# WATER AND CROP BIOMASS DYNAMICS IN A *Cassia siamea* Lam. AND *Zea mays* L. ALLEY CROPPING SYSTEM

by

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# ABSTRACT

Kanja, Francis M. 1994. Water and crop biomass dynamics in a *Cassia siamea* Lam. and *Zea mays* L. alley cropping system. Major advisor: Dr. Kenneth M. Brown.

Key words: Agroforestry, ground water, Kenya, modelling, semi-arid, simulation.

Alley cropping is a crop production system in which food crops are grown in the alleys created by hedgerows of selected tree species, preferably legumes. The objective of this study was to model a *Cassia* /maize alley cropping system in the semi-arid district of Machakos in Kenya. The modelling was done with respect to the system's ground water dynamics as it affects its biomass production. First the dynamics of water in a bare soil was modelled, and then *Cassia* and maize were introduced separately and their biomass production modelled with respect to water. Finally, a combined *Cassia* /maize/ground water model was build and analysed. The model suggests that water is a critical factor in the biomass production of *Cassia* and maize. The main achievement of this project has been to provide a starting point for a framework in which empirical research results can be integrated and interpreted in a more holistic manner.

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# DEDICATION

To my dear parents,
Mr. Kanja Mukuha and Mrs. Ruth Njambi,
who have worked hard to give me an education.

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I wish to thank God the father of our Lord and saviour Jesus Christ whose grace and love have sustained and enabled me to complete this project.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Definition and scope of alley cropping

This study is an effort to model an agroforestry system called *alley cropping* that is presently in use in the semi-arid areas of Kenya. In alley cropping, food crops are grown in alleys formed by hedgerows of planted woody tree or shrub species, preferably legumes (Kang et al. 1981). The hedgerows are periodically cut back (coppiced) and pruned during cropping to prevent shading, reduce competition with the associated crops, and provide green manure and mulch.

The hedgerow species and the food crop share the major resource pools like light (above ground), and water and nutrients (below ground) (Netondo 1991). Alley cropping is a dynamic system in which available resources and environmental conditions vary over time (Buck 1986).

## 1.2 Importance of alley cropping in Kenya

Most of Kenya's total land surface area is arid and semi-arid, and yet the country has a rapidly growing human population. As the arable lands have become overcrowded, considerable migration has occured to these arid and semi-arid areas. Consequently, the latter have assumed increasing social and economic importance (Sang 1986). To adequately feed the growing population, food production must be increased, particularly in the arid and semi-arid regions.

Alley cropping systems have repeatedly shown their potential in sustaining and increasing food production in the humid and subhumid regions of the tropics (Kang et al. 1981; Ssekabembe 1985). Alley cropping has been recommended for the humid tropics primarily as an alternative to shifting cultivation and to improve soil fertility (Kang et al. 1985).

In the semi-arid areas of the tropics, alley cropping has been introduced with mixed success. On the one hand, during seasons of above-average rainfall, crop yields have been sustained and, in some cases, improved. On the other hand, during seasons of below-average rainfall, competition for moisture between the trees and the crops have severely reduced crop yields (Singh et al. 1989). Nevertheless, there is interest in alley cropping as an alternative to conventional cropping systems in the arid and semi-arid areas of Kenya.

## 1.3 **Why model the alley cropping system?**

This study was motivated by two considerations, namely:

1. my own desire to learn about modelling dynamic systems through the experience of actually building a model;

2. the several practical benefits that stem from efforts to model real systems including: (a) the synthesis of present knowledge, (b) the identification of

gaps in present knowledge, and (c) the discovery of new insights into the dynamics of the system's behaviour.

The broad objective of this study was to develop a simulation model for an alley cropping trial in Machakos District, in Kenya, to enhance further understanding of the system's physical and biological processes that determine its overall productivity and sustainability. The modelling effort was carried out specifically with respect to water dynamics.

## 1.4 **Sources of information for modelling**

The information upon which I have based the modelling of the alley cropping system comes from research activities on alley cropping in Kenya. Research into the potential of alley cropping in the semi-arid regions of Kenya has been going on since 1983 at Katumani National Dryland Farming Research Station. The research which is carried out by Dryland Agroforestry Research Project (DARP) is a joint effort between Kenya Forestry Research Institute (KEFRI), Kenya Agricultural Research Institute (KARI), International Centre For Research In Agroforestry (ICRAF), National Dryland Farming Research Station (NDFRS) and Machakos Integrated Development Program (MIDP).

The major aim of DARP is to develop suitable agroforestry technologies for the semi-arid areas of Kenya and other East African countries with a view to improving the quality of life of the inhabitants (Sang et al. 1985). One of its research objectives is to examine the possibilities for maintaining and increasing the productivity of the cropping system of these areas by establishing an alley cropping system. In this study, the hedgerow species is

*Cassia siamea* while the test crop is maize (*Zea mays* L. cv. Katumani composite B).

Other sources of information include literature on agroforestry, tree physiology, crop physiology and soils.

## 1.5 **Methodology of modelling**

The modelling of the *Cassia* /maize alley cropping system has been facilitated by STELLA II$^{TM}$ (1990 High Performance Systems) application software. The model has been developed in four modules, namely: (i) the ground water dynamics of a bare soil; (ii) the *Cassia siamea* biomass dynamics with respect to water; (iii) the maize biomass dynamics with respect to water, and (iv) the biomass dynamics of *Cassia siamea* and maize with respect to ground water.

Ultimately, a model of the biomass dynamics of *Cassia siamea* and maize with respect to both water and nitrogen, the two most critical environmental factors in Machakos semi-arid conditions, should be developed. This was not done in this thesis because of time constraints. The main achievement of this work has been to provide a framework for integrating empirical research results.

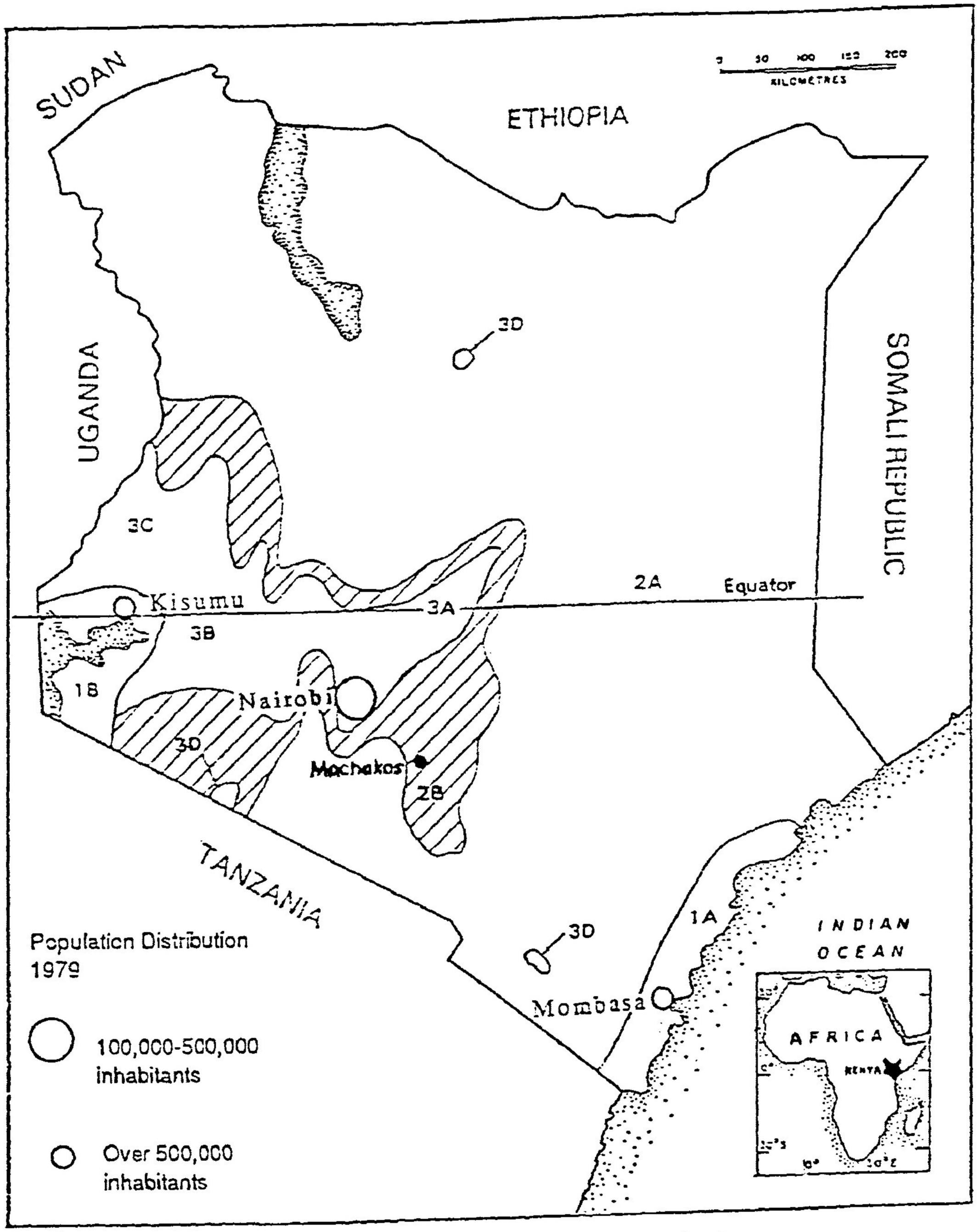
# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Characteristics of Kenya's land

Kenya has a total land surface area of 570,993 km$^2$. Of this, about 83 per cent is characterised as arid and semi-arid receiving less than 900 mm of rainfall per annum. Only about 17 per cent of the land is arable under existing levels of agricultural technology (Figure 1). The arable lands are the only parts of the country that are agriculturally productive, receiving adequate rainfall (greater than 1000 mm per annum) for intensive crop farming. These are also the areas of the greatest population concentration.

The arid and semi-arid lands of Kenya have low agricultural potentials. The major environmental factors that limit crop and livestock production in these marginal areas are rainfall and soil fertility. Rainfall is low and unreliable. In much of the country rainfall is distributed into two rainy seasons of short duration. Each rainy season typically begins with a few days of intense rainstorms. These rainstorms come when the vegetative cover is low and the combined effect is a high rate of erosion (Mungai 1987). The erosion in turn contributes to the loss of top soil and the reduction of soil fertility. The net result of these factors is an often dry and degraded landscape that has little potential for agricultural production.



| Ecological zone | | Rainfall(mm/yr) |
|---|---|---|
| 1A | Coastal Belt | 800-1400 |
| 1B | Lake Basin | 800-1600 |
| 2A | Arid | 150-550 |
| 2B | Semi-arid/Upland Savanna | 450-900 |
| 3A | Central Highlands | 1000-2700 |
| 3B | Kisii/Kericho/Nakuru Highlands | 1100-2700 |
| 3C | Western Highlands | 1100-2700 |
| 3D | Minor Highlands | 800-1200 |

Figure 1. Map of Kenya showing different ecological zones and the Machakos study site. Most of the country's population is concentrated in and around the three main cities shown.

The semi-arid areas are significantly dominated by Low Activity Soils (LAC) whose inherent characteristics and limitations make them unsuitable for conventional, mechanised, and high-input farming methods (Soil Management Support Services 1986). Subsequently, the soil fertility problems in the semi-arid areas are not only related to loss of topsoil but also to the relatively low turn-over of organic matter in the soil.

## 2.2 The effects of population pressure on the land

Kenya has a population growth rate of 3.7 per cent per year (Government of Kenya 1988). This high growth rate has resulted in increased population pressure especially on the arable lands. At the same time, however, there has been a considerable human migration from the high potential areas to the medium and low potential semi-arid areas. These regions have subsequently assumed a greater socio-economic and political importance as small-holding farming and ranching continue to expand from the densely populated areas (Sang 1986).

## 2.3 Agroforestry: A possible solution

Due to an increasing population and low and unsustainable yields in the semi-arid areas, agroforestry has been introduced largely due to evidence that trees and shrubs can be managed to enhance significantly and, to some extent, guarantee the sustainability of agricultural systems (Weber and Stoney 1986). Agroforestry is a low-input technology that can sustain crop production and offer other benefits to the farmer.

Agroforestry is a new word for the old practice of growing woody plants with agricultural crops and/or livestock together on the same piece of land. According to Nair (1984), agroforestry has the most apparent potential in marginal areas and in resource-limiting smallholder systems where monocultural agriculture or forestry may not be most feasible or desirable. Agroforestry involves the deliberate mixture or retention of trees or other woody perennials as part of the crop/animal production enterprises. Thus, as a science, it combines elements of agriculture, whether crop- or animal-based, with elements of forestry in sustainable production patterns on the same piece of land, either simultaneously or sequentially. The reason why the new term agroforestry was coined is because it connotes an interdisciplinary approach to systems of land use. It implies an awareness of interactions and feedback between humans and the environment, and between demand and available resources in a given area, which, under certain conditions, require optimization and sustained management rather than ever-increasing exploitation.

Agroforestry is used primarily to increase agricultural productivity, but it also has the potential to achieve environmental objectives such as halting the spread of deserts and preserving tropical ecosystems. Various types of agroforestry systems exist around the world (Nair 1989).

Ecological interactions between leguminous trees and crops in agroforestry systems are beneficial for three major reasons. First and foremost, leguminous trees have a beneficial effect on soil fertility through nitrogen fixation, greater organic matter production, and recycling of nutrients (Young 1989). Second, a combination of annual crops and trees raises biomass production because differences in rooting depth enable uptake of more water and nutrients (Huxley

1983). Third, trees act as a protective barrier against soil and wind erosion (Ong et al. 1991).

Alley cropping has been recommended for the humid tropics primarily as an alternative to shifting cultivation and to improve soil fertility (Kang et al. 1985). The potential nutrient contribution of alley shrubs is important in so far as the nutrients are made available to arable crops at the time the nutrients are needed (Yamoah et al. 1986b). Thus, a shrub with a large store of nutrients that is released after the food crop is harvested, will be of little value to that crop in terms of nutrient supply. This means that, for a given shrub, information pertaining not only to nutrient content but also the rate of decomposition and release of nutrients is important. Alley cropping is an effective means of using trees and woody shrubs to hasten organic soil fertility restoration (Wilson et al. 1986). Its major feature is the ability of the deep-rooted species to absorb from the lower soil strata soil moisture not available to annual crops. This moisture allows them to remain functional in the dry season, using the abundant radiant energy of this season to run a biological factory that recycles nutrients, fixes nitrogen (when legumes are used), synthesizes organic matter, pumps water into the atmosphere, and shades the soil, thus providing a more favourable environment for the activities of beneficial soil organisms. It has been demonstrated that such a system of management can contribute significant amounts of nutrients to the companion crop which may lead to higher yields without the use of costly fertilizers (Mugendi 1990).

The success of alley cropping systems depends mainly on three factors, namely (i) choice of suitable woody species, (ii) successful establishment of the hedgerows, and (iii) appropriate management of the hedgerows (Kang et al. 1990). The tree species selected must have certain basic characteristics which should include ease of establishment, a deep root system, fast growth, tolerance to pruning, ability to coppice vigorously, high foliage productivity and compatibility with the crop (Kang et al. 1984).

From the early research work carried out at the DARP site on-station trials (1983-1985), it appeared that during the first three seasons of the developmental phase of the alley cropping system, when the *Cassia* hedgerows were establishing, the maize rows adjacent to the hedgerows performed better than the maize rows in the middle of the alleys in terms of dry weights of stover, cobs and grains. This was perhaps due to improved availability of growth factors such as moisture, light and nutrients, particularly moisture for the maize plants caused by (i) less competition owing to the fact that the neighbouring tree seedlings were still small and therefore less competitive than maize, and (ii) more aeration and soil moisture in the hedgerows due to more than average site preparation before planting of the hedges (Sang and Hoekstra 1986). This trend was reversed during the last season of the developmental phase when the maize rows in the middle of the alleys performed better. The trend continued into the operational phase, when the hedges were better developed and coppicing started.

The maize rows closest to the hedgerows were being negatively affected most likely due to competition for soil moisture and nutrients between the now well-developed hedges and maize. When mulch was incorporated into the soil, the maize yield increased in the range of 36-122% between the treated plots (where mulch was incorporated) and the untreated ones (Sang and Hoekstra 1986).

## 2.4 **Characteristics of *Cassia siamea***

*Cassia siamea* is a deep-rooted leguminous lowland evergreen tree species that is believed not to fix atmospheric nitrogen, but is known to hold large amounts of nitrogen in its foliage and appears capable of improving soil nitrogen (Young 1989). It is native to southeastern Asia from Indonesia to Sri Lanka and grows in humid, subhumid, dry and arid climates. In drier areas with 500-700 mm annual rainfall, the tree grows well after the second or third year of planting and is promising for alley cropping on acid soils. It can yield as much as 10 tons/ha dry matter per year (Yamoah et al. 1986b). The tree coppices vigorously, producing 2-5 shoots per stock, and on average, 70% of the biomass consists of leaves as compared to 33-60% for *Gliricidia sepium.* The leaves can potentially provide nutrients for growing crops such as maize, and the branches provide fuelwood which doubles the economic returns when trees and crops are grown together.

Yamoah et al. (1986a) found that *Cassia* prunings decompose at a rate of 85% of dry biomass in 120 days as compared to 100% for *Gliricidia* . They suggested that the slow rate of decomposition of *Cassia* when applied at the surface may be important for soil moisture conservation, soil temperature regulation and weed control. Upon decomposition, *Cassia* leaves can provide nutrients for growing crops, but prunings applied as mulch may lose nitrogen through volatilisation or through leaching in sandy soils. Nutrients are released 3-6 weeks after pruning application. Other benefits of *Cassia* as a multipurpose agroforestry species include soil conservation (Young 1989).

## 2.5 **Dynamics of an alley cropping system**

Since alley cropping is a dynamic system, with available resources and environmental conditions varying over time (Buck 1986), the compatability of growing the perennial tree with the annual crop needs to be ascertained. Major resource pools like light (above ground), and water and nutrients (below ground) will have to be shared (Netondo 1991). Above-ground or atmospheric interactions will include changes in the microclimate, such as shading, temperature, windspeed and humidity (Monteith et al. 1991), while below-ground interactions will include greater exploration and competition for water and nutrients. Competition below-ground is known more from its manifestations in the growth and ultimate yield of the crop components than by its mechanisms (Caldwell 1986). This is especially so in semi-arid regions where rainfall and inherent soil fertility levels are generally low and competition for these scarce resources is bound to be intense. Effective management techniques for alley cropping can affect biomass production and the allocation of the available resources by controlling inter-crop and intra-species competition (Buck 1986).

### 2.5.1 **Water dynamics in a bare soil**

A satisfactory knowledge of the soil profile water movement and storage is essential to the understanding of the water balance in an alley cropping system, and would help in the management of alley cropping. Infiltration, evaporation, and deep percolation depend, to a certain degree, upon the water content of the soil profile (Black et al. 1969). Evaporation rates in semi-arid areas are usually very high. Evaporation from bare wet soil surfaces is primarily influenced by the energy available for evaporation (Ritchie 1972). As surface drying proceeds, evaporation becomes more dependent on the hydraulic properties of the soil near the surface.

According to Singh and Dickinson (1975), the wetting of a soil profile depends on rainfall, the driving variable. When a soil profile is envisaged as comprised of distinct soil zones, wetting occurs in a sequential order from the uppermost zone to the lowest zone, each filling to capacity before discharging to the next lower zone. There is usually a maximum amount of water that a given zone can hold.

When rain occurs, the moisture content of the uppermost zone begins to fill. The amount of water in excess of the maximum capacity of the zone, is percolated down into the next zone. The second zone then fills up to its maximum capacity and then any excess percolates into the third zone.

Under unsaturated conditions, as is mostly the case in the semi-arid areas, the drying of zones is caused by evaporation while under saturated conditions by both evaporation and vertical drainage (Singh and Dickinson 1975). Actual evaporation (AE) is considered to be a function of potential evaporation (PE) and available soil moisture. It is generally agreed that water is almost equally available to plants up to a point where the demand rate for particular evaporation conditions exceeds the supply of water from the soil to plant roots.

Beyond this point, the AE/PE ratio decreases with decreasing soil moisture content.

### 2.5.2 Plant rooting characteristics and competition for soil moisture and nutrients

In all types of vegetation, the main functional problem for competing root systems is competition for scarce water and nutrients. The ability of an organism to grow and reproduce depends on its success in capturing resources from its environment, often in competition with neighbours. When there is only one species in a stand with a uniform genetic base, resources appear to be shared equitably except when overcrowding makes self-thinning unavoidable (Monteith et al. 1991). In stands with more than one species, both above- and below-ground competition for limited resources is inevitable. However, competition can increase production by the system as a whole or can help to stabilize outputs when the supply of resources is erratic. An intercropping experiment in southern Mexico, involving maize and cowpea, clearly indicated an increase in the production of the system as compared to a bush fallow case (Vandermeer 1989).

Mungai et al. (1989a) indicated that both the soil moisture, as determined by amount and distribution of rainfall, and soil nutrients are the most critical factors in Machakos district in ensuring that the productivity potential of the alley cropping system is realised. In seasons of good rainfall, the productivity of the maize in the alleys is higher, row to row, than in the controls. This is probably as a result of increased soil fertility due to mulching in the alleys. During poor rainfall seasons, however, the productivity is reversed in that the maize in the controls perform better than those in the alleys. This latter observation could possibly be attributed to less competition for moisture among individual maize plants in the controls and more competition for moisture between the *Cassia* hedges and the maize plants in the alleys. In other words, soil nutrients become critical in seasons of good rainfall while soil water becomes critical in seasons of poor rainfall.

The degree of competition between the *Cassia* hedges and maize crop will depend on the density of component crops, and more importantly, on the soil horizons from which they predominantly extract water. This would in turn be determined by the rooting depths of the two components. The root length per volume of soil is the relevant parameter with respect to water and nutrient uptake (Bohm 1979; Anderson and Ingram 1989; Van Noordwijk 1989). Under limiting water conditions typical of semi-arid zones, *Cassia* would out-compete maize for water and nutrients because of the overlap of the active roots of the two components in space and time (Umaya 1991). The constant lopping of the *Cassia* hedgerows (done at least once in a cropping season) results in the reduction of the shoot system. This in turn reduces the *Cassia* root system and hence the overlap of the *Cassia* /maize root systems.

Competition for soil moisture and nutrients, the two most critical environmental resources especially in the Machakos semi-arid situation, is inevitable among the physiologically active roots of the tree and crop components in an alley cropping system. The relative distribution of roots with respect to soil depth plays an important role in the water uptake patterns of plants (Gardner 1983). Therefore, knowledge of both spatial and temporal root distribution is extremely important (Netondo 1991). Such knowledge is useful in evaluating the moisture uptake with depth and distance and hence the degree of competition to be expected (Leyton 1983).

Rooting depth is an important issue in situations of potential competition for soil moisture and nutrients between various plant species (Leyton 1983). Plants with deep roots would be expected to survive better during dry periods than ones with shallow roots. Rooting depth is determined by genetic characteristics of the plant and is affected by soil and climatic conditions (Huck 1983; Leyton 1983). Leyton (1983) suggested that a better measure of root activity than rooting depth is the root length density (RLD) expressed as rootlength (m) per $m^3$ of soil. This varies substantially between species with monocots generally having greater RLDs than dicots (Kummerow 1980). Prajapati et al. (1971) found that prosopis roots are confined to the top 20 cm of the soil, which had a high chance of getting wet even when only small showers of rain were received. Root density plays an important role in competition. A plant with a massive root system may be more effective in depleting soil resources in a localized zone than a neighbouring one that has less roots, since the roots occupy a great volume of the soil (Caldwell 1986). However, it should be remembered that it is mainly the fine roots that are responsible for water and nutrient uptake rather than the whole mass of the plant's root system.

Trees in general are assumed to be deep rooting, while annual crops are often shallow rooting. Such a characteristic would be desirable in agroforestry systems such as alley cropping since the roots of trees or shrubs would not greatly overlap with those of annual crops, both spatially and temporally. This would not only mean that the trees or shrubs would compete less with the crops, but that the tree roots could act as a trap for nutrients leached out of the topsoil (Connor 1983; Buck 1986; Jonsson et al. 1988). Spatially, the effective root systems of woody perennials tend to be deeper than non-woody perennials with annual crop components having the shallowest root system (Buck 1986). However, for plants growing under xeric conditions, the roots occupy only the surface layers of the soil (Prajapati et al. 1971).

Root distribution studies have been done under various climatic conditions. In an experiment carried out in the semi-arid environment of India, Singh et al. (1989) found *Leucaena* roots to be more densely concentrated above 1.0 m soil depth for three distances from the hedgerows of 0.5 m, 1.5 m, and 3.0 m respectively. Jonsson et al. (1988) studied the vertical distribution of fine roots (less than 2.0 mm in diameter) of *Cassia siamea, Eucalyptus tereticornis, E. camaldulensis, Leucaena leucocephala and Prosopis juliflora* as well as those of maize grown in close proximity. They found most fine roots of the tree species occupying a similar depth range as that of maize roots. *Cassia* and *Leucaena* had more root mass than maize in the first 60 cm of the soil depth. Kang et al. (1981), on the other hand, only found small amounts of *Leucaena* roots in the surface soil, beyond a distance of 1.0 m from the hedgerows. *Leucaena* was therefore described as having a deep rooting habit, reducing the chances of competition for moisture and nutrients with maize plants.

The presence of competition for soil moisture between perennial trees or shrubs and annual crops is evidenced by different soil moisture profiles and horizontal soil moisture gradients . This has been demonstrated for various tree/crop interactions under varying climatic conditions. Recently, Singh et al. (1989) used polythene root barriers in a *Leucaena* alley cropping system and showed that the presence of the barrier allowed all distances from the hedge to have uniform moisture, but in their absence more moisture occurred further away from the hedge. More soil moisture was also found in the monoculture plots. Under semi-arid conditions of Machakos district, studies on the effect of *Grevillea robusta* hedgerows on maize clearly showed that the drier soils were adjacent to the hedgerows, while the more moist soils were further away (Huxley et al. 1989). In a more humid environment in Nigeria, soil moisture was found to decrease away from the *Leucaena* and *Gliricidia* hedgerows (Lal 1989a). The higher soil moisture content close to the hedgerows may be due to shading, low evaporation (wind effect) and the concentration of water run-off by the hedge barrier. Under conditions of moisture stress, however, *Leuceana* may out-compete adjacently grown maize crop more aggressively than *Gliridicia* (Nair 1987).

### 2.5.3 Effects of soil water on the growth of *Cassia siamea* an maize

Soil water plays an important role in determining the amount of *Cassia* leaf biomass produced at the end of every growing season. The response of *Cassia* to soil water is mediated via its water status (Stanhill and Vaadia 1979). *Cassia* leaf biomass production would be maximised when its water potential is high (Kozlowski et al. 1991).

The rate of growth of *Cassia* is affected by the genetics of the species, climate, soil and the pruning regime. *Cassia* is known to be a prolific biomass producer relative to *Gliricidia* and *Flemingia* and, if all the *Cassia* dry matter should decompose to release nutrients for crop use, a good crop establishment could be expected under alley cropping with *Cassia* (Yamoah et al. 1986a). Using *Leaceana leucocephala, Gliricidia sepium*, and *Sesbania grandiflora* alley cropped with maize and cowpea, Duguma et al. (1988) found that pruning frequencies of three, two and one months progressively reduced dry matter yield as compared with six-monthly pruning. They also found that lower pruning heights had a smaller but still substantial effect. Thus the frequent prunings that are desirable to reduce shading may have an adverse effect on tree growth (Young 1989).

Inadequate soil moisture is often a major limiting factor in agricultural production in many parts of the world, including Kenya, in which approximately 85% of the total land area suffers soil-moisture inadequacy with respect to crop production (Mugah and Stewart 1984). Maize has a total water requirement of about 40 to 60 cm of evapotranspiration (Downey 1971a). The total water used in evapotranspiration varies considerably with the water available, climatic environment, and the soil and water management practices.

The available soil water for maize during its growth and development comes from the amount of growing-season rainfall and from moisture stored in the soil before planting. Rainfall, as a variable to relate to maize growth and yield, is good as an estimator of the available soil moisture and therefore the moisture status of the plant. Water use varies with the stage of development of the maize crop. There is also a considerable variation in water use by maize from season to season (Downey 1971a).

Moisture stress interrupts photosynthesis and checks growth until turgor is restored (Kozlowski et al. 1991). The magnitude of yield reduction from water deficits in maize is dependent upon the growth stage at which the water deficiency occurs, and the severity and duration of the deficiency (Jurgens et al. 1978). Early in the growing season, water is lost through evaporation from a bare soil. As the crop cover increases, transpiration becomes an increasingly dominant factor (Kramer 1983).

## 2.6 **Crop performance in alley cropping systems**

Leuceana (*Leuceana leucocephala* ) and gliricidia (*Gliricidia sepium* ) trees are well known for nitrogen fixation and soil fertility restoration (Guevarra et al. 1978; National Research Council 1984). Wilson et al. (1986) reported that maize grown in alley cropping with both leuceana and gliricidia responded significantly to the addition of the tree leaves to the soil, as compared to treatments where the leaves were removed. When leuceana alley cropping was tested over a five-year period on the low fertility Apomu loamy sand, maize yield declined in the control where leuceana leaves were not applied to the soil, but was maintained and was significantly higher than the control where the leaves were applied. In a field study on alley cropping involving *Gliricidia sepium, Flemingia congesta* and *Cassia siamea* at the IITA, Ibadan, Nigeria, Yamoah et al. (1986a) reported that the overall performance of maize in the alley cropped plots irrespective of their positions in the alleys was better than in the control (sole crop maize) plot.

In the semi-arid Machakos district in Kenya, Mugendi (1990) showed that using *Cassia siamea* loppings as green manure improved the yields and the nutrient levels of maize. He suggested that alley cropping systems may result in the additional nutritional value of the grains as evidenced by higher concentrations of nutrients in the maize grains of the treated plots as compared to the controls. Kang et al. (1986) suggested that the higher maize yields attained in alley cropping under humid conditions may be partly due to improved and maintained chemical, physical and biological soil conditions through the addition of prunings.

## 2.7 Systems dynamic modelling approach

### 2.7.1 Definition and scope of systems approach

A system may be defined as an organised collection of interrelated physical components characterised by a boundary and functional unity (Grant 1986). For example, the human heart, lungs and bloodstream are a physiological system that functions to provide oxygen to the body. The systems approach is a way of thinking about complex systems (Loomis and Whitman 1983). It emphasizes the connections among the various parts that constitute a whole.

The early analyses of biological and engineering systems shared a common emphasis on the way in which system components work together to perform some well-defined function (Roberts et al. 1983). Wierner (1948) both named and sketched the outlines of a new field of inquiry known as cybernetics, which became the study of how biological, engineering, social and economic systems are controlled and regulated. As a broad problem-solving strategy, the concepts of systems analysis have found a wide application in various fields having emerged into an accepted body of theory (Dent and Anderson 1979). For example, Karl Deutsch (1963) laid out a cybernetic view of political processes in his own classic work *The Nerves of Government*. Herbert Simon (1965) proposed a cybernetic view of human intelligence.

The broad principles of cybernetics were first applied to industrial systems by Forrester (1961). His initial work in industrial systems has been subsequently broadened to include other social and economic systems and is now known as the field of system dynamics (Roberts et al. 1983). The system dynamics approach is a powerful technique that uses computers to simulate the dynamics of structured relationships of a system. The result is a simulation model.

Simulation may be considered to embrace two distinct operations. The first is the development or synthesis of a model that adequately represents the system under investigation. It is implied that such a model will react in much the same way as the real system does to changes in its structure or in management strategies. The second operation is an examination of the behaviour of the model in reaction to such changes (Dent and Anderson 1979).

Simulation models are an important adjunct to experimental research (Connor 1983). Simulation models based on soil, crop and weather factors are useful to characterize environments quantitatively in terms of production potential and can be used as tools for planning alternate strategies for cropping and land use (Huda and Ong 1987).

### 2.7.2 **Characteristics of systems dynamic approach**

Systems dynamic behaviour patterns are generated by the working of closed-loop processes (Richmond et al. 1990). There are three critical aspects of the system dynamics approach to developing computer simulation models (Roberts et al. 1983), namely: thinking in terms of cause-and-effect relationships, focusing on the feedback linkages among components of a system, and determining the appropriate boundary between the system and its environment. The following is a brief description of these three aspects.

(i) Causal thinking: This is the key to organising ideas in a systems dynamics study. Typically one would isolate key causal factors and diagram the systems of causal relationships before proceeding to build a computer simulation model.

(ii) Feedback mechanism: While thinking in terms of causal relationships is necessary to cast a problem in a form that can be analysed using system dynamics, it is not sufficient. Causal chains can often be linked together nearly endlessly to create an undisciplined morass of causal relationships. One way to clarify the representation of a system is to focus on circular chains or causal loops rather than one-way causal relationships. Within a causal loop, an initial cause ripples through the entire chain of causes and effects until the initial cause eventually becomes an indirect effect of itself, a process called feedback. A simple causal loop, which can be regarded as a feedback system, is the basic unit in building a systems dynamic model.

There are two types of closed-loop processes which are distinguished by the type of behaviour that each generates. The first type, called a negative feedback loop, generates *homing in* behaviour. It seeks to maintain the status quo by restoring the system to where it was, before something came along to disturb it. The second type, called a positive feedback loop, generates run-away growth or collapse. A positive feedback loop does in actuality generate a *homing in* behaviour, but it does not appear to because the target it tries to *home in* is moving (Richmond et al. 1990). It is like trying to catch your shadow. The faster you pursue, the faster the target recedes. The faster it recedes, the faster you pursue. Combinations of positive and negative loops are capable of generating a wide variety of dynamic behaviour patterns.

(iii) system boundary: A system boundary is a demarcation that determines what is included in the system and what is not. Identifying a system's boundary is the complex process of defining the size, scope, and character of the problem being studied.

# CHAPTER 3

# CHARACTERISTICS OF THE EXPERIMENTAL SITE AND LAYOUT

## 3.1 Site Description

### 3.1.1 Location, climate, soils and vegetation

The experimental site for the alley cropping trial is the Katumani Dryland Agroforestry Research Project site. The site is located in Machakos District in Kenya at about 70 km south east of Nairobi (Figure 2). It is situated at a mean altitude of 1560 m above sea level, and at 1° 33' latitude and 37° 14' longitude.

According to Jama et al. (1989) the site lies within the subhumid to semi-arid climatic zone with an average annual rainfall of about 700 mm. The rainfall is bimodal in nature, with an average of about 270 mm for the first season and 250 mm for the second season. The first rainy season normally runs from late March to the end of May, whereas the second rainy season is from late October to late December. There is a high variation in the amount and distribution of rainfall received annually. The average annual temperature is 19.2° C with the lowest monthly average in August (17.1° C) and the highest in March (21.3° C). The potential evapotranspiration rate is approximately 1800 mm per year, creating a deficit of about 1100 mm per year. The wind blows mainly from an easterly direction (80 to 100 degrees), with average monthly speeds ranging from 7.2 to 12.0 km/hr.

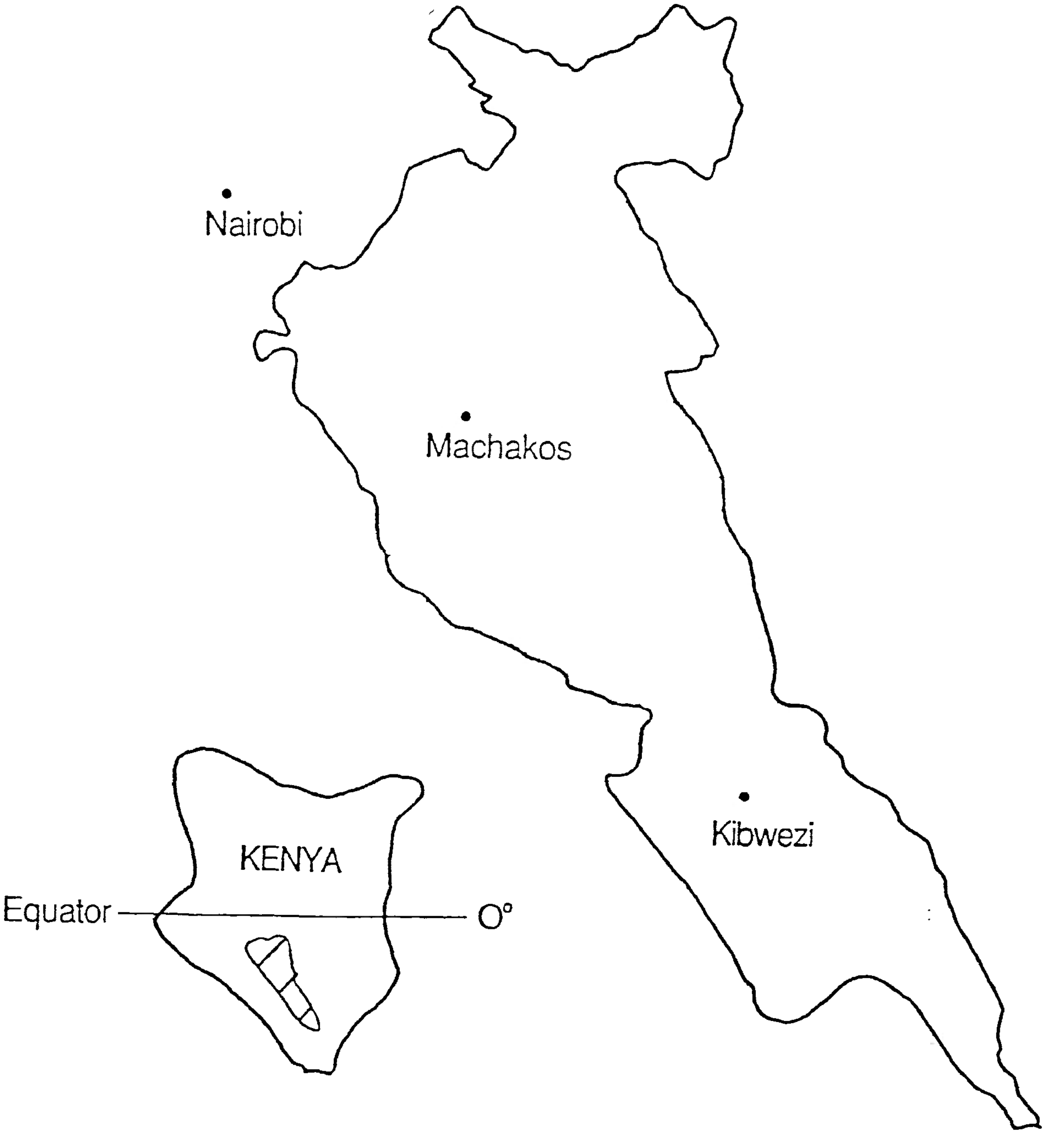


Figure 2. Location of the *Cassia* /maize alley cropping system research trial, in Machakos, Kenya.

The predominant soil type is a well-drained, dark reddish-brown sandy clay (Kibe et al. 1981). It is hard when dry, friable when moist, and sticky plastic when wet. This soil is of moderate fertility (1.0 to 1.5% top soil organic carbon with a pH of 6.0 to 6.5). It has a water-storage capacity of 1000 mm and a medium depth range of 80 to 120 cm. This soil is classified as Oxic Paleustalf (Chromic Luvisol; FAO, and Kenya soil classification systems). It is moderately leached and highly erodible . The natural vegetation is formed predominantly by members of the genus *Acacia* and the genus *Combretum* .

## 3.2 **Design and layout of the experiment**

The experiment was laid out in November 1983 as a one-way, completely randomised design structure with three treatments and four replicates (Table 1). Treatments 1 and 2 are collectively referred to as the agroforestry plots while treatment 3 is referred to as the control.

Within each plot, except control plots (treatment 3), four hedges were established at a between-hedgerow spacing of 3.6 m. In-row spacing for *Cassia siamea* was 0.25 m for treatment 1 and 1.0 m for treatment 2. The dimensions of each plot are 10 m in length and 10.8 m in width (Appendix 1).

At the beginning of every cropping season, *Cassia* is lopped to a height of 0.5 m. The woody materials are separated from leaves and twigs. The leaves and twigs are weighed and then evenly spread in the alleys and ploughed into the soil. Incorporation of mulch is done in such a way that the amount applied corresponds to the prunings in each plot. The established practice is to incorporate loppings obtained at the beginning of the cropping season into the soil while subsequent loppings, if any, are spread out on the soil surface. Mulch is not applied to the control plots.

Table 1. Treatment structure of the Machakos field trial.[a]

| Treatment number | Hedgerow species | Between-row spacing | In-row spacing |
|---|---|---|---|
| | | ................. m | ....................... |
| 1 | *C. siamea* | 3.6 | 0.25 |
| 2 | *C. siamea* | 3.6 | 1.00 |
| 3 [b] | none | — | — |

[a] The design structure is completely randomised with each treatment combination replicated 4 times.

[b] Treatment 3 is the control.

Planting is done before the rains start. Three rows of maize (*Zea mays* L. cv. Katumani composite B) are grown within each alley of the agroforestry plots. Five rows of maize are sown in the control plots. In either case the maize is sown at a 0.9 m between-rows and 0.3 m in-rows. Thus, in the control plots, each hedgerow is replaced by a row of maize. This adds up to a total of nine maize rows for agroforestry plots and thirteen rows for control plots. Maize is normally planted twice a year in conformity with the bimodal pattern of rainfall in this area.

## 3.3 Measurements

### 3.3.1 Meteorological data

Meteorological data were obtained from the International Centre For Research In agroforestry (ICRAF) field station's weather unit, which is located about 100 m from the study site. Meteorological data were collected from the first cropping season of 1986 to the second cropping season of 1989, a total of eight cropping seasons. The meteorological data, collected daily, consisted of rainfall, air temperature, windspeed, total net radiation, potential and actual evaporation, air water vapour pressure and air saturation deficit.

### 3.3.2 Biological data

Since the start of the operational phase of the alley cropping trial (second season of 1985) lopping of *Cassia siamea* hedgerow biomass has been carried out once at the beginning of every cropping season. The amount of green organic matter applied to the plots was measured and recorded. At the harvest of the maize crop, the following measurements were taken: grain, cob, and stover yield (in kilograms) per plant per row. The root distribution and root densities for both *Cassia* and maize for the second season of 1989 and first season of 1990 are also included.

## 3.4 Stella II

I modelled the *Cassia* /maize alley cropping system by means of a simultaneous system of difference equations. I used an Apple Macintosh application program called STELLA II$^{TM}$ (1990 High Performance Systems). Stella is a system dynamics modelling package that can be used to build an understanding of the dynamics generated by systems involving interdependent relationships (Richmond et al. 1990).

The details of the procedures used in formulating and analysing the model are found in the next four chapters. I mainly focused on the dynamics of ground soil water as it interacts with and influences the growth and production of the *Cassia siamea* hedgerows and the maize crop.

# CHAPTER 4

# BARE SOIL/WATER MODEL

## 4.1 Introduction

The real *Cassia* /maize alley-cropping system is exceedingly complex. In order to organize my own thinking about how to model this system, I began by considering a much simpler situation: the ground water dynamics of a soil devoid of plant cover. I further simplified reality by conceiving of the soil as composed of discrete horizontal layers, which I called *zones* . In my model (Figure 3 and Figure 4), there are three such zones as follows:

zone 1: soil surface to 20 cm depth
zone 2: 20 cm to 40 cm
zone 3: 40 cm to 60 cm

I assumed that the water found below 60 cm formed the ground water storage. I based my choice of the soil zones on the work of Netondo (1991) who studied soil moisture distribution for three soil depths of 15-20 cm, 35-40 cm and 55-60 cm, and Umaya (1991) who studied root distribution for both maize and *Cassia* for three soil depths of 0-10 cm, 20-30 cm, and 40-50 cm. Netondo (1991) and Umaya (1991) carried out their research work on the *Cassia siamea* /maize alley-cropping experiment of the Katumani Dryland Agroforestry Research Project, upon which the present study is based as well.

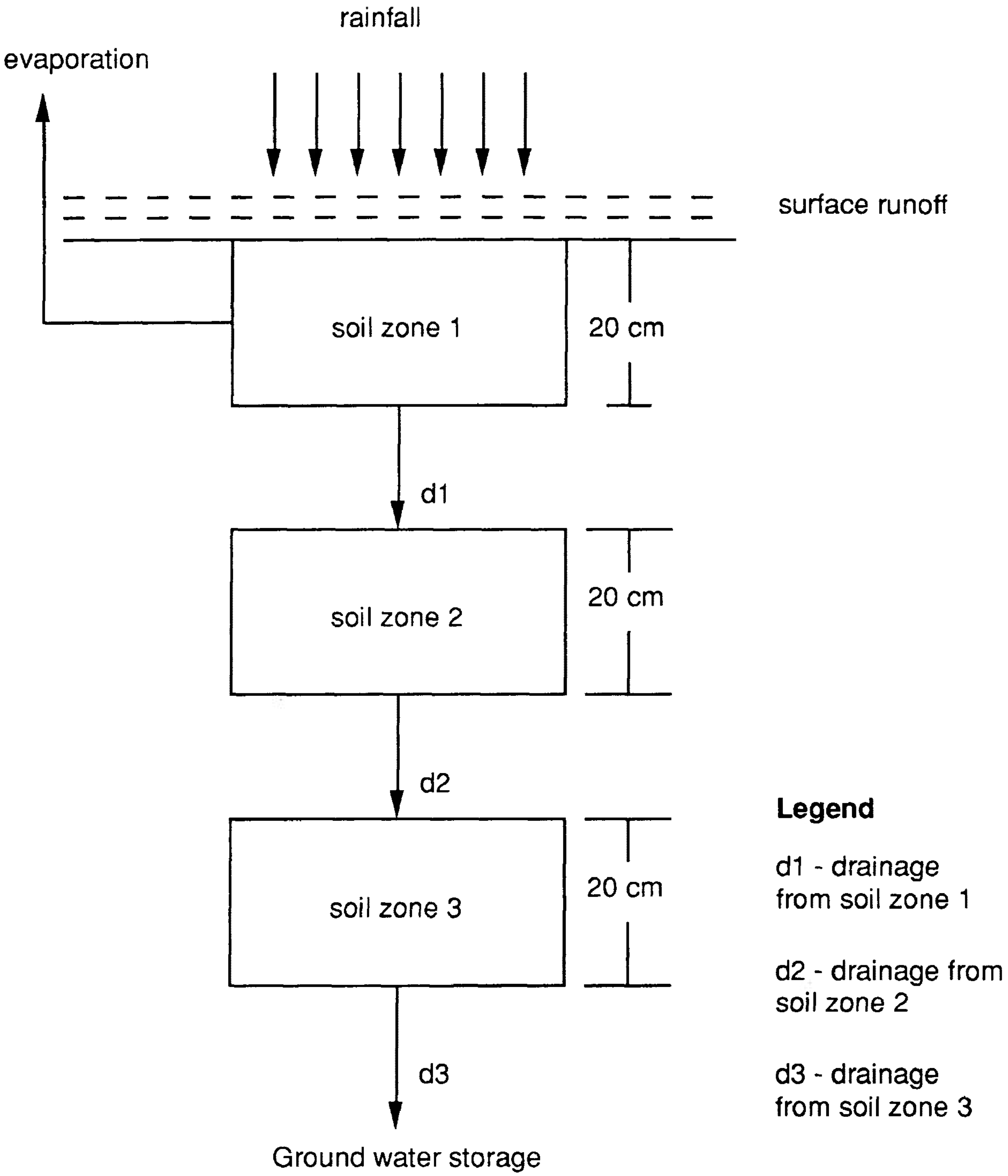
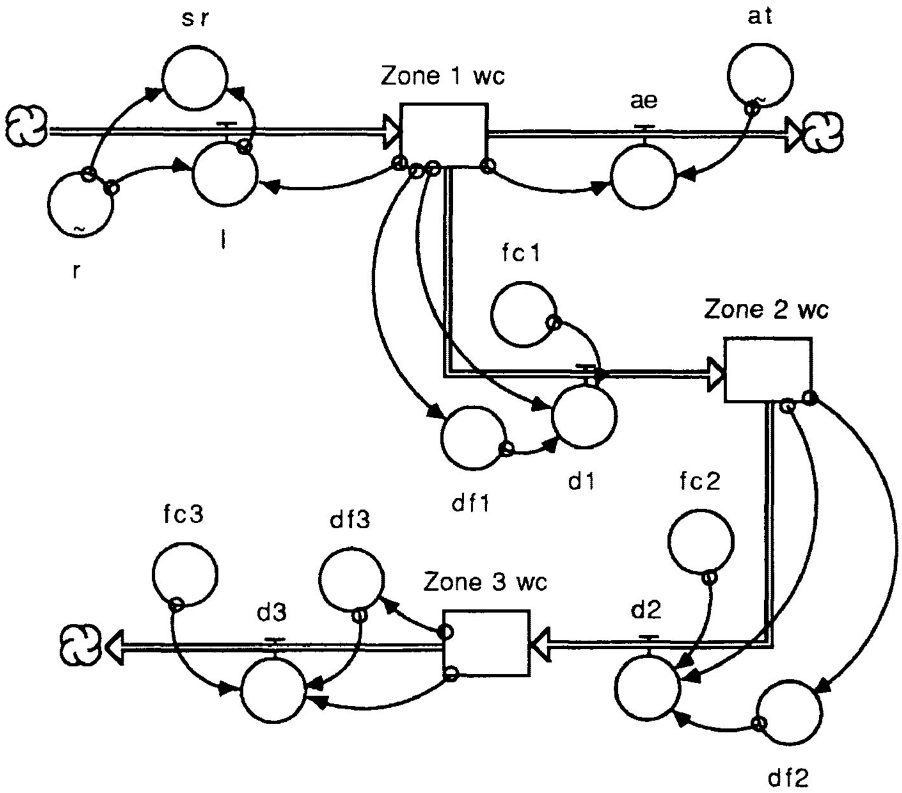


Figure 3. Schematic model of the bare soil/ground water dynamics



**Legend**

zone$_i$ w c = water content of the $_i$th soil zone (kg/ha), where i = 1,2,3.
$d_i$ = water drainage from the $_i$th soil zone (kg/ha), where i = 1,2,3
$df_i$ = water drainage rate from the $_i$th soil zone (kg/ha), where i = 1,2,3.
$fc_i$ = field capacity for the $_i$th soil zone (kg/ha), where i = 1,2,3.
r = rainfall (mm/ha)
I = infiltration (kg/ha)
sr = surface runoff (kg/ha)
ae = actual evaporation from zone 1 (kg/ha)
at = actual temperature ($^{o}$ C)

Figure 4. Structure of the bare soil/ground water simulation model.

The soil water dynamics within each zone obeys the following rule:

$$\text{Zone}_i(t) = \text{Zone}_i(t-\Delta t) + I_i \Delta t - d_i \Delta t \tag{1}$$

where:

$t$ = time;

$\Delta t$ = a discrete step in time (e.g. 1 day);

$\text{Zone}_i(t)$ = the ground water content of zone i at time t (kg $ha^{-1}$);

$I_i$ = the water influx into zone i during $\Delta t$ (kg $ha^{-1}$ $day^{-1}$);

$d_i$ = the water outflow from zone i during $\Delta t$ (kg $ha^{-1}$ $day^{-1}$).

In plain language, this rule is read, " The ground water content of zone i at time t *is equal to* the water content of the same zone at time (t- $\Delta t$) *plus* the influx of water to zone i during $\Delta t$ *minus* the outflow of water from zone i during $\Delta t$."

## 4.2 Details of the model

The actual details of the model vary somewhat from zone to zone. I assumed that the entire soil profile is homogeneous and that each of the three soil zones is homogeneous and isotropic. Thus, the field capacities are the same in each of the soil zones. I also assumed that the rate at which water drains into the next soil zone is the same for all the three soil zones. The single state variable in this model was the average soil water content of a 20 cm thick soil zone.

### 4.2.1 **Rainfall distribution**

Rainfall is the driving variable for the bare soil/ground water model. I modelled the historical (from the first rainfall season of 1986 to the second rainfall season of 1989) rainfall pattern of the ICRAF'S Machakos field station by means of a graphical function[1]. Each rainfall data point is a daily average amount of rainfall. Since my interest was to look at the water dynamics of the first and second rainfall seasons, I calculated the median of the rainfall data for all the four first seasons and all the four second seasons. This formed my new raw rainfall data to which I subjected the *smoothing procedure of running medians* (Tukey 1977). I used the median because it is less sensitive to the extreme values of the data (McCall 1982).

I used the *smoothing procedure of running medians* to separate the underlying trend (smooth) from the noise in the raw rainfall data . The raw rainfall data can be thought of as the sum of two components:

rainfall data = smooth + rough (noise)

The objective of smoothing is to extract the *smooth* from the data. To begin smoothing, I looked at the first 3 input values and extracted their median. Then, I slid the interval along one value and extracted a second median. I repeated this procedure up to the end of the data sequence. This formed the first pass of running medians or what Tukey (1977) calls 3-smooth. I performed a second pass using the running medians of the 3-smooth. This gave me a second set of running medians or 3R-smooth. I used the 3R-smooth data to

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[1] A graphical function is used in Stella II program to depict a relationship between two variables. It is used in place of an equation.

second set of running medians or 3R-smooth. I used the 3R-smooth data to construct the rainfall distribution graph ( Figure 5). I stopped at the 3R-smooth because the medians were not significantly different from the ones of 3-smooth. The idea is to calculate running medians until the results are stable. Appendix 2 clearly demonstrates this procedure.

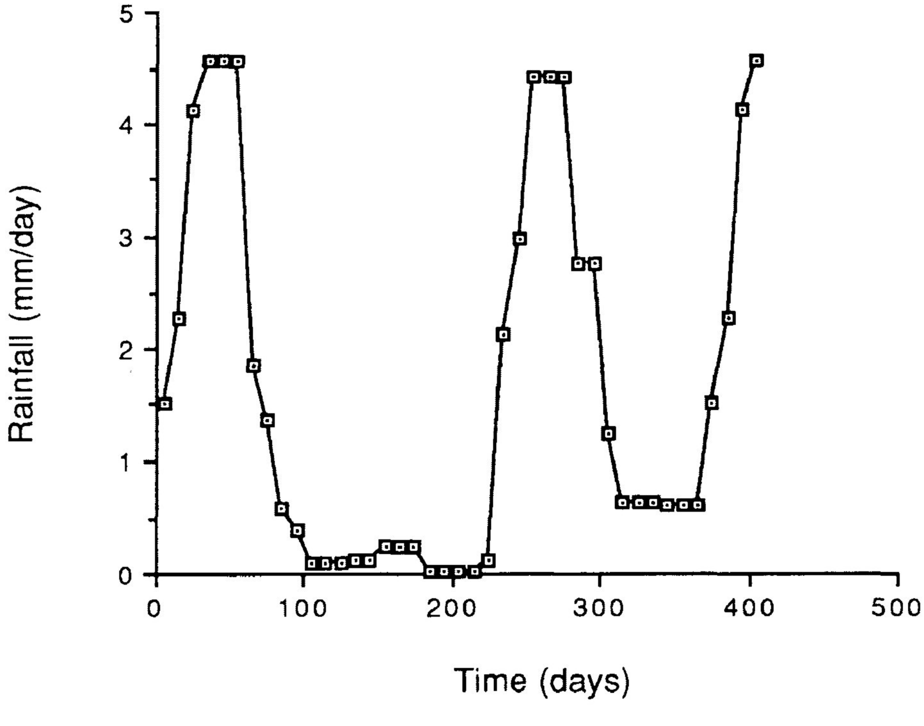


Figure 5. The median rainfall distribution for ICRAF'S Machakos field station from 1986 to 1989.

During a simulation run, STELLA looks at the rainfall graphical function on a particular day and reads the rainfall for that day. This amount of water is then taken to be the current input to zone 1. Appendix 3 gives all the mathematical equations for the variables in the bare soil/ground water model.

The dry period following rains for the first cropping season is, on average, much longer than the dry period that follows rains for the second cropping season (Figure 5).

### 4.2.2 **Water dynamics of zone 1**

On a daily basis, zone 1 receives water from the atmosphere in the form of rainfall. This rainfall is measured in mm but, since I follow the water dynamics in *Cassia* and maize in terms of how many kilograms of water per hectare there is, I multiplied the daily rainfall input per hectare by 10000 to convert into kilograms of water per hectare. I did this conversion at the infiltration stage.

Once simulated rainfall is received at the soil surface, some infiltrates into zone 1 and results in an increase of the soil water already held in that zone and some runs off on the soil surface. I modelled the amount of rainfall that infiltrates into the soil as a function of rainfall for that day and the water content for zone 1. If the water content of zone 1 is below the field capacity, then all of the simulated rainfall infiltrates into zone 1. Otherwise, infiltration is modelled as follows:

$$\text{Infiltration} = 10000{*}\text{Rainfall}\ {*}(2-(1/450000){*}\text{zone 1 w c}) \qquad (2)$$

In equation (2) I assumed that the amount of rainfall that infiltrates into the soil linearly depends on the amount of moisture content of zone 1 (Figure 6). I also assumed a field capacity of 450000 kg $ha^{-1}$ and a maximum retentive capacity of 900000 kg $ha^{-1}$ for zone 1 (Ulsaker and Kilewe 1983). The coefficient of 10000 that appears before the variable rainfall in equation (2) is the conversion factor for rainfall. The rest of the coefficients in equation (2) are based on the above assumptions.

On the other hand, I modelled surface runoff as the difference between the rainfall and the infiltration. The amount of runoff from a given area depends on the rainfall intensity and the infiltration rate (Singh 1992). Thus, the model works on the principle that if the infiltration rate exceeds the rainfall intensity, no runoff will occur; on the other hand, if the rainfall intensity exceeds the infiltration rate, then runoff will occur.

I modelled the dynamics of the soil water content of soil zone 1 by means of the following difference equation:

$$\text{Zone 1 w c}(t) = \text{Zone1 w c}(t-\Delta t) + (I - ae - d1)*\Delta t \qquad (3)$$

where all the terms are as defined in Figure 4.

Thus, the amount of rainfall that infiltrates into zone 1 is subject to one of the following three fates:

(i) some of it may be evaporated from the soil surface back into the atmosphere

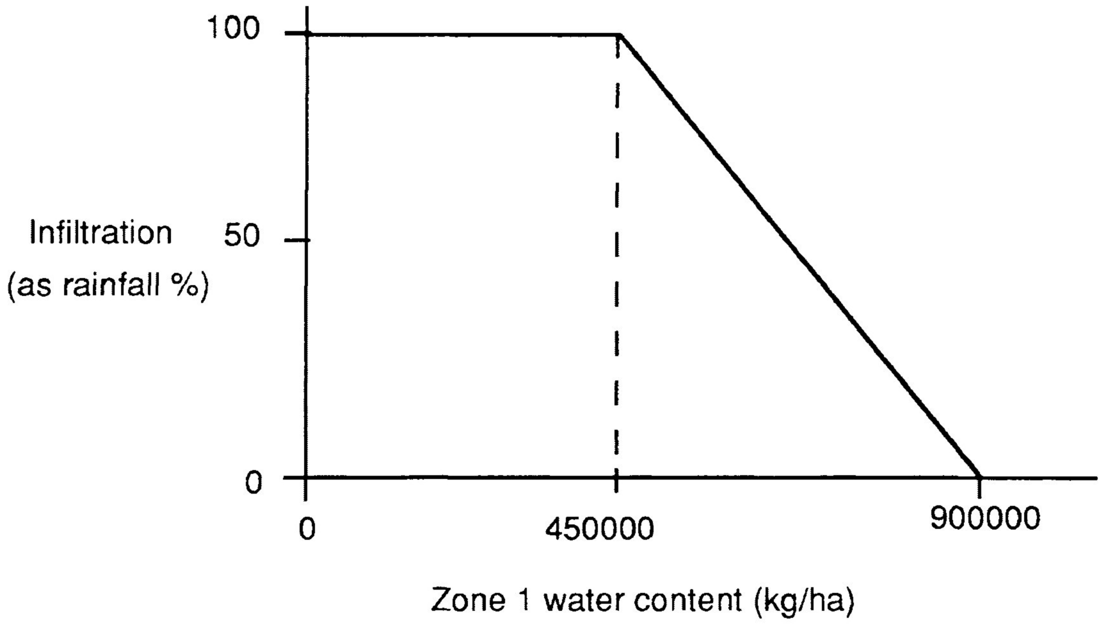


Figure 6. The hypothesized relationship between the amount of infiltration and the zone 1 water content.

(ii) some of it may be held in zone 1

(iii) some of it may percolate into zone 2.

With regard to the water evaporated back into the atmosphere, I modelled the actual evaporation as a function of the water content of zone 1 and the air temperature as follows:

$$\text{Actual evaporation} = (-0.5 + 500^{*}\text{actual temperature})^{*}\ \text{zone 1 w c} \qquad (4)$$

The linear component (in parenthesis) of equation (4) represents my model of the relationship between the potential evaporation and the actual air temperature (Singh 1992). The logic I used for defining the actual evaporation from zone 1 is as follows:

Actual evaporation = If zone 1 water content $\leq$ 200000 then 0 else (If (zone 1 water content $>$ 200000 and zone 1 water content $<$ 360000) then (Exp(4.33*$10^{-6}$)*(zone 1 water content - 200000))-1)*(-0.5 + 500*actual air temperature) else -0.5 + 500*actual air temperature. (5)

Thus, I assumed that evaporation is zero up to the point at which the zone 1 water content is 200000 kg/ha. The rate of evaporation then increases exponentially as the zone 1 water content rises above the 200000 mark up to 360000 kg/ha (80% of the zone 1 field capacity) of water (Ritchie, 1972) (Figure 7).

I then modelled air temperature as a graphical function depicting the actual average temperature from the first cropping season of 1986 to the second cropping season of 1989, as recorded at ICRAF'S Machakos field station (Figure 8).

Once zone 1 reaches its field capacity, any excess drains into zone 2. The following equation defines the logic by which drainage from zone 1 to zone 2 occurs:

d1 = If zone 1 w c $>$ fc1 then (zone1 wc-fc1)*df1 else 0 (6)

where the values for fc1 and df1 are 450000 kg/ha and Max(0,(1/600000*zone1 wc - 0.75)) respectively.

The linear equation for the value of df1 represents my model for the relationship between the water drainage rate from zone 1 and its water content. To obtain this equation, I assumed that the drainage rate is zero up to a field capacity of 450000 kg/ha. Beyond this point, I assumed a linear increase of water drainage rate to a maximum of 0.75 when the zone is at its maximum water retentive capacity of 900000 kg/ha (Figure 9). This same argument applies to df2 and df3 discussed later in the text. The Max(maximum) function that is used in the definition for drainage rates ensures that they do not take on negative values.

Drainage of water from zone 1 will depend on how much water there is and the field capacity of soil zone 1. Water will drain into zone 2 only if the water content in zone 1 is greater than its field capacity.

### 4.2.3 Water dynamics of zone 2

Zone 2 receives water form zone 1 at a rate determined by equation (6). Once zone 2 has filled and reached its field capacity, any excess drains into zone 3. The following equation defines the logic by which drainage from zone 2 to zone 3 occurs:

$$d2 = \text{IF zone 2 w c} > fc2 \text{ then (zone 2 wc} - fc2)*df2 \text{ else } 0 \qquad (7)$$

where the values for fc2 and df2 are 450000 kg/ha and Max(0,(1/600000*zone 2 w c - 0.75)) respectively.

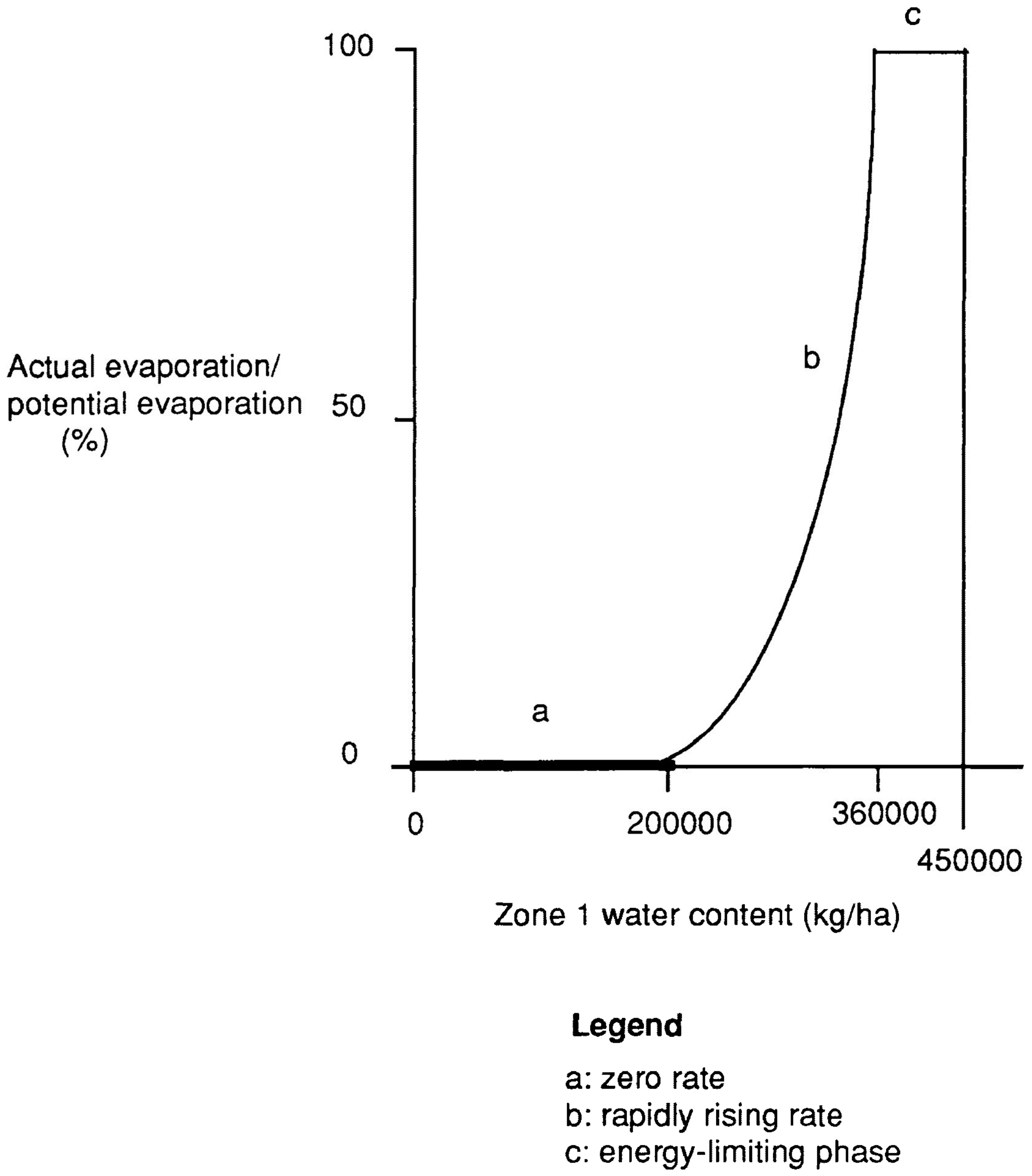


Figure 7. Relationship between actual evaporation/potential evaporation ratio and soil water content in zone 1. Three phase evaporation process concept is indicated by a, b and c. (Adapted from Gardner, 1983).

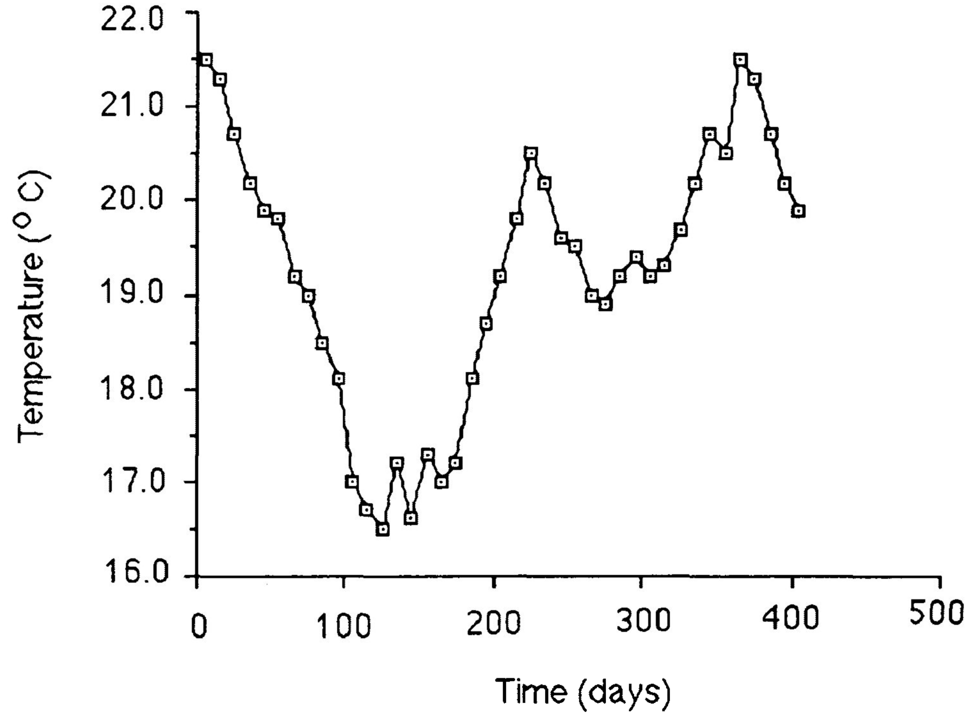


Figure 8. The distribution of the average temperatures recorded from first season of 1986 to second season of 1989. (Data source: ICRAF'S Machakos field station weather unit).

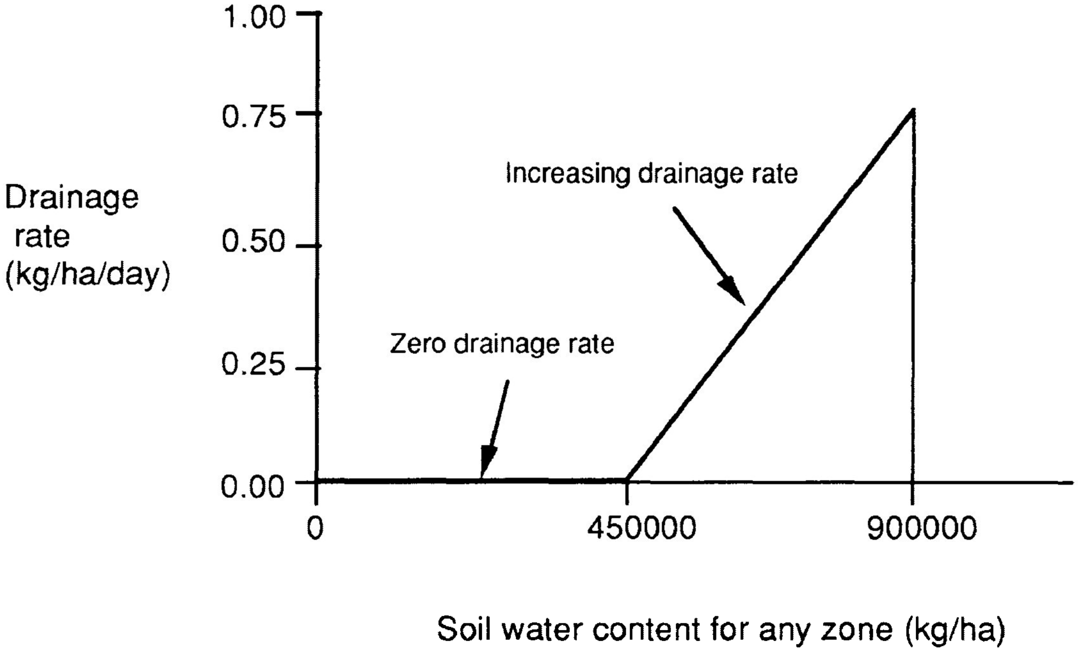


Figure 9. The hypothesized relationship between the water drainage rate from any one soil zone to the next.

Drainage of water from zone 2 will depend on how much water is held in it and its field capacity. Water will drain into zone 3 only if the water content in zone 2 is greater than its field capacity.

### 4.2.4 Water dynamics of zone 3

The ground water dynamics of zone 3 are analogous to those of zone 2. Zone3 receives water from zone 2 at a rate determined by equation (7). Once zone 3 reaches its field capacity, any excess drains into ground water storage.

The following equation defines the logic by which drainage from zone 3 to ground water storage occurs:

$$d3 = \text{If zone 3 w c} > \text{fc3 then (zone 3 wc-fc3)*df3 else 0} \tag{8}$$

where the values for fc3 and df2 are 450000 kg/ha and Max(0,(1/600000*zone 3 w c - 0.75)) respectively.

Again, the drainage of water from zone 3 will depend on how much water is held in it and its field capacity. Water will drain into zone 3 only if the water content in zone 3 is greater than its field capacity.

## 4.3 Simulation results and discussion

The results for simulating the bare soil/ground water model are presented in Table 2 and Figure 10. The soil water contents in all the three soil zones very closely reflect the rainfall distribution pattern over the two seasons under consideration. The top soil zone (0-20 cm in depth) is the most sensitive to changes in rainfall and registers these changes almost immediately. The second soil zone (20-40 cm in depth) is not as sensitive as zone 1 but is more sensitive than zone 3 (40-60 cm in depth). During the intervening dry period, the first soil zone loses water most rapidly while the third is the slowest in losing its water content. The second soil zone is intermediate. This pattern results from the timing of drainage that flows from one soil zone to the other. Drainage from zone 1 starts before the one from zone 2 while drainage from zone 2 starts before the one from zone 3 (Table 2). It is also noteworthy that the drying of the soil profile occurs relatively more gradually while the wetting of the same is more rapid.

The results indicate that during the intervening dry period, zone 1 has less water content than zone 2 and zone 3. This may be explained by the fact that zone 1 loses water through two ways: (i) evaporation and (ii) drainage; while zone 2 and zone 3 lose their water through drainage only. In the real system, however, the difference in water contents between zone 1, on the one hand, and zone 2 and zone 3, on the other hand, may not be as great as what the model shows.

The amount of rainfall that infiltrates into the soil profile is relatively high. Not surprisingly, the higher the daily rainfall input the higher the surface runoff and vice versa. The minimum daily rainfall input that produces some surface runoff in this model is 0.5 mm.

The combined effect of evaporation and the initial drainage of water from zone 1 results in the decrease of its water content, thereby decreasing its water potential and causing upward water movement against gravity (Kramer 1983). Although I did not take this phenomenon into account, the bare soil/ground water model, nevertheless, accounts for the movement of water into and out of the upper soil profile (first 60 cm depth), and for the water stored within the soil profile. I believe that the real bare soil/water system must behave qualitatively along much the same lines as the model. However, I have no actual quantitative data to validate this claim.

Table 2. Simulation results for the bare soil/ground water model.

| Time (days) | Rainfall (mm) | Zone 1 water content (kg/ha) | Zone 2 water content (kg/ha) | Zone 3 water content (kg/ha) | Infiltration (kg/ha) | Actual evaporation (kg/ha) | Surface runoff (kg/ha) | Actual temperature (° C) |
|---|---|---|---|---|---|---|---|---|
| 5 | 1.5 | 373114 | 400000 | 400000 | 15100 | 10750 | 0 | 21.5 |
| 10 | 1.9 | 402566 | 400000 | 400000 | 18900 | 10700 | 0 | 21.4 |
| 15 | 2.3 | 451269 | 400000 | 400000 | 22636 | 10650 | 64 | 21.3 |
| 20 | 3.2 | 513475 | 408496 | 400000 | 27400 | 10500 | 4500 | 21.0 |
| 30 | 4.3 | 562947 | 538152 | 422474 | 32432 | 10224 | 10868 | 20.4 |
| 45 | 4.5 | 568770 | 568623 | 567475 | 33491 | 9950 | 12009 | 19.9 |
| 60 | 3.2 | 556526 | 564241 | 567791 | 24425 | 9750 | 7575 | 19.5 |
| 75 | 1.4 | 502484 | 513365 | 523894 | 12102 | 9500 | 1598 | 19.0 |
| 90 | 0.5 | 450206 | 482054 | 494972 | 4798 | 9150 | 2 | 18.3 |
| 105 | 0.1 | 363586 | 467473 | 477319 | 900 | 8500 | 0 | 17.0 |
| 120 | 0.1 | 288182 | 462069 | 469246 | 900 | 3859 | 0 | 16.6 |
| 135 | 0.1 | 256963 | 459233 | 464823 | 1100 | 2406 | 0 | 17.2 |
| 165 | 0.2 | 250807 | 456291 | 460146 | 2500 | 2091 | 0 | 17.0 |
| 180 | 0.1 | 252791 | 455429 | 458764 | 1350 | 2266 | 0 | 17.6 |
| 210 | 0.0 | 219116 | 454263 | 456888 | 300 | 841 | 0 | 19.5 |
| 225 | 0.1 | 216532 | 453850 | 456222 | 1200 | 761 | 0 | 20.5 |
| 240 | 2.5 | 374396 | 453510 | 455674 | 25450 | 9950 | 0 | 19.9 |
| 255 | 4.4 | 561327 | 533779 | 477070 | 33190 | 9750 | 10910 | 19.5 |
| 285 | 2.8 | 545827 | 553749 | 559713 | 21723 | 9599 | 5877 | 19.2 |
| 300 | 2.0 | 528174 | 534719 | 537727 | 16567 | 9650 | 3483 | 19.3 |
| 315 | 0.6 | 470263 | 493698 | 507162 | 6016 | 9650 | 284 | 19.3 |
| 330 | 0.6 | 415515 | 470735 | 482182 | 6300 | 9974 | 0 | 19.9 |
| 345 | 0.6 | 356872 | 463523 | 471546 | 6100 | 10064 | 0 | 20.7 |
| 375 | 1.5 | 343134 | 458011 | 462902 | 15100 | 9143 | 0 | 21.3 |
| 390 | 3.2 | 500264 | 459252 | 460758 | 28337 | 10224 | 3563 | 20.4 |
| 400 | 4.3 | 563347 | 550150 | 505415 | 32394 | 10024 | 10906 | 20.0 |

Table 2. (Continued)

| Time (days) | Drainage from zone 1 (kg/ha) | Drainage from zone 2 (kg/ha) | Drainage from zone 3 (kg/ha) | Drainage rate from zone 1 (no units) | Drainage rate from zone 2 (no units) | Drainage rate from zone 3 (no units) |
|---|---|---|---|---|---|---|
| 5 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| 10 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| 15 | 3 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| 20 | 6715 | 0 | 0 | 0.1 | 0.0 | 0.0 |
| 30 | 21265 | 12951 | 0 | 0.2 | 0.1 | 0.0 |
| 45 | 23511 | 23453 | 2300 | 0.2 | 0.2 | 0.2 |
| 60 | 18913 | 21752 | 23124 | 0.2 | 0.2 | 0.2 |
| 75 | 4591 | 6692 | 9101 | 0.1 | 0.1 | 0.1 |
| 90 | 0 | 1712 | 3371 | 0.0 | 0.0 | 0.0 |
| 105 | 0 | 509 | 1244 | 0.0 | 0.1 | 0.2 |
| 120 | 0 | 243 | 617 | 0.0 | 0.0 | 0.0 |
| 135 | 0 | 142 | 366 | 0.0 | 0.0 | 0.0 |
| 165 | 0 | 66 | 172 | 0.0 | 0.0 | 0.0 |
| 180 | 0 | 49 | 128 | 0.0 | 0.0 | 0.0 |
| 210 | 0 | 30 | 79 | 0.0 | 0.0 | 0.0 |
| 225 | 0 | 25 | 65 | 0.0 | 0.0 | 0.0 |
| 240 | 0 | 21 | 54 | 0.0 | 0.0 | 0.0 |
| 255 | 20656 | 11698 | 1221 | 0.2 | 0.1 | 0.0 |
| 285 | 15305 | 17940 | 20062 | 0.2 | 0.2 | 0.2 |
| 300 | 10185 | 11962 | 12827 | 0.1 | 0.1 | 0.1 |
| 315 | 684 | 3183 | 5446 | 0.0 | 0.1 | 0.1 |
| 330 | 0 | 717 | 1726 | 0.0 | 0.0 | 0.1 |
| 345 | 0 | 305 | 774 | 0.0 | 0.0 | 0.0 |
| 375 | 0 | 107 | 277 | 0.0 | 0.0 | 0.0 |
| 390 | 4211 | 143 | 193 | 0.1 | 0.0 | 0.0 |
| 400 | 21413 | 16717 | 5118 | 0.2 | 0.2 | 0.1 |

**Note**: I assumed a homogeneous and isotropic soil profile and therefore the three soil zones have a similar field capacity of 450000 kg/ha.

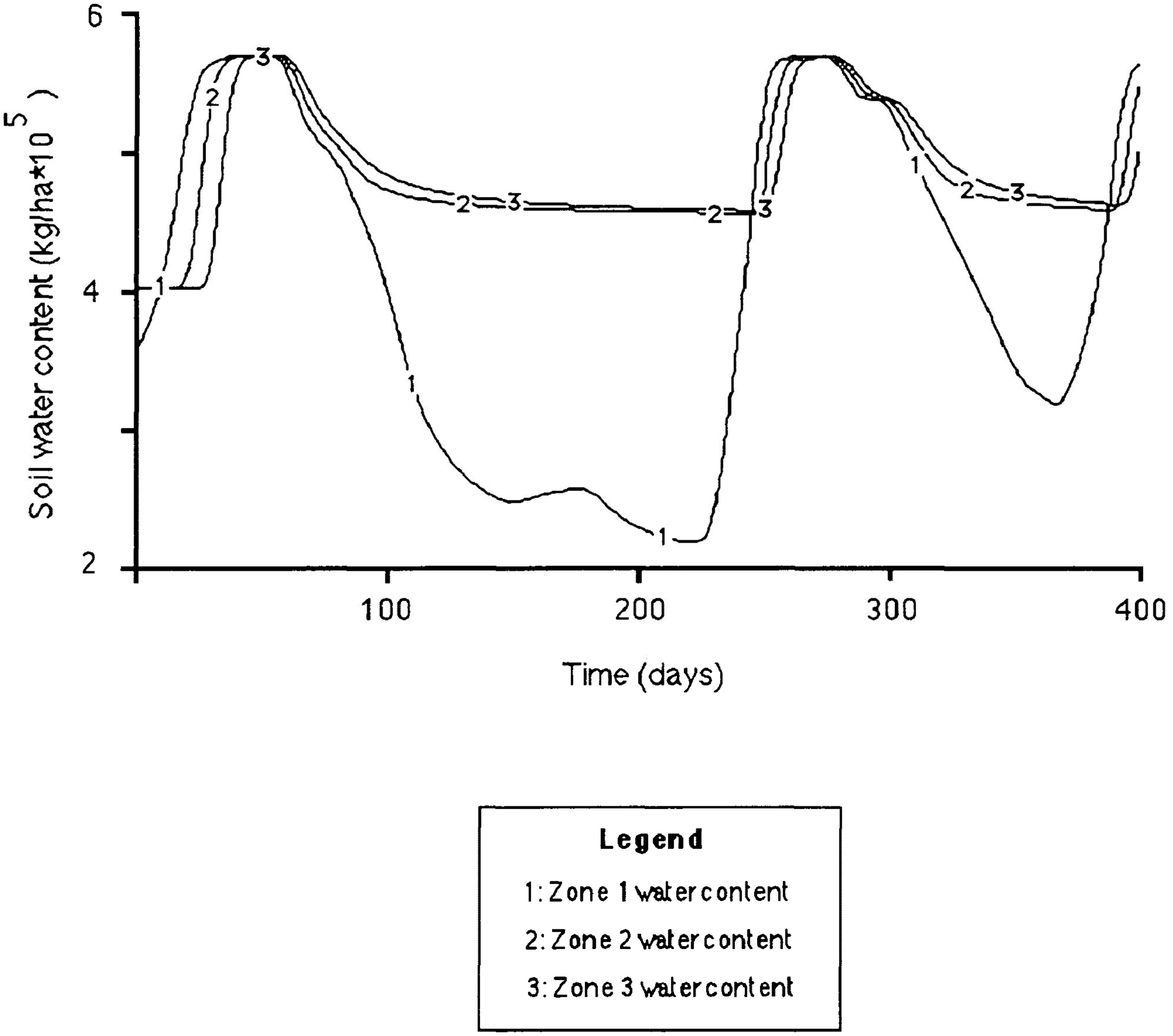


Figure 10. The simulated soil water contents for soil zone 1, soil zone 2 and soil zone 3.

# CHAPTER 5

# CASSIA/WATER MODEL

## 5.1 Introduction

In chapter 4, I analysed the dynamics of ground water of a soil devoid of plant cover where rainfall was the driving variable. In this chapter, I analysed the biomass dynamics of the *Cassia siamea* with respect to water. I considered the *Cassia* above-ground biomass in an environment where water is treated as a simple constant input.

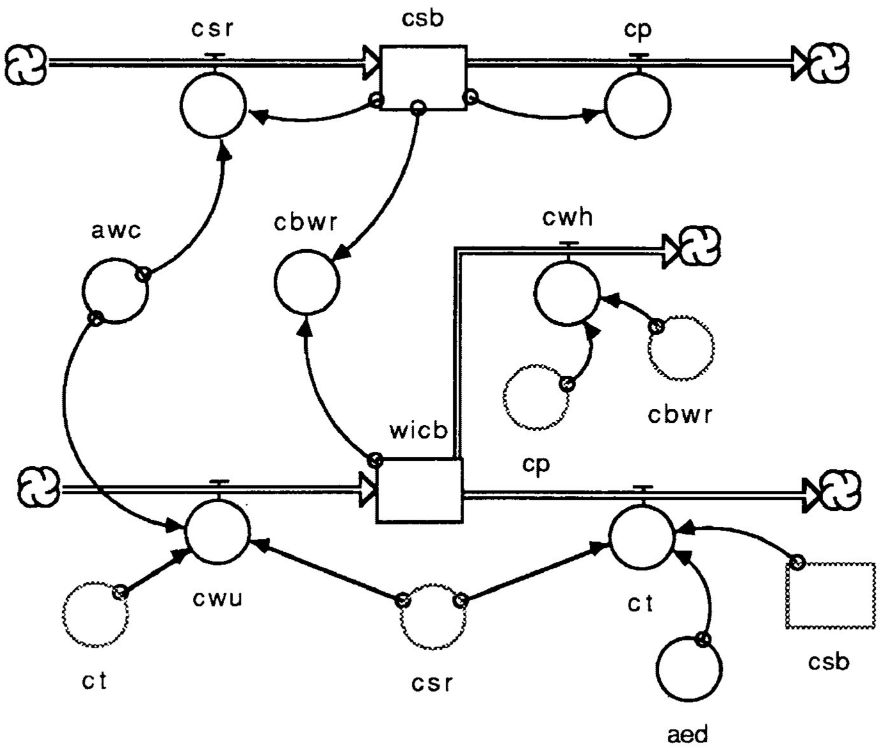
## 5.2 Details of the model

### 5.2.1 Overall structure of the model

The *Cassia* /water model (Fig. 11) has two state variables, namely (i) *Cassia* shoot biomass and (ii) water in *Cassia* biomass. The variable "*Cassia* shoot biomass" reflects the amount of transpiring and photosynthesizing leaf surface. On the other hand, the "water in *Cassia* biomass" variable represents the water content of the above-ground biomass of *Cassia* . These two variables interact dynamically because (a) the amount of water transpired by *Cassia* depends upon the current size of the *Cassia* crown and (b) the*Cassia* shoot regrowth depends in part upon the current amount of ground water available.

### 5.2.2 Dynamics of *Cassia* shoot biomass

During any time step ($\Delta t$), the current stock of *Cassia* shoot biomass may



**Legend**

csb - *Cassia* shoot biomass (kg/ha)
csr - *Cassia* shoot regrowth (kg/ha)
cp - *Cassia* pruning (kg/ha)
cbwr - *Cassia* biomass water ratio (dimensionless)
cwu - *Cassia* water uptake (kg/ha)
cwh - *Cassia* water harvest (kg/ha)
awc - Available water content (kg/ha)
wicb - Water in *Cassia* biomass (kg/ha)
ct - *Cassia* transpiration (kg/ha)
aed - Air evaporative demand (kPa)

Figure 11. Structure of the *Cassia* /water simulation model.

increase as a result of *Cassia* shoot regrowth or decrease as a result of pruning. The general relationship is expressed by the following difference equation:

$$csb(t) = csb(t-\Delta t) + csr\Delta t - cp\Delta t \qquad (9)$$

where:

$t$ = time;

$\Delta t$ = a discrete step in time (e.g. 1 day);

$csb(t)$ = *Cassia* shoot biomass at time t (kg $ha^{-1}$);

$csr\,\Delta t$ = *Cassia* shoot biomass regrowth during $\Delta t$ (kg $ha^{-1}$ $day^{-1}$);

$cp\,\Delta t$ = *Cassia* shoot biomass removed by pruning during $\Delta t$ (kg $ha^{-1}$).

The *Cassia* shoot regrowth is itself a function of both the current amount of *Cassia* shoot biomass and the amount of available water in the soil (the constant water input in this case). In this simulation, the second crop cycle has the same duration as the first, whereas in the real system in Machakos, the second cycle is a few weeks shorter than the first. As a result, the Stella-year is longer than 365 days. In the simulation, *Cassia* shoot regrowth occurred only when two conditions were met, namely: (i) the simulation period was between day 0 and day 204 for the first cropping season or between day 224 and day 389 for the second cropping season, and (ii) the available water content for use by *Cassia* was greater than or equal to 250000 kg $ha^{-1}$. The assumption here was that a water content that was below 250000 kg $ha^{-1}$ was unavailable to *Cassia*. In a more compact way, the logic that defined the relationship between *Cassia* shoot regrowth and *Cassia* shoot biomass was as follows:

csr = If ((time < 204 or (time ≥ 224 and time < 389)) and (awc ≥

```
250000) then ((1.6/10^12)*awc*csb*(50000 - csb)) else 0    (10)
```

where the symbols csr, awc and csb are as defined in Figure (11), and

204 = time when *Cassia* is first pruned (days);
224 = time when *Cassia* starts the regrowth cycle (days);
389 = time when *Cassia* is pruned the second time (days);
250000 = the minimum amount of water below which it is unavailable to *Cassia* (kg ha-1);
1.6/10^12 = a constant that determines the form of the parabolic curve as shown in Figure 12;
50000 = the ultimate limiting value for *Cassia* shoot biomass.

(Appendix 4 contains all the mathematical equations for the variables in the *Cassia* /water model).

The hypothetical functional relationship between the *Cassia* shoot regrowth and the existing *Cassia* shoot biomass is shown in Figure 12. The relationship is parabolic and the maximum *Cassia* shoot regrowth is determined by the degree of *Cassia* shoot biomass hydration as well as the ultimate limiting value for *Cassia* biomass. When it is well hydrated, *Cassia* achieves its maximum productivity. Below the optimal hydration, productivity is reduced in proportion to the level of water stress. I used 50,000 kg $ha^{-1}$ to represent the ultimate limiting value for *Cassia* biomass (Ola-Adams, 1975). The form of the parabolic curve is determined by the constant $1.6*10^{-12}$ in equation (10).

The periods in the simulation in which *Cassia* shoot biomass grew were also between day 0 and day 204 for the first cropping season and day 224 and 389 for the second cropping season. Therefore, *Cassia* pruning was ordinarily zero, but on two occassions, namely, on days 204 and 389, *Cassia* shoot biomass was reduced by pruning.

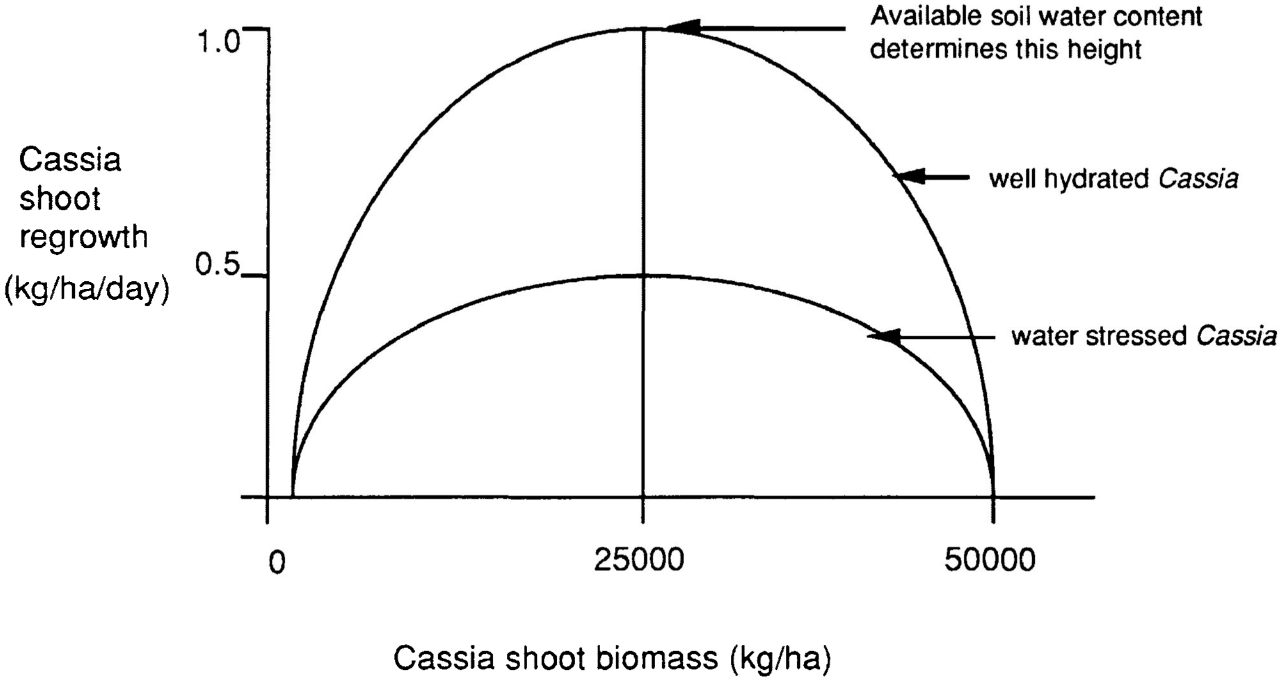


Figure 12. The hypothesized relationship between the *Cassia* shoot regrowth and the *Cassia* shoot biomass.

*Cassia* shoot biomass is always pruned to leave 100 kg $ha^{-1}$ with which to start the next growing period. Pruning was defined by means of a "pulse function" as follows:

$$cp = 1/dt * pulse\ (csb - 100, 204, 185) \qquad (11)$$

where pulse (csb-100,204,185) instructs STELLA to prune all but 100 kg $ha^{-1}$ of *Cassia* shoot biomass on day 204 and at 185 day interval thereafter.

### 5.2.3 **Dynamics of water in *Cassia* shoot biomass**

*Cassia* water status is a function of the amount of available soil water as well as the *Cassia* water uptake and water transpiration. During any time step ($\Delta t$), the current stock of water in *Cassia* shoot biomass may increase as a result of *Cassia* water uptake or decrease as a result of *Cassia* transpiration or water "harvest" at the time of pruning. The general relationship is expressed by the following difference equation:

$$wicb(t) = wicb(t-\Delta t) + cwu\Delta t - ct\Delta t - cwh\Delta t \qquad (12)$$

where:

$t$ = time;

$\Delta t$ = a discrete step in time (e.g. 1 day);

$wicb(t)$ = water in *Cassia* shoot biomass at time t (kg $ha^{-1}$);

$cwu\Delta t$ = *Cassia* water uptake during $\Delta t$ (kg $ha^{-1}$);

$ct\Delta t$ = *Cassia* shoot biomass transpiration during $\Delta t$ (kg $ha^{-1}$);

$cwh\Delta t$ = *Cassia* water harvest during $\Delta t$ (kg $ha^{-1}$).

I used the following logic to model the *Cassia* water uptake:

cwu = If (time < 204 or (time ≥ 224 and time < 389)) and (awc ≥ 250000) then (ct + (7/3) *csr) else 0 (13)

where awc, csr, 204, 224, 389 and 250000 are as defined in equation (10), and

cwu = *Cassia* water uptake (kg $ha^{-1}$ $day^{-1}$);

ct = *Cassia* transpiration (kg $ha^{-1}$ $day^{-1}$);

(7/3)*csr = The amount of water that is taken up as a result of processing the daily *Cassia* shoot regrowth in kg $ha^{-1}$ $day^{-1}$. (I assumed that fresh *Cassia* shoot biomass contains 70% of water while 30% is dry matter).

During simulation the *Cassia* water uptake is zero immediately after coppicing and before the start of the next regrowth cycle and is also zero when the available water content is less than 250,000 kg $ha^{-1}$. In the present *Cassia* /water model, available water content is given as a constant input of 300,000 kg $ha^{-1}$.

Squire et al. (1987), have proposed that the total water transpired by a crop over the course of the growing season varies with the following:

(i) the total biomass produced during that season;

(ii) the average daily maximum saturation deficit and

(iii) the dry matter: water ratio that is characteristic of the crop species in question.

Using some of their ideas, I modelled *Cassia* transpiration as follows:

$$ct = \text{If ((time} < 204 \text{ or (time} \geq 224 \text{ and time} < 389) \text{ then } (8*10^{-6}*csb/aed + 700*csr) \text{ else } 0 \quad (14)$$

where:

ct = *Cassia* transpiration (kg $ha^{-1}day^{-1}$);

csb = *Cassia* shoot biomass (kg $ha^{-1}$);

700 *csr = the amount of water processed during the *Cassia* shoot regrowth in kg $ha^{-1}$ $day^{-1}$ (700 is the assumed number of kilograms of water used in the production of 1 kg of *Cassia* dry matter).

aed = Air evaporation demand (kPa);

$8*10^{-6}$ = An appropriate factor to scale down the values of *Cassia* transpiration. I found this factor by trial and error method.

I assumed that the air evaporative demand in Machakos experimental site was equivalent to the vapour pressure saturation deficit of the region as recorded at ICRAF's field station weather unit. The higher the air evaporative demand, the lower the *Cassia* transpiration. The following equation defined the air evaporative demand:

$$aed = \text{Max}(0.2,\text{normal}(0.75,0.4,10000)) \quad (15)$$

Thus, I considered air evaporative demand as normally distributed with a mean of 0.75 and a standard deviation of 0.4. The Max(maximum) function that I used in the definition for air evaporative demand ensured that the latter did not go below a value of 0.2.

The amount of water per unit of *Cassia* biomass was given by the factor *Cassia* biomass water ratio. This ratio is obtained simply by dividing "water in *Cassia* biomass" into the "*Cassia* shoot biomass". The *Cassia* biomass water ratio is important because it determines how much water is lost from the system through pruning.

### 5.3 **Simulation results and discussion**

The simulation results for all the factors and variables in the *Cassia* /water model are presented in Table 3 and Figure 13. In the model the pattern of *Cassia* biomass accumulation during a regrowth cycle increases continuously and exponentially. The *Cassia* shoot regrowth increases in the same manner as the *Cassia* biomass. Water in *Cassia* biomass similarly increases exponentially as the *Cassia* biomass during a regrowth cycle. In nature, these results may also be the case, although I do not have data to demonstrate this. Nonetheless I know, for example, that each regrowth cycle lasts only for a few months. Thus, by the time *Cassia* is pruned at the end of a regrowth cycle, the continuous and exponential growth phase may still be on.

The *Cassia* water uptake and the *Cassia* transpiration are closely related in that their respective values do not differ greatly. Their values also seem to follow the pattern of *Cassia* biomass accumulation whereby they increase continuously and exponentially throughout a regrowth cycle. However, *Cassia* water uptake is always higher than *Cassia* transpiration. This may be expected in nature under normal growing conditions. Kramer (1983) contends that of all the water absorbed by plants, about 95% is lost by transpiration and 5% or less is used in metabolism and growth.

*Cassia* pruning and *Cassia* water harvest are both zero for all the growing season except when pruning occurs on day 204 and day 389. The amount of water harvested is proportional to the amount of *Cassia* biomass that is pruned. The values for *Cassia* biomass water ratio and available water content are 2.3 and 300000 kg ha$^{-1}$, respectively, throughout the growing season. For this reason I did not include them in Table 3.

At the end of the first season, the simulated *Cassia* biomass production was 5623.2 kg ha$^{-1}$ while the equivalent for the second season was 3502.6 kg ha$^{-1}$. Thus, the model gave a higher biomass production in the first season than in the second. Since the supply of water is constant, the fact that the second growing season is of a shorter duration than the first season may be why there is a difference in the biomass production levels for the two cropping seasons.

Table 3. Simulation results for the *Cassia* / water model.

| Time (days) | Cassia shoot biomass (kg/ha) | Cassia shoot regrowth (kg/ha) | water in Cassia biomass (kg/ha) | Cassia water uptake (kg/ha) | Cassia transpiration (kg/ha) | Cassia pruning (kg/ha) | Cassia water harvest (kg/ha) | Air evaporative demand (kPa) |
|---|---|---|---|---|---|---|---|---|
| 5 | 56.3 | 1.3 | 131 | 948 | 945 | 0 | 0 | 0.7 |
| 10 | 63.4 | 1.5 | 148 | 1067 | 1063 | 0 | 0 | 1.0 |
| 15 | 71.3 | 1.7 | 166 | 1201 | 1197 | 0 | 0 | 0.2 |
| 20 | 80.3 | 1.9 | 187 | 1351 | 1347 | 0 | 0 | 0.8 |
| 30 | 101.7 | 2.4 | 237 | 1712 | 1706 | 0 | 0 | 0.9 |
| 45 | 145.1 | 3.5 | 339 | 2439 | 2431 | 0 | 0 | 0.8 |
| 60 | 206.8 | 4.9 | 483 | 3472 | 3461 | 0 | 0 | 0.7 |
| 75 | 294.7 | 7.0 | 688 | 4938 | 4922 | 0 | 0 | 1.6 |
| 90 | 419.6 | 10.0 | 979 | 7013 | 6990 | 0 | 0 | 1.0 |
| 105 | 596.8 | 14.2 | 1392 | 9939 | 9906 | 0 | 0 | 1.0 |
| 135 | 1201.1 | 28.1 | 2803 | 19759 | 19694 | 0 | 0 | 1.2 |
| 150 | 1697.2 | 39.4 | 3960 | 27637 | 27546 | 0 | 0 | 0.5 |
| 165 | 2388.5 | 54.6 | 5573 | 38338 | 38210 | 0 | 0 | 1.0 |
| 180 | 3342.3 | 74.9 | 7799 | 52572 | 52397 | 0 | 0 | 0.8 |
| 204 | 5623.2 | 0.0 | 13121 | 0 | 0 | 5548 | 12946 | 0.2 |
| 205 | 75.0 | 0.0 | 175 | 0 | 0 | 0 | 0 | 0.6 |
| 225 | 76.8 | 1.8 | 179 | 1293 | 1288 | 0 | 0 | 0.2 |
| 240 | 109.5 | 2.6 | 256 | 1842 | 1836 | 0 | 0 | 0.6 |
| 255 | 156.2 | 3.7 | 364 | 2625 | 2616 | 0 | 0 | 0.6 |
| 270 | 222.6 | 5.3 | 519 | 3736 | 3724 | 0 | 0 | 0.2 |
| 285 | 317.2 | 7.6 | 740 | 5312 | 5295 | 0 | 0 | 0.2 |
| 315 | 642.0 | 15.2 | 1498 | 10682 | 10647 | 0 | 0 | 0.2 |
| 330 | 911.4 | 21.5 | 2127 | 15082 | 15032 | 0 | 0 | 0.3 |
| 360 | 1822.8 | 42.2 | 4253 | 29605 | 29507 | 0 | 0 | 0.2 |
| 375 | 2562.6 | 58.3 | 5979 | 40981 | 40845 | 0 | 0 | 0.2 |
| 389 | 3502.6 | 0.0 | 8173 | 0 | 0 | 3428 | 7998 | 0.7 |
| 390 | 75.0 | 0.0 | 175 | 0 | 0 | 0 | 0 | 0.4 |
| 400 | 75.0 | 0.0 | 175 | 0 | 0 | 0 | 0 | 0.4 |

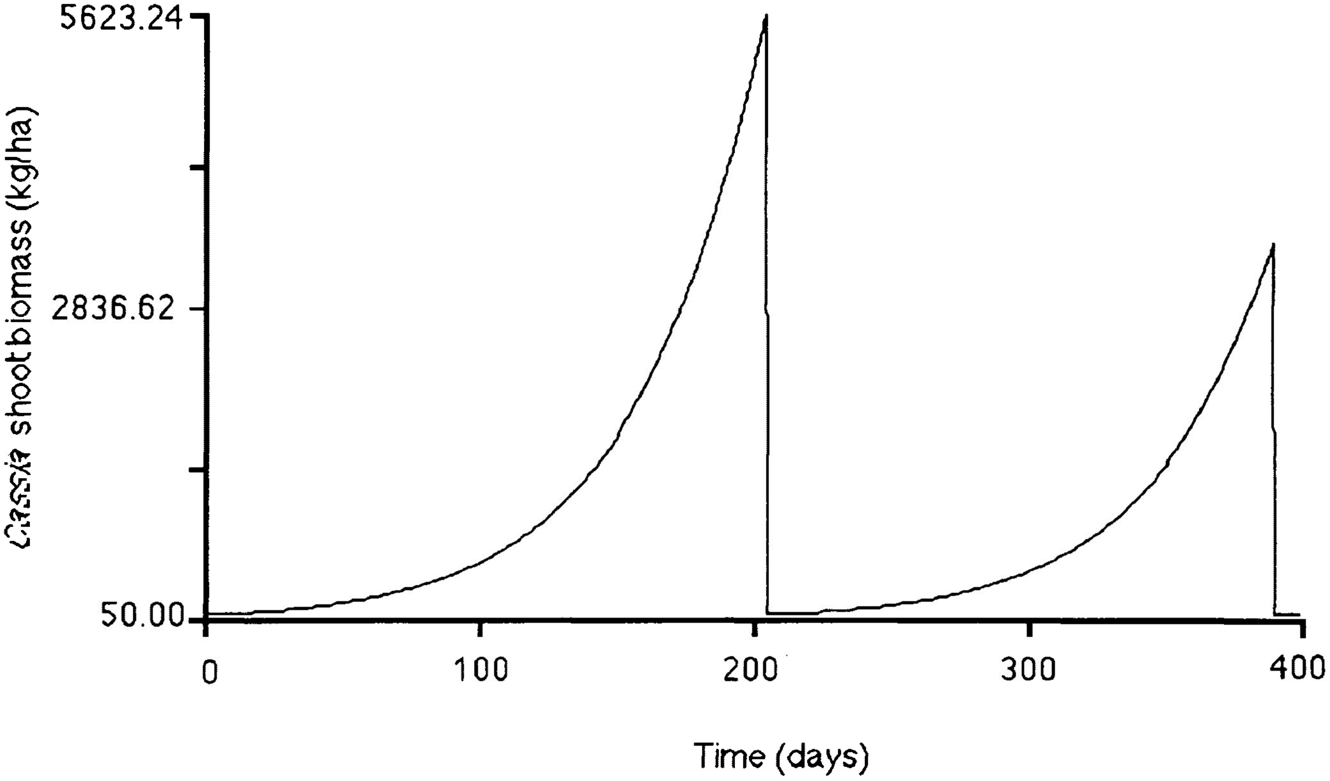


Figure 13. The simulated *Cassia* shoot biomass from first season of 1986 to second season of 1989.

# CHAPTER 6

# MAIZE/WATER MODEL

## 6.1 Introduction

In this chapter, I analysed the biomass dynamics of the maize crop (*Zea mays* L.) with respect to water. Similar to the *Cassia* /water model in chapter 5, I considered the above-ground biomass of maize in an environment where water is treated as a simple constant input.

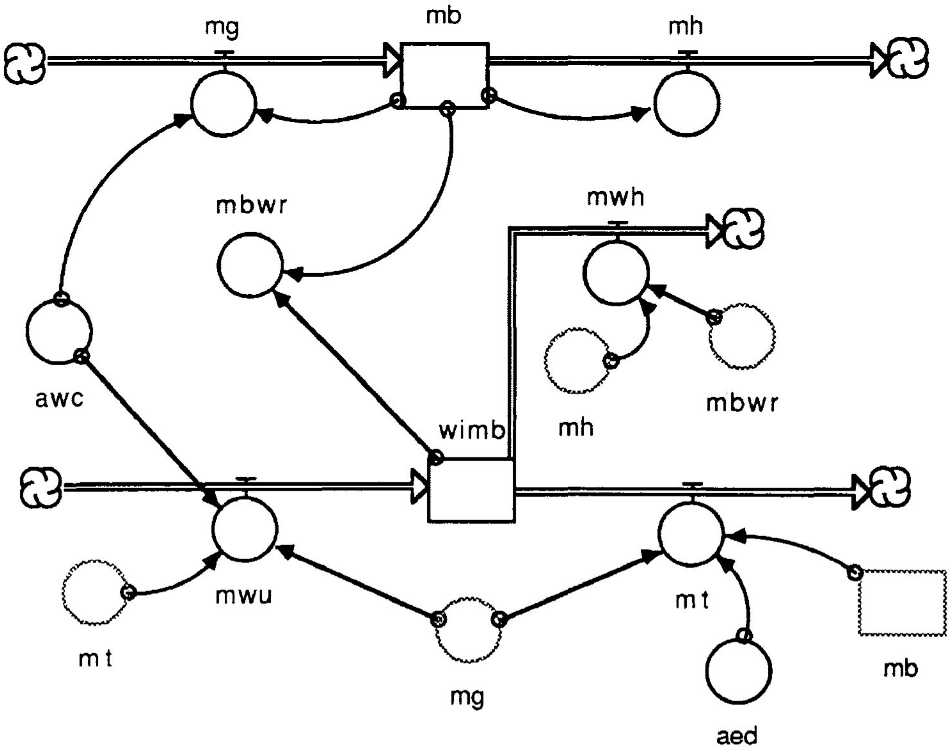
## 6.2 Details of the model

### 6.2.1 Overall structure of the model

Just like the *Cassia* /water model, the maize /water model (Fig. 14) has two state variables, namely (i) maize biomass and (ii) water in maize biomass. The variable "maize biomass" reflects the amount of transpiring and photosynthesizing leaf surface. On the other hand, the "water in maize biomass" variable represents the water content of the above-ground biomass of maize . These two variables interact dynamically because (a) the amount of water transpired by maize depends upon the current size of the maize crown and (b) the maize shoot regrowth depends in part upon the current amount of ground water available.

### 6.2.2 Dynamics of maize biomass

During any time step ($\Delta t$), the current stock of maize biomass may increase as



**Legend**

mb - maize biomass (kg/ha)
mg - maize growth (kg/ha)
mh - maize harvest (kg/ha)
mbwr - maize biomass water ratio (dimensionless)
mwu - maize water uptake (kg/ha)
mwh - maize water harvest (kg/ha)
awc - Available water content (kg/ha)
wimb - Water in maize biomass (kg/ha)
mt - maize transpiration (kg/ha)
aed - Air evaporative demand (kPa)

Figure 14. Structure of the maize/water simulation model.

a result of maize growth or decrease as a result of maize harvest. The general relationship is expressed by the following difference equation:

$$mb(t) = mb(t-\Delta t) + mg\Delta t - mh\Delta t. \quad (16)$$

where:

$t$ = time;

$\Delta t$ = a discrete step in time (e.g. 1 day);

$mb(t)$ = maize biomass at time t (kg $ha^{-1}$);

$mg\,\Delta t$ = maize biomass growth during $\Delta t$ (kg $ha^{-1}$ $day^{-1}$);

$mh\,\Delta t$ = maize biomass removed at harvest during $\Delta t$ (kg $ha^{-1}$).

Maize growth is a function of both the current amount of maize biomass and amount of available water in the soil. In this simulation, the Stella-year is longer than 365 days (cf. section 5.2.2). In the simulation, maize growth occured only when two conditions were met, namely: (i) the simulation period was between day 0 and day 114 for the first cropping season or between day 224 and day 334 for the second cropping season, and (ii) the available water content for use by maize was greater than or equal to 300000 kg $ha^{-1}$. The assumption was that a water content that was below 300000 kg $ha^{-1}$ was unavailable to maize. In an equation format, this logic was as follows:

$$mg = \text{If } ((time < 114 \text{ or } (time \geq 224 \text{ and } time < 334)) \text{ and } (awc \geq 300000) \text{ then } ((2.3/10\text{^}10)*awc*mb*(1800 - mb)) \text{ else } 0 \quad (17)$$

where the symbols mg, awc and mb are as defined in Figure (14), and

114 = time when maize is harvested at the end of the first cropping season (days);

224 = time when maize starts to grow for the second cropping season (days);

334 = time when maize is harvested at the end of the second cropping season (days);

300000 = the minimum amount of water below which it is unavailable to maize (kg ha-1);

2.3/10^10 = a constant that determines the form of the parabolic curve as shown in Figure 15;

1800 = the ultimate limiting value for maize biomass.

(Appendix 5 contains all the mathematical equations for the variables in the maize/water model).

The hypothetical functional relationship between the maize growth and the existing maize biomass is shown in Figure 15. The relationship is parabolic and the maximum maize growth is determined by the degree of maize biomass hydration as well as the ultimate limiting value for maize biomass. When it is well hydrated, maize achieves its maximum productivity. Below the optimal hydration, productivity is reduced in proportion to the level of water stress. I used 1800 kg $ha^{-1}$ to represent the ultimate limiting value for maize biomass. The choice of 1800 kg $ha^{-1}$ is based on the average seasonal maize biomass production achieved at the DARP plots of 1800 for the period under consideration here. The form of the parabolic curve is determined by the constant $2.3*10^{-10}$ in equation (17).

The periods in the simulation in which maize biomass grew were also between day 0 and day 114 for the first cropping season and day 224 and 334 for the second cropping season. Therefore, maize harvest was ordinarily zero, but on two occasions, namely, on days 114 and 334, maize biomass was reduced by harvesting.

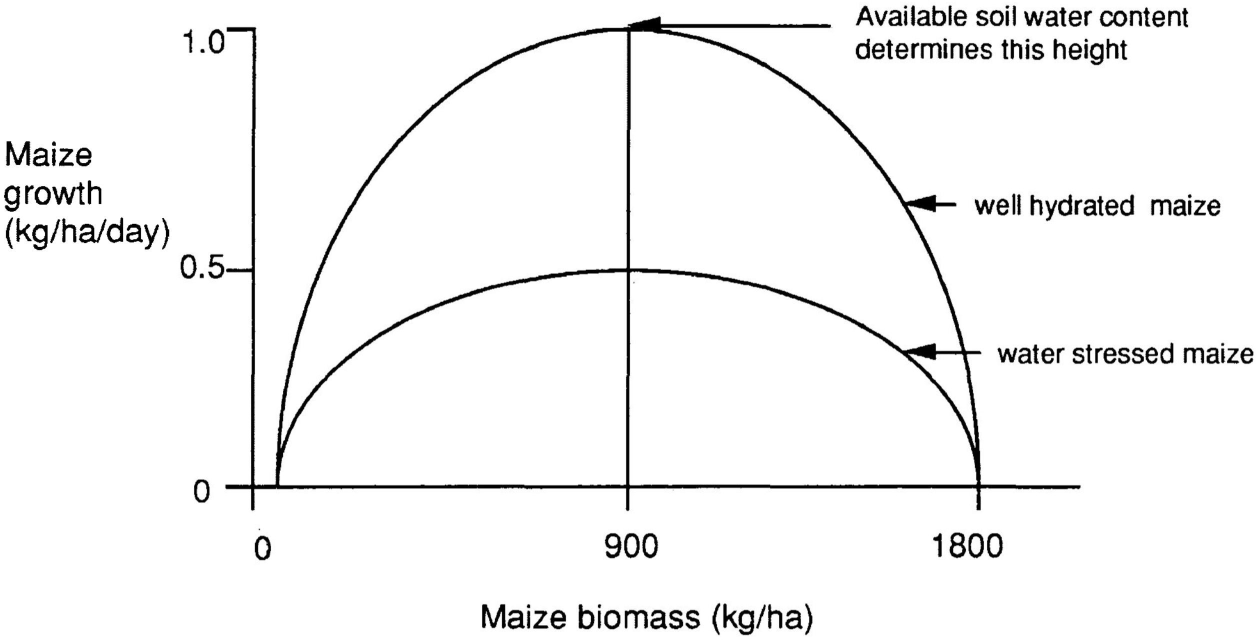


Figure 15. The hypothesized relationship between the maize growth and the maize biomass.

Maize biomass is always harvested to leave 10 kg $ha^{-1}$ with which to start the next growing period. Harvest was defined by means of a "pulse function" as follows:

$$mh = 1/dt*pulse\ (mb-10,114,220) \quad (18)$$

where pulse (mb-10,114,220) instructs STELLA to harvest all but 10 kg $ha^{-1}$ of maize biomass on day 114 and at 220 day interval thereafter.

### 6.2.3 **Dynamics of water in maize biomass**

Maize water status is a function of the amount of available soil water as well as the maize water uptake and water transpiration. During any time step ($\Delta t$), the current stock of water in maize biomass may increase as a result of maize water uptake or decrease as a result of maize transpiration or water "harvest" at the time of harvest. The general relationship is expressed by the following difference equation:

$$wimb(t) = wimb(t-\Delta t) + mwu\Delta t - mt\Delta t - mwh\Delta t \quad (19)$$

where:

$t$ = time;

$\Delta t$ = a discrete step in time (e.g. 1 day);

$wimb(t)$ = water in maize biomass at time t (kg $ha^{-1}$);

$mwu\Delta t$ = maize water uptake during $\Delta t$ (kg $ha^{-1}$);

$mt\Delta t$ = maize biomass transpiration during $\Delta t$ (kg $ha^{-1}$);

$mwh\Delta t$ = maize water harvest during $\Delta t$ (kg $ha^{-1}$).

I used the following logic to model maize water uptake:

$$\text{mwu} = \text{If (time} < 114 \text{ or (time} \geq 224 \text{ and time} < 334)) \text{ and (awc} \geq 300{,}000\text{)}$$
$$\text{then (mt} + (7/3) * \text{mg) else } 0 \qquad (20)$$

where awc, mg, 114, 224, 334 and 300000 are as defined in equation (17) and Figure (14), and:

mwu = maize water uptake (kg $ha^{-1}$ $day^{-1}$);
mt = maize transpiration (kg $ha^{-1}$ $day^{-1}$);
(7/3)*mg = The amount of water that is taken up as a result of processing the daily maize growth in kg $ha^{-1}$ $day^{-1}$. (As was the case for *Cassia* shoot biomass, I assumed that the fresh maize biomass contains 70% of water while 30% is dry matter).

During simulation, the maize water uptake is zero immediately after harvesting and before the start of the next growth cycle and is also zero when the available water content is less than 300000 kg $ha^{-1}$. In the present maize/water model, available water content is given as a constant input of 300,000 kg $ha^{-1}$.

I modelled maize transpiration as follows:

$$\text{mt} = \text{If ((time} < 114 \text{ or (time} \geq 224 \text{ and time} < 334)$$
$$\text{then } (8 * 10^{-6} * \text{mb/aed} + 350 * \text{mg) else } 0 \qquad (21)$$

where:

mt = maize transpiration (kg $ha^{-1}day^{-1}$);
mb = maize biomass (kg $ha^{-1}$);

350 *mg = the amount of water processed during the maize growth in kg $ha^{-1}$ $day^{-1}$. (350 is the assumed number of kilograms of water used in the production of 1 kg of maize dry matter);

aed = Air evaporation demand (kPa);

$8*10^{-6}$ = An appropriate factor to scale down the values of maize transpiration. I found this factor by trial and error method.

The same assumptions about air evaporative demand for *Cassia* were applied for the maize (equation (15) in section 5.2.3).

The amount of water per unit of maize biomass was given by the factor maize biomass water ratio. This ratio is obtained simply by dividing "water in maize biomass" into the "maize biomass". As is the case for *Cassia* , the maize biomass water ratio is important because it determines how much water is lost from the system upon harvesting.

## 6.3 **Simulation results and discussion**

The simulation results for all the factors and variables in the maize /water model are presented in Table 4 and Figure 16. In the model the pattern of maize biomass accumulation during a growth cycle starts slowly and then increases rapidly and exponentially and then tapers off towards maturity, exhibiting a sigmoid growth pattern. The maize growth, which feeds into the maize biomass stock, increases in the same manner as the maize biomass. Water in maize biomass increases in like manner as the maize biomass during a growth cycle. In nature, these results may also be the case, although I do not have data to demonstrate this.

The respective values for maize water uptake and maize transpiration do not differ greatly. Their values seem to follow the same pattern as the maize biomass accumulation whereby as they increase they exhibit the sigmoid growth pattern. Again, as was the case for *Cassia* , maize water uptake is consistently higher than maize transpiration. This may be expected in nature under normal growing conditions.

Maize harvesting and maize water harvest are both zero for all the growing season except when harvesting occurs on day 114 and day 334. The amount of water harvested is proportional to the amount of maize biomass that is harvested. The values for maize biomass water ratio and available water content (constant input) were 2.3 and 300000 kg ha$^{-1}$ throughout the growing season. I therefore did not include these in Table 4.

The simulated maize biomass production for both the first season and the second season was 1800 kg ha$^{-1}$. The fact that there is no difference in the biomass production levels for the two cropping seasons may be explained by the constant supply of water as well as the fact that both the first and the second cropping season are of the same duration.

Table 4. Simulation results for the maize / water model.

| Time (days) | Maize biomass (kg/ha) | Maize growth (kg/ha) | Water in maize biomass (kg/ha) | Maize water uptake (kg/ha) | Maize transpiration (kg/ha) | Maize harvest (kg/ha) | Maize water harvest (kg/ha) | Air evaporative demand (kPa) |
|---|---|---|---|---|---|---|---|---|
| 5 | 19.6 | 2.8 | 46 | 989 | 982 | 0 | 0 | 0.7 |
| 10 | 38.2 | 5.4 | 89 | 1907 | 1894 | 0 | 0 | 0.9 |
| 15 | 73.7 | 10.2 | 172 | 3611 | 3587 | 0 | 0 | 0.2 |
| 20 | 140.2 | 18.7 | 327 | 6600 | 6556 | 0 | 0 | 0.8 |
| 30 | 452.4 | 49.1 | 1055 | 17290 | 17176 | 0 | 0 | 0.9 |
| 45 | 1343.7 | 49.4 | 3135 | 17390 | 17275 | 0 | 0 | 0.8 |
| 60 | 1741.0 | 8.3 | 4062 | 2913 | 2894 | 0 | 0 | 0.7 |
| 75 | 1794.2 | 0.8 | 4186 | 297 | 295 | 0 | 0 | 1.6 |
| 90 | 1799.4 | 0.1 | 4199 | 29 | 28 | 0 | 0 | 1.0 |
| 105 | 1799.9 | 0.0 | 4200 | 3 | 3 | 0 | 0 | 1.0 |
| 114 | 1800.0 | 0.0 | 4200 | 0 | 0 | 1790 | 4177 | 1.4 |
| 115 | 10.0 | 0.0 | 23 | 0 | 0 | 0 | 0 | 0.9 |
| 165 | 10.0 | 0.0 | 23 | 0 | 0 | 0 | 0 | 1.0 |
| 205 | 10.0 | 0.0 | 23 | 0 | 0 | 0 | 0 | 0.6 |
| 225 | 11.4 | 1.6 | 27 | 580 | 577 | 0 | 0 | 0.2 |
| 240 | 84.0 | 11.6 | 1196 | 4088 | 4061 | 0 | 0 | 0.6 |
| 255 | 501.4 | 52.4 | 1170 | 18468 | 18346 | 0 | 0 | 0.6 |
| 270 | 1393.1 | 45.6 | 3250 | 16079 | 15972 | 0 | 0 | 0.2 |
| 285 | 1749.3 | 7.1 | 4082 | 2517 | 2500 | 0 | 0 | 0.2 |
| 300 | 1795.0 | 0.7 | 4188 | 254 | 253 | 0 | 0 | 1.0 |
| 315 | 1799.5 | 0.1 | 4199 | 25 | 24 | 0 | 0 | 0.2 |
| 330 | 1800.0 | 0.0 | 4200 | 2 | 2 | 0 | 0 | 0.3 |
| 334 | 1800.0 | 0.0 | 4200 | 0 | 0 | 1790 | 4177 | 1.1 |
| 335 | 10.0 | 0.0 | 23 | 0 | 0 | 0 | 0 | 0.5 |
| 400 | 10.0 | 0.0 | 23 | 0 | 0 | 0 | 0 | 0.4 |

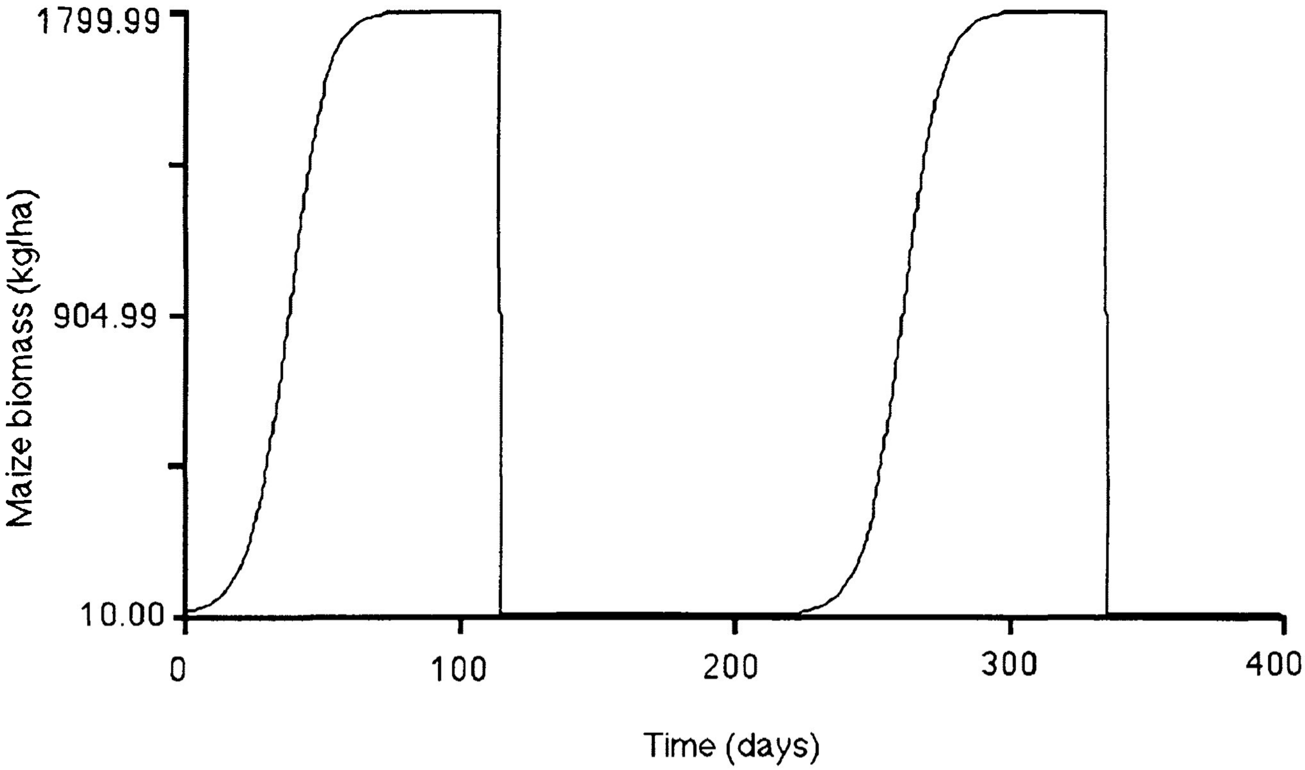


Figure 16. The simulated maize biomass from first season of 1986 to second season of 1989.

# CHAPTER 7

# CASSIA/MAIZE/SOIL WATER MODEL

## 7.1 Introduction

In this chapter, I combined the three models that I analysed in the three preceding chapters, that is, the bare soil/ground water model, the *Cassia* /water model and the maize/water model. This resulted in a much larger model that I called the *Cassia* /maize/ground soil water model. The *Cassia* /maize/ground soil water simulation model (Figure 18) is an interactive system that shows the points of interaction between the three subsystems. Figure 17 is a structural model showing my general concept of the way the three subsystems interact with one another. Since I have already discussed most of the parameters found in this model in the preceding chapters, I will confine myself to the details of the interactions of the subsystems.

## 7.2 Details of the model

### 7.2.1 Overall structure of the model

The *Cassia* /maize/ground soil water model has all the state variables that were identified and discussed in the previous chapters. These variables are (i) maize biomass (ii) water in maize biomass (iii) *Cassia* shoot biomass (iv) water in *Cassia* biomass (v) soil zone 1 water content (vi) soil zone 2 water content and (vii) soil zone 3 water content. In developing this model, I assumed that:

(i) *Cassia siamea* exploits water from both soil zone 1 and soil zone 2 and,

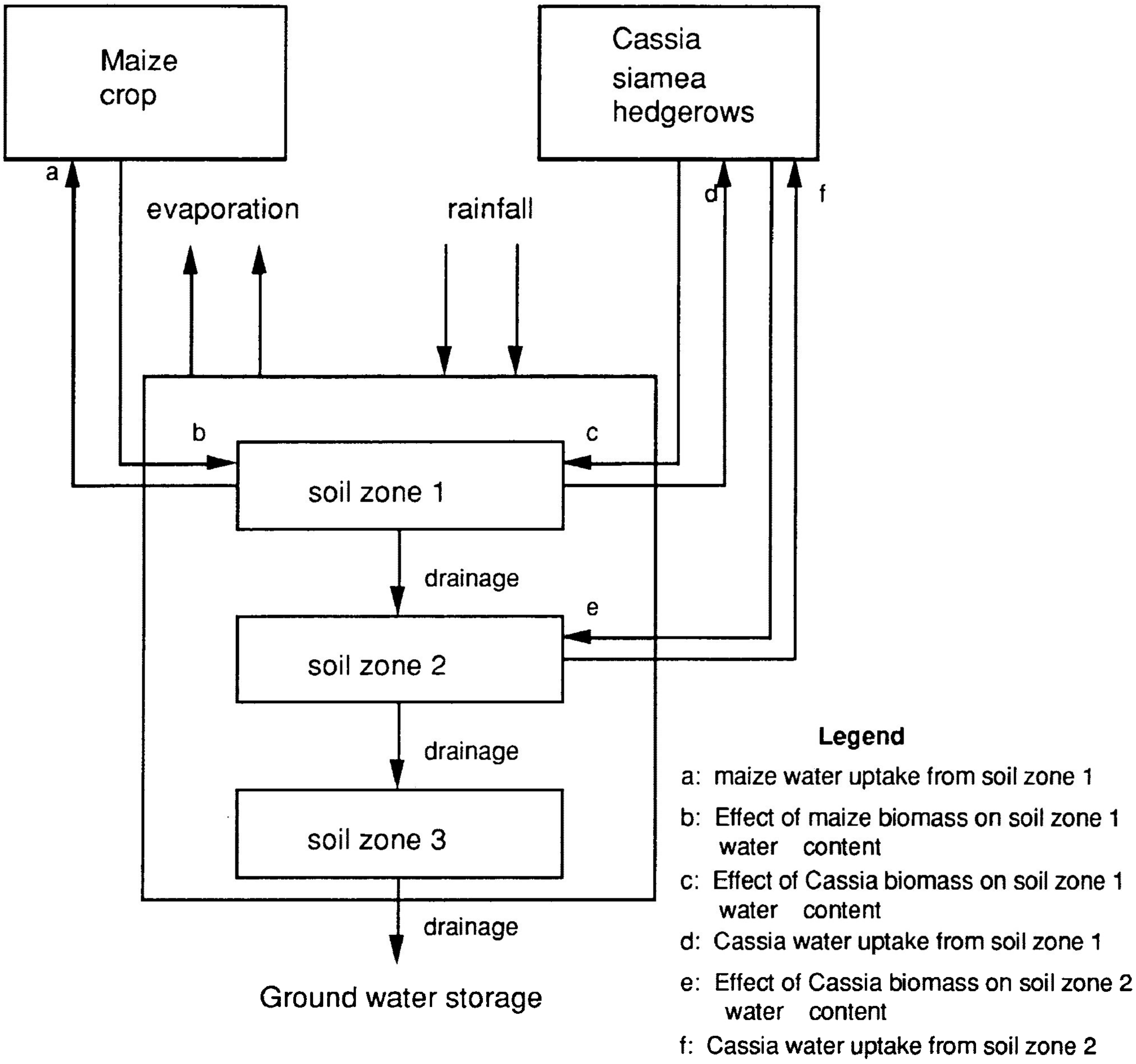


Figure 17. Schematic model of the *Cassia*/maize/ground soil water dynamics.

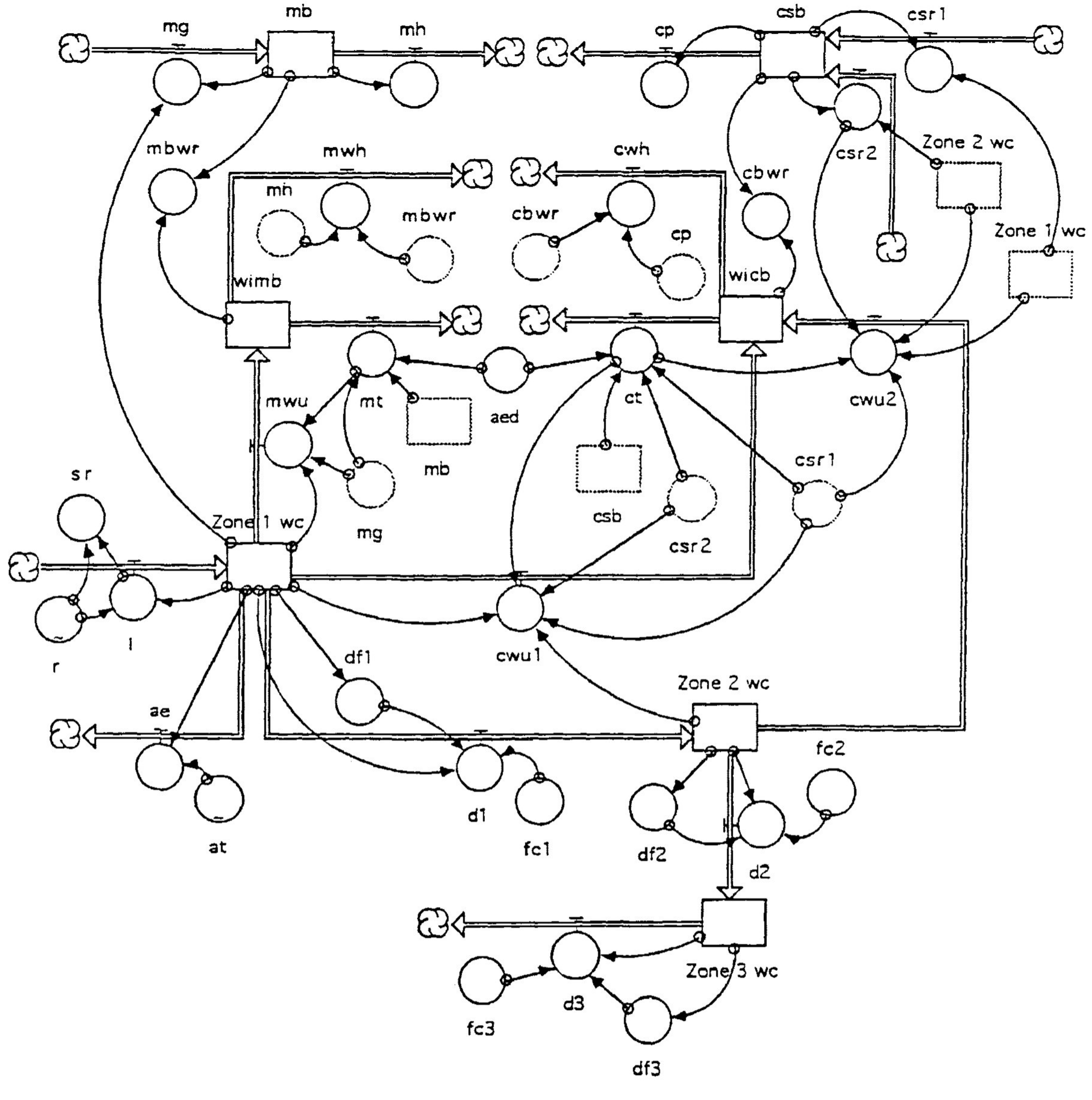


Figure 18a. Structure of the *Cassia* /maize/ground water model (see legend on the next page).

**Legend**

mb - maize biomass (kg/ha)
mg - maize growth (kg/ha)
mh - maize harvest (kg/ha)
mbwr - maize biomass water ratio (dimensionless)
mwu - maize water uptake (kg/ha)
mwh - maize water harvest (kg/ha)
wimb - Water in maize biomass (kg/ha)
mt - maize transpiration (kg/ha)
csb - *Cassia* shoot biomass (kg/ha)
csr1 - *Cassia* shoot regrowth due to water uptake from soil zone 1 (kg/ha)
csr2 - *Cassia* shoot regrowth due to water uptake from soil zone 2 (kg/ha)
cp - *Cassia* pruning (kg/ha)
cbwr - *Cassia* biomass water ratio (dimensionless)
cwu1 - *Cassia* water uptake from soil zone 1 (kg/ha)
cwu2 - *Cassia* water uptake from soil zone 2 (kg/ha)
cwh - *Cassia* water harvest (kg/ha)
wicb - Water in *Cassia* biomass (kg/ha)
ct - *Cassia* transpiration (kg/ha)
aed - Air evaporative demand (kPa)
zone $_i$ w c =water content of the $_i$th soil zone (kg/ha), where i = 1,2,3.
$d_i$ = water drainage from the $_i$th soil zone (kg/ha), where i = 1,2,3
$df_i$ = water drainage rate from the $_i$th soil zone (kg/ha), where i = 1,2,3.
$fc_i$ = field capacity for the $_i$th soil zone (kg/ha), where i = 1,2,3.
r = rainfall (mm/ha)
I = infiltration (kg/ha)
sr = surface runoff (kg/ha)
ae = actual evaporation from soil zone 1 (kg/ha)
at = actual temperature ($^{o}$ C)

Figure 18 b. Legend.

(ii) maize exploitation of water is confined to soil zone 1 only.

### 7.3 **Dynamics of maize biomass and its water content**

The processes of maize growth and the resulting biomass accumulation and maize harvest are the same for this model as they were for the maize/water model (section 6.22). This also applies to the processes of water uptake and transpiration by maize (section 6.2.3). (Appendix 6 contains all the mathematical equations for the variables in the *Cassia* /maize/ground soil water model).

### 7.4 **Dynamics of *Cassia* shoot biomass and its water content**

For purposes of modelling, I decided to differentiate the fact that the total *Cassia* shoot regrowth is composed of two parts: the part that results from the direct water uptake by *Cassia* from soil zone 1 (referred to henceforth as *Cassia* shoot regrowth 1) and the part that results from the direct water uptake from soil zone 2 (referred to henceforth as *Cassia* shoot regrowth 2).

Thus, at any time step ($\Delta t$), the current stock of *Cassia* shoot biomass may increase as a result of *Cassia* shoot regrowth 1 or *Cassia* shoot regrowth 2 or both or decrease as a result of pruning. This relationship is expressed by the following difference equation:

$$csb(t) = csb(t-\Delta t) + csr1\Delta t + csr2\Delta t - cp\Delta t \qquad (22)$$

where:

$t$ = time;

$\Delta t$ = a discrete step in time (e.g. 1 day);

$csb(t)$ = *Cassia* shoot biomass at time t (kg $ha^{-1}$);

csr1$\Delta$t = *Cassia* shoot regrowth from water uptake in zone1 during $\Delta$t (kg ha$^{-1}$);

csr2$\Delta$t = *Cassia* shoot regrowth from water uptake in zone 2 during $\Delta$t (kg ha$^{-1}$);

cp$\Delta$t = *Cassia* shoot biomass removed by pruning during $\Delta$t (kg ha$^{-1}$).

The logic that defined the relationship between, on the one hand, both *Cassia* shoot regrowth 1 and *Cassia* shoot regrowth 2 and, on the other hand, *Cassia* shoot biomass, is as follows:

(i) csr1 = If ((time $<$ 204 or (time $\geq$ 224 and time $<$ 389)) and (zone 1 wc $\geq$ 250000)) then ((4/10^13)*zone 1 wc*csb*(50000-csb)) else 0 (23)

where the symbols csr1 and csb are as defined in equation (22), and

zone 1 wc = soil zone 1 water content (kg ha$^{-1}$);

204 = time when *Cassia* is first pruned (days);

224 = time when *Cassia* starts the regrowth cycle (days);

389 = time when *Cassia* is pruned the second time (days);

250000 = the minimum level of water below which it is unavailable to *Cassia* (kg ha-1);

4/10^13 = a constant that determines the form of the *Cassia* shoot biomass curve;

50000 = the ultimate limiting value for *Cassia* shoot biomass.

(ii) csr2 = If ((time $<$ 204 or (time $\geq$ 224 and time $<$ 389)) and (zone 2 wc $\geq$ 250000)) then ((4/10^13)*zone 2 wc*csb*(50000-csb)) else 0 (24) where the symbols are as defined in equation (23) and, zone 2 wc is soil zone 2 water content.

I then modelled *Cassia* water uptake from soil zone 1 and soil zone 2 separately:

(i) cwu1 = If ((time $<$ 204 or (time $\geq$ 224 and time $<$ 389))
and (zone 1 wc $\geq$ 250000)) then (if zone 2 wc $>$ 250000 then (0.5*ct
+ (7/3)*csr1) else ct + (7/3)*(csr1 + csr2)) else 0 (25)

where:

cwu1 = *Cassia* water uptake from soil zone 1 (kg $ha^{-1}$ $day^{-1}$);
zone 1 wc = soil zone 1 water content (kg $ha^{-1}$);
zone 2 wc = soil zone 2 water content (kg $ha^{-1}$);
0.5*ct = Half of *Cassia* transpiration that directly results from *Cassia* water uptake 1 (kg $ha^{-1}$ $day^{-1}$);
7/3*csr1 = the amount of water that is taken up as a result of processing the daily *Cassia* shoot regrowth from water uptake in soil zone 1 (kg $ha^{-1}$);
7/3*csr2 = the amount of water that is taken up as a result of processing the daily *Cassia* shoot regrowth from water uptake in soil zone 2 (kg $ha^{-1}$);

(ii) cwu2 = If ((time $<$ 204 or (time $\geq$ 224 and time $<$ 389))
and (zone 2 wc $\geq$ 250000)) then (if zone 1 wc $>$ 250000 then (0.5*ct
+ (7/3)*csr2) else ct + (7/3)*(csr1 + csr2)) else 0 (26)

where the symbols are as defined in equation (25).

I modelled *Cassia* transpiration using the following logic:

$$ct = \text{If ((time} < 204 \text{ or (time} \geq 224 \text{ and time} < 389) \text{ then } (8*10^{-6} *csb/aed + 700*(csr1 + csr2)) \text{ else } 0. \quad (27)$$

where:

ct = *Cassia* transpiration (kg $ha^{-1}day^{-1}$);

csb = *Cassia* shoot biomass (kg $ha^{-1}$);

700 *(csr+csr2) = the amount of water processed during the total *Cassia* shoot regrowth (kg $ha^{-1}$ $day^{-1}$);

aed = Air evaporation demand (kPa).

$8*10^{-6}$ = An appropriate factor to scale down the values of *Cassia* transpiration. I found this factor by trial and error method.

csr1 and csr2 are as defined in equation (22 above).

## 7.5 Simulation results and discussion

The simulation results for the *Cassia* /maize/ground soil water model are presented in Table 5 and Figure 19 and Figure 20. In general, the soil moisture contents in all the three soil zones very closely reflect the rainfall distribution pattern over the two seasons under consideration. I would expect soil zone 1 to be the zone of most water competition. The results show that soil zone 1 water content fluctuates from relatively very high values to very low values. The high values are the direct response to infiltration while the low values are as a result of both *Cassia* and maize water uptake as well as evaporation. The second soil zone, from which *Cassia* draws part of its water requirements, holds relatively less water than zone 1 especially when the rains are still falling. During the dry periods when most of the rains have stopped, soil zone 2 dries relatively more slowly than soil zone 1. For a time during the first dry period in the simulation, both soil zone 1 and soil zone 2 water contents go below the value of 250000 kg $ha^{-1}$ and *Cassia* stops growing because water is no longer available for growth. Soil zone 3 is relatively stable in its water content due to the fact that neither *Cassia* nor maize exploits its water requirements from it.

The pattern of biomass accumulation for both *Cassia* and maize is the same as found earlier (see sections 5.5 and 6.5, respectively). The amount of simulated *Cassia* biomass at the end of the first and second seasons are 893.4 kg/ha and 1057.8 kg/ha, respectively. For maize, the simulated amounts of biomass harvested at the end of the first and second seasons are 1799.8 kg/ha and 1799.6 kg/ha, respectively. The figures for *Cassia* are much lower than what was found for the pure stands of *Cassia* with a constant water input (section 5.3). This may be because of the low water levels below 250000 kg ha-1, for both soil zone 1 and zone 2, especially during the dry periods in the regrowth cycle. The model may be improved by using different parameter values to achieve more realistic values for *Cassia* biomass. On the other hand, the simulated maize biomass in the *Cassia* /maize/ground water model is about the same as was simulated by the maize crop model under a constant water input (section 6.3).

The simulated *Cassia* biomass production for the *Cassia* /maize/ground water model significantly falls short of what is realised in the real system at

Machakos. The *Cassia* biomass produced in the real system for the first season and the second season are, on average, 5833.4 kg $ha^{-1}$ and 4612.1 kg $ha^{-1}$ respectively. Thus, the model simulates less *Cassia* biomass than the real system for both seasons.

On the other hand, the simulated maize biomass compares very closely with the field data for the first season which is on average 1800 kg ha-1. However, the average maize biomass harvested in the second season is, on average, 1350 kg $ha^{-1}$ which is significantly lower than the model output.

Table 5. Simulation results for the *Cassia* /maize / soil water model.

| Time (days) | Rainfall (mm) | Infiltration (kg/ha) | Surface runoff (kg/ha) | Actual temperature (° C) | Actual evaporation (kg/ha) | Zone 1 water content (kg/ha) | Zone 2 water content (kg/ha) | Zone 3 water content (kg/ha) |
|---|---|---|---|---|---|---|---|---|
| 5 | 1.51 | 15100 | 0 | 21.5 | 8633 | 336146 | 347607 | 350000 |
| 15 | 2.27 | 22700 | 0 | 21.3 | 10650 | 405216 | 341951 | 350000 |
| 30 | 4.33 | 34880 | 0 | 20.4 | 10224 | 537508 | 411471 | 350000 |
| 45 | 4.55 | 39638 | 0 | 19.9 | 9950 | 507978 | 499479 | 376891 |
| 60 | 3.20 | 26046 | 0 | 19.5 | 9750 | 533725 | 524856 | 461327 |
| 75 | 1.37 | 12606 | 0 | 19.0 | 9500 | 485932 | 486501 | 499222 |
| 90 | 0.48 | 4800 | 0 | 18.3 | 9150 | 413343 | 442763 | 474760 |
| 105 | 0.09 | 900 | 0 | 17.0 | 4443 | 297111 | 396678 | 465100 |
| 114 | 0.09 | 900 | 0 | 16.7 | 1966 | 248755 | 368985 | 462258 |
| 115 | 0.09 | 900 | 0 | 16.7 | 1915 | 247689 | 365312 | 462008 |
| 130 | 0.10 | 950 | 0 | 16.8 | 1418 | 235934 | 311743 | 459197 |
| 145 | 0.11 | 1100 | 0 | 16.6 | 1234 | 232010 | 262006 | 457458 |
| 160 | 0.25 | 2500 | 0 | 17.2 | 1668 | 241051 | 249536 | 456275 |
| 175 | 0.25 | 2500 | 0 | 17.2 | 2094 | 250339 | 249536 | 455417 |
| 190 | 0.02 | 200 | 0 | 18.4 | 1491 | 234690 | 249536 | 454766 |
| 204 | 0.03 | 290 | 0 | 19.1 | 919 | 221168 | 249536 | 454286 |
| 205 | 0.03 | 300 | 0 | 19.2 | 893 | 220539 | 249536 | 454255 |
| 220 | 0.07 | 750 | 0 | 20.2 | 659 | 214640 | 249536 | 453843 |
| 235 | 2.11 | 21100 | 0 | 20.2 | 5255 | 296751 | 249536 | 453505 |
| 250 | 3.70 | 30706 | 0 | 19.5 | 9774 | 526043 | 261978 | 453221 |
| 280 | 3.59 | 32046 | 0 | 19.0 | 9524 | 497745 | 500471 | 499372 |
| 295 | 2.76 | 24019 | 0 | 19.4 | 9700 | 508386 | 485668 | 48797 |
| 325 | 0.63 | 6300 | 0 | 19.7 | 9849 | 385775 | 436367 | 470970 |
| 334 | 0.63 | 6300 | 0 | 20.1 | 7809 | 332538 | 411263 | 465832 |
| 335 | 0.63 | 6300 | 0 | 20.2 | 7494 | 328184 | 408416 | 465414 |
| 350 | 0.61 | 6100 | 0 | 20.6 | 4689 | 286656 | 363931 | 461058 |
| 375 | 1.51 | 15100 | 0 | 21.3 | 5402 | 294760 | 281564 | 457533 |
| 389 | 3.01 | 30060 | 0 | 20.5 | 10249 | 402994 | 246470 | 456396 |
| 390 | 3.19 | 31900 | 0 | 20.4 | 10224 | 422805 | 246470 | 456328 |
| 400 | 4.33 | 32505 | 0 | 20.4 | 10024 | 562186 | 337528 | 455718 |

Table 5. (Continued)

| Time (days) | Drainage from zone 1 (kg/ha) | Drainage from zone 2 (kg/ha) | Drainage from zone 3 (kg/ha) | Drainage rate from zone 1 (no units) | Drainage rate from zone 2 (no units) | Drainage rate from zone 3 (no units) | Cassia shoot biomass (kg/ha) | Cassia shoot regrowth 1 (kg/ha/day) |
|---|---|---|---|---|---|---|---|---|
| 5 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 106.8 | 0.7 |
| 15 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 122.9 | 1.0 |
| 30 | 12763 | 0 | 0 | 0.1 | 0.0 | 0.0 | 157.7 | 1.7 |
| 45 | 5602 | 4080 | 0 | 0.1 | 0.1 | 0.0 | 211.6 | 2.1 |
| 60 | 11683 | 9339 | 214 | 0.1 | 0.1 | 0.0 | 286.9 | 3.0 |
| 75 | 2152 | 2220 | 4038 | 0.1 | 0.1 | 0.1 | 387.4 | 3.7 |
| 90 | 0 | 0 | 1022 | 0.0 | 0.0 | 0.0 | 509.0 | 4.2 |
| 105 | 0 | 0 | 380 | 0.0 | 0.0 | 0.0 | 640.2 | 3.8 |
| 114 | 0 | 0 | 250 | 0.0 | 0.0 | 0.0 | 719.0 | 0.0 |
| 115 | 0 | 0 | 240 | 0.0 | 0.0 | 0.0 | 724.2 | 0.0 |
| 130 | 0 | 0 | 141 | 0.0 | 0.0 | 0.0 | 800.5 | 0.0 |
| 145 | 0 | 0 | 93 | 0.0 | 0.0 | 0.0 | 871.3 | 0.0 |
| 160 | 0 | 0 | 66 | 0.0 | 0.0 | 0.0 | 889.1 | 0.0 |
| 175 | 0 | 0 | 49 | 0.0 | 0.0 | 0.0 | 889.1 | 4.4 |
| 190 | 0 | 0 | 38 | 0.0 | 0.0 | 0.0 | 893.4 | 0.0 |
| 204 | 0 | 0 | 31 | 0.0 | 0.0 | 0.0 | 893.4 | 0.0 |
| 205 | 0 | 0 | 30 | 0.0 | 0.0 | 0.0 | 100.0 | 0.0 |
| 220 | 0 | 0 | 25 | 0.0 | 0.0 | 0.0 | 100.0 | 0.0 |
| 235 | 0 | 0 | 20 | 0.0 | 0.0 | 0.0 | 101.6 | 0.6 |
| 250 | 9638 | 0 | 17 | 0.1 | 0.0 | 0.0 | 116.3 | 1.2 |
| 280 | 3799 | 4246 | 4063 | 0.1 | 0.1 | 0.1 | 205.7 | 2.0 |
| 295 | 5681 | 2120 | 2404 | 0.1 | 0.1 | 0.1 | 275.1 | 2.8 |
| 325 | 0 | 0 | 733 | 0.0 | 0.0 | 0.0 | 479.4 | 3.7 |
| 334 | 0 | 0 | 418 | 0.0 | 0.0 | 0.0 | 550.9 | 3.6 |
| 335 | 0 | 0 | 396 | 0.0 | 0.0 | 0.0 | 559.0 | 3.6 |
| 375 | 0 | 0 | 95 | 0.0 | 0.0 | 0.0 | 920.1 | 5.3 |
| 389 | 0 | 0 | 68 | 0.0 | 0.0 | 0.0 | 1057.8 | 0.0 |
| 390 | 0 | 0 | 67 | 0.0 | 0.0 | 0.0 | 100.0 | 0.0 |
| 400 | 20976 | 0 | 55 | 0.2 | 0.0 | 0.0 | 100.0 | 0.0 |

Table 5. (Continued)

| Time (days) | Cassia shoot regrowth 2 (kg/ha) | Cassia water uptake 1 (kg/ha) | Cassia water uptake 2 (kg/ha) | Water in Cassia biomass (kg/ha) | Cassia transpiration (kg/ha) | Cassia pruning (kg/ha) | Cassia water harvest (kg/ha) | maize biomass (kg/ha) |
|---|---|---|---|---|---|---|---|---|
| 5 | 0.7 | 512 | 512 | 249 | 1020 | 0 | 0 | 15.4 |
| 15 | 0.8 | 644 | 643 | 287 | 1283 | 0 | 0 | 41.2 |
| 30 | 1.3 | 1048 | 1047 | 368 | 2088 | 0 | 0 | 261.8 |
| 45 | 2.1 | 1491 | 1491 | 494 | 2971 | 0 | 0 | 1093.0 |
| 60 | 3.0 | 2121 | 2121 | 669 | 4227 | 0 | 0 | 1697.7 |
| 75 | 3.7 | 2626 | 2626 | 904 | 5234 | 0 | 0 | 1789.9 |
| 90 | 4.5 | 3029 | 3030 | 1188 | 6038 | 0 | 0 | 1798.8 |
| 105 | 5.0 | 3078 | 3081 | 1494 | 6139 | 0 | 0 | 1799.8 |
| 114 | 5.2 | 0 | 3673 | 1678 | 3661 | 0 | 0 | 1799.8 |
| 115 | 5.2 | 0 | 3663 | 1690 | 3650 | 0 | 0 | 10.0 |
| 130 | 4.9 | 0 | 3449 | 1868 | 3438 | 0 | 0 | 10.0 |
| 145 | 4.5 | 0 | 3151 | 2033 | 3140 | 0 | 0 | 10.0 |
| 160 | 0.0 | 0 | 0 | 2074 | 0 | 0 | 0 | 10.0 |
| 175 | 0.0 | 3071 | 0 | 2074 | 3061 | 0 | 0 | 10.0 |
| 190 | 0.0 | 0 | 0 | 2084 | 0 | 0 | 0 | 10.0 |
| 204 | 0.0 | 0 | 0 | 2084 | 0 | 793 | 1851 | 10.0 |
| 205 | 0.0 | 0 | 0 | 233 | 0 | 0 | 0 | 10.0 |
| 220 | 0.0 | 0 | 0 | 233 | 0 | 0 | 0 | 10.0 |
| 235 | 0.0 | 423 | 0 | 237 | 421 | 0 | 0 | 10.0 |
| 250 | 0.6 | 643 | 642 | 271 | 1281 | 0 | 0 | 47.0 |
| 280 | 2.1 | 1436 | 1436 | 480 | 2863 | 0 | 0 | 1242.5 |
| 295 | 2.7 | 1910 | 1910 | 642 | 3807 | 0 | 0 | 1718.6 |
| 325 | 4.1 | 2741 | 2742 | 1119 | 5465 | 0 | 0 | 1798.9 |
| 334 | 4.5 | 2845 | 2847 | 1285 | 5673 | 0 | 0 | 1799.6 |
| 335 | 4.5 | 2859 | 2861 | 1304 | 5700 | 0 | 0 | 10.0 |
| 375 | 5.1 | 3656 | 3656 | 2147 | 7287 | 0 | 0 | 10.0 |
| 389 | 0.0 | 0 | 0 | 2468 | 0 | 958 | 2235 | 10.0 |
| 390 | 0.0 | 0 | 0 | 233 | 0 | 0 | 0 | 10.0 |
| 400 | 0.0 | 0 | 0 | 233 | 0 | 0 | 0 | 10.0 |

Table 5. (Continued)

| Time (days) | Maize growth (kg/ha) | Maize water uptake (kg/ha) | Water in Maize biomass (kg/ha) | Maize transpiration (kg/ha) | Maize harvest (kg/ha) | Maize water harvest (kg/ha) | Air Evaporative demand (kPa) |
|---|---|---|---|---|---|---|---|
| 5 | 1.5 | 521 | 36 | 518 | 0 | 0 | 0.5 |
| 15 | 4.7 | 1654 | 96 | 1644 | 0 | 0 | 1.9 |
| 30 | 34.6 | 12203 | 611 | 12123 | 0 | 0 | 0.6 |
| 45 | 62.8 | 22129 | 2550 | 21983 | 0 | 0 | 1.2 |
| 60 | 14.8 | 5227 | 3961 | 5192 | 0 | 0 | 0.2 |
| 75 | 1.4 | 496 | 4176 | 493 | 0 | 0 | 1.4 |
| 90 | 0.1 | 51 | 4197 | 50 | 0 | 0 | 1.2 |
| 105 | 0.0 | 0 | 4199 | 0 | 0 | 0 | 1.0 |
| 114 | 0.0 | 0 | 4199 | 0 | 1790 | 4176 | 0.8 |
| 115 | 0.0 | 0 | 23 | 0 | 0 | 0 | 0.7 |
| 130 | 0.0 | 0 | 23 | 0 | 0 | 0 | 0.7 |
| 160 | 0.0 | 0 | 23 | 0 | 0 | 0 | 1.1 |
| 175 | 0.0 | 0 | 23 | 0 | 0 | 0 | 0.7 |
| 190 | 0.0 | 0 | 23 | 0 | 0 | 0 | 0.2 |
| 204 | 0.0 | 0 | 23 | 0 | 0 | 0 | 1.0 |
| 205 | 0.0 | 0 | 23 | 0 | 0 | 0 | 0.6 |
| 220 | 0.0 | 0 | 23 | 0 | 0 | 0 | 0.5 |
| 235 | 0.0 | 0 | 23 | 0 | 0 | 0 | 1.1 |
| 250 | 6.9 | 2443 | 110 | 2426 | 0 | 0 | 1.0 |
| 280 | 55.2 | 19436 | 2899 | 19308 | 0 | 0 | 0.7 |
| 295 | 11.4 | 4008 | 4010 | 3982 | 0 | 0 | 0.2 |
| 325 | 0.1 | 44 | 4197 | 44 | 0 | 0 | 1.0 |
| 334 | 0.0 | 0 | 4199 | 0 | 1790 | 4176 | 1.4 |
| 335 | 0.0 | 0 | 23 | 0 | 0 | 0 | 0.6 |
| 375 | 0.0 | 0 | 23 | 0 | 0 | 0 | 0.2 |
| 389 | 0.0 | 0 | 23 | 0 | 0 | 0 | 0.5 |
| 390 | 0.0 | 0 | 23 | 0 | 0 | 0 | 0.2 |
| 400 | 0.0 | 0 | 23 | 0 | 0 | 0 | 0.5 |

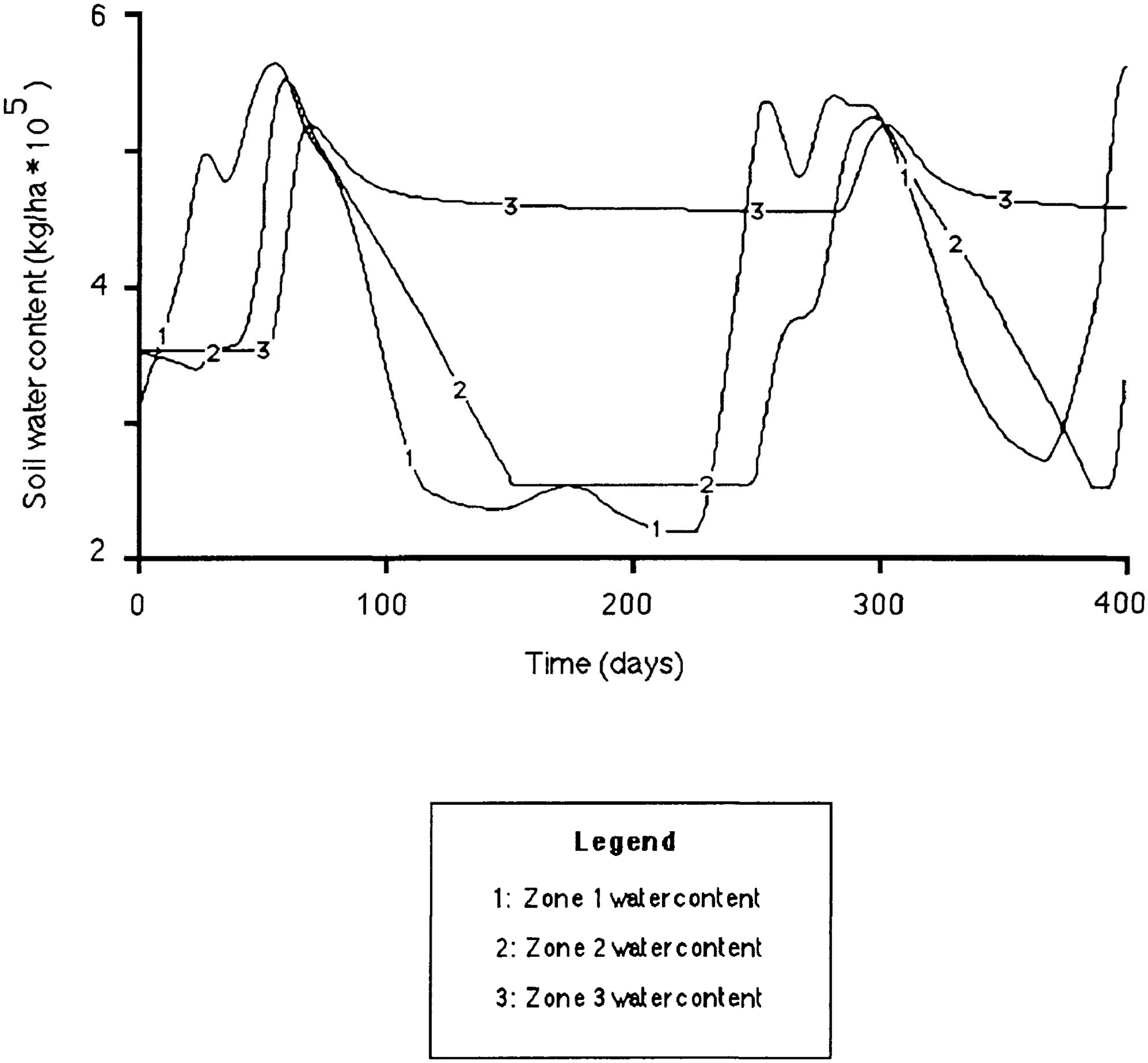


Figure 19. The simulated soil water contents for soil zone 1, soil zone 2 and soil zone 3 for the *Cassia*/ maize/ ground soil water model.

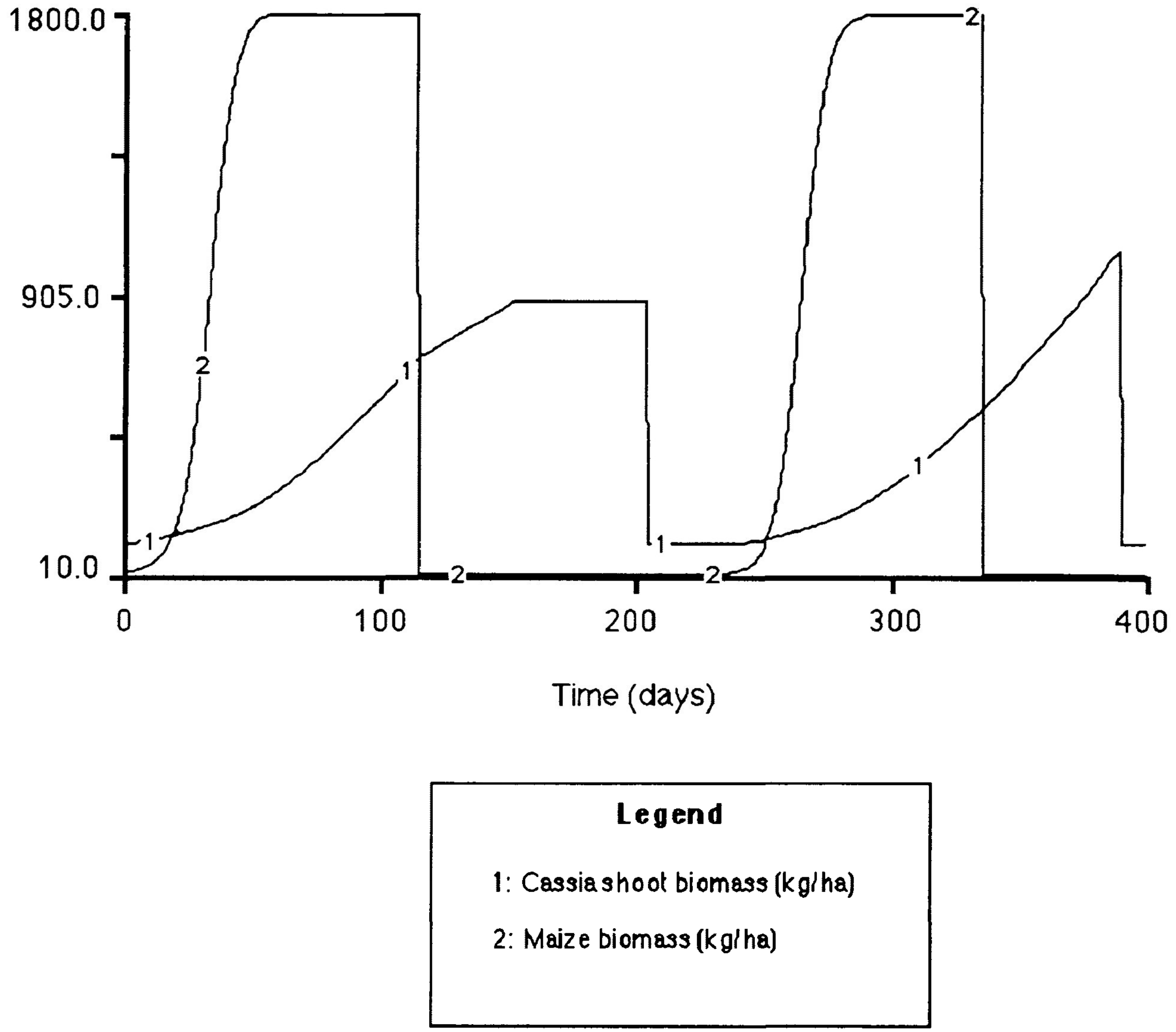


Figure 20. The simulated *Cassia* shoot biomass and maize biomass for the *Cassia* /maize/ground soil water model.

# CHAPTER 8

## DISCUSSION

The objective of this study was to model an alley cropping system in which *Cassia siamea* and maize were used as the hedgerow and crop species, respectively. The effort was successful to a certain degree but not completely.

In the sections below, I first describe what I think an ideal *Cassia* /maize alley cropping model would entail. Then I evaluate the strengths and weaknesses of the model I have developed. Finally, I suggest the nature of additional work that needs to be done, relative to the ideal model, to address the weaknesses of my model.

### 10.1 **Characteristics of an ideal Cassia/maize alley cropping model**

An ideal model will have the following generic features:

(i) include the *important* environmental factors of the real system;

(ii) include the *important* components of the real system;

(iii) include the *important* environment-to-component structure of the real system;

(iv) include the *important* component-to-component structure of the real system;

(v) accurately reflect the *important* quantitative details of all environment-to-component and all component-to-component relationships in the real system;

(vi) be at the *right* level of resolution.

What is *important* and what is *right*, however, can only be judged relative to the model's intended use. Thus, for example, modelling the effects of soil texture on infiltration might be an important and right thing to do in an alley-crop model intended for an agronomist or a soil scientist, but perhaps not the thing to do in an alley-crop model intended for an agricultural economist.

I set out to describe the characteristics of a *Cassia* /maize alley crop model that is ideally suited to the needs of an agroforester who wishes to use the model to design, through simulation experimentation, alley cropping systems to meet the diverse needs for his farmer clients. Thus, for my purposes, the crucial test is whether the model behaves like the real system from the point of view of an agroforester.

The ideal model of *Cassia* /maize alley cropping system will include the variables that are involved in the interaction of *Cassia siamea* with maize, and those involved in the interaction of each of these crops with the environment. Only those variables that are critical to the solution of the stated objective are to be included in the ideal model.

Ecological interactions between *Cassia siamea* and maize in a real alley cropping system can be viewed in terms of the above- and below-ground utilization of physical resources (Ong et al. 1991). The above-ground interactions are mediated by such variables as light, rainfall, temperature, saturation water vapour pressure deficit, humidity, and wind. These variables are the ones that comprise the aerial environment of the alley cropping system. On the other hand, the below-ground interactions involve such variables as water and nutrients (Monteith et al. 1991; Ong 1991).

Alley cropping improves soil fertility through mulching, and can also provide fodder especially during dry seasons (Kang et al. 1985; Singh et al. 1989). Thus, the overriding agroforestry objective of alley cropping is to maximize tree biomass production and crop yield. The components of a real *Cassia* /maize alley cropping system therefore include the *Cassia* hedges, maize crop, the stock of soil water content and soil nutrient pool.

An ideal agroforestry model would allow the agroforester to design an alley cropping system that is tailored to the client's unique situation and special needs. Such a model would allow the client's situation to be described in terms of soil attributes, rainfall patterns, and so on. Then, it would allow the agroforester to explore the effects of design parameters, such as *Cassia* hedgerow orientation, in-row and between-row spacing of the *Cassia*, and pruning height of *Cassia*, on the yield of the maize crop. An "optimum" design will be one that meets the client's needs whatever these might be. For example, one client may want a design that maximizes maize yield in a year of average rainfall. Another client, however, may want a design that maximizes maize yield in a year of minimum rainfall.

Total *Cassia* and maize biomass can each be partitioned into two components, namely: above-ground biomass and below-ground biomass. In the above-ground, the ideal model would allow the agroforester to determine the amount of shading cast on the maize crop by *Cassia.* Thus, the agroforester would be able to determine an optimum combination of *Cassia* spacing, pruning height and orientation that would minimize shading on the maize crop without jeopardizing the production of biomass for mulch. Lawson and Kang (1990) noted that the biomass produced by the hedgerow species mainly determines the extent of interference with the radiation incident on the maize crop.

The ideal model would also help the agroforester in exploring the root dynamics of *Cassia siamea* and maize and the effects that each species has on the other's water supply. In the on-going field alley cropping trial at Machakos, the root system of *Cassia siamea* hedges are well established in the alleys. Thus, the *Cassia siamea* hedges have a competitive edge over the maize crop with respect to both water and nutrients. This becomes more pronounced as time goes on due to the expanding *Cassia* root system. An ideal model should help the agroforester by reflecting these time-dependent changes realistically. Thus, the model would allow the agroforester to explore the effects of a dry season and a wet season on the productivity of *Cassia siamea* and maize.

Rainfall is normally the driving force in the recharge of soil water around the root zones of *Cassia siamea* and maize. The water and nutrient uptake by *Cassia* and maize are a function of the *Cassia* and maize demand and soil supply. This demand is a product of factors determining requirements for growth and maintainance, such as inherent growth rate, plant maturity, and climate (Gillespie 1989). An ideal model would allow the agroforester to simulate the uptake and the resulting effect of available soil water and soil nutrients on the biomass production of the *Cassia* hedges and maize yield.

I will now compare the model that I have just described in my thesis in order to judge its relative strengths and weaknesses.

## 10.2 Strengths of the Cassia/maize alley cropping model presented in this study

A comparision of my model (Figure 18) with the real alley cropping system indicates that there are some structural similarities between them. For example, when rainfall occurs in the real system, some is intercepted by *Cassia* and maize, some turns into runoff, and the rest enters into the soil. My model accounts for two of the three parts of rainfall, that is, runoff and infiltration. I have also modelled the movement of water, once it infiltrates into the soil, by dividing the soil profile into three soil zones.

The division of the soil profile is not only meant to account for water movement but also to help in modelling the soil zones from which *Cassia* and maize draw their water requirements. Figure 10 and Figure 19 both show the simulated soil moisture contents for the three soil zones. The behaviour that is exhibited by the simulated soil moisture contents is qualitatively much the same as what I would expect a real system to show. However, I have no validation data.

My model (Figure 18) also represents the essential processes in the growth and harvesting of *Cassia* and maize. The growth rate of *Cassia* depends, among other factors, on the standing crop of *Cassia* and the available soil water. The same is true of the growth rate of maize. The available soil water is itself a function of rainfall and the water uptake by both *Cassia* and maize. The processes involved in the uptake of water by both species are shown in the model. The model also shows the evaporative demand for water from both *Cassia* and maize. Thus, there are a few important structural similarities between my model and the real system.

## 10.3 **Weaknesses of the Cassia/maize alley cropping model presented in this study**

The present model falls short of the ideal model in at least three general ways: (i) some of the quantitative relationships are approximate (ii) some variables that are needed for system design have not been included, and (iii) the dynamic behaviour of the model is different from that of the real system in some ways.

Considering the first of these shortfalls in greater detail, it is noteworthy that some of the relationships are only approximations of what must be the actual field situation. For example, I hypothesized a relationship between the amount of rainfall that infiltrates into the soil and the soil zone 1 water content in which I assumed a 100% infiltration up to the point when the field capacity for zone 1 is reached (Figure 6). This may not be true in all situations. Furthermore, the linear decrease of infiltration after the field capacity of soil zone 1 is reached may not be the exact case in the field. This same argument may also apply to the hypothesized relationship between the water drainage rate from one soil zone to the next and the water content of the soil zone from which the drainage occurs (Figure 9).

For the case of the second shortfall, I note that there are several variables that would be required to design alley cropping systems that I have not included in my model. To begin with, I did not include light. It is therefore not possible to use the model to simulate the effects of solar radiation on *Cassia* and maize biomass production. Furthermore, it is difficult to model the dynamics of soil temperature across the alleys and their effects on the mulch decomposition rate and hence maize yield, without light being taken into account. Secondly, I did not include rainfall interception which can be important for a species with a dense crown like *Cassia* growing in a region of low rainfall as is the case for Machakos. Thirdly, I did not include such design parameters as the inter- and intra-row spacings, the orientation of the alleys, the pruning regimes of *Cassia* hedgerows and, the spatial distribution of the root systems of *Cassia* and maize. Thus, the model cannot be used to determine the optimum combination of spacing, pruning height and the orientation of the alleys. Due to the fact that I did not include spatial distribution of the root systems of *Cassia* and maize, the model cannot be used to simulate accurately the uptake of water by *Cassia* and maize.

Turning now to the third shortfall, there are ways that my model's simulated results differ from those that I expect from the real system. These include the behaviour of *Cassia* shoot biomass growth pattern whereby it starts to slow down during the first dry spell owing to lack of water. The simulated values for *Cassia* shoot biomass at the time of pruning are 893.4 and 1057.8 kg ha$^{-1}$ for the first and second season, respectively. These values are only a small fraction of those produced by the real system, which are, on average, 5833.4 and 4612.1 kg ha$^{-1}$ for the first and second season, respectively.

Another weakness of my model is its inability to account for maize grain yield directly.

## 10.4 **Addressing my model's weaknesses**

### 10.4.1 **Areas for further model development**

The model could be improved in both of the general areas noted in the previous section.

One area for improvement would be to elaborate the model to include a variable such as light. Lawson and Kang (1990) noted that increasing the alley cropping *Cassia* biomass production is desirable but, at a certain point, it results in undesirable competition for the use of incident solar radiation between *Cassia* and maize. Thus, one of the critical environmental factors that will need to be modelled is light interception. Kang et al. (1985) showed a substantial improvement in the radiation received by maize and cowpea crops grown between *Leuceana* hedgerows following the pruning of the hedgerows. Thus, the time and frequency of *Cassia* pruning will have a major influence on how much radiation is received by maize. This will in turn determine the maize yield, if maize growth is not limited by either water or nutrients (Monteith et al. 1991).

Of equal importance in determining how much radiation reaches maize is the in- and between-row spacings of *Cassia* and maize. The wider the in-row and between-row spacings of *Cassia*, the less the shading effect on maize. However, this would result in reduced *Cassia* biomass production.

Rainfall interception has been shown by Monteith et al. (1991) to account for about 20% of the incident rainfall in an alley cropping system with *Leucaeana.* Thus, it would be important to elaborate the model by including rainfall interception.

Umaya (1991) showed that *Cassia* and maize in an alley cropping system share some of the soil volume that they both occupy, and this inevitably leads to competition for resources, mainly water and nutrients. I would expect the *Cassia* /maize alley cropping system to behave differently in, say, year 2 than in year 5, because of the expanding root system of *Cassia* hedges into the alleys. The between-row spacing of *Cassia* hedges will partly determine how fast the roots from one *Cassia* hedgerow take to meet the roots from an adjacent hedgerow. Thus, the inter- and intra-row spacings of both *Cassia* and maize will determine the dynamics of water and nutrients uptake by the species. It would be vital for the model to account for the changing root distribution as the system grows old. Further, it would be important to find out how long the *Cassia* can bear the constant pruning without losing its capacity to produce biomass.

Another area for improvement would be to calibrate the model better using additional field data. In some cases, these data do not presently exist and field experiments must be conducted in order to obtain them. The details of the necessary empirical research are found in the section that follows.

Finally, the next step in model building should be to subject the model to sensitivity analysis. In deciding which variables to include in my model, I depended on my experience with the alley cropping systems in Machakos and other parts of Kenya and the scientific literature on agroforestry. Although there may be nothing wrong with this approach, a better procedure would have included a sensitivity analysis. This might have given me information on how sensitive the model's response is to small changes in the values of its coefficients. Such information indicates the relative importance of each coefficient in the model.

### 10.4.2 **Empirical field research**

In order to answer the questions that will lead to the improvement of my model and make it more useful as a tool for designing alley cropping systems, the following areas of research need to be investigated:

(i) An experimental trial on both spacing and pruning regime of *Cassia* /maize alley cropping system should be laid out. This should be done such that a number of spacings are considered. For example, there may be about five different between-row spacings and five different in-row spacings. Different pruning heights should also be considered in the same trial. The amount of radiation reaching maize at different growth stages should be determined and the corresponding height and crown spread of *Cassia* hedges recorded. This will allow the refining of management techniques such as the height and frequency of *Cassia* pruning, and the planting spacing of *Cassia* and maize designed to reduce the amount of *Cassia* /maize interface.

(ii) The effect of soil moisture on the growth rates of both *Cassia* and maize needs to be determined empirically. Instead of measuring a single and final yield value for both *Cassia* and maize, the growth and development of both species should be measured regularly throughout a growing season.

(iii) A more detailed study of root distributions and densities of *Cassia* and maize and their interactions should be done. This could be done on the same experimental trial as the spacing and pruning regime proposed in (i).

(iv) A determination of the correlation of maize stover and grain for both a wet and dry season should be carried out. This can be achieved by running both field and green house experiments. The field study would be to observe and analyse the effect of wet and dry season on grain over several years. The green house experiment, on the other hand, would be to control the watering regime to try and understand the mechanisms that trigger crop failure during dry periods.

In conclusion, I believe that this work has provided a framework for integrating empirical research results. Such a framework promotes the understanding of the dynamic nature of alley cropping systems and brings to light gaps in the empirical knowledge base. My contribution in this thesis is a small step in the long path of obtaining an ideal framework for integrating all the variables involved in an agroforestry system such as alley cropping. Nonetheless, for the reasons just stated, I believe it has been a worthwhile project and, on a personal note, it has given me a useful learning experience in modelling dynamic systems.

# LITERATURE CITED

Anderson, J.M. and J.S. Ingram (ed.) 1989. Tropical soil biology and fertility. A handbook of methods. CAB international, Wallingford, U.K. pp. 59-69.

Black, T.A., W.R. Gardner and G.W. Thurtell. 1969. The Prediction of Evaporation, Drainage, and Soil Water Storage for a Bare Soil *in* Soil Sci. Soc. Amer. Proc. 33:655-660.

Bohm, W. 1979. Methods of studying root systems. Ecological studies No. 33. Springer-verlag, Berlin. pp. VII-VIII, 117-119, and 122-138.

Brown, K.M. 1991. Exploratory data analysis: classnotes for a shortcourse. Lakehead University.

Buck, M.G. 1986. Concepts of resource sharing in agroforestry systems. Agro. syst. 4:191-203.

Caldwell, M.M. 1986. Competition between root systems in natural communities. pp.167-188 *in* Gregory, P.J., J.V. Lake and D.A. Rose (ed.) Root development and function. Cambridge University Press, Cambridge, London.

Connor, D.J. 1983. Crop models: components of and contributors to models of agroforestry plant associations. pp. 249-256 *in* Huxley P.A. (ed.) Proc. of a consultitative meeting: Plant research and agroforestry. ICRAF, Nairobi, Kenya. April 8-15 1981. 617p.

Dent J.B. and J.R. Anderson. 1979. Systems, management and agriculture. pp. 3-14 *in* Yaron, D and C.S. Tapiero (ed.) Operations research in agriculture and water resources. Proceedings of the ORAGWA international conference held in Jerusalem, November 25-29, 1979.

Deutsch, K. 1963. The Nerves of Government. New York: The Free Press.

Downey, L.A. 1971a. Effect of gypsum and drought stress on maize (*Zea mays* L.). Growth, light absorption, and yield. Agron. J. 63: 569-572.

Duguma, B., B.T. Kang and D.U.U. Okali. 1988. Effect of pruning intensities of three woody leguminous species grown in alley cropping with maize and cowpea on an alfisol. Agro. syst. 6:19-35.

Forrester, J.W. 1961. Industrial dynamics. Cambridge, Mass.: MIT Press.

Gardner, H.R. 1983. Soil Properties and Efficient Water Use: Evaporation of Water from Bare Soil. pp.65-71 *in* Taylor, H.M., W.R. Jordan and T.R. Sinclair (ed.) Limitations to Efficient Water Use in Crop Production.

Gillespie, A.R. 1989. Modelling nutrient flux and interspecies root competition in agroforestry interplantings. Agro. syst. 8:257-265.

Government of Kenya. 1988. National Development Plan for the period 1989-1993, Nairobi, Kenya. 262p.

Grant, W.E. 1986. Systems analysis and simulation in wildlife and fisheries sciences. John wiley & sons. New York, Chichester, Brisbane, Toronto and Singapore. 338p.

Guevarra, A.B., A.S. Whitney and J.R. Thompson. 1978. Influence of intra-row spacing and cutting regimes on growth and yield of leuceana. Agronomy journal 70: 1033-1037.

Huck, M.G. 1983. Root distribution, growth, and activity with reference to agroforestry. pp. 527-542 *in* Huxley P.A. (ed.) Plant research and agroforestry. ICRAF, Nairobi. Kenya.

Huda, A.K.S. and C.K. Ong 1987. Crop simulation models and some implications for agroforestry systems. pp. 115-124 *in* Reifsnyder, W.S. and T.O. Darnhofer (ed.) Meteorology and Agroforestry. Nairobi, Kenya. February 9-13, 1987. 546p.

Huxley, P.A. 1983. Some characteristics of trees to be considered in agroforestry. pp.3-12 *in* Huxley P.A. (ed.) Plant Research and Agroforestry. ICRAF, Nairobi, Kenya.

Huxley, P.A., T. Darnhofer, A. Pinney, E. Akunda and D. Gatama. 1989. The tree/crop interface. A project designed to generate experimental methodology. Agro. Abstr. 2:127-145. .

Jama, B., P.K.R. Nair and P.W. Kurira. 1989. Comparative growth performance of some multipurpose trees and shrubs grown in Machakos District, Kenya. Agro. syst. 9:17-27.

Jonsson, K., L. Fidjeland, J.A. Maghembe and P. Hogberg. 1988. The vertical distribution of fine roots of five tree species and maize in Morogoro, Tanzania. Agro. syst. 6:63-69.

Jurgens, S.K., R.R. Johnson and J.S. Boyer. 1978. Dry matter production and translocation in maize subjected to drought during grain fill. Agronomy journal 70: 678-682.

Kang, B.T., C.B.M. Van der Kruijs and D.C. Couper. 1986. Alley cropping for food production in humid and subhumid tropics. pp. 16-26 *in* Kang, B.T. and L. Reynolds (ed.) Alley Farming in the Humid and Subhumid Tropics. Proc. of an international workshop held at Ibadan, Nigeria, 10-14 March, 1986. International Development Research Centre (IDRC), Ottawa, Ontario, Canada.

Kang, B.T., G.F. Wilson and L. Sipkens. 1981. Alley cropping maize (*Zea mays* L. ) and Leuceana (*Leuceana leucocephala* Lam.) in southern Nigeria. Plant and soil 63: 165-179.

Kang, B.T., G.F. Wilson and T.L. Lawson. 1984. Alley cropping as a stable alternative to shifting cultivation. International institute of Tropical Agriculture, Ibadan, Nigeria.

Kang, B.T., H. Grimme and T.L. Lawson. 1985. Alley cropping sequentially cropped maize and cowpea with *Leuceana* on a sandy soil in southern Nigeria. Plant and soil 85: 267-277.

Kang, B.T., L. Reynolds, A.N. Atta-Krah. 1990. Alley farming. pp. 315-359 *in* Advances in agronomy, Vol. 43.

Kibe, J.M., H. Ochung' and P.N. Macharia. 1981. Soil and vegetation of the I.C.R.A.F. Experimental Farm (Machakos District). Kenya soil Survey. 68p.

Kozlowski, T.T., P.J. Kramer and S.G.Pallardy. 1991. The physiological ecology of woody plants. Academic Press, Inc. 657p.

Kramer, P.J. 1983. Water Relations of Plants. Academic Press, Inc. 489p.

Kummerow, J. 1980. Adaptation of roots in water-stressed mature vegetation. pp. 57-73 *in* Turner, N.C. and P.J. Kramer (ed.) Adaptation of plants to water and high temperature stress. John wiley & sons, New York, Chichester, Brisbane.

Lal, R. 1989a. Agroforestry systems and soil surface management of a tropical alfisol: Soil moisture and crop yields. Agro. syst. 8:7-29.

Lawson T.L. and B.T. Kang. 1990. Yield of maize and cowpea in an alley cropping system in relation to available light. In Agricultural and Forest Meteorology, 52:347-357.

Leyton, L. 1983. Crop water use: Principles and some considerations to agroforestry. pp.379-400 *in* Huxley P.A. (ed.) Plant research and agroforestry. ICRAF, Nairobi. Kenya.

Loomis, R.S. and C.E. Whitman. 1983. Systems analysis in production ecology. pp. 209-220 *in* Huxley P.A. (ed.) Plant research and agroforestry. ICRAF, Nairobi. Kenya.

McCall, C.H. JR. 1982. Sampling and statistics Handbook for research. The Iowa state University press. 340pp.

Monteith, J.L., C.K. Ong and J.E. Corlett. 1991. Microclimatic interactions in agroforestry systems. Forest Ecological management 45:31-44.

Mugah J.O. and J.I. Stewart, 1983. The Effect of leaf area index on water requirements of Katumani composite B maize. pp. 97-105 *in* Dryland farming research in Kenya. East African Agricultural and Forestry Journal Special Issue vol. 44.

Mugendi, D.N. 1990. Plant nutrient aspects of mulch incorporation in alley cropping trials of semi-arid Machakos, Kenya. Msc thesis, U. of Nairobi. 81pp.

Mungai, D.N. 1987. A microclimatological investigation of yield differences in alley cropping trials in the semi-arid areas of Machakos District, Kenya. A Phd thesis proposal approved by the U. of Nairobi. 21pp.

Mungai, D.N., C.L. Coulson and C.J. Stigter. 1989a. Economic considerations of alley cropping for food production in semi-arid areas. Paper presented at the commonwealth Science Council Agroforestry programme workshop in Swaziland, 17-21 April, 1989.

Nair, P.K.R., 1984. Soil productivity aspects of agroforestry. ICRAF, Nairobi, Kenya. 85pp.

Nair, P.K.R., 1987. Agroforestry in the context of land clearing and development in the tropics. pp. 29-44 *in* Lal R. et al (ed.) Tropical Land Clearing for Sustainable Agriculture. IBSRAM proc. series 3, Bangkok, Thailand. (*Cited in* Lal 1989a).

Nair, P.K.R., 1989.(ed) Agroforestry systems in the tropics. Kluwer Academic Publishers in co-operation with Icraf. 665p.

National Research Council, 1984. Leuceana: Promising Forage and Tree Crop for the Tropics. Second Edition. National Academy Press, Washington, D.C. 100p.

Netondo, G.W. 1991. Assessment of competition for water between *Cassia siamea* Lam. and *Zea mays* L. using various parameters, in alley cropping under semi-arid conditions in Machakos District, Kenya. M.sc. thesis, U. of Nairobi. 119pp.

Ola-Adams, B.A. 1975. Dry matter production and nutrient content of a stand of coppiced *Cassia siamea* Lam in Ibadan Fuel plantation. pp. 63-66 *in* Nigerian Journal of forestry vol.5.

Ong, C.K. 1991. Interactions of light, water, and Nutrients in Agroforestry systems. pp. 107-124 *in* by Avery M.E., M.G.R. Canell and C.K. Ong (ed.) Biophysical Research For Asian Agroforestry. 292p

Ong, C.K., J.E. Corlett, R.P. Singh and C.R. Black. 1991. Above and below ground interactions in agroforestry systems. pp. 45-57*in* Forest Ecological Management Journal Vol. 45.

Prajapati, M.C., B. Verma., S.P. Mittal., K.T.N. Nambiar and B.S. Thippannavar. 1971. Effects of lateral root development of *Prosopis juliflora* DC. roots on agricultural crops. *Ann. Arid Zone* 10: 186-193.

Richmond B., S. Peterson, D. Boyle and M. Newcomb. 1990. STELLA 11 user's guide. 218p.

Ritchie, J.T. 1972. Model for Predicting Evaporation from a Row Crop with Incomplete Cover *in* Water Resources Research. VOL. 8, NO. 5: 1204-1213.

Roberts, N., D.F. Andersen, R.M. Deal, M.S. Garet and W.A. Shaffer. 1983. Introduction to Computer Simulation: A system dynamics modeling approach. Addison-Wesley publishing company. 562p.

Sang, F.K. 1986. Alley cropping under semi-arid conditions in Kenya. pp.123-136 *in* Kang, B. T. and L. Reynolds (ed.) proc. of an international workshop on Alley farming in the humid and subhumid tropics, Ibadan, Nigeria, March 10-14 1986. 251pp.

Sang, F.K. and D.A. Hoekstra. 1986. On-station hedgerow trial results of the development phase. Research report no. 3, Darp, Machakos, Kenya.

Sang, F.K., D.A. Hoekstra and R. Okumu. 1985. Preliminary results of on-station green manure trials with leaves from *Leuceana leucocephala* , *Cassia siamea* and *Terminalia brownii.* Report no.1, Darp , Machakos, Kenya.

Simon, H.A. 1965. The new science of management decision. pp.53-111*in* In the Shape of automation. New York: Harper and Row.

Singh, R.P., C.K. Ong and N. Saharan. 1989. Above and below ground interactions in alley-cropping in semi-arid India. Agro. syst. 9:259-274.

Singh, V.P. 1992. Elementary Hydrology. Prentice Hall, Englewood Cliffs, NJ. 973p.

Singh, V.P. and W.T. Dickinson. 1975. An analytical method to determine daily soil moisture. Proc. of second World congress on Water Resources IV:355-65, New Delhi, India.

Soil Management Support Services (SMSS). 1986. Proc. of a symposium on Low Activity Clay (LAC) Soils, Washington, D.C. Technical monograph No. 14. (*Cited in* Kang et al. 1990).

Squire, G.R., C.K. Ong and J.L. Monteith. 1987. Crop growth in semi-arid environments. pp. 219-231 *in* Proc. of the international pearl millet workshop, Hyderabad, India: ICRISAT. April 7-11 1986.

Ssekabembe, C.K. 1985. Perspectives on hedgerow intercropping. Agro. syst. 3: 339-356.

Stanhill, G. and Y. Vaadia, 1979. Factors Affecting Plant Responses to Soil Water. pp. 446-457 *in* Yaron, D. and C.S. Tapiero (ed.) Operations Research In agriculture and water resources. Proc. of the ORAGWA International Conference held in Jerusalem, Nov. 25-29, 1979.

Tukey, J.W. 1977. Exploratory data analysis. Addison-Wesley publishing company. 687pp.

Ulsaker, L.G. and A.M. Kilewe. 1983. Runoff and soil erosion for an alfisol in Kenya. pp. 210-241 *in* Dryland Farming Research in Kenya. East African agricultural and forestry Journal. Special issue Vo. 44.

Umaya, G.O. 1991. The spacial and temporal distribution of the active roots of *Cassia siamea* Lam. and *Zea mays* L., in alley cropping under semi-arid conditions in Machakos District, Kenya. Msc thesis, U. of Nairobi. 100pp.

Van Noordwijk, M. 1989. Methods for quantification of root distribution pattern and root dynamics in the field. *in* Methodology in soil-K research, proc. 20th collq. IPI, Baden bei Wien, 1987. Worblaufen/Bern, IPI [1989] p. 263-281.

Vandermeer, J. 1989. The Ecology of Intercropping. Cambridge University Press. Cambridge. 237p.

Weber, F.R. and C. Stoney. 1986. Reforestation in arid lands. 335p.

Wiener, N. 1948. Cybernetics or control and communications in the Animal and the Machine. New York: John wiley.

Wilson, G.F., B.T. Kang and K. Mulongoy. 1986. Alley cropping: Trees as sources of green manure and mulch in the tropics. *in* Biological agriculture and Horticulture 3:251-267.

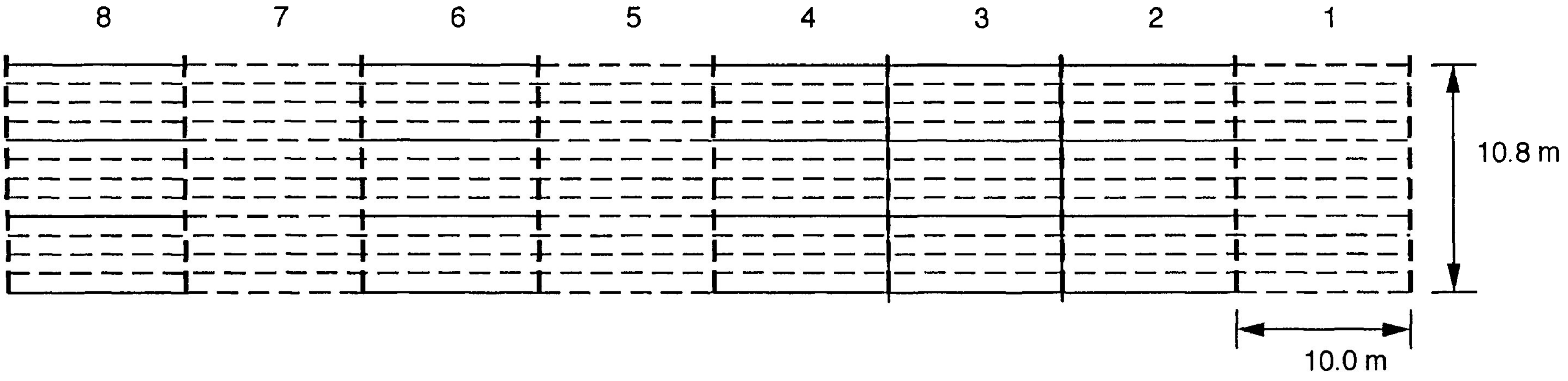
Yamoah, C.F., A.A. Agboola and G.F. Wilson. 1986b. Nutrient contribution and maize performance in alley cropping systems. Agro. syst. 4: 247-254.

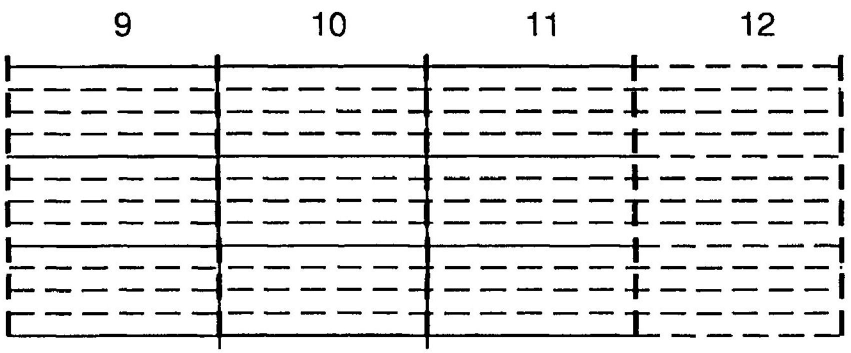
Yamoah, C.F., A.A. Agboola and K. Mulongoy. 1986a. Decomposition, nitrogen release and weed control by prunings of selected alley cropping shrubs. Agro. syst. 4:239-246.

Young, A. 1989. Agroforestry for Soil Conservation. C. A. B. International. ICRAF, Nairobi, 276pp.

# APPENDICES

## CASSIA SIAMEA /MAIZE ALLEY CROPPING TRIAL LAYOUT IN MACHAKOS, KENYA.





Legend

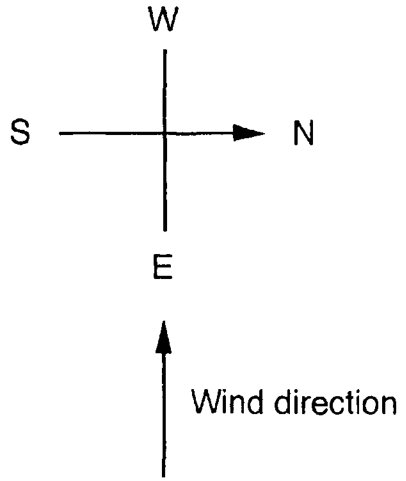
1-12 = Plot numbers

| Treatment | Plot no. |
|---|---|
| Control | 1,5,7,12 |
| C0.25 m | 2,3,8,10 |
| C1.0 m | 4,6,9,11 |

- - - Maize rows

—— Cassia hedgerows

▬ ▬ ▬ Plot boundary



# APPENDIX II

## AN ILLUSTRATION OF THE SMOOTHING PROCEDURE OF RUNNING MEDIANS USING RAINFALL DATA FROM ICRAF'S MACHAKOS FIELD STATION FOR 1986 TO 1989.

| Rainfall input | Running median #1 (code =3)[a] | Running median #2 (code = 3R)[a] |
|---|---|---|
| 15.1 | | |
| 22.7 | 22.7 | |
| 41.1 | 41.1 | 41.1 |
| 64.5 | 45.5 | 45.5 |
| 45.5 | 64.5 | 45.5 |
| 67.1 | 45.5 | 45.5 |
| 18.5 | 18.5 | 18.5 |
| 13.7 | 13.7 | 13.7 |
| 5.8 | 5.8 | 5.8 |
| 3.8 | 3.8 | 3.8 |
| 0.9 | 0.9 | 0.9 |
| 0.8 | 0.9 | 0.9 |
| 2.6 | 0.8 | 0.9 |
| 0.3 | 1.1 | 1.1 |
| 1.1 | 1.1 | 1.1 |
| 2.7 | 2.5 | 2.5 |
| 2.5 | 2.5 | ....... and so on |
| 3.4 | ....... and so on | |
| ...... and so on | | |

---

[a] Tukey (1977) uses a shorthand to denote various smooths. A single pass with running medians is called a 3-smooth. Repeated passes with running median is called a 3R-smooth, and so on. (Adapted from Brown, K.M. (1991) Exploratory data analysis: Classnotes for a shortcourse at Lakehead University, Ontario, Canada).

## APPENDIX III

## EQUATIONS FOR THE BARE SOIL/GROUND WATER MODEL.

```
☐  zone_1_wc(t) = Zone_1_wc(t - dt) + (I - ae - d1) * dt
   INIT Zone_1_wc = 350000
   Inflows:
   I = If zone_1_wc ≤ 450000 then 10000*r else 10000*r*(2-
   (1/450000)*zone_1_wc)
   Outflows:
   ae = If zone_1_wc ≤ 200000 then 0 else (if (zone_1_wc > 200000 and
   Zone_1_wc ≤ 360000) then (exp(0.00000433*(zone_1_wc-200000))-
   1)*(-0.5 + 500)*at else -0.5 + 500*at)
   d1 = If zone_1_wc > fc1 then (zone_1_wc-fc1)*df1 else 0
☐  zone_2_wc(t) = zone_2_wc(t - dt) + (d1 - d2) * dt
   INIT Zone_2_wc = 400000
   Inflows:
   d1 = If zone_1_wc > fc1 then (zone_1_wc-fc1)*df1 else 0
   Outflows:
   d2 = If zone_2_wc > fc2 then (zone_2_wc-fc2)*df2 else 0
☐  zone_3_wc(t) = zone_3_wc(t - dt) + (d2 - d3) * dt
   INIT zone_3_wc = 400000
   Inflows:
   d2 = If zone_2_wc > fc2 then (zone_2_wc-fc2)*df2 else 0
   Outflows:
   d3 = If zone_3_wc > fc3 then (zone_3_wc-fc3)*df3 else 0
○  df1 = max(0,(1/600000*zone_1_wc-0.75))
○  df2 = max(0,(1/600000*zone_2_wc-0.75))
○  df3 = max(0,(1/600000*zone_3_wc-0.75))
○  fc1 = 450000
○  fc2 = 450000
○  fc3 = 450000
○  sr = If 10000*r > I then (10000*r-I) else 0
⊘  at = graph(time)
   (5.00, 21.5), (15.0, 21.3), (25.0, 20.7), (35.0, 20.2), (45.0, 19.9), (55.0,
   19.8), (65.0, 19.2), (75.0, 19.0), (85.0, 18.5), (95.0, 18.1), (105, 17.0),
   (115, 16.7), (125, 16.5), (135, 17.2), (145, 16.6), (155, 17.3), (165,
   17.0), (175, 17.2), (185, 18.1), (195, 18.7), (205, 19.2), (215, 19.8), (225,
```

20.5), (235, 20.2), (245, 19.6), (255, 19.5), (265, 19.0), (275, 18.9), (285, 19.2), (295, 19.4), (305, 19.2), (315, 19.3), (325, 19.7), (335, 20.2), (345, 20.7), (355, 20.5), (365, 21.5), (375, 21.3), (385, 20.7), (395, 20.2), (405, 19.9)

r = graph(time)
(5.00, 1.51), (15.0, 2.27), (25.0, 4.11), (35.0, 4.55), (45.0, 4.55), (55.0, 4.55), (65.0, 1.85), (75.0, 1.37), (85.0, 0.58), (95.0, 0.38), (105, 0.09), (115, 0.09), (125, 0.09), (135, 0.11), (145, 0.11), (155, 0.25), (165, 0.25), (175, 0.25), (185, 0.02), (195, 0.02), (205, 0.03), (215, 0.03), (225, 0.12), (235, 2.11), (245, 2.98), (255, 4.41), (265, 4.41), (275, 4.41), (285, 2.76), (295, 2.76), (305, 1.25), (315, 0.63), (325, 0.63), (335, 0.63), (345, 0.61), (355, 0.61), (365, 0.61), (375, 1.51), (385, 2.27), (395, 4.11), (405, 4.55)

# APPENDIX IV

## EQUATIONS FOR THE CASSIA/WATER MODEL.

```
☐ csb(t) = csb(t - dt) + (csr - cp) * dt
  INIT csb = 50
  Inflows:
  csr = If ((time < 204 or (time ≥ 224 and time < 389 )) and (awc ≥
  250000)) then ((1.6/10^12)*awc*csb*(50000-csb)) else 0
  Outflows:
  cp = pulse(csb-75,204,185)
☐ wicb(t) = wicb(t - dt) + (cwu - ct - cwh) * dt
  INIT wicb = 350/3
  Inflows:
  cwu = If time < 204 or (time ≥ 224 and time < 389 ) and (awc ≥ 250000)
  then ct + (7/3)*csr else 0
  Outflows:
  ct = If ((time < 204 or (time ≥ 224 and time < 389 ))) then
  (0.000008*csb/aed + 700*csr) else 0
  cwh = cbwr*cp
○ aed = max(0.2,normal(0.75,0.4,10000))
○ awc = 300000
○ cbwr = wicb/csb
```

# APPENDIX V

## EQUATIONS FOR THE MAIZE/WATER MODEL.

```
☐ mb(t) = mb(t - dt) + (mg - mh) * dt
  INIT mb = 10
  Inflows:
  mg = If ((time < 114 or (time ≥ 224 and time < 334 )) and (awc ≥
  300000)) then ((2.3/10^10)*awc*mb*(1800-mb)) else 0
  Outflows:
  mh = pulse(mb-10,114,220)
☐ wimb(t) = wimb(t - dt) + (mwu - mt - mwh) * dt
  INIT wimb = 70/3
  Inflows:
  mwu = If time < 114 or (time ≥ 224 and time < 334 ) and (awc ≥ 300000)
   then mt+ (7/3)*mg else 0
  Outflows:
  mt = If ((time < 114 or (time ≥ 224 and time < 334 ))) then
  (0.000008*mb/aed + 350*mg) else 0
  mwh = mbwr*mh
○ aed = max(0.2,normal(0.75,0.4,10000))
○ awc = 350000
○ mbwr = wimb/mb
```

# APPENDIX VI

## EQUATIONS FOR THE CASSIA/MAIZE/GROUND SOIL WATER MODEL.

```
□ csb(t) = csb(t - dt) + (csr1 + csr2 - cp) * dt
  INIT csb = 100
  Inflows:
  csr1 = If ( (time < 204 or (time ≥ 224 and time < 389)) and (zone_1_wc ≥
  250000 ) ) then ((4/10^13)*zone_1_wc*csb*(50000-csb)) else 0
  csr2 = If ( (time < 204 or (time ≥ 224 and time < 389)) and (zone_2_wc ≥
  250000 ) ) then ( (4/10^13)*zone_2_wc*csb*(50000-csb) ) else 0
  Outflows:
  cp = pulse(csb-100,204,185)
□ mb(t) = mb(t - dt) + (mg - mh) * dt
  INIT mb = 10
  Inflows:
  mg = If ( (time < 114 or (time ≥ 224 and time < 334)) and (zone_1_wc  ≥
  300000) ) then ( (1.6/10^10)*zone_1_wc*mb*(1800-mb) ) else 0
  Outflows:
  mh = pulse(mb-10,114,220)
□ wicb(t) = wicb(t - dt) + (cwu1 + cwu2 - ct - cwh) * dt
  INIT wicb = 700/3
  Inflows:
  cwu1 = If ( (time < 204 or (time ≥ 224 and time < 389)) and (zone_1_wc
  ≥ 250000) ) then  ( if zone_2_wc > 250000 then (0.5*ct + (7/3)*csr1) else
   ct + (7/3)*(csr1 + csr2) ) else 0
  cwu2 = If ( (time < 204 or (time ≥ 224 and time < 389)) and (zone_2_wc
   ≥ 250000) ) then ( if zone_1_wc > 250000 then (0.5*ct + (7/3)*csr2) else
   ct + (7/3)*(csr1 + csr2) ) else 0
  Outflows:
  ct = If ( (time < 204 or (time ≥ 224 and time < 389 )) ) then
  (0.000008*csb/aed + 700*(csr1+csr2)) else 0
  cwh = cbwr*cp
□ wimb(t) = wimb(t - dt) + (mwu - mwh - mt) * dt
  INIT wimb = 70/3
  Inflows:
  mwu = If ( (time < 114 or (time ≥ 224 and time < 334)) and (zone_1_wc ≥
  300000) ) then (mt + 7/3*mg) else 0
  Outflows:
  mwh = mbwr*mh
```

```
   mt = If  (time < 114 or (time ≥ 224 and time < 334)) then
   (0.00003*mb/aed + 350*mg) else 0
☐  zone_1_wc(t) = zone_1_wc(t - dt) + (I - d1 - ae - mwu - cwu1) * dt
   INIT zone_1_wc = 300000
   Inflows:
   I = If zone_1_wc ≤ 10000*90 then min(10000*r,10000*(2-
   (1/450000)*zone_1_wc)*r) else 0
   Outflows:
   d1 = If zone_1_wc > fc1 then (zone_1_wc-fc1)*df1 else 0
   ae = If zone_1_wc ≤ 200000 then 0 else (If (zone_1_wc > 200000 and
   zone_1_wc ≤ 360000)  then (exp(0.00000433*(zone_1_wc-200000))-
   1)*(-   0.5+ 500*at) else -0.5+ 500*at
   mwu = If ( (time < 114 or (time ≥ 224 and time < 334)) and (zone_1_wc ≥
   300000) ) then (mt + 7/3*mg) else 0
   cwu1 = If ( (time < 204 or (time ≥ 224 and time < 389)) and (zone_1_wc
    ≥ 250000) ) then  ( if zone_2_wc > 250000 then (0.5*ct + (7/3)*csr1)
   else ct + (7/3)*(csr1 + csr2) ) else 0
☐  zone_2_wc(t) = zone_2_wc(t - dt) + (d1 - d2 - cwu2) * dt
   INIT zone_2_wc = 350000
   Inflows:
   d1 = If zone_1_wc > fc1 then (zone_1_wc-fc1)*df1 else 0
   Outflows:
   d2 = If zone_2_wc > fc2 then (zone_2_wc-fc2)*df2 else 0
   cwu2 = If ( (time < 204 or (time ≥ 224 and time < 389)) and (zone_2_wc
   ≥ 250000) ) then ( if zone_1_wc > 250000 then (0.5*ct + (7/3)*csr2) else
    ct + (7/3)*(csr1 + csr2) ) else 0
☐  zone_3_wc(t) = zone_3_wc(t - dt) + (d2 - d3) * dt
   INIT zone_3_wc = 350000
   Inflows:
   d2 = If zone_2_wc > fc2 then (zone_2_wc-fc2)*df2 else 0
   Outflows:
   d3 = If zone_3_wc > fc3 then (zone_3_wc-fc3)*df3 else 0
○  aed = max(0.2,normal(0.75,0.4,1000000))
○  cbwr = wicb/csb
○  df1 = max(0,(1/600000*zone_1_wc-0.75))
○  df2 = max(0,(1/600000*zone_2_wc-0.75))
○  df3 = max(0,(1/600000*zone_3_wc-0.75))
○  fc1 = 450000
○  fc2 = 450000
○  fc3 = 450000
```

```
mbwr = wimb/mb
sr = If 10000*r > l then (10000*r-l) else 0
at = graph(time)
  (5.00, 21.5), (15.0, 21.3), (25.0, 20.7), (35.0, 20.2), (45.0, 19.9), (55.0,
   19.8), (65.0, 19.2), (75.0, 19.0), (85.0, 18.5), (95.0, 18.1), (105,
   17.0), (115, 16.7), (125, 16.5), (135, 17.2), (145, 16.6), (155, 17.3),
  (165, 17.0), (175, 17.2), (185, 18.1), (195, 18.7), (205, 19.2), (215,
  19.8), (225, 20.5), (235, 20.2), (245, 19.6), (255, 19.5), (265, 19.0), (275,
   18.9), (285, 19.2), (295, 19.4), (305, 19.2), (315, 19.3), (325, 19.7), (335,
   20.2), (345, 20.7), (355, 20.5), (365, 21.5), (375, 21.3), (385, 20.7),
  (395, 20.2), (405, 19.9)
r = graph(time)
  (5.00, 1.51), (15.0, 2.27), (25.0, 4.11), (35.0, 4.55), (45.0, 4.55), (55.0,
  4.55), (65.0, 1.85), (75.0, 1.37), (85.0, 0.58), (95.0, 0.38), (105, 0.09),
   (115, 0.09), (125, 0.08), (135, 0.11), (145, 0.11), (155, 0.25), (165,
   0.25), (175, 0.25), (185, 0.02), (195, 0.02), (205, 0.03), (215, 0.03),
   (225, 0.12), (235, 2.11), (245, 2.98), (255, 4.41), (265, 4.41), (275,
  4.41), (285, 2.76), (295, 2.76), (305, 1.25), (315, 0.63), (325, 0.63),
   (335, 0.63), (345, 0.61), (355, 0.61), (365, 0.61), (375, 1.51), (385, 2.27),
  (395, 4.11), (405, 4.55)
```