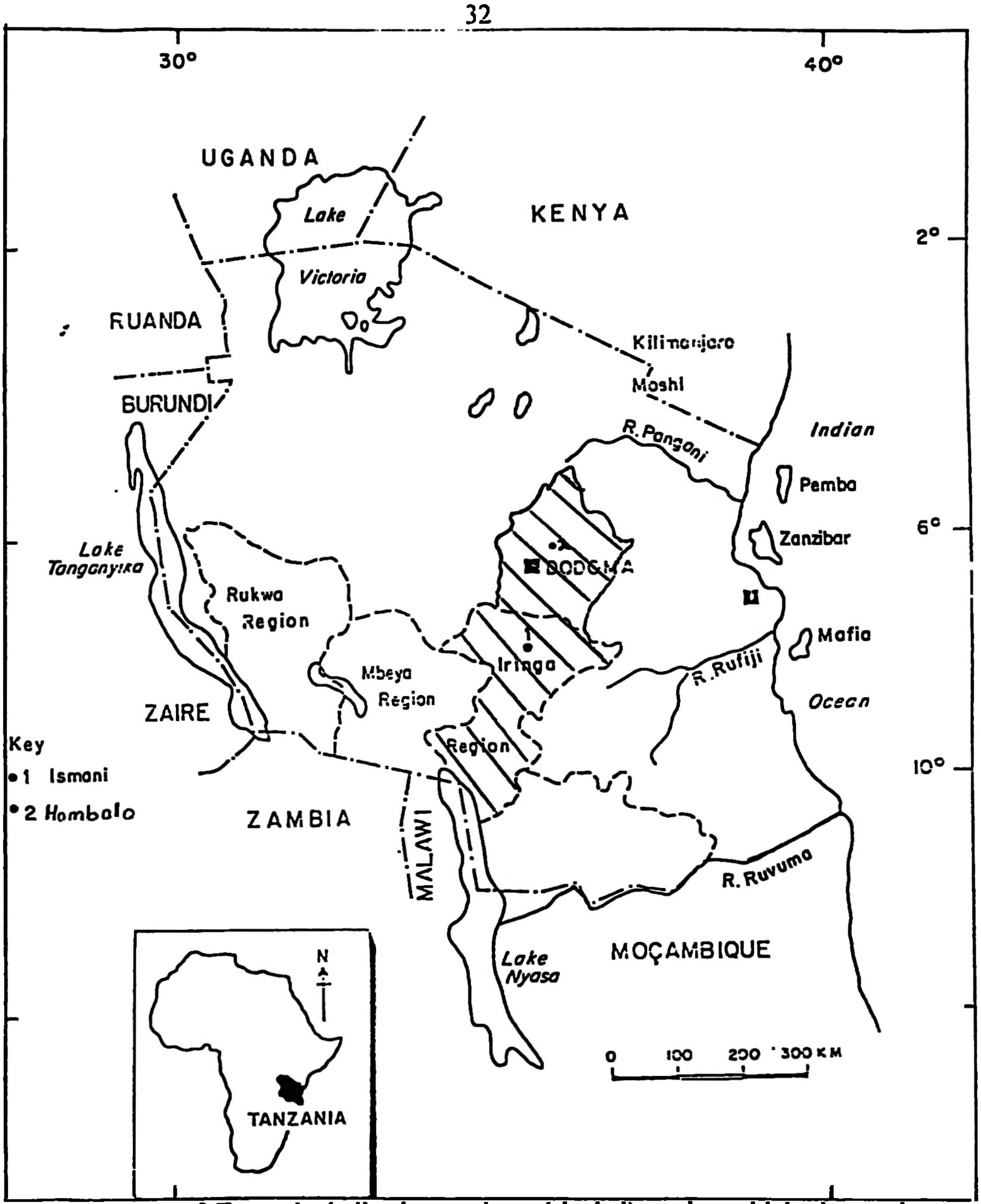


Figure 1 Map of Tanzania indicating regions (shaded) under which the study was conducted.

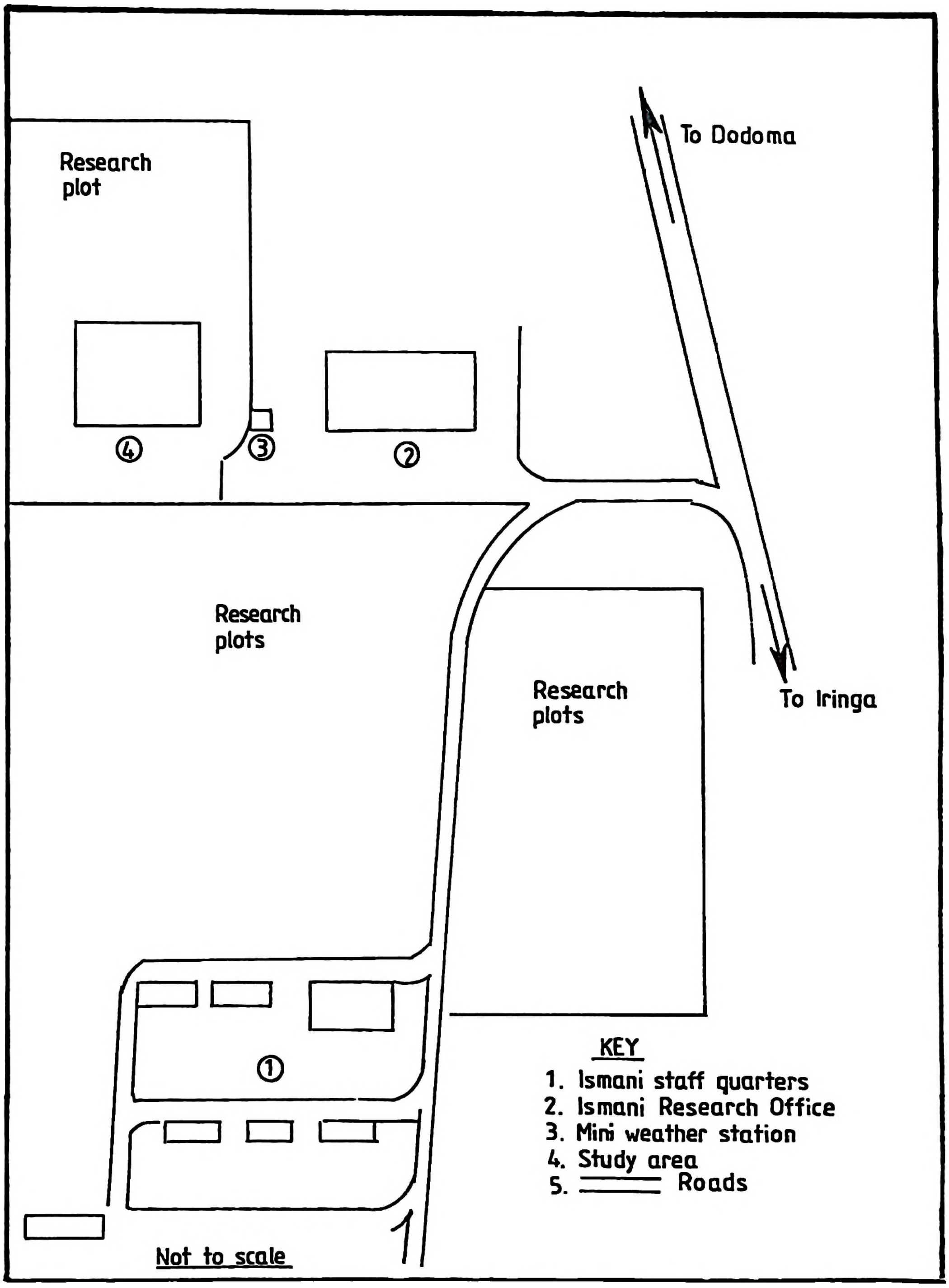


Figure 2 Location of the experimental site in Ismani Research station.

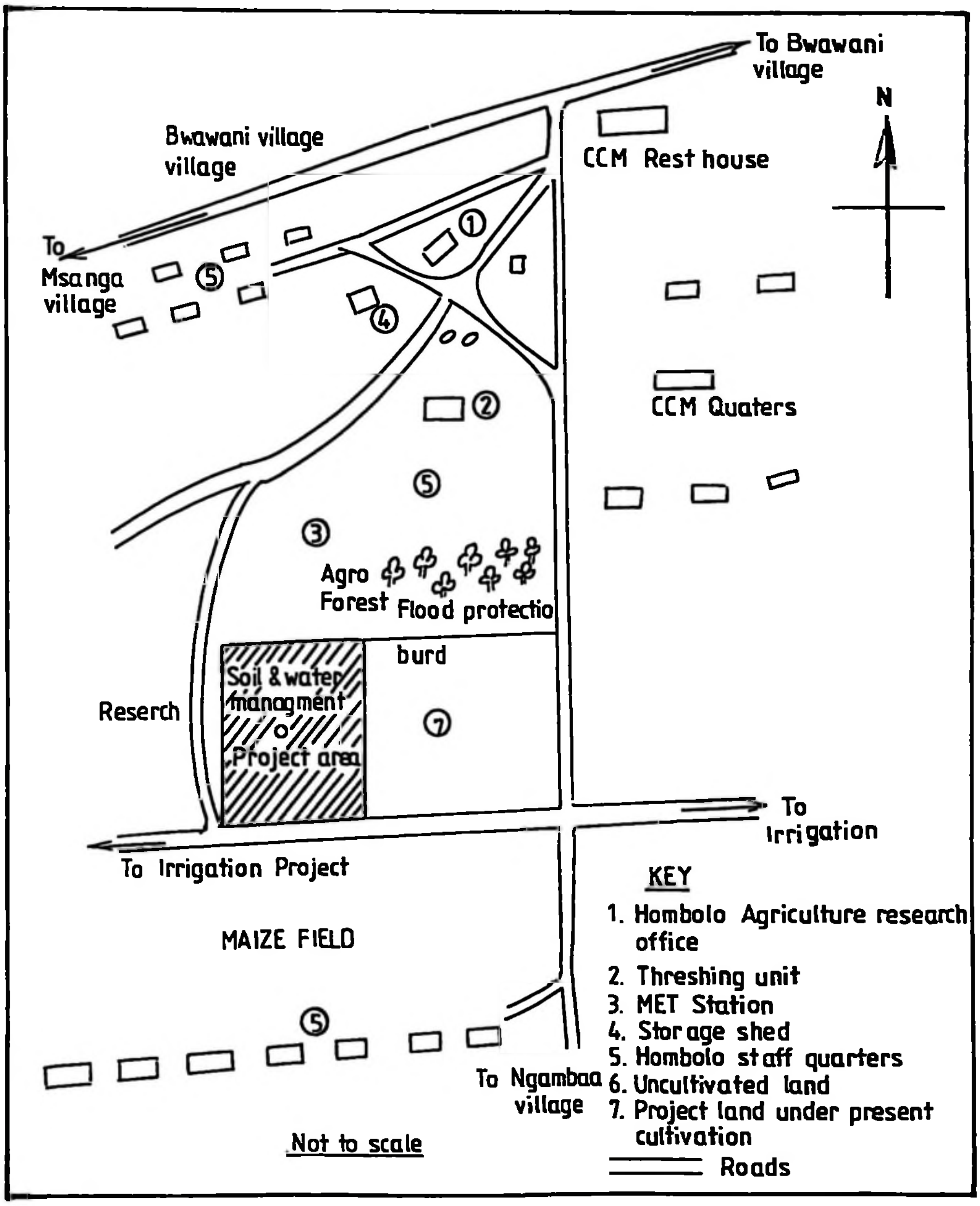


Figure 3 Location of the experimental site in Hombolo Bwawani village.

a mean temperature of 24°C. June is the coldest month and November/December is the hottest month.

The soils are dominated by gneiss (rich in silicon) with granite. The soils are classified as Dystric Regosol in the FAO - UNESCO System and as Typic Utorthent in the US Soil Taxonomy (Mahoo and Kaaya, 1993). The soils in Hombolo are sandy loam. The total porosity of the topsoil is about 20%. The surface horizon structure is weakly developed. The profile is characterized by an ochric epipedon. Nearly the whole profile is dominated by quartz minerals. The moisture and temperature regimes of the soil are Ustic and Thermic, respectively (SUA, 1993). The area was fallow for the previous seven years. However, the native vegetation in the surrounding area consists of scattered *Hyperrhenia spp*, *Adansonia digitata* and *Acacia spp* bushes. Exotic species have also been introduced by the Agricultural Research Institute, Hombolo. These include *Leucaena spp* and *Senna spp.*

3.2 Experimental Design

At both Ismani and Hombolo two plots were laid side by side, one for the shaded treatment and the other for the unshaded treatment. The microlysimeters were laid out in a 2 x 4 factorial design with 4 blocks. There were 32 microlysimeters in all (for each group): 16 in the shaded treatment and 16 in the bare treatment for each group. There were four groups sets of microlysimeters used in 8 Days because each group set was used for only two days.

3.3 Construction of materials

3.3.1 Microlysimeter construction

Larger area microlysimeters were constructed from grey rigid unplasticised polyvinyl chloride (UPVC) pipes of the following dimensions: internal diameter of 10 cm and outside diameter of 11.2 cm; lengths (depths) of 10 cm and 20 cm. The smaller area microlysimeters were constructed from black poylvinyl chloride (PVC) pipes with the following dimensions: internal diameter of 4.6 cm and outside diameter of 5 cm: lengths of 10 cm and 20 cm. A hacksaw was used to cut the pipes to the desired lengths. After cutting, the microlysimeters were inwardly tapered using a file to facilitate insertion into the soil (Figure 4).

3.3.2 Microlysimeter bottom cover cutting

Microlysimeter bottom covers were obtained by cutting a the polythene sheet. Polythene sheet covers (approximately 6 to 8 diameter cm) were cut for the 5 cm diameter microlysimeters. Polythene sheet covers of a diameter of 12 to 13 cm were cut for the 11 cm diameter microlysimeters. A pair of scissors was used for cutting the microlysimeter covers. The covers were used to seal the microlysimeter bottom to prevent free water drainage from the microlysimeter.

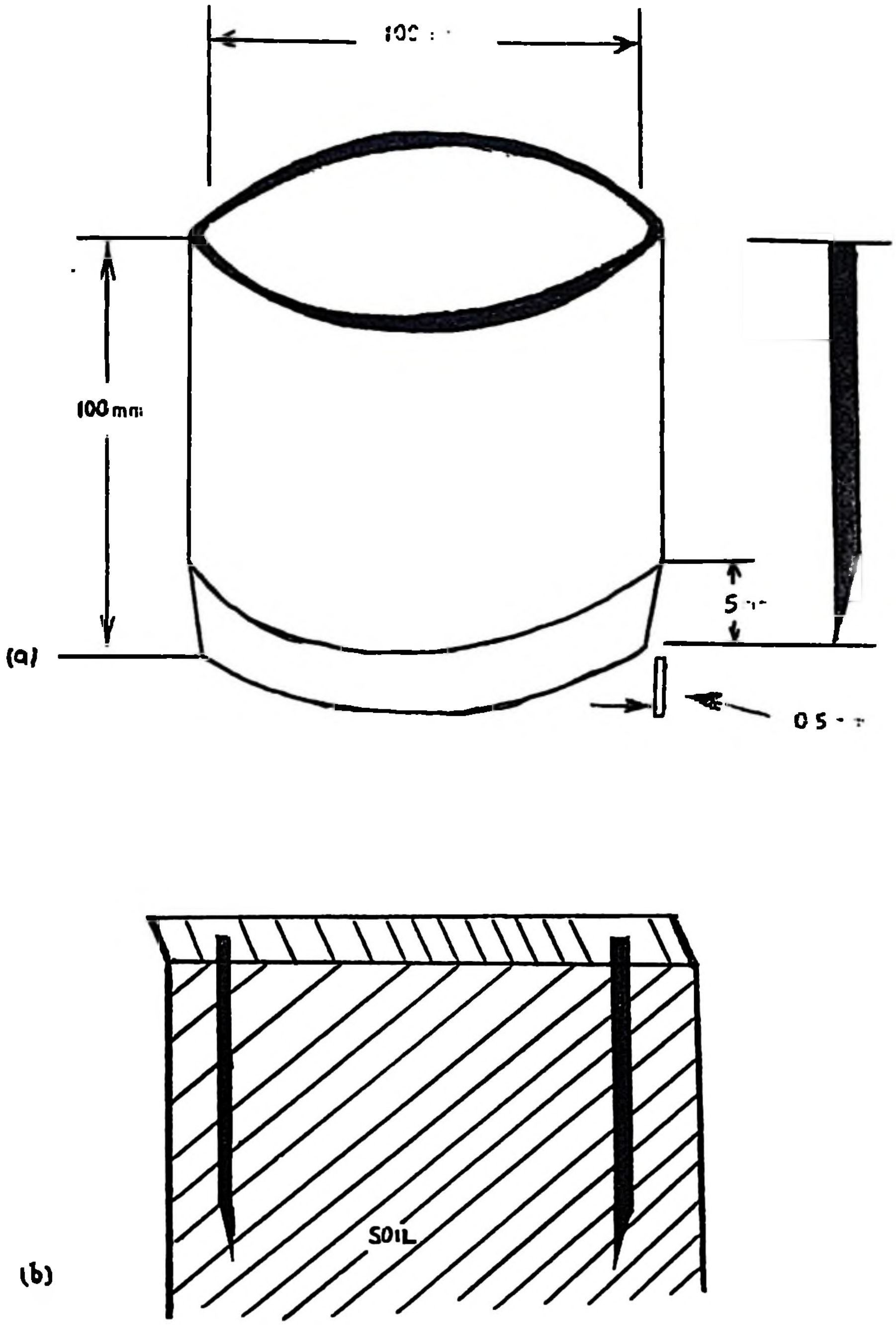


Figure 4 (a) Microlysimeter tapered inwardly at the base.
(b) Microlysimeter awaiting extraction.

3.3.3 Lining (casing) material construction

Lining material was constructed from the same material used to make the microlysimeters. The size of the casing was about 0.1 cm wider than the microlysimeter to facilitate easy lifting. The lining materials had interval diameters of 11.3 cm and 5.1 cm for large area microlysimeter and small area microlysimeter, respectively.

3.4 Cultural practices

3.4.1 Plot size and layout

Two plots were used in this experiment. One for the shaded and the other for unshaded (bare) treatment. Both plots were 1 x 4 m. They were laid adjacent to each other. They were 1 m apart to maximize homogeneity. The width of 1 metre for each plot was chosen to ensure accessibility of microlysimeters from any direction of the plots and to eliminate chances of stepping into the plots which could disturb the study. The plots were laid in a West-East direction to minimize shading the bare plot.

3.4.2 Land preparation

The land was first cleared by removing weeds and crop residues. Both plots were dug using a hand hoe (jembe). Digging was done to a uniform depth of 30 cm. The soil was later worked to a fine tilth. Finally, the plots were levelled to ensure even water distribution.

3.4.2.1 Plot demarcation

Plot demarcation was done using polythene sheets placed in each experimental plot to minimize lateral percolation of water and prevent "runoff" or "runon" of water in case of rain. The polythene sheet was inserted to a depth of about 20 cm around the edges. At the soil surface the polythene sheet was turned backwards over an external band that was about 10 cm high.

3.4.3 Irrigation

Application of 60 mm of water was done using 2 hose pipes (one for each plot) with fine roses at the end. The plots were irrigated at the same time.

3.5 Working materials installation

3.5.1 Installation of the net

Wood for supporting the net was installed on the plot to be covered by the net. The corner pillars were 40 cm above the soil. Net installation was done at 1900h. The net surface area was 2 x 6 m over the shaded treatment. The net was placed on the wooden frames (Plate 1) The net was not allowed to overlap on any side so that air circulation could not be hindered.

3.5.2 Microlysimeter installation

Five to six hours after irrigation, the 128 microlysimeters were pushed into the soil (in the soil core extraction area). Each group separate from another. All microlysimeters were installed flush with soil surface as much as possible.

3.5.3 Lining material installation

The lining material (tubes) were then installed in the microlysimeter mounting area (Plate 2). Soil in the lining material was removed using a trowel and hands. The use of lining material facilitated easy storage of microlysimeters. It also allowed rapid removal and replacement of the microlysimeters. Such was required for weighing, three times a day, with minimum disturbance of the surroundings during the study.

3.6 Working procedure

The first group of microlysimeters was dug up, and cleaned on the outside. On the bottom the soil was cut flush with the base of the microlysimeter. After trimming excess soil from the microlysimeter, a polythene sheet was used to cover the bottom of the microlysimeter. The cover was then sealed with a water proof masking tape. The microlysimeters were then weighed for initial weight, using a Campbell portable balance accurate to ±1 g, and then, placed in the lining. The following morning, at 6 00h the microlysimeters were reweighed. The procedure was repeated at noon (12 00h) and in the evening, at 18 00h. The following day the same procedure was

Plate 1 The pair of plots: shaded (left) and unshaded (right).

Plate 2 Lining material in the microlysimeter mounting area.

followed but after the evening weighing, the first group of microlysimeters was removed and replaced by the second group. The same procedure (above) was followed for the second batch of microlysimeters, after which the third and fourth groups followed.

3.6.1 Weighing

A portable balance (Campbell type) was used to determine weight loss. The balance was accurate to ±1g. The balance was placed on a solid, level pad which was constructed specifically for that purpose. A cardboard box was used to cover the balance during the weighing. This was done to protect the balance from wind disturbance. All weighings were done in the field.

3.7 Instrumentation in the field

3.7.1 Weather station

Since the experiment was done in conjunction with two other Soil Physics projects, Seedbed Physical Properties and Crop Emergence Project (NR, Project EMC X0237) coordinated by the University of Aberdeen) one automatic weather station (Campbell, CR 10) was used for all the three (Plate 3). The weather station was installed before cultivation on 18/10/1994 (in Ismani) and on 18/11/1994 (in Hombolo). It was installed to record air temperature, humidity, rainfall, solar radiation, wind speed and wind direction.

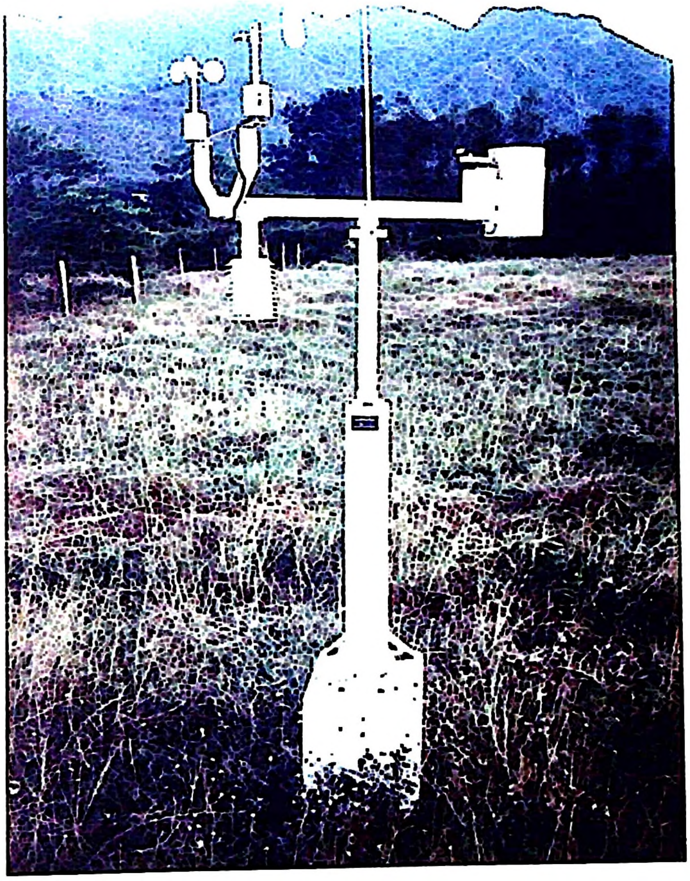


Plate 3 The automatic weather station used in the study.

3.7.2 Radiometers

Net radiation was measured above either treatment plot using net radiometers (Radiation and Energy Balance Systems, Ltd).

On the shaded plot, it was put a few centimetres below the net. The data was recorded on the data logger. Due to limited radiometer resources, the radiometers were shared amongst the project experiments and as such this experiment used them for only two out of 8 days in Ismani and only once in Hombolo.

3.7.3 Temperature probes

Soil temperatures at depths of 5 cm and 10 cm (half the depths of microlysimeters) were monitored using thermistors and the data were recorded by a data logger. The probes were installed by digging a small pit to 10 cm depth. The stainless steal head was inserted to the wall of the small pit at the desired depths i.e. 5 cm and 10 cm depths.

3.7.4 Data logger

A field data logger (Campbell type)was used to record weather station information. It was battery powered.

3.7.5 Relay multiplexer

The primary function of the multiplexer (which was used in this study) was to increase the number of sensors that may be scanned by the datalogger. It was housed in a 210 X 165 X 35 mm anodized aluminium case. The aluminium case was intended to reduce temperature gradients across the multiplexer terminal strips (Plate 4). It was battery powered (12 V DC).

Plate 4 The aluminium case housing the multiplexer.

3.8 Materials used

3.8.1 Shading material

Radiation regimes were created by shading using a black plastic net (Alnet, San type). The net radiation was determined using net radiometers (Plate 5). Only one size of the net was used, providing about 50% cover. The net was removed for 10 - 15 minutes each time measurements were being made.

Plate 5 Net radiometer used in the field: one under net (in the shaded plot) and one in the bare plot.

3.8.2. Microlysimeters

Microlysimeters were used in the study as described by Boast and Robertson (1982), Shawcroft and Gardner (1983), Allen (1990) and Daamen *et al.* (1993). Different sized microlysimeters were compared to determine if their evaporation rates were different. The sizes are shown in Table 3. The microlysimeters were constructed from different coloured UPVC pipes with different rigidity. The 5 cm diameter microlysimeters were black and more flexible. The 10 cm diameter microlysimeters were grey and rigid.

Table 3 Heights and diameters of microlysimeters used in the study.

	height (cm)	**diameter(cm)**	
(a)	**10**	**10**	**standard microlysimeter**
(b)	**10**	**5**	
(c)	**20**	**10**	
(d)	**20**	**5**	

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Evaporation and days

Table 4(a) shows mean evaporation for the eight days of the study at both Ismani (clayey) and Hombolo (sandy soil). The pattern of average daily evaporation was similar from the first day to the third day with the first day having high evaporation rate on both clayey and sandy soils. This was the energy limiting stage i.e. stage 1 of evaporation (Idso *et al.*, 1974). In the subsequent two days evaporation was reduced by almost 50% (Table 4(a). Similar results were obtained by Lascano and van Bavel (1986). These reductions are partly due to the formation of a depositional surface seal caused by slaking under flood irrigation (Lascano and Hatfield, 1992) which might have occurred during the irrigation. For the clayey soil, there was a constant stage in reduction, a linear falling stage. Such was also observed by Lemon (1956). Distinctions between evaporation stages were not clearly defined, particularly between stage two and three. Many other workers support this (e.g van Bavel and Hillel, 1976). This could have been caused by the interrupting rains on both sites. At Ismani, day 4 had an evaporation rate as high as on day 1 due to the rains which fell on the afternoon of day 3. This was followed by significantly less ($P< 0.05$) evaporation on days 5 - 7 (similar to day 2). The soil may have dried to the point that the evaporation rate approached constance, which caused both soil heat flow and sensible heat flow to sharply increase in the last three days as observed also by Horton *et al.*(1984). Evaporation at Hombolo showed the same trend. In the sandy textured soils of Hombolo evaporation consistently decreased from day 1 to day 6, only to increase on day 7 because of the rains that fell on the night of day 6 of the experiment.

Table 4 (a) Mean evaporation (mm) for both clayey and sandy soils. Means with the same superscript within column are not significantly different ($P < 0.05$).

Day	n	Clayey soil	n	Sandy soil
1	128	1.53 ± 0.09^{a}	128	2.04 ± 0.09^{a}
2	128	0.76 ± 0.05^{b}	128	1.18 ± 0.04^{c}
3	96	0.78 ± 0.05^{b}	128	1.07 ± 0.03^{c}
4	128	1.51 ± 0.06^{a}	128	0.66 ± 0.03^{d}
5	128	0.78 ± 0.04^{b}	128	0.66 ± 0.02^{d}
6	128	0.74 ± 0.02^{b}	128	0.40 ± 0.01^{e}
7	128	0.74 ± 0.02^{b}	128	1.69 ± 0.06^{b}
8	128	0.53 ± 0.01^{c}	128	1.13 ± 0.06^{c}

4.2 Evaporation and soil texture

Results of the effect of soil texture on evaporation presented in this study are from two different sites with different climatic conditions and obtained on different dates. There is a difference of ten days between the data collection dates of the two different sites. Calculations to determine the effect of soil texture on evaporation were done for the first three days because there was rain in Ismani on the afternoon of the third day and at Hombolo on the night of day 6. So it was only sensible to consider results from the first three days when conditions in the two sites were similar.

Table 4 (b) Average daily cooperation comparison for soil texture

N	Mean	Stderr	F value	Pr> F
384	1.25	0.05	26.72	0.01*

* Significantly different at P< 0.01

(b) General Linear Model Procedure comparing evaporation from clayey soil and sandy soil during the first three days after irrigation.

Table 4(b) shows the average daily evaporation for the different textured soils i.e. clayey soil of Ismani and sandy soil of Hombolo during the first 3 days of recording. Sandy soils evaporated significantly (P< 0.01) more water than clayey soils

(Table 4(b). Similar results were obtained by Vossen (1990) working on Botswana soils and by Nath and Singh (1984) working on sandy soils in India. The results could have been influenced by the fact that sandy soils warm up more quickly than clayey soils because they (sandy soils) have a lower heat capacity (Mavi, 1986). Some workers (e.g. Miller and Aarstad, 1973), found that evaporation was greater in sandy soils.

4.3 Evaporation and period of the day

The rate of evaporation per period in a day is presented in Table 5. The two periods of the day showed significant differences in evaporation under both clayey and sandy soils ($P < 0.05$). There was significantly more evaporation in the morning than in the afternoon in the clayey soils (Fig 5). Marshall and Holmes (1988) reported that cooling by radiation from the ground surface often causes an early morning accumulation of moisture in a rather thin layer near the surface of the soil. During the daytime, heating of the surface layers creates a vapour pressure gradient tending to make water vapour move not only upwards into the atmosphere at the soil surface but also downwards towards the cooler soil. The surface then cools at night to a temperature lower than that of the deeper soil and the vapour moves upward into the surface soil. Generally, however, vapour movement in response to a temperature gradient in soils is overridden by the greater fluxes in the liquid phase during evaporation (Marshall and Holmes, 1988). It has been shown that the surface zone soil moisture content fluctuates in a manner corresponding to the diurnal fluctuation of evaporativity (Hillel, 1977). Another reason for more evaporation in MP could be the rapid drying of the soil surface during the morning hours which may have resulted from bidirectional movement of water (Jackson *et al.*, 1973). Soil water from the surface to about 1 cm moved upwards, whereas below about 1 cm depth the water moved downward. The reason could be that gravity pulls the water downwards, yet some water movement upwards could be brought about by diffusion as water occupies spaces left by evaporating water.

Table 5 **Mean evaporation (mm) for the two periods of the day.**

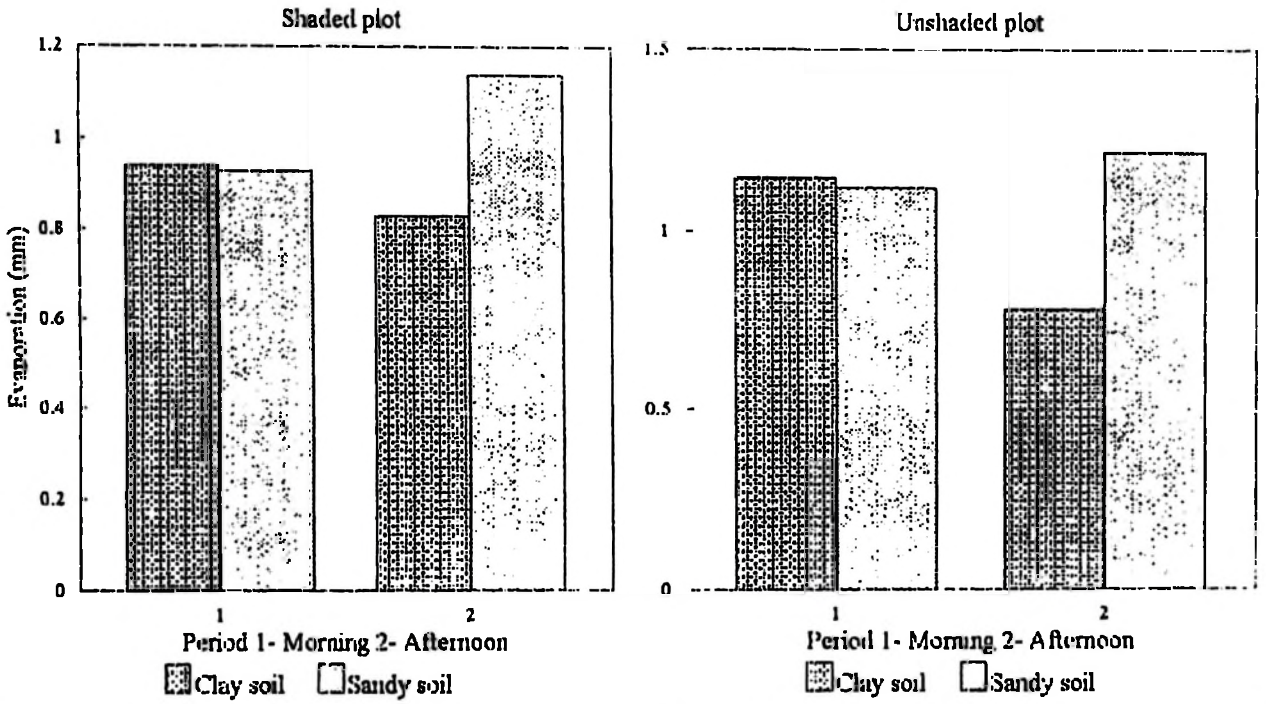
	n	Clayey soils	n	Sandy soil
Day's period				
Morning	512	1.04 ± 0.03^a	512	1.03 ± 0.04^a
Afternoon	480	0.80 ± 0.03^b	512	1.18 ± 0.04^a

Means with the same superscripts within the column are not significantly different ($P < 0.05$).

4.3.1 Evaporation with period in each day

Results for the daily mean evaporation for morning and afternoon periods (MP and AP, respectively) are presented in Fig 5. On the first day the MP evaporated more

more water than AP under clayey soils (although the difference was not significant). The reverse was observed on the sandy soils. Day 2 had the same trend of results as day 1 except that evaporation in the AP under clayey soils was significantly reduced. Day 3 data for the AP under clayey soils were not presented because it rained and negative numbers were obtained during the calculations. The sandy soils still had the MP evaporating less than the AP. The rest of the days followed the same trend as the first two days i.e. MP evaporated more than AP under clayey soils and the opposite was observed under the sandy soils although the difference was reduced each day particularly under sandy soils.



a,b c and d are levels of statistical difference. Bars with same letters are not significantly different ($P< 0.05$) (within the plot)

Figure 5. Mean evaporation (mm) in the morning and afternoon periods for shaded and unshaded plot

4.4 Evaporation and shading

The results of the effect of shade on evaporation for this study are presented in Table 6.

Table 6 Mean evaporation (mm) for shaded and unshaded plots both peroids.
Means with the same superscripts within the column are not significantly different ($P < 0.05$).

		n	Clay soil	n	Sandy soil
Shading	Shaded	496	0.88 ± 0.03^{b}	496	1.03 ± 0.03^{b}
	Unshaded	496	0.97 ± 0.03^{a}	496	1.17 ± 0.05^{a}

The results show that shading in this study was effective in reducing evaporation in clayey soil ($P < 0.05$) and in sandy soils ($P < 0.01$) (See also radiometer data in Appendix VIII). The results agree with those of Hanson and Rauzi (1977) and Judd and McAneney (1984), although the latter used live shade. But Daamen *et al.* (1993), found no significant difference between the shaded and unshaded plots in Niger sandy soils. Cracking of soil in the microlysimeters was observed on the bare plot of the clayey soils of Ismani. This might have contributed to the high evaporation rate of the bare plot (Gupta and Ranade, 1987). The higher radiation input dried the bare plot more rapidly than it did on the shaded plot. The lowered water content of the bare plot probably resulted in decreased soil thermal conductivity (Horton, 1984). The results of the shaded plot may have been affected by a decrease in turbulent transfer of water vapour to the atmosphere caused by the shade, a decrease in capillary continuity of the surface layer, or a decrease in capillary flow and the moisture holding capacity of the surface soil layer (Mavi, 1986).

On wet soils, in the shaded plot, net radiation was low (Appendix viii), latent heat flux took energy away from the soil surface, and the sensible heat flux went from air to the soil surface and contributed additional energy for soil water evaporation (Luo *et al.*, 1992).

On drying soils in the bare plot, most net radiation may have been converted to latent heat and soil temperature was higher than air temperature during the day. Ground heat was thus conducted down to deep soil layers. With a dry soil surface and shade, little solar radiation reached the bottom of the plot and as such evaporation was small (Lou *et al.*, 1992).

4.4.1 Evaporation as affected by shading with period of the day

Results of the effect of interaction between shade and period of the day on evaporation are given in Appendix vi. The shaded plot in the clayey soil shows the morning period evaporating more than the afternoon period. This is probably because of more available water in the morning due to constant supply from lower layers of the soil during the night yet the sandy soils had MP evaporating less (although not significantly so) than the AP. Similar results were obtained in the bare plot.

4.5 Effect of microlysimeter diameter on evaporation

In Table 7 are the results of the effect of the two different sizes of microlysimeters on evaporation.

Table 7 Mean evaporation (mm) for the different microlysimeters diameters.

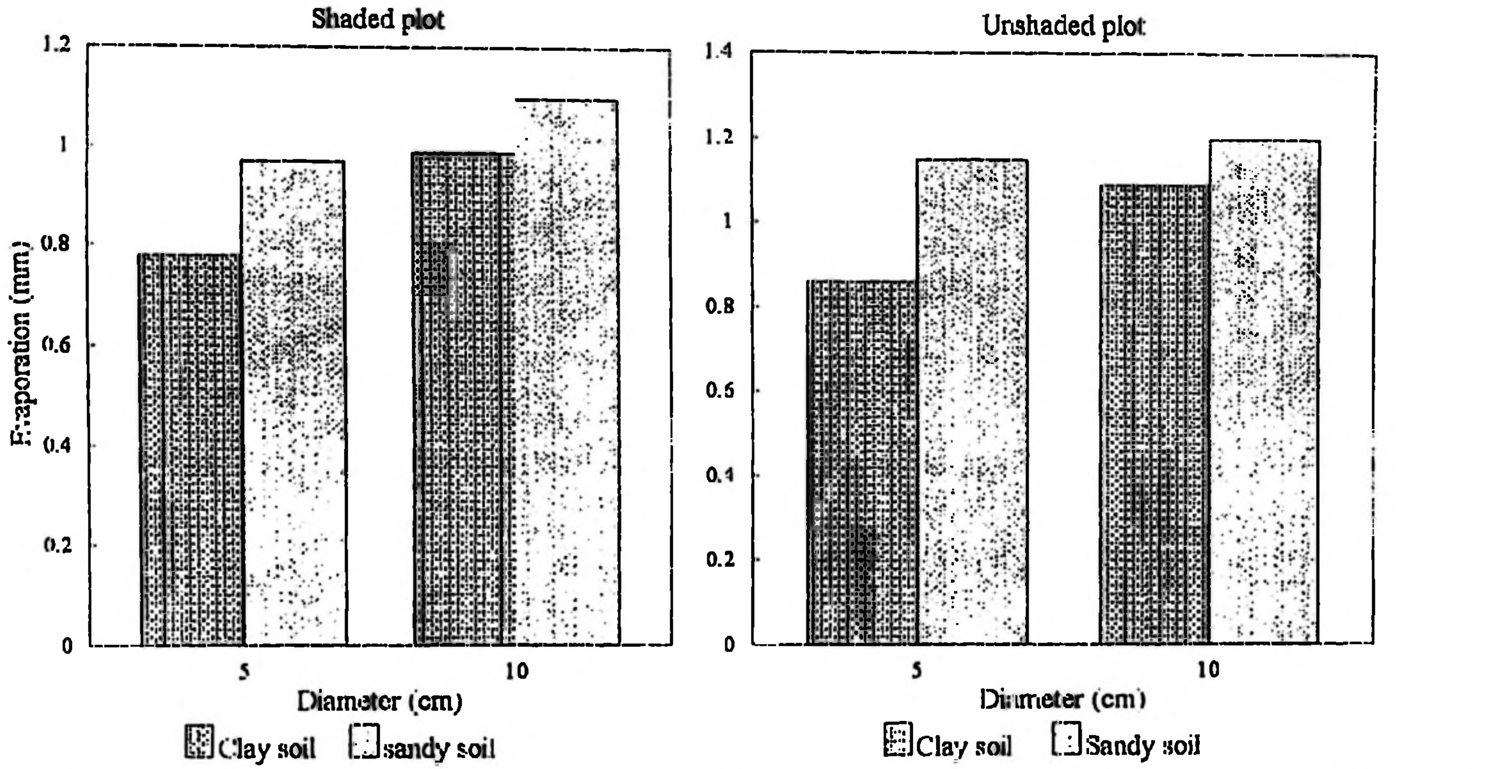
Diameter	n	Clay soil	n	Sandy soil
5 cm	496	0.92 ± 0.03^{b}	496	1.06 ± 0.04^{b}
10 cm	496	1.04 ± 0.03^{a}	496	1.15 ± 0.04^{a}

Means with the same superscripts within the column are not significantly different ($P<0.01$).

The 10 cm diameter microlysimeters lost significantly more water than the 5 cm microlysimeters [($P < 0.01$) for clayey soils and ($P < 0.05$) for sandy soils, (see also Fig 6)].

The results are different from those found by Daamen *et al.* (1993) in Niger on sandy soils. They found no significant difference between evaporation amounts from the diameters when they used 15 cm and 5 cm diameter microlysimeters. This could be due to the fact that in the current study, the SAM had their soils inside the microlysimeters low because there was soil compaction during insertion. Improper tapering of the cutting edge might also have contributed to the observed compaction, hence the lower evaporation on SAM. From Day 1 to 4 the SAM lost less water compared to the LAM in shaded and bare plots in both clayey and sandy soils. On the fifth day the clayey soils had the same magnitude of evaporation for both shaded and unshaded plots but under the sandy soils the SAM evaporated more water than the LAM. Day 6 and 7 results were like the first four days results i.e. LAM evaporating more than the SAM.But the sandy soils gave similar results only for the shaded plot. The bare plot gave different results.

The last day (Day 8), had the SAM evaporating less than their larger counterparts for both shaded and bare plots under clay soils. The sandy soils differed in both shaded and bare plots, where SAM evaporated more than LAM. The results are difficulty to explain.



a, b and c are levels of statistical difference. Bars with same letters are not significantly different ($P < 0.05$)

Figure 6. Mean evaporation (mm) as affected by microlysimeter diameter in both shaded and unshaded plots

4.6 Evaporation and microlysimeter depth

Two depths of microlysimeters were used in this study. They were 10 cm and 20 cm. This study found no significant difference between shallow depth microlysimeters (SDM) (10 cm) and deep microlysimeters (DDM) (20 cm) (See Appendix vii).

Many researchers have found similar results (Daamen *et al.*, 1993). It seems up to 20 cm depth does not affect evaporation.

4.7 Evaporation and soil temperature

Soil temperature was determined using temperature probes which were at depths of 5 cm and 10 cm. Soil temperature at 5 cm (r^2=0.36) and 10 cm (r^2=0.02) did not affect evaporation in clayey soils in the shaded plot. Even the bare plots showed low correlation (See Table 8). But the Hombolo soils showed high correlation. Shade seems to have increased the soil temperature and thus enhanced evaporation. Such findings are contrary to those by Luo *et al.* (1992), Flerchinger and Pierson (1991) and by Aase and Siddoway (1980). Marshall and Holmes (1988) observed that soil temperature gradients can cause water to move in the vapour phase, also in the direction of decreasing temperature in response to the vapour pressure gradient. Vapour pressure of water is strongly affected by temperature (Bond and Willis, 1971).

Table 8 Regression Analysis for soil temperature.

Depth	Texture	Shading	R^2	a	b	regression equation
5 cm	clay	shaded	0.36	-2.45	0.29	-2.45 ± 0.29x
		bare	0.03	-0.42	0.30	-0.42 ± 0.30x
	sandy	shaded	0.65	7.17	0.24	7.17 ± 0.24x
		bare	0.47	9.08	0.39	9.08 ± 0.39x
10 cm	clay	shaded	0.02	2.09	0.36	2.09 ± 0.36x
		bare	0.00	0.69	0.33	0.69 ± 0.33x
	sandy	shaded	0.67	7.00	0.24	7.00 ± 0.24x
		bare	0.50	11.01	0.38	11.01 ± 0.38x

4.8 Evaporation and windspeed

Wind was normally at 129^0 direction in Ismani and 126^0 in Hombolo (Appendix iv). The weather data show higher windspeeds in Hombolo compared to Ismani. This may be the reason why the sandy soils had higher evaporation rates. According to Vitkerich (1963): "even a wind velocity of 3 metres per second, called a weak wind in meteorology, causes evaporation to increase by a factor of 2-3 and at times 20". The low windspeed at the Ismani location might have been caused by the tall grass (1-2 high) around the plots (within 8 m of the plots) which acted as windbreak.

Table 9 **Regression Analysis for windspeed.**

Soil Texture	Shading	R^2	a	b	Regression Equation
Clay	shaded	0.02	1.04	0.42	$1.04 \pm 0.42x$
	bare	0.02	1.06	0.44	$1.06 \pm 0.44x$
Sandy	shaded	0.59	-0.92	0.31	$-0.92 \pm 0.31x$
	bare	0.39	-1.16	0.55	$-1.16 \pm 0.55x$

4.8.1 Clayey soils

Windspeed did not significantly affect evaporation at Ismani (r^2=0.02).

4.8.2 Sandy soils

Windspeed significantly affected evaporation in Hombolo with variations in windspeed accounting for up to 59% of the variations in the observed evaporation (r^2=0.59) (Table 9). The first day had the highest windspeed and there was high evaporation although water also was not a limiting factor. Day 6 had the lowest rate of evaporation and a low windspeed. The data (Appendix IV) show some effect of advection. During the first few days when the soil was still wet (at least the top soil) there was a high evaporation rate. As the days progressed and the top soil dried, the evaporation rate diminished. There was also an element of turbulence of wind near the soil surface which might have played a part in the partitioning of energy into latent and sensible heat. The wind turbulence removed large quantities of vapour from the layer immediately adjacent to the soil surface (Hounam, 1971), although Marshall (1959), argued that wind gustiness is rather a minor cause of vapour transfer.

4.9 Evaporation and Relative humidity

The data for relative humidity for this study is presented on Appendix V. Relative humidity had no effect on evaporation in this study, probably because it remained low through the study.

4.10 Soil wetness

Flooded soils lost more water. Although this was not directly measured in this study, it can be inferred from the results of evaporation on days (Table 4). The rate of evaporation decreased rapidly as a dry soil layer formed a barrier to the evaporative process (Smith, 1975). Some researchers (Hounam, 1971), argue that the nature of the catchment surface also has a significant influence on the energy balance through its ability to reflect radiation and to re-radiate heat according to the temperature of it's surface. This is affected by the nature of the surface and, in particular, its water content. Wet surfaces appear optically darker than dry surfaces thus absorbing more heat energy and reducing the albedo (Hounam, 1971). It has been observed (Phillip, 1991) that depending on the ambient meteorological conditions and on the water distribution in the upper soil horizon (5-15 cm), the rate of evaporation of water at the soil surface may be governed either by meteorological conditions or by soil conditions. The meteorology will tend to be limiting for wet soil surfaces, with the transmission of water through the soil to the surface becoming limiting as the soil surface dries (Phillip, 1991).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The study reported herein was undertaken to investigate the effect of shade and soil texture on soil evaporation using microlysimetric methods. Another objective of the study was to find out if larger diameter microlysimeters (10 cm) were losing more water than the small diameter microlysimeters (5 cm). The study also looked into the effect of microlysimeter depth. Microlysimeter depths used were 10 cm and 20 cm. Lastly, the study determined if evaporation consistently decreased with time following irrigation or rainfall.

The study was done at two sites with different soil texture. The first site was Ismani in Iringa region (clayey soils), and the second site was Hombolo in Dodoma region (sandy soils). The land was prepared by digging using a hand hoe and brought to a fine tilth. Two plots of 1 X 4 m each were made for the experiment. Irrigation water was applied and the microlysimeters were then inserted into the soil. Shading on one plot was provided by a net which was shading radiation at about 50%. Net radiometers were used to determine the amount of net radiation falling on the plots (Data in Appendix VIII). Evaporation rate was determined by weighing the microlysimeters, and calculating the differences in weight. Weighing was done three times a day: at 6.00h, 12.00h, and at 18.00h local time.

The major findings and conclusions from this study are summarized below.

5.1 Shade

The study found that shade significantly affects evaporation in the soil. The bare plot evaporated more than the shaded plot. It was also observed in this study that shade keeps soil moist a little longer and reduced soil temperature. So it lowered water evaporation.

5.2 Soil texture

The study showed that sandy soils evaporate more water than the clayey soils. The conclusion is based on the first three days of the study. The exception was on the day when there was rainfall following irrigation on the clayey soils.

5.3 Microlysimeter diameter

The study found out that the large diameter microlysimeters lost more water than the smaller diameter microlysimeters, although this was reversed towards the end of the study. It can be concluded from this that the 10 cm microlysimeters seem the most adequate since they do not lead to too much soil compaction inside them.

5.4 Microlysimeter depth

Microlysimeter depth does not significantly affect the rate of evaporation. So the 10 cm deep microlysimeter can be used because it is more economical to bury and disturb the soil less compared to the 20 cm deep microlysimeter.

5.5 Evaporation and day

The study found that evaporation rate decreases with time from the day of irrigation or rain. The first day normally has the highest evaporation rate. The second day evaporates about half the amount of water of the first day's evaporation. The third day evaporates more or less the same as second day. However, this observation was based only on 3 pairs of days when there was no rainfall at both sites and may, therefore be inconclusive. Under normal conditions, the fourth up to 7 days would evaporate down to a constant rate as water availability decreases. It is recommended that more studies be done in dry seasons so that no rain can disturb the experiment.

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Appendices

Appendix I.

Symbols for Table 2.1

R_n	net radiation (W m^{-2})
S	total flux of energy into storage between levels of net radiometer and soil heat flux plate (W m^{-2})
G	soil heat flux (W m^{-2})
T	mean temperature in Linacre (°C)
e	vapour pressure (mb)
r_{STO}	stomatal resistance in Shuttleworth (1976) (s m^{-1})
r_H	aerodynamic resistance to transfer of sensible heat (s m^{-1})
r_V	aerodynamic resistance to transfer of water vapour (s m^{-1})
$R^{H,A}$	boundary layer resistance of the vegetative elements for sensible heat flux in Shuttleworth (1976) (s m^{-1})
$R^{V,A}$	boundary layer resistance of the vegetative elements for latent heat flux in Shuttleworth (1976) (s m^{-1})
r_{ST}	bulk stomatal resistance in Thom (1972) (s m^{-1})
r_S	surface resistance in Monteith (1965) (s m^{-1})
r_a	aerodynamic resistance (s m^{-1})
m	aerodynamic factor in Thom and Oliver (1977)
n	stomatal factor in Thom and Oliver (1977)
r_{sD}	surface resistance under totally dry conditions in Thom and Oliver (1977) (sm^{1})
r_s	equivalent surface resistance in Thom and Oliver (1977)(sm^{-1})
n	number of hours of sunshine in Penman (1948) (hr)
T_{max}	mean daily maximum temperature (°C)
T_{min}	mean daily minimum temperature (°C)
e_{09}	vapour pressure measured at mid morning (mb)
U	wind run in Penman 1948) (miles day^{-1})

Appendix II

Weather data from the two sites

IIa

Iringa Meteorological Station (Nduli Airport) for November 1994.

Date	Tmin (°C)	Tmax (°C)	Rainfall (mm)	Rel humidity (%)	Windspeed (km'hr)	Sunshine (hr)
1	17.0	25.7	0.0	46	184.08	5.7
2	16.9	27.8	0.0	38	179.35	10.7
3	16.4	27.7	0.0	42	122.07	8.0
4	15.9	29.3	0.6	38	115.17	8.4
5	16.0	27.7	0.0	44	112.01	6.6
6	14.9	26.8	0.0	41	83.28	7.2
7	13.8	28.1	0.0	41	97.72	8.2
8	14.4	28.2	0.0	40	77.16	5.4
9	14.7	30.0	5.5	47	62.26	6.6
10	14.4	29.0	0.0	41	98.64	8.7
11	13.9	29.9	0.0	32	139.47	8.7
12	14.7	29.9	0.0	29	180.30	12.0
13	14.7	29.1	0.0	35	110.72	12.0
14	16.6	30.1	0.0	29	106.51	9.8
15	15.2	29.9	0.0	35	75.90	11.4
16	13.4	29.1	Trace	33	137.05	8.0
17	14.6	29.8	0.0	28	124.54	11.1
18	13.4	28.9	0.0	25	120.03	11.0
19	13.0	29.4	0.0	32	78.18	11.9
20	14.5	30.5	0.0	33	93.78	10.6
21	14.8	31.0	0.0	29	86.64	8.1
22	13.8	30.7	0.0	29	102.83	10.8
23	13.5	29.7	0.0	25	88.03	11.9
24	15.5	31.5	0.0	27	63.21	11.2
25	16.1	31.4	0.0	36	93.08	10.7
26	16.5	30.1	0.0	21	89.82	7.0
27	17.4	30.3	0.0	51	87.75	6.6
28	15.5	28.8	0.0	50	94.12	4.3
29	17.3	28.3	0.0	50	89.61	4.9
30	15.5	26.8	0.0	41	119.62	3.2

IIb
Hombolo Meteorological Station

Date	Tmim (°C)	Tmax (°C)	Rainfall (mm)	Drybulb (°C)	Wtbulb (km'hr)	Windspeed (hr)	Sunshine (hr)
1	19.9	27.9	0.0	23.25	19.15	360.21	6.3
2	18.2	29.6	1.8	25.90	19.3	263.06	10.5
3	18.2	29.1	0.0	25.95	19.30	332.27	8.5
4	18.0	32.0	0.0	27.85	19.55	384.88	12.5
5	20.0	30.9	0.0	26.60	19.55	377.99	9.1
6	19.0	30.4	0.0	25.80	18.45	359.86	9.1
7	19.1	29.5	0.0	26.10	18.35	259.06	12.0
8	19.0	32.9	0.0	27.85	18.25	404.22	12.3
9	19.6	33.6	0.0	28.05	19.25	272.24	12.1
11	20.0	34.3	0.0	29.75	19.35	327.32	12.2
12	27.7	33.1	0.0	28.70	19.75	323.13	12.6
13	20.4	32.5	0.0	28.50	18.50	271.94	10.1
14	20.6	30.6	0.0	26.60	18.90	452.21	4.3
15	20.5	33.0	0.0	28.50	19.1	280.06	11.5
16	18.3	32.0	0.0	26.80	18.80	348.67	8.2
17	19.0	32.0	0.0	26.95	17.80	357.35	12.3
18	18.5	32.3	0.0	28.00	17.45	336.01	12.5
19	18.6	33.0	0.0	28.25	17.45	335.76	12.4
20	18.7	34.5	0.0	29.60	18.05	327.69	12.2
21	18.5	33.0	0.0	28.75	18.85	367.45	12.4
22	19.0	32.9	0.0	27.50	18.00	345.25	12.3
23	19.0	34.7	0.0	29.20	17.95	345.52	12.5
24	19.5	35.2	0.0	29.75	19.00	306.42	12.2
25	21.6	35.5	0.0	30.35	20.00	297.71	11.9
26	21.6	32.2	0.0	28.85	19.26	192.25	5.3
27	19.5	32.6	15.9	27.75	20.05	314.00	7.3
28	20.4	32.9	0.0	28.80	18.80	357.51	7.7
29	20.0	32.6	27.65	18.90	18.90	279.51	7.7
30	20.9	32.6	0.0	28.30	19.25	375.68	10.9

Appendix III

Average daily evaporation (mm) and soil temperature at 5 cm and at 10 cm.

	Bare plote			Shaded plot		
	5 cm	10 cm	Evp'n (mm)	5 cm	10 cm	Evap'n (mm)
Clay soils						
Day 1	-	-	1.49	-	-	1.57
2	28.58	26.39	0.73	23.19	22.71	0.79
3	28.40	26.62	0.92	23.58	22.97	0.63
4	29.23	26.31	1.52	27.78	22.83	1.49
5	31.21	28.03	0.89	25.40	23.99	0.68
6	30.27	28.43	0.74	25.05	24.30	0.73
8	27.73	24.92	0.59	25.84	22.36	0.47
Sandy soils						
1	-	-	1.73	-	-	2.35
2	30.79	31.23	1.22	26.36	26.58	1.14
3	31.69	30.53	1.04	27.48	27.86	1.10
4	33.40	32.00	0.65	28.86	29.29	0.67
5	34.50	33.17	0.70	29.92	30.33	0.63
6	32.39	31.74	0.41	28.87	28.88	0.39
7	30.95	30.15	1.92	27.11	26.92	1.46
8	31.49	30.28	1.11	26.42	26.81	1.14

Note: Soil temperature data was not available on the first day.

Appendix IV

Windspeed, (km hr^{-1}) and daily evaporation (mm)

	Clay soils		Sandy soils	
	Windspeed	Evap'n	Windspeed	Evap'n
Shaded plot				
Day 1	97.72	1.49	367.45	1.73
2	77.16	0.79	345.25	1.14
3	62.26	0.63	345.52	1.10
4	98 .64	1.49	306.42	0.67
5	139.47	0.68	297.71	0.63
6	180.30	0.73	192.25	0.39
7	110.72	0.67	314.00	1.46
8	106.51	0.47	357.84	1.14
Bare plot				
Day 1	97.72	1.57	367.45	2.35
2	77.16	0.79	345.25	1.22
3	62.26	0.63	345.52	1.04
4	98.64	1.49	306.42	0.65
5	139.47	0.68	297.71	0.70
6	180.30	0.73	192.25	0.41
7	110.72	0.67	314.00	1.92
8	106.51	0.47	357.84	1.11

Appendix V

Relative humidity (%) sunshine hours (hrs) and air temperature (°C) with daily evaporation (mm).

	Rel humidity	Sun hrs	Air temp.	Evaporation	
Clay soils				Shaded	Bare
Day 1	41	8.2	20.95	1.49	1.57
2	40	5.4	21.30	0.79	0.73
3	47	6.6	22.35	0.63	0.92
4	41	8.7	21.70	1.49	1.52
5	32	8.7	21.90	0.68	0.89
6	29	12.0	22.30	0.73	0.74
7	35	12.0	21.90	0.67	0.80
8	29	9.8	23.35	0.47	0.59
Sandy soils					
Day 1	34	12.4	27.75	1.73	2.35
2	33	12.3	25.95	1.14	1.22
3	37	12.5	26.85	1.10	1.04
4	35	12.2	27.35	0.67	0.65
5	33	11.9	28.55	0.63	0.70
6	33	5.3	26.90	0.39	0.41
7	26	7.3	26.55	1.46	1.92
8	33	12.2	26.65	1.14	1.11

Appendix VI

Average evaporation (mm) of shaded and bare plots per period of the day

		Clayey soils	Sandy soils
	Day period		
Shaded	Morning	0.94 ± 0.04	0.93 ± 0.04
	Afternoon	0.83 ± 0.05	1.14 ± 0.05
Bare	Morning	1.15 ± 0.05	1.12 ± 0.06
	Afternoon	0.78 ± 0.03	1.22 ± 0.07

Appendix VII

Mean evaporation for the different depths of the microlysimeters.

		n	Clayey soils	Sandy soils
Depth	10 cm	496	0.94 ± 0.03	1.09 ± 0.04
	20 cm	496	0.92 ± 0.04	1.11 ± 0.04

Appendix VIII

Average net radiation (Wm^{-2}) for the days the radiometers were used.

		Bare plot	Shaded plot
	Ismani		
Day	3 (09/11/94)	213.97	123.36
	7 (13/11/94)	522.19	270.91
	8 (14/11/94)	511.47	269.98
	Hombolo		
Day	3 (23/11/94)	378.75	210.51
	4 (24/11/94)	269.14	113.03