The University of Reading

Light Interception and Water Use in Boundary planting Agroforestry Systems

A Thesis

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by

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Abstract

A field study was conducted to examine light interception and water use between upper-storey trees (*Alnus acuminata, Casuarina equisetifolia, Grevillea robusta, Maesopsis eminii and Markhamia lutea*) and annual crops, maize (*Zea mays)* and beans (*Phaseolus vulgaris*), in a sub-humid environment in Uganda, East Africa from 1996 to 1998.

The presence of the trees significantly ($p<0.001$) reduced the yield of the associated crops when compared to sole crops. Maize yields were reduced to a distance of 5 m from the tree lines in the last season (August-November 1998) by 59, 58, 49, 33 and 25% in the *Casuarina*, *Maesopsis*, *Markhamia*, *Grevillea* and *Alnus* plots respectively. Bean yield reductions during the August-November 1997 season were 60, 43, 27, 22 and 23% for *Maesopsis*, *Markhamia*, *Casuarina*, *Grevillea* and *Alnus* plots respectively.

The fraction of the incoming photosynthetically active radiation (PAR) incident on the maize crop was significantly ($p<0.001$) reduced by the presence of the trees to a distance of 5 m from the tree lines in the last season. *Maesopsis*, *Casuarina*, *Markhamia*, *Grevillea* and *Alnus* reduced the fraction of the incoming PAR by 59, 31, 31, 29 and 23% respectively. Mean fractional PAR interception by the maize crop associated with the different tree species, to 5 m distance from the trees, was 0.28, 0.32, 0.35, 0.54 and 0.53 in the *Maesopsis*, *Markhamia*, *Casuarina*, *Grevillea* and *Alnus* plots respectively. The lateral extent of tree shading can be predicted from knowledge of tree height, canopy height and spread. The modeled shading effects of the trees showed that tall trees (*Casuarina*) or trees with wide canopies (*Maesopsis*, *Casuarina*) have significantly bigger shading effects on associated crops than short or trees with narrow canopies (*Markhamia*). The relationship between the amount of the incoming PAR intercepted by the maize crop and the biomass produced showed a significant positive correlation.

Tree root densities decreased with increasing distance from the tree lines and with depth. The tree species showed varying patterns of root development. The proportion of tree roots within 2 m distance from the tree lines were 83, 77, 70, 69 and 58% for *Alnus*, *Casuarina*, *Markhamia*, *Grevillea* and *Maesopsis* respectively. The mean number of roots within the top 90 cm of the soil were found to be 79, 77, 75, 71 and 64% for *Markhamia*, *Grevillea*, *Alnus*, *Casuarina* and *Maesopsis* respectively. The presence of the trees significantly ($p<0.01$) reduced maize root densities upto 4 m (*Maesopsis*, *Markhamia*), 2 m

(*Casuarina*, *Alnus*) and 1 m (*Grevillea*) distances from the tree lines.

Water uptake patterns by the tree species closely followed their rooting patterns. The tree plots significantly ($p<0.05$) lost more water than sole maize plots. Plot averages of seasonal water loss were 590, 630, 640, 662, 682 and 698 mm for sole maize, *Alnus*, *Markhamia*, *Grevillea*, *Maesopsis* and *Casuarina* plots respectively. These high water losses from the trees were associated with greater soil water depletion than in sole crop plots. Maximum soil water depletion in the upper 1.8 m of the soil profile during the last season was 160, 158, 148, 133, 84 and 100 mm for *Casuarina*, *Maesopsis*, *Grevillea*, *Markhamia*, *Alnus* and sole maize respectively. The trees significantly ($p<0.01$) reduced water use by maize plants upto 5 m distance from the tree lines with the effect varying according to species. *Casuarina* and *Maesopsis* had the greatest effect followed by *Markhamia*. *Grevillea* and *Alnus* had the least effect on maize water use. Water use by the trees decreased with increasing distance from the tree lines and in the last season, individual trees used 134, 124, 112, 113 and 85 kg of water day^{-1} for *Maesopsis*, *Casuarina*, *Grevillea*, *Markhamia* and *Alnus* respectively.

Total soil evaporation (E_s) was greatly reduced by the tree canopies compared to under the maize canopy and bare soil. Total E_s under the tree canopy was 49% of bare soil, while under the maize canopy it was 71% of bare soil.

The evaluation of this agroforestry system (three years of intercropping) in terms of resource use indicated that interplanting *Maesopsis* and *Grevillea* with maize had a marginal advantage over sole cropping in terms of water use and light utilization.

Dedication

This thesis is dedicated to my parents, the late Mathias Otwelle and Miktaberi Icar, who brought me up in a loving and caring manner. They taught me to work hard, be obedient and patient in life. It is these virtues that have helped me develop in my career. I also dedicate this thesis to my late wife Alice Ipudai whose memories the family will always cherish. May the Lord rest her soul in internal peace.

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CHAPTER ONE

INTRODUCTION

1.1 Background Information

The research undertaken of which this thesis is an output, is part of the East African Agroforestry Research Networks for Africa (E.A AFRENA) project in Uganda. The project is jointly implemented by the Government of Uganda and the International Center for Research in Agroforestry (ICRAF). It is funded by the United States Agency for International Development (USAID) and the European Union (EU). The countries participating in the network are:- Uganda, Kenya, Rwanda, Burundi, Tanzania and Ethiopia. The major aims of the network are: -

- to plan, develop and implement appropriate agroforestry technologies for the farming systems in the region,
- to ensure the transfer and adoption of these technologies by the farmers,
- to assess the impact of these technologies in the region, and
- to ensure the institutionalization of agroforestry in the participating countries.

The major technologies that the network is developing address issues on:-

- soil conservation and soil productivity enhancement,
- provision of wood and wood products, and
- provision of tree fodder for small holder dairy systems.

1.2 Problems of Agricultural production in East and Central Africa

The highlands of East and Central Africa lie between elevations of 1200 and 3200 m above sea level (asl) and cover about 30% of the total land area in the region (Plate 1.1). This highland zone is of significant importance because of its high agricultural potential and because its natural resources are being seriously degraded. Rainfall in the area normally exceeds 1000 mm per year and temperatures are moderate. The human population is high rising up to over 1000 persons per km^{-2} because the zone is attractive to human settlement. About 90% of the population depend on subsistence agriculture, cultivating both food and cash crops. Like the rest of tropical Africa, the region is faced with problems of food shortages; degradation of non-renewable resources, and decreasing accessibility to fuel-wood and other wood-based products. Food shortages are caused by an increase in population pressure coupled with an inadequate response in terms of agricultural production. Population pressure has led to shorter fallow periods or continuous cropping leading to low soil organic matter content and water infiltration rate, increased runoff, soil erosion and loss of nutrients. Intensive cropping on hill slopes has resulted in increased soil erosion [Thomas 1988; Lewis and Nyamulinda 1996] and reduced soil water storage, which in turn has led to low agricultural productivity.

The demand for timber, fuelwood, poles and other wood based products in the region has outstripped production leading to the depletion of many indigenous forests [Hamilton 1984; Burnett 1985; Thorhaug and Miller 1986]. In addition, population increase has led to more forests and marginal lands being cleared for agricultural and livestock production [Allen and Barnes 1984; Kleinert 1985; Cooper *et al*, 1996].

Under these circumstances, the agroforestry approach of incorporating woody perennials (trees/shrubs) into existing farming systems may constitute a sound practice [Nair 1983; Neumann 1983]. Trees and shrubs have the potential of providing wood products (e.g. fuelwood, food, and fodder) as well as providing services such as soil erosion control [Young 1987; Lal 1989; Kakuru 1993; Kiepe and Rao 1994; Young 1997] and soil fertility improvement [Campbell *et al.*, 1994; Buresh 1995; Palm 1995; Buresh and Tian 1997].





Plate 1.1 The typical landscape in the highlands of East and Central Africa.

1.3 Agroforestry as a sustainable form of Land Use

Agroforestry systems are generally defined as farming systems where trees and crops and/or animals interact within the same farm area, either spatially or temporally. The combining of trees or woody perennial shrubs with annual crops, through spatial zonation, may increase the biological and/or economic productivity of the land in addition to providing service functions such as soil fertility conservation or erosion control [ICRAF, 1993].

Agroforestry has had several definitions [Somarriba 1992], but has recently been re-defined as "a dynamic ecologically-based natural resource management system, that through the integration of trees into farms and range-lands, diversifies and sustains small holder production for increased economic, social and environmental benefits" [Leakey 1996]. Agroforestry systems have been classified into two groups:- those that are sequential such as fallows, where crops are grown either in natural (herbaceous) fallows or in fields previously improved by growing trees; and those that are simultaneous such as boundary/upper-storey tree planting and alley cropping, where crops are grown together with trees simultaneously [Cooper *et al* 1996]. Leakey [1996] suggests that agroforestry practices should be seen as stages in the development of an agro-ecosystem such that the increasing integration of trees into land use systems can be seen, as the passage towards a natural agroforest of increasing ecological integrity. Thus, the integration of various agroforestry practices is like the formation of patches in an ecosystem, each of which is composed of many niches, and where the niches are occupied by different organisms. This makes the system ecologically stable and biologically diverse.

The use of trees as part of the farming system depends on two attributes [Arnold and Dewees 1997]. First, trees maintain and restore the physical environment needed to sustain crop production mainly through the restoration of soil fertility. Second, tree products play a role in helping sustain the rural household economy. These products include those used directly by households (food, fuel, and construction materials), those used as inputs to agriculture (fodder and mulches) and those used as raw materials for making agricultural implements. They also provide members of the household with income and employment. Other uses include establishment of trees to ensure land tenure and for cultural activities. The product and service functions offered by trees, underline the potential for agroforestry to alleviate rural poverty [Sanchez 1995]. However, farmers

will only obtain sustainable yield benefits from agroforestry practices when trees acquire water, light and nutrient resources that crops cannot [Cannell *et al.*, 1996]. Benefits from trees can only be realized if losses due to competition between the trees and crops are minimized and if trees offer high value products [Leakey and Simons 1998] that can compensate for crop losses due to competition.

1.4 Boundary / Upper-storey Tree planting Agroforestry

One of the most promising agroforestry technologies that can help reduce land degradation while at the same time reducing pressure on indigenous forests in the East and Central Africa region is the upper-storey and/or boundary tree planting [Hoekstra and Djimde 1988]. The technology has the potential of benefitting about 20 million people in the region. It makes use of areas that are usually under-utilized on the farms, is less labor intensive and can provide tree products such as timber, poles, fuelwood, mulch and/or fodder. It is a practice where tall upper-storey trees are planted either on the boundaries of annual or perennial crops plots or are scattered within them (Plate1.2). Many farmers do practice boundary planting, as it is less complex than other agroforestry practices.

The main drawback of the practice, however, is the competition that occurs between the trees and adjacent crops for light, nutrients and water [Neumann and Pietrowicz, 1987; Ong *et al*, 1992b]. Research results [Neumann and Pietrowicz 1987; Mwihomeke 1990; Okorio *et al,* 1994; Akyeampong *et al* 1999] and on-farm surveys [Hoekstra *et al,* 1991; Nielsen *et al* 1995] in the region have shown that competition for growth resources affects crop growth and yield in areas influenced by the trees. The suppressive effect of boundary/upper-storey trees on annual crops has also been reported in other regions [Malik and Sharma 1990; Puri and Bangarwa 1992; Kater *et al*, 1992; Kessler 1992; Yadar *et al.*, 1993; Dhyani *et al.*, 1996; Maheta *et al.*, 1996]. In some cases, however, the trees have been found to improve crop yields [Peden *et al.*, 1993; Chirko *et al.*, 1996a; Akyeampong *et al* 1995; 1999].





Plate 1.2. Boundary tree plantings of *Grevillea robusta* with maize (top) and coffee (bottom) in Tororo, eastern Uganda.

1.5 Aims and Objectives of the Study

Given the foregoing background and review of the relevant literature in Chapter 2, the main objective of this study was to determine fractional light interception and water use by upper-storey trees and annual crops grown in close association in a sub-humid environment in Uganda, East Africa. It was hypothesized that the introduction of trees onto cropland would influence crop dry matter production and increase total water use. In more detail, the specific hypotheses tested in this study were that:-

1. Trees influence crop dry matter production by reducing the fraction of photosynthetically active radiation (PAR) intercepted by the crop as a result of: -
    - direct effect of shading which reduces the PAR above the crop canopy, and/or
    - reduction of crop leaf area index (LAI) caused by competition for growth resources, and
2. The inclusion of trees onto cropland will increase total water use at the expense of deep drainage.

The objectives of the work presented in this thesis were to:-

1) Measure:-
    - the fraction of incident radiation reaching the crop canopy and how it varied with distance from the tree.
    - the fraction of incident radiation intercepted by the crop canopy and how it varied with distance from the tree.
2) Develop a simple model for predicting the effect of tree shading on the amount of radiation incident on the crop canopy, which will be applied to interpolate between the spot measurements in (1) in order to carry out seasonal integrations. A second application is to use the combined measurement/modelling approach to investigate the effect of differences between tree species in canopy architecture on crop shading.
3) Determine whether reduced crop growth close to the trees was attributable to shading alone.
4) Determine water use by different tree species grown in association with crops, and

5) Determine whether the observed water uptake patterns were consistent with the observed rooting patterns of the trees and crops.

1.6 Thesis Outline

This thesis is composed of eight Chapters. This Chapter (1) gives the general background to the study on problems of agricultural production in the East African region, agroforestry as a sustainable form of land use and the potential and the limitations of boundary/upperstorey tree planting agroforestry. It also presents the objectives of the study and the hypotheses that were tested. Chapter 2 gives a review of the relevant literature on biophysical interactions in agroforestry systems in general and in boundary/upperstorey tree planting agroforestry in particular. The review also covers light and water use in agroforestry systems with special reference to boundary/upperstorey tree planting agroforestry. Finally, the Chapter reviews current models of light interception in agroforestry systems. Chapter 3 describes the site conditions, the tree species and crops used in the study including their establishment, management and assessments. It also describes the measurements made on light interception, water uptake and the distribution of tree and crop roots.

Chapter 4 presents the results of the tree and crop growth analyses, while Chapter 5 presents and discusses the results of the fraction of PAR reaching the maize crop canopy and the fraction that the crop canopy intercepted. The Chapter also outlines the aims and objectives of modeling the shading effect of trees, the methodology used and the results of the modeling process. The last section of the Chapter discusses the results in relation to crop growth and yield presented in Chapter 4 and related studies. The distribution of tree and crop roots is presented in Chapter 6, while water use by the different tree species associated with crops is presented in Chapter 7. The last section of Chapter 7 discusses the research findings in relation to the distribution of tree and crop roots (Chapter 6) and their influence on crop growth and yield (Chapter 4). The discussion also relates the current results to other studies in the area. In the final Chapter (8), a general discussion is given and major conclusions drawn from the results of the study are made.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This Chapter presents a review on the relevant literature on the topic of study. The biophysical interactions in agroforestry systems are given in section 2.2, while light capture and its utilization in agroforestry systems is presented in section 2.3. Sections 2.4 and 2.5 review water use and rooting patterns in agroforestry systems respectively.

2.2 Biophysical Interactions in Agroforestry Systems

2.2.1 Introduction

The nature and intensity of interactions in agroforestry systems are determined by the rate and extent to which biophysical resources of water, nutrients and light are captured and utilized by the components of the agroforestry system [Rao *et al.*, 1998]. The net effect of these interactions is often determined by the influence of the tree component on the other components and is usually expressed in quantifiable responses such as soil fertility changes, microclimate modification, or resource availability and utilization.

The exploitation of interactions between woody (tree/shrub) and non-woody (annual crops) components is supposed to be the key to the success of all agroforestry systems. Therefore, a better understanding of these interactions provides a strong scientific basis for the improvement of traditional as well as evolving agroforestry systems. Recently, research on interactions in agroforestry systems has received increasing attention and there have been various reviews on the topic. Anderson and Sinclair [1993] and Nair *et al.* [1994] have given reviews from an ecological perspective, while Ong and Huxley [1996] reviewed the quantitative and physiological aspects of biophysical interactions in agroforestry systems. Rao *et al* [1998] gave a synthesis of the agronomic significance of biophysical interactions in the major agroforestry systems, and stressed the importance of the management implications of these interactions.

In the study of biophysical interactions in agroforestry, efforts have been made to extrapolate from research on annual intercropping, on the assumption that the principles of interactions between component species for growth resources are common in all types of plant associations. However, agroforestry systems are much more complex than annual intercropping systems, because there are major differences in the nature and arrangement of components, and therefore, also on the nature and extent of interactions. Of considerable importance is the fact that the components in agroforestry systems are "unequal", the trees being dominant and perennial. Thus, interactions in agroforestry systems are continuous, rather than seasonal as in annual systems, and the course and extent of interactions are largely determined by the system's tree component [Ong *et al* 1996].

Interaction has been defined as the effect of one component of the system on the performance of another component and/or the overall system [Nair 1993]. As far as resource capture and utilization in simultaneous agroforestry systems such as boundary tree planting are concerned, the interaction effect (I) on crop yields can be expressed as [Cannell *et al*, 1996]: -

$$I = F + C + M + P + L + A \qquad (2.1)$$

where:-

F = relates to soil fertility interaction,

C = relates to competitive interactions for water, nutrients and radiation,

M = relates to micro-climate interactions,

P = relates to pest and disease interactions,

L = relates to soil conservation interaction, and

A = relates to allelopathy interaction.

Many of the above interactions are interdependent, therefore, cannot be experimentally estimated independent of each other. Moreover, some factors may be interdependent over time [Cannell *et al.*, 1996]. In agroforestry systems, the interactions can be above or below ground or both. Below ground interactions include factors like root distribution, effects on soil nutrition and competition for soil water. Above ground interaction factors centre on the energy balance of the system where the tree canopy causes shading and sheltering of the under-storey. This will influence the under-storey's light interception and

microclimate, such as air temperature, humidity and wind speed. Changes in the latter will affect the aerodynamic transfer within and above the under-storey.

2.2.2 Resource Capture and Utilization in Agroforestry Systems

It has long been argued that a sound understanding of the processes and mechanisms involved in resource capture and use, and their interactions with the environment, is essential for the development of more relaible and productive systems [Trenbath 1976; Willey 1979]. The basic principle underlying the concept of resource capture is that complementary or competitive interactions between species depend on their ability to "capture and use the most limiting essential growth resources effectively" [Monteith 1981]. Capture *(c)* of the limiting resource depends on the number, surface area, distribution and effectiveness of the individual elements within the canopy or root system of the species or mixture involved. The use of the acquired resources depends on the conversion coefficient *(e)* of the species involved and environmental influences such as temperature extremes or drought. Biomass production *(B)* over a time period *(t)* may be expressed as: -

$$B = c \,.\, e \,.\, t \qquad (2.2)$$

where B has units of $g\ m^{-2}$ of land area; the mean values of c and e have units of $MJ\ m^{-2}$ and $g\ MJ^{-1}$ respectively when the limiting resource is light, and mm and $g\ kg^{-1}\ H_2O$ when the limiting resource is water; t has dimensions of days.

Despite the apparent simplicity of the principles involved and the potential benefits, few attempts have been made to quantify resource capture in intercropping systems in general, and agroforestry systems in particular [Ong *et al* 1996]. This has largely been due to the technical difficulties and the expense involved in intensive studies of light and water use [Sinoquet and Caldwell 1995], and the complexity of the modeling framework required to synthesize the results [Kropff and van Laar 1992]. Recent advances in microprocessor technology have, however, made the quantification of resource capture in these systems much easier [Ong *et al* 1996]. Another problem in agroforestry systems is the numerous combinations of species, spacing and fertilizer treatments that are possible.

2.2.2.1 Competition in Resource Capture and Utilization

Van Dermeer [1989] suggests that competition may be more severe between similar species than between species with contrasting growth habits. However, the opportunity for complementarity of resource use between species is restricted by the fact that all plants are competing for the same finite resources of light, water, CO_2 and nutrients. Thus, there is extensive overlap between species in their resource requirements. Various workers [Van DenBeldt *et al* 1990; Ong *et al* 1991a; Monteith *et al* 1991; Ong and Black 1994] have reviewed competition in plants in relation to agroforestry. The components of agroforestry systems often differ greatly in size, with the result that the growth of the smaller under-storey species may be inhibited by shading, and possibly also by competition for water and nutrients. Competition for light is the primary limitation when water and nutrients are freely available. However in many tropical systems, water (e.g. semi-arid regions) or nutrient availability (e.g. acidic, leached or degraded soils) rather than light is the major limiting factor [Ong *et al* 1991].

When resources are not limiting, densely planted monocultures usually provide the most efficient resource capture systems. However, where one (or more) resource (s) is (are) limiting, it may be possible to improve productivity by using species mixtures. This is because the component species capture more of the available resources or use them more efficiently for growth than monocultures. In such instances, mixtures may provide a greater yield than the combined yield of the corresponding sole crops [Ofori and Stern 1987].

Recent research on competitive interactions in agroforestry systems has tended to concentrate on establishing the relative importance of above ground and below ground competition for resources [Synadon and Harris 1981; Corlett *et al* 1992a, b] and on complementarity or resource sharing [Ong and Black 1994]. Determining the relative importance of above ground and below ground interactions is difficult [Donald 1958], although methods such as root separation have been applied in some studies [Marshall and Willey 1983; Singh *et al* 1989; Okorio *et al* 1994; Chirko *et al* 1996b]. This is achieved by using vertical polythene barriers and trenches to separate the roots of the trees and crops.

2.2.2.2 Complementarity in Resource Capture and Utilization

Complementarity has been defined as " the efficiency with which mixtures of species capture and utilize limiting growth resources" [Ong and Black 1994]. The concept of complementarity in the use of resources is central to the assumption that mixtures of trees and crop species may lead to increased productivity in agroforestry [Ong and Black 1994]. Complementarity in resource use in agroforestry systems occurs when trees acquire resources of light, water and nutrients that crops cannot acquire. Complementarity must also lead to more efficient conversion of resources to products such that total productivity increases [Cannell *et al* 1996; Ong *et al* 1996; Hagger and Ewel 1997; Hooper 1998]. The potential for complementarity in agroforestry has largely been based on the assumption that benefits occur when grain legumes are grown in mixtures with cereal crops [Willey 1979]. However, in agroforestry, trees have a network of fine roots in the soil at the time the crop is planted giving the trees an advantage in soil water and nutrient uptake [van Noordwijk *et al* 1996]. Depending on the tree species, environment, age and management, tree competition may limit the potential for complementarity of resource use in agroforestry.

Complementarity in resource use occurs through three possible mechanisms [Ong and Black 1994]: - partitioning of resource use in space (spatial complementarity); partitioning of resource use in time (temporal complementarity); and the use of different resources by different species [Ong and Black 1994; Hagger and Ewel 1997; Hooper 1998]. Spatial partitioning of resource use occurs when mixed species are able to acquire environmental resources from different locations at the same time [Anderson and Sinclair 1993]. Temporal complementarity occurs when plants have different patterns of growth or life spans [Hooper 1998] so that the periods of maximum demand for resources of different species are separated in time [Ahmed and Rao 1982]. Temporal resource sharing concerns phenological mechanisms, and leads to enhanced productivity due to the capture of more resources rather than changes in the efficiency of resource utilization [Willey *et al* 1986; Ong and Black 1994]. Examples include increased light and water use by growing combinations of fast and slow growing crops such as sorghum and pigeon pea [Willey *et al* 1986] or maize and pigeon pea [Sivakumar and Virmani 1980]. The other example is the timing of canopy development for combinations of tree and crop such as *Faidherbia albida* and pearl millet [Brenner 1991].

2.2.3 Resource Capture and Utilization in Boundary/Upper-storey tree planting Agroforestry

Trees in cropland systems are categorized into three distinct systems, that is, scattered trees, boundary plantings, and intercropping with annual crops between widely spaced rows of trees [Rao *et al* 1998]. The degree of tree/crop interactions increases with increasing tree density, from low density in scattered tree systems to high density in tree/crop intercropping systems. Scattered or dispersed trees in cropland, often known as " parklands ", are a widespread traditional practice in the semi-arid tropics, while boundary plantings and intercropping systems are commonly practiced throughout the tropics. In these systems the trees are deliberately planted and managed to provide poles, timber, fruits and/or fodder. Boundary plantings involve trees on farm and field boundaries, soil conservation structures and terrace risers. Boundary or upper-storey agroforestry systems use widely spaced rows of trees such as *Populus deltoids* in northern India [Singh *et al* 1993; Singh *et al* 1998] or upper-storey trees such as *Cedrela odorata, Grevillea robusta, Albizia species, Markhamia lutea* found in East Africa [Hoekstra *et al* 1991; Akyeampong *et al* 1995; Nielsen *et al* 1995]. They are usually found in perennial (banana, coffee) and annual (bean, maize) fields.

Three distinct tree/crop interaction zones can be distinguished in boundary/upper-storey tree planting agroforestry systems [Rao *et al* 1998]. These are:- (1) a zone of light and root competition, mostly under the tree crown, (2) a zone of root competition, some area beyond the tree crown, and (3) open cropped areas that are relatively free from the interference of the trees. The extent of the first two interaction zones depends on the tree species, climate and soil, and spreads progressively over time with age and size of the tree. An understanding of these zones is essential for determining the optimum tree density and development of appropriate pruning regimes to maximize resource use and productivity of the system. The major tree/crop interactions that affect crop yields in this agroforestry system, and that are relevant to this review, are soil water relations and tree shading (light competition).

2.2.3.1 Competition for Growth Resources

Compared to other agroforestry systems, very few studies have been carried out in this agroforestry system to determine resource capture and utilization between the trees and crops. Results, have however, been reported in a semi-arid [Wallace *et al* 1996; ICRAF 1996; Odhiambo 1999] and sub-humid [Livesley 1999] areas of Kenya and in other areas [Chauhan *et al* 1995; Williams and Gordon 1995; Zhang 1996; Newman *et al* 1998]. Despite being a common agroforestry practice in the sub-humid tropics, few studies on resource use have been reported, especially in the sub-humid environment of East Africa.

Competition for light in this agroforestry system is unlikely where lopping of foliage for livestock feeding is practiced [Tejwani 1994], or where trees drop their leaves during the rainy season when crops are grown [Vandenbeldt and Williams 1992]. However, shade can be a major problem under large, unmanaged, and/or evergreen trees [Kessler 1992; Jonsson *et al* 1999]. In such cases, as little as 20% of incoming photosynthetically active radiation (PAR) reaches the under-storey crops thereby affecting their growth and productivity. While competition for light is the major factor limiting crop production under the tree canopies, competition for water could be the major factor beyond the crown areas.

Above ground competition for light and below ground competition for water may both be important under boundary/upper-storey tree plantings, as was demonstrated in a study in Uganda that used a root mesh to prevent lateral root spread [Okorio *et al* 1994]. Without the root mesh, crop yields adjacent to the trees ranged from 20 to 55% of yields in the treeless plots. When the root mesh was installed to 0.5-m depth and 0.5 m away from the trees, yields increased by 16 to 152%. However, the presence of the root mesh did not restore crop yields to open area levels, suggesting the existence of above ground competition for light. Another study in Burundi also using a root mesh, found below ground competition between beans on the one hand and bananas and *Grevillea* on the other, to be more important than competition for light in a multi-strata agroforestry system [Akyeampong *et al* 1999]. Aboveground competition for light can be reduced by side pruning of branches [Kessler 1992], while below ground competition for water by periodic root pruning either by deep ploughing or by use of axes and hoes [Roger and Rao 1990; Rao *et al* 1990; van Roode 1992].

2.2.3.2 Effect of Trees on Crop Yields

Crop yields under the trees in this agroforestry system may be unaffected during the early years of tree growth, but could increase or decrease when the trees grow large, depending on the tree species. Any positive influence of trees on crop yields would not be expected for many years, e.g. 20 to 40 years [Poschen 1986; Rhoades 1997], as trees modify the soil environment slowly. However, in Uganda, the positive effect of *Alnus acuminata* on crop yields was noted only after 3 years of growth [Peden *et al* 1993]. Similar observations have been reported for *Paulownia* trees in China [Chirko *et al* 1996a] and *Grevillea robusta* in Burundi [Akyeampong *et al* 1999]. On the other hand, the negative effect of trees in this system due to competition for growth resources of water and light can be noted within a few years. The slow growing trees, such as *Faidherbia albida* and *Acacia* species, may not influence crop yields for many years after their establishment [Okorio and Maghembe 1994]. However, fast growing trees such as *Poplar* species, *Eucalyptus* species, *Cordia abyssinica*, and *Maesopsis eminii* reduce crop yields a few years after their establishment [Ralhan *et al* 1992; Okorio *et al* 1994; Akyeampong *et al* 1995].

Crop yield increases have been reported under open and well managed canopies of fully-grown trees. There are many reported yield increases under *Faidherbia albida* [Charreau and Vidal 1965; Poschen 1986; Depommier *et al* 1992]. These yield increases under the trees are attributed to the combined effects of improved soil fertility, soil water and microclimate. Crop yield declines, in the order of 50 to 70%, relative to yields in the open are noted mostly under canopies of large, evergreen, and/or unmanaged trees [Kessler 1992; Kater *et al* 1992; Puri and Bangarwa 1992; Yadar *et al* 1993; Wilson *et al* 1998]. A significant negative correlation between crop yield and light under the tree canopies indicated that shade was the major factor in crop yield reduction under the trees. Pruning the tree branches [Kessler 1992] and coppicing the trees [Tilander *et al* 1995] reduces light competition and provides tree products such as fuelwood and fodder, and additional benefits through enhanced fruit production in certain tree species [Timmer *et al* 1996].

The effect of boundary/upper-storey trees on crop yields depends on the site and age of trees. Malik and Sharma [1990] found that 3.5 year-old *Eucalyptus tereticornis* on field boundaries reduced crop yields by 41% upto 10 m from the tree row. Similarly, crop yield losses were observed 2 years after tree establishment, with different tree species showing different patterns of competition depending on growth rates and rooting patterns [ICRAF

1996]. The fast growing *Grevillea robusta* and the slow growing *Croton megalocarpus* depressed crop yields only over a short distance (<3 m). At 3 m from the tree row, crop yields in these plots approached that of the control, but *Gliricidia sepium* adversely affected yields up to 4 m from the tree row. Although *Senna spectabilis* had faster height growth than the other tree species, it depressed yields least, probably because of its limited canopy and deeper rooting. *Melia volkensii*, which produced the most growth, was also the most competitive species. It depressed crop yields for up to 5 m from the tree row because of its large canopy and probably the lateral spread of its roots near the soil surface. At 6 m from the tree rows, there was little impact of any of the tree species on crop yields.

Tree species and distance from the trees significantly affected the yield of wheat interplanted with *Eucalyptus*, *Grewia optiva* and *Morus alba* [Khybri *et al* 1992]. The trees were planted in lines in a north-south orientation and were spaced 5 m between individual trees. Eucalyptus had the greatest depressing effect on wheat yields, and as the age of the trees increased, the effect also increased from 4% in the first year to 61% in the ninth year. Corresponding values for *Grewia* and *Morus* were 5% to 52% and 13% to 58% respectively. Wheat yields at various distances from the tree lines showed the lowest values within 1 m. Wheat yields decreases were 40% for 1 m, 33% for 1-2 m, 26% for 2-3 m and 16% for 3-5 m distances from the tree lines. As the distance from the trees increased, the depressing effect decreased. Earlier work by Khybri *et al* [1986] revealed the effect extended up to 3 m, which subsequently increased to 5 m as the trees grew bigger. Similar patterns were observed when a rice crop was grown in the trial.

Large differences among species for competitiveness were also observed 3 years after tree establishment on field boundaries [Okorio *et al* 1994]. Over 3 to 4 m from the tree row, crops yield reduction ranged from 60% yield loss, adjacent to the fast growing *Maesopsis eminii*, to 38% in the slow growing *Markhamia lutea*. However, there was, a 19% yield increase adjacent the slow growing and nitrogen fixing *Alnus acuminata*. In Burundi, *Grevillea robusta* was found to have a positive effect on banana yield, while under low fertility regimes, the yields of interplanted beans were equal to or greater than those in plots without trees [Akyeampong *et al* 1999]. It appears that trees become competitive with age and increased size. Rao and Muthuva (unpublished), cited by Rao *et al* [1998] found that a row of unpruned *Leuceana* trees progressively reduced maize yields over 7.5 m on each side of the tree row. After a certain number of years, however, the competitive effect of trees might be independent of tree age because all trees will have attained a large

size [Khybri *et al* 1992]. Rao *et al* [1998] recognize that inspite of large yield increases or decreases under the trees, the overall effect of the trees on crop yields could be small because in this agroforestry system only a small proportion (about 10%) of the area is subjected to tree/crop interactions.

2.3 Light Capture and Utilization in Agroforestry Systems

2.3.1 Theory

Solar energy is the ultimate source of energy for the physiological processes of plants. Radiant energy is converted into chemical energy by the leaves and stored by the plants for further use. The interception and utilization of light, therefore, limits dry matter production of actively growing plants. Light regimes in plant canopies are influenced by several physical and biological factors such as solar position, plant structure, leaf geometry, size, anatomy, age, height and arrangement of the plants in the field. Moreover, the success and survival of individuals in mixtures depends upon how they intercept, compete for and respond to light [Ludlow 1978]. Competition for light occurs when the presence of one plant reduces the net photosynthesis of another by reducing the amount of radiant energy it receives.

In the context of photosynthesis, the solar spectrum can be divided into two fractions. The waveband between 400 and 700 nm, which most plants use for photosynthesis, is referred to as photosynthetically active radiation *(PAR)*. In the tropics, the ratio of PAR to total solar radiation has been found to be 0.51 for clear sky conditions and 0.63 for cloudy conditions [Stigter and Musabilha 1982]. The fraction of PAR in the incoming solar radiation at the top of a crop canopy can be separated into that reflected by the canopy and that which is effectively available to plants (Net), that is:-

$$Net\ PAR = Incoming\ PAR - Reflected\ PAR \qquad (2.3)$$

Part of the Net PAR is absorbed by the plants, while the other is transmitted to the ground, that is:-

$$Net\ PAR = Transmitted\ PAR + Absorbed\ PAR \qquad (2.4)$$

Experimentally, the absorbed PAR is estimated by the difference between the net and transmitted PAR, though more commonly the interception of PAR by canopies is assessed from the difference between incoming PAR and transmitted PAR.

Solar radiation received directly from the sun is called direct or beam radiation. Its irradiance on a horizontal surface is proportional to the sine of the solar angle, which varies during the day and with latitude and season. Some of the solar radiation is, however, scattered by gas molecules of the atmosphere (e.g. dust, clouds) and is received as diffuse radiation. Diffuse radiation is richer in PAR than direct radiation as it emanates from the whole sky hemisphere and its proportion of total radiation increases with cloudiness [Szeicz 1974a]. Because of the greater penetration of diffuse light and the progressive absorption of direct light, the proportion of diffuse to direct increases with depth in the canopy.

Within plant canopies, solar radiation is absorbed, transmitted or reflected by plant organs and thus becomes progressively reduced in energy and altered in spectral composition as it passes through them. Alternatively, it may pass unaltered through the canopy as sunflecks. Light interception increases as leaf area index increases either with time or with depth in the canopy. The latter results in an exponential decrease in light within canopies, the rate of which varies with canopy structure and properties of solar radiation [Szeicz 1974b]. Light penetration is greater into canopies of erect rather than horizontal or diaphotonastic leaves, clumped or random as opposed to regular foliage, and low rather than high leaf density [Ross 1975].

Shading below full sunlight reduces the growth of individual plants, therefore, during active growth, the receipt of solar energy is a major factor limiting the growth of plants adequately supplied with water and nutrients [Monteith 1972]. Preferential access to incident radiation is the major factor determining competitiveness for light and plant height is the most important single attribute determining competitiveness for light [Ludlow 1978].

2.3.2 Light Interception in Sole and Mixed cropping systems

Intercepted radiation *(Si)* in sole crops is normally taken as the difference between the quantity of solar radiation incident upon the canopy *(S)* and that transmitted to the soil *(St)*. However, this method of determining intercepted radiation makes no allowance for the fraction that is reflected from the canopy surface (5-20%) and this fraction depends on leaf angle, surface characteristics and moisture content [Ong *et al* 1996]. Light interception by crops growing in different climatic regions can be compared by using the ratio of *Si/S* to describe fractional interception *(f)*, rather than absolute values for intercepted radiation. Fractional interception for a specific canopy is hardly affected by the absolute value of *S*, but shows great seasonal variation depending on developmental stage, leaf area index, plant height, canopy structure and plant water status. When water is freely available, fractional interception is related to leaf area index *(L)* in many sole crops by the expression (Beer's Law):-

$$f = 1 - exp(-kL) \qquad (2.5)$$

where k is an extinction coefficient for the canopy which is dependent on leaf angle and distribution. Fractional interception, therefore, increases as k and L increases. Light penetration into the canopy is greater when the leaves are erect (low k values) than when they are horizontally oriented (high k values). The optimum arrangement for effective light interception is a progressive change from erect leaves near the top of the canopy to more horizontal leaves deeper in the canopy. The k values range from 0.30 to 0.45 in crops with erect leaves (e.g. cereals) to about 0.80 in species with evenly distributed leaves (e.g. groundnuts, cassava) [Squire 1990].

The amount of radiation intercepted by a crop depends on the quantity of solar radiation received, canopy duration and fractional interception. Mean f values calculated over the life cycle of the crop are generally smallest in short duration cereals (c. 0.5) and legumes (c 0.15) and largest in perennial species (c. 0.9), mainly because of the differing durations of ground cover [Squire 1990]. A primary goal of agroforestry is to increase fractional interception *(f)* values and hence overall dry matter production; this contrasts with intercropping where improvements in productivity are often attributable to increased conversion coefficient *(e)* values [Ong *et al* 1996].

The relationship between fractional interception and canopy characteristics defined by equation 2.5 above assumes that the canopy is a homogeneous arrangement of randomly distributed leaves, and that there is no spatial variation in light transmission. These conditions, however, are not met in intercropping or agroforestry systems because of the extensive horizontal and vertical variation in canopy structure. This is introduced by the different species combinations, differences in planting dates and arrangements and plant height [Ong *et al* 1996]. Canopy architecture is also constantly changing in mixed cropping systems because of the differing growth rates and duration of the component species [Azam-Ali 1995]. An example of "temporal complementarity" for light in intercrops involves mixtures of short duration cereals and longer duration legumes. In such systems, light interception typically tracks the sole crop initially, falls sharply when the short duration component is harvested and then increases again as the canopy of the slower growing, long duration legume continues to enlarge [Sivakumar and Virmani 1980].

2.3.2.1 Relationship between Light Interception and Biomass production

Many workers have measured the fraction (f) of radiant energy intercepted by the foliage of crop stands exposed to sunlight (irradiance S) and demonstrated a strong correlation between standing biomass (B) and the accumulation of intercepted radiant energy (f*S). This relationship has been summarized in terms of a "light use efficiency" ($e = B/(f * S)$) either for the whole growing season or for defined phases of crop development [Monteith 1994]. Light use efficiency (LUE) is the conversion factor between the amount of radiation intercepted or absorbed by a plant canopy and the corresponding amount of biomass produced [Arkebauer *et al* 1994].

Since Monteith [1972, 1977] first proposed the hypothesis that dry matter production was proportional to the interception of solar radiation, many workers have demonstrated the validity of this relationship for different crops [Sivakumar and Virmani 1984; Unsworth *et al* 1984; Gallagher and Biscoe 1978] and trees [Cannell *et al* 1987; Cannell *et al* 1988; Milne *et al* 1992]. In this analysis, the cumulated solar radiation intercepted or absorbed by a plant canopy during the season or growth phase is plotted against dry matter produced and the slope of this curve is referred to as the light use efficiency. It is expressed as the quantity of above ground dry matter produced per unit of intercepted radiation (g MJ^{-1}). Dry matter production is proportional to mean canopy photosynthetic rates because

respiratory and photorespiratory losses of carbon generally comprise a conservative fraction of assimilation within individual species [Squire 1990].

Although Demetriades-Shaw *et al* [1992, 1994] have criticized this procedure, many workers consider it appropriate [Arkebauer *et al* 1994; Kiniry 1994; Monteith 1994]. A definition of light use efficiency involves three distinct factors [Norman and Arkebauer 1991a, b]. One is the form of carbon involved, whether it is net CO_2 uptake by the above ground dry matter or total plant dry matter including roots. The second factor is the characterization of the radiation, whether it is intercepted solar radiation, absorbed solar radiation, intercepted photosynthetically active radiation or absorbed photosynthetically active radiation. A third factor is the time-scale over which the LUE is computed. Cumulative changes in carbon or biomass and radiation interception or absorption can be determined on an instantaneous, hourly, daily, weekly, seasonal or annual basis. Because of the different definitions of LUE, its reported values show large variations [Charles-Edwards 1982; Ong *et al* 1996]. Light use efficiency has become a very useful component in modeling crop growth and yield as it allows the maximum growth and yield potential of a specific crop in a given environment to be assessed [Muchow *et al* 1990; Amir and Sinclair 1991].

When water and nutrient supplies are not limiting, dry matter production *(B)* by a crop stand may be formalized as [Monteith 1981; Corlett *et al* 1992b]: -

$$B = S.f.e.t \qquad (2.6)$$

where:- S represents mean daily solar radiation ($MJ\ m^{-2}day^{-1}$), f is the seasonal mean fractional interception, e is the seasonal mean conversion coefficient ($g\ MJ^{-1}$), and t is the canopy duration in days. The conversion coefficient *(e)* is, therefore, a key factor in determining the quantity of dry matter produced.

2.3.3 Light Interception in Agroforestry systems

The complexity of the interactions on light use in agroforestry depends on the design, composition and maturity of the systems involved. In the first cropping season after planting the trees, the system bears comparison to conventional intercropping systems

because the trees have not yet achieved their full competitive vigour and stature. In more mature systems, the nature and extent of the interactions will vary according to planting arrangement. In alley-cropping systems, a concave gradient of decreasing competition for light between the tree and crop component may be observed towards the centre of the alley [Lawson and Kang 1990; Corlett *et al* 1992b]. The situation is more complex with dispersed arrangements, particularly when the trees are not planted on a regular grid pattern.

An additional complication in light interception studies in agroforestry systems is that shading affects the radiation environment experienced by the under-storey crops. The main source of light for these species is diffuse radiation, which has penetrated unintercepted through gaps in the over-storey canopy, and transmitted radiation that has previously been intercepted and transmitted by the foliage of the tree canopy. The former is relatively rich in PAR and so is used with apparently greater efficiency for dry matter production [Sinclair *et al* 1992], while the latter may be severely depleted in PAR. Detailed measurements of PAR interception are, therefore, essential for a full understanding of the influence of the dominant tree component on the light use, growth and productivity of under-storey crop species.

Wallace [1997] has developed a simple theoretical framework for light interception model for two species mixtures. In a system where species 1 is very much taller than species 2, the fraction of the incident radiation intercepted by the first canopy (tree component) is given by the equation: -

$$F_1^{\,d} = 1 - exp\,(-K_1 * L_1) \qquad (2.7)$$

where the superscript d refers to the condition that species 1 is dominant and K_1 and L_1 are the extinction coefficient and leaf area index of the first canopy. The equivalent fraction of incident radiation intercepted by the second canopy (crop component) is: -

$$F_2^{\,s} = [exp\,(-K_1 * L_1)] * [1 - exp(-K_2 * L_2)] \qquad (2.8)$$

where the superscript s refers to the condition that the species 2 is subordinate and K_2 and L_2 are the extinction coefficient and leaf area index of the second canopy. When the two species are of comparable heights, their fractional light interceptions will be described by

the equations: -

$$F_1 = F_1^{\,s} + f*[F_1^{\,d} - F_1^{\,s}] \qquad (2.9)$$

and

$$F_2 = F_2^{\,s} + (1-f)*[F_2^{\,d} - F_2^{\,s}] \qquad (2.10)$$

where f is a scaling factor between 0 and 1 which is a function of the two species heights, h_1 and h_2. This factor f is an expression of the dominance of one species over another. The total fraction of incident radiation intercepted by the mixture of both species is:-

$$F_1 + F_2 = F_1^{\,d} + F_2^{\,s} = 1-[exp.(-K_1*L_1 - K_2*L_2)] \qquad (2.11)$$

The above formulation shows that the total light intercepted by the mixture ($F_1 + F_2$) is independent of the individual species heights, whereas the individual fractions, F_1 and F_2, are not.

2.3.4 Light Interception in Boundary/Upper-storey tree planting Agroforestry

Vertical gradients in light interception are important depending on the relative heights of the tree and crop components. In this agroforestry system, the crop is shorter and has a much smaller leaf area than the tree component. It is, therefore, at a competitive disadvantage relative to the trees with large canopies. Because the canopies are separated vertically, the relationship between the two species can be analyzed as a permanent shading of the crop by the tree. In this case, it is possible to treat the tree and crop canopies as vertically discrete strata intercepting light [Ong *et al* 1996], therefore, the quantification of light interception and conversion by each component is done by using sensors located above and below the tree and crop canopies. A review of studies on light interception in this agroforestry system is given in the following paragraphs.

In on-farm field trials conducted in China to characterize wheat yield in plots oriented east, west and north from the canopy of a north-south row of 11-year old *Paulownia* trees, Chirko *et al* [1996b] found wheat yields to be significantly higher on the east compared to west and south. No yield differences were detected between west and north orientations.

The percentage of the photosynthetic photon flux density (Qp) under the trees was greater in the east than west and north by an average of 9.5%. There were no significant differences in soil nutrients and soil moisture between the orientations. A related root barrier and no root barrier study revealed that the tree and crop root interaction had no effect on wheat yields, indicating no yield differences due to root competition. They conclude that the key factor causing wheat yield differences, was the amount of photosynthetic photon flux density at different orientations under the tree. Earlier, Chirko [1993] found both time of day and the duration of tree canopy shade, had an impact on wheat yield in a transect running perpendicular to a north-south row of *Paulownia* trees. Shading which occurred early and late in the day when the sun was low on the horizon, had less impact on crop yield than shading that occurred during midday when Qp was at its maximum.

In another study, line plantings of 7-year old *Paulownia* trees had light transmissivities that ranged from 50, 55, and 35%, for 3, 7.5 and 12 m respectively from the lines of trees [Newman *et al* 1998]. Maize yields were 63% of sole crops and light was found to be the key limiting factor in the system. Zhang [1996] working in a temperate climate in the UK found that a line of Poplar trees shaded under-storey grass to a distance of 2 m from the tree line. The amount of the incident radiation reaching the grass beneath the trees was 49% compared to that in the open.

Several studies in the literature show that unpruned hedgerows behave like upper-storey trees in terms of light competition with crops. Daniel *et al* [1991], using lines of unpruned pigeon pea interplanted with various crops, found that shading by the pigeon pea extended upto 1 m and the shading on the under-storey crop ranged from 46 to 57%. Unpruned 2-year old black locust trees (*Robinia pseudoacacia*) imposed serious competition for light on the interplanted maize crop [Ssekabembe *et al* 1997]. The amount of PAR reaching the under-storey maize crop in the unpruned hedges ranged from 22 to 25% compared to that in the open. Miah *et al* [1995] found that the unpruned hedgerows of *Gliricidia sepium, Acacia auriculiformis* and *Acacia mangium* reduced light incidence on the understorey rice and mungbean crops by 53 to 59%, thereby causing reduction in crop yields. Similarly, Corlett *et al* [1992b] found that reductions in millet yield of 69 to 77% relative to sole millet was attributable to reductions in mean daily solar radiation and mean seasonal fractional light interception by *Leuceana leucocephala*. The shading effect of the shrub was greater on the eastern side than on the west and was more pronounced when the

lopping frequency of the hedge was reduced. The removal of competition for water by irrigation did not increase maize yields in unpruned *Leuceana* hedge because its greater canopy development increased shading [Howard *et al* 1995].

2.3.5 Methods of Measuring Light Interception in Cropping Systems

Light interception by plants can be measured directly or indirectly. Sheehy [1985], Pearcy [1989] and Sinoquet and Caldwell [1995] have written reviews on the main methods for measuring intercepted radiation by crops.

In direct measurements, radiation sensors measure downward and upward radiation fluxes within the canopy [Sinoquet and Caldwell 1995]. In particular, sensors located at the upper and lower bounds of the canopy allow one to obtain a radiative balance of the whole canopy [Varlet-Grancher and Bonhomme 1974]. Plant scientists have used two types of sensors, the energy (PAR) sensor and the photon (quantum) sensor [Newman 1989], to measure light interception by plants. The quantum sensor is often preferred for measurements of photochemical efficiency in relation to absorbed PAR, whilst the energy sensor is preferred for the measurement of PAR in relation to canopy transmissivities [Blackburn and Proctor 1983]. Tube solarimeters sensitive to radiant energy over the whole spectrum and the quantum sensors, which respond to the wavelength band from 400 to 700 nm, are the most commonly used sensors for measuring light interception by plant canopies.

Estimation of light partitioning from radiation measurements is feasible only if component foliage are segregated in distinct layers. Such is the case in vertically stratified intercropping like shrub/grass mixtures [Tournebize and Sinoquet 1994], row intercropping like sorghum/groundnut intercrop [Azam-Ali *et al* 1990] or agroforestry systems such as upper-storey trees/ annual crops [Torquebiau and Akyeampong 1994]. McNaugton *et al* [1992] has developed an experimental device for measuring the radiative balance of isolated trees. If species foliages are mixed within the same space, measurements of "free" radiation are unable to give an estimation of light partitioning between the inter-crop components, except if assumptions about the canopy structure are made. Walker *et al* [1988] estimated light partitioning from direct sunlight transmittance by assuming that vertical distribution of leaf area was the same for the species in pure and mixed stands

when the plant heights were equal. An alternative way is the use of small lightweight sensors that can be mounted on leaf surfaces [Gutschick *et al* 1985].

As opposed to homogeneous monocrops, measuring light capture in intercrops requires a great number of sensors in order to integrate variation due to the canopy structure and distinguish light interception between species. Low-cost sensors are useful in avoiding experimental limitations in other types of radiation field measurements. New sensors such as Amorphous Silicium Cells (ASC) correctly measure quanta fluxes in the PAR waveband [Chartier *et al* 1989]. Newman [1985, 1989] used low-cost E cell coulometers for longtime integration. Tracking systems that move sensors along a transect provide an alternative way to integrate spatial variation [Pech 1986, Matthews *et al* 1987].

Digital image analysis provides new opportunities for evaluating light partitioning in intercrops. Research in Hawaii has developed a system for photographing individual rows of plants in intercrops, digitizing the images and discriminating the foliage, then recreating a view of the entire intercrop on computer by overlaying each rows foliage data in its appropriate spatial position [Sinoquet and Caldwell 1995]. Each picture element in the computerized intercrop can then be sampled to identify which species intercepted the corresponding beam of light. Unfortunately, this method is restricted to row and strip intercrops in which there is no intermixing of foliage between the rows.

Indirect estimation of the light interception consists of measuring variables that are strongly dependent on light capture. Such methods include single leaf photosynthesis [Beyschlag *et al* 1990], plant CO_2 assimilation or transpiration and dry matter production [Rimmington 1985; Sinoquet *et al* 1990]. However, indirect estimation methods always involve additional mechanisms that may themselves fluctuate as the result of resource availability. Consequently, the general reliability of such approaches is questionable, but they may be "useful" in providing estimates, especially in case of mixed foliages [Sinoquet and Caldwell 1995].

Generally, the experimental approaches and instrumentation required to quantify light interception are well established and relatively straightforward in monocultures. However, the problems involved in monitoring the spatial and temporal variation in mixed communities, such as agroforestry, are much greater. The scale of the spatial heterogeneity is relatively modest and capable of resolution in annual row intercrops [Marshall and

Willey 1983; Azam-Ali *et al* 1990], but is much greater in horizontal and vertical planes in agroforestry systems, particularly those involving large over-storey trees. Another factor adding to the complexity of light use studies in agroforestry systems is the extended time scale and constantly changing relationship between the tree and crop components.

Furthermore, in annual intercrops, the measurement period is normally confined to one season, whereas the tree component of agroforestry systems is present and usually actively using resources throughout the year. Tree size and the extent of their interaction with associated crops may alter rapidly during the cropping cycle and from year to year [Ong *et al* 1996]. Thus, the nature of the interactions and the partitioning of the light resource between the trees and crops are constantly changing, with the result that intensive studies are required to obtain a sound quantitative understanding of the processes involved.

2.3.6 Modeling the Shading effect of Trees

Knowledge on the architecture of tree crowns is needed in modeling the spatial distribution of radiation in tree/forest under-storey [Pukkala *et al* 1993]. Thus an accurate description of crown shape is an important component of many physiological process models. The interception of light by a crown and the radiation environment in the under-storey depends on many factors such as solar angle, LAI, the three-dimensional distribution of LAI, extinction coefficient of the canopy, transmission and reflection coefficients of the leaves [Pukkala *et al* 1991]. The distribution of leaf area in space within an individual tree crown primarily determines the fraction of incident solar radiation intercepted by the tree and that reaching the under-storey [Wang and Jarvis 1990].

Modeling of light interception in discontinuous canopies in relation to productivity has been carried out for tree orchards [Jackson and Palmer 1979; Palmer 1981] and forests [Norman and Jarvis 1975; Kuuluvainen and Pukkala 1987; Pukkala *et al* 1993; Stenberg *et al* 1994]. Whilst such models could predict the light interception in a given configuration of canopies in an agroforestry system, a greater understanding of canopy development and structure for widely spaced trees is required. Most of the models of light interception deal with one vertical dimension [Wang and Baldocchi 1989] or two dimensions usually applied to crops where a horizontal homogeneity is assumed [Sinoquet and Bonhomme 1992].

Some models, which consider three dimensions, use idealized trees or geometrical shapes arranged in a regular array [Charles-Edwards and Thorpe 1976; Pukkala *et al* 1991; Begue 1993]. West and Welles [1992] model the structure of individual trees (Eucalyptus sp.) as sets of spheres and then apply a light interception model to that arrangement of spheres. The model MAESTRO developed by Wang and Jarvis [1990] based on the ellipsoidal model pioneered by Norman and Welles [1983] is a comprehensive approach to the problem. It includes physiological traits of the trees being simulated and is able to simulate photosynthesis and transpiration as well as radiation interception. Baldochi and Collineau [1994] have thoroughly reviewed the subject recently. However, to adequately describe the heterogeneity of light environment within crowns or canopies, de Castro and Fecher [1998] suggest the use of a three dimensional model. The ERIN model described by Wallace [1997] can be applied to a canopy containing any number of species.

Kuuluvainen and Pukkala [1987] studied the effect of crown shape and spatial distribution of trees on distribution and amount of shade in a forest stand. They developed a method for calculating the light extinction probability caused by individual tree crowns or the entire forest canopy. A canopy composed of vertically extended narrow tree crowns has a high efficiency in light absorption [Kellomaki *et al* 1985]. Crown shape was found to have a strong influence on the spatial distribution of its shade. During the course of the day, the shaded area of a narrow crown is smaller and more concentrated around the tree than the shaded area caused by a broad crown. Therefore, the between-tree shading is smaller in stands composed of trees with narrow crowns, when compared to trees with broad crowns. With a particular crown shape and stand density, the spatial distribution of trees has only a small influence on the total amount of shading in a forest stand. However, with regular tree distribution (e.g. tree lines), the spatial variation of shading probability is smaller than in random tree distribution.

2.4 Water Use in Agroforestry Systems

2.4.1 Theory

2.4.1.1 Water Uptake by Plants

Actively growing plants that provide full ground cover and are well supplied with water exert minimal control over transpiration and transpire at rates determined by the evaporative demand of the atmosphere. The maximum rate of water use for prescribed environmental conditions has been termed potential evaporation *(Eo)* [Penman 1948; Monteith 1965]. Potential evaporation defines the upper limit to the actual evapo-transpiration *(E_t)*, which is smaller than *Eo* when ground cover is incomplete, the soil surface is dry or water stress enforces stomatal closure. Although atmospheric conditions predominantly determine *Eo*, it is the attributes of the vegetation that limit transpiration and determine evapo-transpiration, in water limiting environments [Ong *et al* 1996]. These attributes may be divided into canopy characteristics that influence the movement of water from within the leaf to the atmosphere and rooting characteristics that influence the supply of water to the plant.

The root system is usually distributed in a non-random manner within the soil because the spatial variation in the rooting environment is large. Factors that influence rooting depth and density include the content and distribution of water, nutrients and oxygen and the presence of compacted or stony layers [Van Noordwijk *et al* 1992]. The quantity of water available for plant growth depends on rainfall, soil storage capacity and ability of the root system to exploit the available reserves effectively [Gardner 1960; Fitter 1986]. The depth of the soil profile and its extractable water content determines the maximum quantity of water potentially available to the crop.

Absorption of water occurs down the water potential gradient established between the roots and the surrounding soil by transpirational water losses from the canopy. In very broad terms, the flux of water *(F)* may be described as [Gardner 1965]:-

$$F = (\Psi s - \Psi r) / (Rs + Rr) \qquad (2.12)$$

where Ψs and Ψr denote soil and root water potentials and *Rs* and *Rr* represent the

hydraulic resistances to water flow for soil and root respectively. Thus the rate of absorption and hence plant water status depend critically on both soil moisture content and rooting depth and density, since the latter determines the total volume of soil that is colonized. The hydraulic resistance of roots depends on the total surface area and the radial conductance of roots to water movement, and is normally expressed per unit length rather than surface area [Loomis and Connor 1992]. The most effective means for plants to maintain absorption and hence transpiration on drying soils is through sustained root proliferation [Passioura 1993]. Deep, densely branched root systems may be more able to sustain absorption over extended periods, but are achieved only at the cost of increased assimilate investment to support their growth and maintenance respiration [Loomis 1985].

The balance between transpiration and absorption depends on both atmospheric and soil moisture conditions. The root systems of well-watered crops generally extract water at rates close to the prevailing potential evaporation *(Eo)* [Ong *et al* 1996]. In dry soil, absorption depends on the size and distribution of the root system and soil moisture content than atmospheric conditions. The driving force for transpiration depends predominantly on temperature and atmospheric humidity [Monteith 1986]. The shading effect of trees in agroforestry systems tends to reduce air temperature and wind speed and increase the atmospheric humidity experienced by the crops, thereby decreasing evaporative demand. In agroforestry systems, the dominant upper-storey species is a C3 species, which has a lower light-saturated photosynthetic rate and water use ratio. So the beneficial micro-climatic changes experienced by associated crops may be largely eliminated by the fact that the under-storey is often a C4 cereal that does not respond favorably to shading [Ong *et al* 1996].

2.4.1.2 Limits to water extraction

The quantity of water available to crops in a drying soil depends on the rate at which roots extend through the profile [Eissenstat 1992]. Measurements of soil moisture content indicate that the progress of " extraction" or "drying " fronts downwards through the soil profile is closely related to that of the " rooting front" [Robertson *et al* 1993]. The rate of water extraction has been found to be greater in sandy soils than in clay soils [Squire *et al* 1984]. Extraction of water from drying soils is limited by two factors: - absorption is initially slow when roots reach specific horizons because of the low rooting density; and by the time the roots have proliferated sufficiently to achieve maximum extraction, soil water

content may have decreased to the point where it restricts absorption [Ong *et al* 1996]. Thus, the principal limitation on water uptake by annual crops growing on stored moisture is the rate at which roots extend and proliferate. However, a very different situation applies for woody perennial species, which have established root systems at the on-set of the rainy season, and are therefore well placed to exploit the available moisture rapidly [Gregory 1996b]. This may be an important aspect of detrimental tree/crop interactions in agroforestry systems where roots of both components are distributed within the same soil volume and are competing for the same resource pool [Ong *et al* 1996].

2.4.1.3 Relationship between Water use and Dry matter production

As with light, the quantity of dry matter produced *(B)* depends on the quantity of water captured *(mm)* and the "efficiency" ($g\ kg^{-1}\ H_2O$) with which it is used in dry matter production. The ratio of dry matter produced to water transpired is known as the *water use ratio* (e_w). Dry matter production may be expressed as:-

$$B = e_w \Sigma E_t \qquad (2.13)$$

where ΣE_t represents cumulative transpiration. As for light, the quantity of dry matter produced is often linearly related to the quantity of water transpired [Azam-Ali 1983; Cooper *et al.*, 1987]. There is a close interdependence of CO_2 and water vapor exchange during photosynthesis and transpiration; whenever the stomata open to permit entry of CO_2 into the leaves, water is lost by transpiration.

The efficiency with which the transpired water is used in dry matter production is a critical factor in crop production. Water use ratio *(e_w)* can be calculated on various time-scales, ranging from instantaneous measurements of the ratio of net CO_2 fixation to transpirational water loss, to season long estimates based on measurements of dry matter accumulation and crop water use. The value of water use ratio is usually calculated on the basis of "*transpired*" water rather than evapo-transpiration *(E_t)* since water evaporated from the soil plays no part in dry matter production. Soil evaporation *(Es)* dominates evapo-transpiration *(E_t)* early in the season but transpiration becomes increasingly important as the canopy enlarges [Ong *et al* 1996]. As indicated earlier, dry matter production is often linearly related to the quantity of water transpired [Tanner 1981; Connor *et al* 1985].

2.4.2 Water use in Agroforestry systems

Agroforestry systems offer the opportunity for spatial and temporal complementarity of water use, resulting in an improved exploitation of available moisture relative to sole crops. However, the opportunity for significant complementarity may be limited unless the component species differ appreciably in their rooting patterns [Jena and Misra 1988] or duration. The former would permit the exploitation of different soil reserves, while the latter would allow continued extraction of residual moisture following the harvest of the shorter duration crop. The hypothesis that annual crops cannot fully utilize available water and that agroforestry systems may improve productivity by using a large proportion of the annual rainfall has gained support in recent years [Ong *et al* 1996]. It is theoretically possible that the inclusion of trees or shrubs may improve rainfall use efficiency either directly or indirectly. The trees can directly use more rain through transpiration or indirectly by improved transpiration efficiency, that is, more dry matter produced per unit of water transpired. The former effect could be achieved by either spatial or temporal "complementarity" in the constituent species, and the latter by modifying the plant microclimate [Wallace *et al* 1996].

Drainage losses from tropical crops are rarely quantified and are therefore largely unknown [Ong *et al* 1991c]. This is one of the terms in the water balance that can be modified by the presence of trees. Trees utilize water outside the rooting zone of annual crops and also outside the crop-growing season [Huda and Ong 1989]. Improved rainfall utilization also occurs via the substantial reductions in runoff that can be achieved in agroforestry systems, particularly on sloping land [Young 1989]. With their elevated canopies, the trees in an agroforestry system may modify the microclimate in such a way as to increase the overall water use efficiency of the understorey crop. Shading of the ground may significantly reduce soil evaporation and Wallace *et al* [1999] predict that a tree canopy can reduce annual soil evaporation by between 12 and 24% of rainfall. Reduced soil evaporation allows for an increase in the amount of water available in the soil for transpiration by the crops or trees.

Another form of microclimatic modification which may improve transpiration efficiency is the reduction in the within-canopy vapor pressure deficit as a result of transpiration from the second canopy and/or soil evaporation. Transpiration efficiency is inversely proportional to the vapor pressure deficit of the air [Monteith 1988], implying plants will

use more water to fix a given amount of carbon when the air is drier. The shading of the crop may also reduce its transpiration without a proportional decrease in photosynthesis. In this case, reduced radiation input to the crop would increase the transpiration efficiency and potential benefits depend on the degree of shading. Shading of a crop by a tree canopy may, therefore, reduce surface soil and air temperatures to give beneficial effects on crop growth [Vandenbeldt and William 1992]. Crop growth and rates of development increase with temperature up to an optimum temperature and decline thereafter.

However, trees also contribute to loss of rainfall through evaporation of canopy interception, and modify soil water conditions under canopies by redistribution of intercepted rain through stem flow and canopy drip [Wallace 1996]. Rainfall interception by plant canopies is the first process involved in water partitioning between species in mixtures [Busseire 1995]. Depending on the space occupation and physical properties of the tree foliage, the redistribution of rainfall may affect two stages of water relations between the components. Firstly, the amount of intercepted water stored in the canopy may modify the transpiration rate of each component in the system by re-evaporation from the wet surfaces. Secondly, the dripping of water through stem flow and leaf drip may influence water distribution at the soil surface and hence water availability to the under-storey.

Trees may cause up to 50% loss of rainwater for small storms (< 15-mm precipitation) but a 10 to 20% loss for larger storms (> 15 mm) through evaporation of intercepted water. Individual trees on annual basis may account for 10 to 30% loss of rainfall in agroforestry systems in the tropics [Ong and Black 1994; Breman and Kessler 1995]. However, Wallace *et al* [1999] predicted that the reduction in soil evaporation under tree canopies would be sufficient to offset the increased losses due to canopy interception in a semi-arid environment. Their model demonstrated how annual total soil evaporation varied with soil type and rainfall. The largest amounts of evaporation and greatest saving in soil evaporation due to canopy shade were found in clay and sandy loam soils, and the least were found in sandy soils. Rainfall intensity and annual totals were shown to be important determinants of soil evaporation under tree canopies.

Several studies on water use in agroforestry systems, especially between tree hedges and the annual crops planted in the alleys have been reported. Hedgerow plantings of sole *Leuceana* extracted more of the available soil moisture than either sole crops or intercrops

of sorghum or pigeon pea [Ong *et al* 1992a]. However, in this and other experiments in the semi-arid tropics, severe competition between the extremely vigorous *Leuceana* and associated annual crops reduced crop yields by 50-80% [Rao *et al* 1990; Corlett *et al* 1992b]. Results from these and other studies emphasize the potential of agroforestry for increasing rainfall utilization and productivity. However, the influence of planting density and the arrangement of trees on community water use and the productivity of its components is complex.

2.4.3 Water Use in Boundary/Upperstorey tree planting Agroforestry

Recent research on water use has concentrated in agroforestry systems that are less competitive with crops than alley cropping. Scattered trees in cropland and boundary tree planting with perennial pigeon pea, *Faidherbia albida* and *Grevillea robusta* have shown the potential of these systems to increase water utilization and hence productivity [Ong *et al* 1996]. However, very few studies have been carried out on water use by trees and associated crops in boundary/upperstorey agroforestry systems. Those reported in the literature are summarized in the following paragraphs.

Water use between rows of 2-year old *Grevillea robusta* trees and annual crops (maize and beans) was assessed in a semi-arid environment of Machakos in Kenya [Odhiambo 1999]. Water uptake was found to be greater in the tree plots than in sole crop plots. The trees exclusively utilized water from deep soil horizons, while there was an overlap in water use in surface horizons between the trees and crops. This suggested partial complementarity in water use between the two components. Root competition for water was found to reduce soil water availability for successful crop establishment within 6 m from the trees. It is concluded that competition for water between the trees and the crops was responsible for the decline in yields in this agroforestry system. At the same site, Howard *et al* [1997] examined the extent of below ground complementarity on water use between young *Grevillea robusta* trees (planted 3x4 m) and the interplanted cowpea (*Vigna unguiculata*). Sap flow was measured in the *Grevillea* trees before and after removing the soil from around the base of the trees within the crop-rooting zone to a depth of 60 cm. This was to prevent any water uptake except from beneath this zone. The degree of below ground complementarity was established by determining the proportion of the total sap flow through the trees, which was drawn from beneath the crop-rooting zone. After excavation,

the trees maintained sap flows of up to 85% of the unexcavated values, suggesting a high degree of below ground complementarity on water use.

Livesely [1999] determined water use between maize and line plantings of 3-year old *Grevillea robusta* trees and *Senna spectabilis* hedges, in a sub-humid environment of Nyabeda in Western Kenya. The amount of stored water was found to increase with increasing distance from the *Grevillea* trees and it is concluded that in this environment, *Grevillea* trees abstracted and transpired about twice as much water as *Senna* hedges because the former had twice the rate of biomass growth.

Three and half year-old *Eucalyptus tereticornis* trees planted in lines and spaced at 1.5 m were found to extract 5 times more water than the interplanted mustard crop from 1-150 cm soil profile in a semi-arid environment in India [Malik and Sharma 1990]. The yield of the mustard crop was negatively related to moisture extraction. Moisture extraction decreased with increasing distance from the tree line, and the profile water content varied from 195 mm near the tree line (0-2 m) to 322 mm away from the trees (8-10 m). Percent moisture extraction ranged from 62% at 1 m away from the tree, to 28% 9 m away from the tree line. It is concluded that the main reason for reduction in crop yield was moisture extraction by *Eucalyptus* trees. In a similar environment, soil moisture content (0-90 cm depth) under a line of *Eucalyptus* hybrid trees inter-planted with wheat was found to be less than that in *Grewia optiva* and *Morus alba* plots [Khybri *et al* 1992]. The highest soil moisture was found in plots without the trees. Soil moisture contents under the trees were 170 mm for *Eucalyptus*, 190mm for *Grewa* and 222 mm for *Morus*.

Rhoades [1995] determined seasonal soil moisture patterns beneath *Faidherbia albida* in Malawi, Southern Africa. Soil moisture in the surface layer (0-15 cm) was found to be 4 to 53% higher beneath the *F. albida* trees than in the open. There were no differences in the 15-30 cm depth. Generally, the tree canopies were found to moderate soil moisture shifts so that canopy sites fluctuated less than the open sites. Similar results were found beneath canopies of different trees scattered in croplands in Mexico [Farrell 1990]. In Senegal, improved water conditions to a depth of 120 cm beneath *F. albida* crowns were found [Dancette and Poulain 1969]. This was attributed to reduced evaporation under the trees, which affected the tree water uptake from lower depths.

Yunusa *et al* [1995] determined soil moisture storage in an agroforestry system consisting of pine trees grown with or without ground cover of rye grass and Lucerne. Both the cover crops and the trees influenced soil moisture storage patterns. Soil moisture content at all depths was higher in the control (trees without cover crop) than in the pasture cover crops (trees and rye grass, trees and Lucerne) for all positions in the plots. For the two cover crops, soil moisture was similar in the top 40 cm of the profile. However, at the lower depths, the profile was drier under Lucerne than rye grass, especially at positions away from the tree rows. This was attributed to the extensive root system of Lucerne that enabled it to exploit the soil profile at all depths and even beyond the 90-cm depth.

2.4.4 Methods of Measuring Water Use in Agroforestry systems

The difficulties involved in partitioning light interception within agroforestry systems apply also to water, especially when attempting to quantify the extent of the spatial and temporal variation. These problems are compounded by the fact that the rooting environment is much more heterogeneous than the atmospheric environment, necessitating greater replication to obtain reliable estimates of water use. It is also difficult to sample plant roots and soil moisture utilization in agroforestry systems. Three broad approaches have been used to determine water use by the components of mixed communities and these are:- estimation using transpiration models, estimation using the water balance method and the direct measurement of transpiration by each component.

2.4.4.1 Estimating Transpiration using Transpiration Models

Transpiration by each component may be estimated using transpiration models based on light interception by each component. This approach assumes that the Penman-Monteith equation may be modified to calculate transpiration within multi-species stands provided that radiation interception by each component may be calculated using a single or dual source transpiration model which requires as inputs variables above-canopy net radiation, temperature and vapor pressure deficit [Wallace 1995; Wallace and Verhoef 2000]. This method has recently been used to determine transpiration by Poplar trees inter-planted with pasture grass [Zhang 1996].

2.4.4.2 Estimating Transpiration using Water Balance Method

In this method, all the terms contributing to the soil water balance are measured with the exception of transpiration. Total transpiration is determined indirectly from the balance of all other components, namely precipitation, interception losses, run-off, soil surface evaporation, deep drainage and soil moisture content within the rooting zone. Several of the terms are difficult to quantify reliably, particularly as they may show extensive spatial variation. Techniques for quantifying the components of the water balance are discussed by Wallace [1996].

All water balance methods of determining transpiration rely on the basic water balance equation:-

$$P = \Delta S + D + R + ET \qquad (2.14)$$

where P is precipitation, ET is evapo-transpiration, D is drainage, R is runoff, and ΔS is the change in water storage in the soil or other defined system (e.g. a catchment). The major problem of the method is that the accuracy of determining ET is dependent on the cumulative errors in the four terms of the equation. The most accurate estimates of ET are obtained if all these terms are independently measured, although such complete information is rarely available.

Soil moisture content *(S)*, is a key variable in the water balance. The amount of water that enters the soil profile is the combined effects of rainfall, infiltration and runoff. Changes in soil water content near the soil surface (<15 cm) are usually measured by gravimetric sampling, but new techniques have been developed which allow rapid and automatic measurement of surface soil water content. Time Domain Reflectometry (TDR) now permits rapid automated measurements from all depths [Topp and Davies 1985]. The TDR technique monitors rapid (e.g. hourly) changes in soil water content and needs calibration for different soils, since it is affected by soil bulk density and mineral and organic matter content [Roth *et al.*, 1992; Robinson *et al* 1994). Another new technique for measuring soil water content is the use of manually operated probes such as the Surface Insertion Capacitance Probe (SCIP) [Robinson and Dean 1993] and the Theta probe (Delta T Services). These probes have two steel prongs, which can be inserted into the soil to a depth of 5 to 10 cm.

Changes in soil water content in deeper soil layers (>15 cm) is most frequently measured using a neutron probe [Bell 1987]. In the neutron probe technique, fast neutrons emitted from a radiation source lowered down aluminum tubes installed vertically in the soil are back scattered as slow neutrons by hydrogen nuclei in the soil. With appropriate calibration against gravimetric measurements of soil moisture content, the counts of back-scattered slow neutrons are used to provide periodic non-destructive measurements of water content throughout the soil profile. These are then used as part of the water balance to estimate water uptake from specific horizons and, by summation, total water extraction from the soil profile colonized by the roots. The resolution of this technique limits the time scale over which it can be used, as water content changes cannot usually be detected for periods much shorter than one week.

A major difficulty with the neutron probe approach is that it is often impossible with deep rooting species or in stony soils, to install neutron probe access tubes to the full depth of the rooting system without causing unacceptable damage to the surface horizons. Compaction, smearing of the soil surface in contact with the tube or close contact between the tube and soil must be avoided since these factors alter infiltration and drainage characteristics. Eastham *et al* [1988] found that unknown quantities of water were withdrawn by *Eucalyptus* from below their maximum measurement depth of 5.6 m. In such cases, water use is underestimated to an extent related to the quantity of water extracted from horizons below the maximum measurement depth. A direct consequence is underestimation of transpiration by the tree if calculated as the difference between total water use and measurements of transpiration by the crop

2.4.4.3 Direct Measurement of Transpiration by each component

This approach is preferable since water use by each component is determined separately. The result is that the values obtained are subject only to errors inherent in the techniques specifically used to obtain those values. Techniques that are applied to determine transpiration by trees or crops include diffusion porometry, small chamber gas analysis, deuterium labeling and sap flow techniques. Porometry and small chamber systems allow daily or seasonal time-courses of transpiration to be constructed, but are extremely labor-intensive if both components are to be monitored routinely. They cannot be used when the foliage is wet, a major problem during periods of frequent rainfall or dew. Deuterium labeling avoids these problems and permits estimation of transpiration over periods of

several days, but is relatively expensive and requires sophisticated monitoring equipment. However, the advent of relatively simple and reliable sap flux techniques now permits continuous, non-destructive measurements of transpiration by trees and crops over longer periods.

a) Diffusion Porometry

The two types of diffusion porometry that are most commonly used for field studies are the dynamic diffusion type (transit or van Bavel) and the steady-state type (null-point). The transit type is relatively simple but requires frequent, relatively straightforward calibration [Potter 1992]. In these porometers, a small area of leaf is temporarily enclosed in a small cup containing a humidity sensor. Dry air that is drawn from a silicon gel reservoir is passed through the crop until relative humidity falls to a preset level and the time required for water vapor emitted from the leaf to raise humidity by a small fixed increment is the determined. This cycle is automatically repeated until a stable value is obtained. The counts obtained are converted to diffusive resistances or conductances from calibrations constructed using a plate containing perforations of known diffusive resistance.

The steady-state instrument is relatively simple, but calibration, though less frequently required, may be more difficult. Stomatal resistance is determined from measurements of the equilibrium relative humidity produced by transpiration from the enclosed leaf and an inflow of dry air [Bell and Squire 1981]. Steady-state instruments require a vigorously stirred chamber, which is usually relatively large, whereas the cup of transit porometers is unstirred and relatively small. Thus transit porometers sample small areas and can measure both leaf surfaces separately, whereas steady-state instruments sample larger leaf areas and measure both leaf surfaces simultaneously.

The porometry approach provides instantaneous values of transpiration, in contrast with the neutron probe or deuterium labeling. It also permits examination of the variation in transpiration associated with differences in leaf age and position or distance from the nearest tree. In this method, the canopy is usually sub-divided into two or three layers depending on canopy height when whole-canopy transpiration is to be estimated, and separate measurements of the required input variables are made for each layer. Total transpiration is obtained by summing the values for each layer. Several workers have adopted this approach [Azam-Ali 1983; Wallace *et al* 1990; Roberts *et al* 1993]. The

major shortcoming of the porometry approach is its highly intensive, yet discontinuous nature and the great spatial and temporal variability of the input variables. Repeated measurements are necessary to establish reliable diurnal and seasonal patterns.

b) Sap Flux methods

Methods that provide direct, continuous and non-destructive measurements of transpiration by intact plants under field conditions have concentrated on sap flux methods such as the magneto-hydrodynamic, heat pulse and heat balance approaches.

The magneto-hydrodynamic method involves applying a uniform magnetic field perpendicular to the direction of flow through the stem and permits sap flow to be measured non-destructively over extended periods in species with woody stems [Sheriff 1972]. As the fluid passes through the line of magnetic flux, a voltage is induced whose magnitude and sign may be used to determine the volume and direction of sap flow. The measurements are independent of physical variables such as temperature and fluid viscosity. The voltage output is linearly related to sap flux, though the slope of the relationship varies with species and stem diameter. Individual calibrations over a range of stem diameters are, therefore, required.

The heat pulse technique was first derived by Huber [1932] and has been adopted and modified for a range of woody species [Cohen *et al* 1981, 1983; Doley and Grieve 1966; Sabatti *et al* 1993]. The technique has been applied to relatively large trees, but modified versions have been used with apparent success in small plants [Heine and Farr 1973; Stone and Shirazi 1975]. The technique involves injecting brief pulses of heat using small resistance probes or plates embedded in the sapwood and then monitoring their axial progress using thermocouples or thermistors installed downstream in the flow path. The time required for the pulses to travel from their source to the point of detection is used to estimate sap velocity. The heat pulse technique has frequently been used for relative studies rather than absolute measurements of sap fluxes in trees. Several reports suggest that the velocities obtained may systematically underestimate the true values in thick stemmed plants [Sabatti *et al* 1993].

The heat balance method is based on the measurement of heat balance rather heat pulse velocity. Vieweg and Ziegler [1960] initially devised the method, but numerous variants

have been described [Baker and Van Bavel 1987; Sakuratani 1984, 1990; Ishida *et al* 1991; Marshall *et al* 1994; Howard *et al* 1997; Khan and Ong 1995]. In this approach, the sap flux is determined by balancing the fluxes of heat into and out of a segment of stem. As sap flux changes, so too must the heat input required to compensate for the altered convective flux of heat away from the heated area and to maintain the heat balance constant. The changes in heat input provide the basis for the measurement of sap flow.

The heat balance approach permits daily transpiration by the components of agroforestry systems to be followed continuously and more accurately than is possible using diffusion porometry or soil water balance approaches [Ong *et al* 1996]. The daily values obtained in this way can be used to calculate cumulative transpiration. Although the heat balance approach may provide reliable measurements of transpiration in relatively small stems, great care is required to avoid over estimates (10-47%) in larger stems. These errors may be overcome by use of corrections and precautions described by Khan and Ong [1995].

c) Small Chamber Gas Analysis

Ventilated chambers operated as open-exchange systems allow continuous measurement of whole tree transpiration [Field *et al* 1989; Leuning and Foster 1990]. The problem with the method is that the micro-environment of the plant is substantially changed because the enclosure alters the canopy boundary layer [Denmead 1984], vapor pressure deficit [Lee 1966] and radiation budget [Denmead 1984; Leuning and Foster 1990]. Transpiration measurements by this method have frequently been at the single leaf scale or individual potted plants in the laboratory, and less frequently in the field [e.g. Greenwood and Beresford 1979]. This has been attributed to the difficulties of taking measurements in the field.

d) Deuterium Labeling

This method of estimating transpiration is based on the total counts of Hull [1958]. A known quantity of deuterium oxide (D_2O) is injected into the stem of a plant and samples of transpired water collected over a period of time from bags enclosing foliage at different positions in the crown. The method has been used to measure the transpiration of Eucalyptus trees [Calder *et al* 1986; Calder *et al* 1992; Dye and Olbrich 1993].

2.5 Rooting Patterns in Agroforestry Systems

2.5.1 Introduction

The technical problems involved in studying roots mean that many below ground processes remain poorly understood [Atkinson 1996]. Rooting characteristics of plants are important for understanding nutrient and water uptake patterns, in relation to aboveground growth [Russell 1977; Fogel 1985]. In addition, knowledge of the distribution of different categories of roots can provide indications of mutualistic and competitive tree/crop interactions below ground in agroforestry systems [Singh *et al* 1989; Ong *et al* 1991a; Ong *et al* 1992b; Hauser 1993]. Therefore, the knowledge on the distribution of tree and crop roots in the soil profile is necessary in designing appropriate agroforestry systems [Oldeman 1983].

Interactions between trees and crops for below ground resources are often as important as those for light and above ground space [Anderson and Sinclair 1993]. However, the below ground degree of potential competition or complementarity between trees and crops, is usually more difficult to assess than that for shorter-lived crops. Because of their longer lifetime, tree root systems have the chance to explore larger areas and exploit zones of rich localized supply of water and/or nutrients. If these zones are largely out of reach of annual crops, then the trees can increase the total production of the system, although they may not improve crop growth. This is especially true for deep-rooted trees, which can exploit deep soil water reserves and nutrients below the crop root zone [Van Noordwijk *et al* 1996]. The considerable genotype x environment interactions [Kerfoot 1963] mean that there are no "typical" root developments of tree and crop species. When transferred to a substantially different soil type, soil fertility status or climatic zone [Vandenbeldt 1991], they change their rooting patterns. Simple observation methods are thus needed to "ground-truth" generalization about root patterns [Van Noordwijk *et al* 1996].

Determining the spatial distribution of the fine roots (< 2mm) provides an indication of the active uptake surface and competitive capacity of the tree or crop [Caldwell 1987]. The root density of most trees and crops decreases exponentially with depth, unless specific soil layers restrict or stimulate root development [Van Noordwijk *et al* 1996]. Exceptions from this exponential pattern can be found in relatively deep-rooted trees such as *Dactyladenia* (Acioa) on acid soils [Ruhigwa *et al* 1992] or *Eucalyptus camaldulensis* [Jonsson *et al*

1988]. Rooting density also decreases with increasing distance from the plant in the horizontal direction [Van Noordwijk *et al* 1996].

2.5.2 Rooting patterns in Agroforestry systems

Complementarity in root distribution is supposed to be the key to the success of simultaneous agroforestry systems. Evidence for this hypothesis is widespread. In China *Paulownia* trees are widely intercropped with various crops such as wheat and maize. The majority of *Paulownia* fine roots are found at 40-100 cm depth, below the crop root zone [Zhu Zsao-Hua *et al* 1986]. The apparent success of this intercropping system is mainly due to complementarity in fine root distribution [Chirko *et al* 1996b], accompanied by favorable above ground tree morphology [Huxley *et al* 1994]. Horizontally separated root systems could also be the basis for complementarity in coconut-cocoa-pineapple multi-storey agroforestry systems [Nelliat *et al* 1974].

Understanding the growth of roots and the capture of resources is central to the development of practical agroforestry systems. Roots of trees and crops are often similarly distributed and the lateral extent of tree roots has frequently been underestimated [Gregory 1996a]. A key issue in predicting water and nutrient uptake by trees in simultaneous agroforestry systems is the extent to which the trees are able to exploit resources unavailable to crops. Because of their perennial nature, trees frequently have a deeper root system than annual crops but the deep roots are often confined to a few zones of cracked subsoil. Tree roots have been found to extend many meters laterally, leading to unintentional competition below ground for resources which in turn may depress yields in sole-crop controls [Coe 1994]. Huxley [1983] suggested that the different rooting depths of tree and crops should increase resource capture without introducing intense belowground competition. However, the presence of deep roots alone does not guarantee complementarity in water use and knowledge of root distribution is of limited value in the absence of corresponding information concerning water and nutrient uptake [Howard *et al* 1997]. The greatest rooting density of most agroforestry trees coincides with that of crops [Jonsson *et al* 1988; Dhyani *et al* 1990; Ruhigwa *et al* 1992]. Unfortunately, there are few quantitative studies of root growth in agroforestry systems. Most of the studies to date have been largely observational and concerned mainly in comparing the distribution of tree and crop roots with a view to assessing whether spatial complementarity of resource use

might be achieved [Gregory 1996a].

2.5.3 Rooting patterns in Boundary/Upperstorey Agroforestry systems

Below ground interactions between trees and crops are fairly well understood for intensively managed hedgerow intercropping systems in humid areas, but less so for agroforestry systems such as boundary/upperstorey tree planting. There is scant information on the rooting patterns of boundary/upperstorey trees and the associated crops. Recently, studies have been done in the semi-arid and sub-humid areas of Kenya. Odhiambo [1999] working in a semi-arid environment of Machakos determined the root distribution of a line of *Grevillea* trees and a maize crop using the minirhizotron technique. There was an overlap of crop and tree roots in the top 50 cm of soil where the majority of crop and tree roots occurred. Tree roots were found to comprise 61 to 73% of the total root length, and the maize root length was reduced by 50% in the plots with *Grevillea* trees. Total root length for *Grevillea* was 2.21 cm/cm^3 and it decreased with increasing distance from the trees. In the sub-humid area of Nyabeda in western Kenya, Livesley [1999] found the root length density of *Grevillea robusta* trees in the upper 15 cm of the soil at the beginning of the rainy season to be 0.55 cm/cm^3. The tree root density decreased exponentially with depth but decreased little with increasing distance from the tree row in the upper 100 cm. After the cropping season, the root length density in the upper 60-cm decreased with increasing distance from the tree row. The tree had 4.9% of its total root length below 150 cm at the start of the growing season but increased to 11.5% during the maize cropping season.

In sub-humid and drought prone temperate regions of China, *Paulownia* roots were found to have a distinctive morphology with two defined root zones:- an upper zone (0-80 cm) and a lower zone (> 80 cm). In the top zone, 98% of fine roots are found within 4-m radius of the tree. Only 12% of these fine roots were in the upper 40 cm with 70-85% located between 40-100 cm depth [Zhu Zsao-Hua *et al* 1986]. In contrast, nearly 80% of wheat roots occurred in the top 40 cm of the soil indicating the roots occupy different zones [Chirko *et al* 1996b].

2.5.4 Methods of measuring Rooting patterns in Agroforestry Systems

Anderson and Ingram [1993] have reviewed the basic methods for observing and quantifying tree and crop roots. Several methods have been used to study the distribution of tree and crop roots in agroforestry systems. These include manual root excavation, pin-board monolith methods, use of minirhizotrons, root mapping, root coring and fractal root branching methods. All these methods are briefly described in the following paragraphs.

The manual root excavation technique has been used to characterize the structural root system of various tree species [Groot and Soumare 1995]. In the method, selected trees are excavated by digging a pit around each trunk to a radius of 2 m. Soil is removed using shovels, small picks, hoes and knives. The soil around the roots is then removed using paintbrushes. Only roots with diameters > 2 mm are usually considered. For each sample tree, a number of primary roots (e.g. four) are excavated and total root length determined. Most of the fine roots break off during excavation and only a qualitative picture of the root system is obtained, but the method allows the width and depth of the root system and its branching pattern to be determined.

Root distribution of trees and crops can be investigated by the use of the pin-board monolith method [Schuurman and Goedewaagen 1971; Bohm 1979]. Soil samples, measuring for example 100x 60x 10 cm, are taken perpendicular to the tree radius of the sample trees. Monolith samples can be obtained by pin-boards made by inserting U-shaped pins (made of stainless steel) in plywood. The type of crop and practical considerations (e.g. ease of handling and washing of samples) determine the size of the pin-board. If a coarse mesh screen is put on the pins before the board is pushed into the soil, the screen keeps the roots in their original location while washing the sample. After washing away the soil, the root system can be lifted on the mesh screen, photographed and/or cut according to soil layers, depth and/or distance to the plant to obtain root biomass or root length. Although the method is time consuming, it gives good information per unit effort spent. Major weaknesses are that roots may break or be displaced during washing.

Minirhizotrons, transparent tubes installed in the soil to facilitate root observation, have become a valuable tool for the evaluation of the dynamics of root growth [Taylor 1987]. Two types of minirhizotrons have been used to quantify root systems; the flexible and

rigid-walled minirhizotrons [Gijsman *et al* 1991]. Despite the ease of root quantification using this technique, doubts remain concerning the validity of minirhizotron-derived values. The primary concern is that rooting patterns in the vicinity of the observation tube may not reflect growth in the bulk soil farther away from the tube [Gregory 1996a]. This could be the case if gaps, fissures, or regions of increased or reduced soil density were artificially created during the placement of the observation tubes. The second problem is that minirhizotrons usually underestimate the quantity of roots in the upper layers of the soil while overestimating root density with depth, so that there is difficulty in extrapolating results to reflect the root system in the whole profile [Beyrouty *et al* 1987; Upchurch 1987]. The flexible-walled minirhizotron appears to minimize these problems, while the rigid-walled minirhizotrons tend to overestimate root length density in compacted soil. The method has recently been used to quantify tree (*Grevillea robusta)* and crop root distribution in an agroforestry system in Machakos, Kenya [Odhiambo 1999].

Another method frequently used to quantify tree and crop root distribution in agroforestry systems is root coring. It is a relatively non-destructive method that allows multiple root sampling [Van Noordwijk 1993]. In the method, soil samples are collected by means of a corer, usually a metallic pipe with 10-15 cm diameter. The samples are taken at varying depths and distances from the line of trees and/or crops. The collected soil samples are soaked overnight in water and later sieved (e.g. using 0.5 mm sieves) to separate roots from soil. The roots are then kept in polythene bags and stored in a refrigerator in commercial vinegar solution for 24 to 36 hours. The roots are later sorted manually from organic debris and soil. They are stained with methyl violet, and scanned or otherwise to determine root length density. Several workers have used this method to quantify root biomass and distribution in agroforestry systems [Jonsson *et al* 1988; Livesely 1999].

Root trenching and then mapping of roots is another technique that has been used to determine the root distribution of tree and crop roots in agroforestry systems [Rao *et al* 1993; Huxley 1994; Torquebiau and Kwesiga 1996]. In the method, a trench of the desired depth and length is dug next to the tree and/or crop whose root distribution is to be determined. Once the trench is dug, its walls are smoothened with a sharp knife and then softened with a light spray of water to remove about 2 mm of soil to expose roots. The roots are then further exposed using sharp objects. A wooden frame or transparent waterproof paper with a grid is placed over the wall surface. Root distribution down the soil profile and away from the tree/crop line is mapped by counting the number of roots in

each grid or by marking them on paper. The major problem with the method is that fine roots may be overlooked.

New developments are based on the fractal root branching models and the allometry between proximal root diameter and other functional root characteristics [Van Noordwijk *et al* 1992]. The lateral spread of a tree's root system has been found to be a simple and effective indicator of the extent of below ground interaction [van Noordwijk and Purnomosidhi 1995]. Van Noordwijk *et al* [1994] have developed a model that estimates the total length and volume of a tree's structural root system from proximal root diameters and simple, fractal branching properties. In the method, the length of the longest root roughly indicates exploration of the soil volume, whereas the total length, or surface area of live roots, indicates the exploitation of most nutrients and water [de Willigen and Van Noordwijk 1991].

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter describes the site where the study was conducted, the tree species and the crops that were planted in the trial. It also gives details on the experimental design used and the establishment, management and the assessment of the trees and crops during the study. Finally it describes the methods that were used in the measurement of light interception, water use and root distribution by the trees and crops.

In order to assess the effect of different upper-storey trees on crop growth and yield, five tree species were inter-cropped with maize (*Zea mays*) and beans (*Phaseolus vulgaris*) in rotation annually from 1996-1998. The tree species planted were:- *Alnus acuminata, Casuarina equisetifolia, Grevillea robusta, Maesopsis eminii* and *Markhamia lutea*. These tree species were chosen for the study because they are popular with farmers in the region. The other factor considered in their selection was the shape of canopy. They were selected in order to have contrasting tree canopy shapes such as the wide spreading and dense canopy of *Maesopsis*, the narrow tall canopy of *Markhamia* and the conical and fairly open canopy of *Casuarina*. The two crops chosen for the study are widely planted by farmers in the region.

Tree growth was assessed in terms of survival, total tree height, diameter at breast height (DBH) and canopy growth (crown height and width). Measurements were done twice every year at the beginning of each rainy season. The growth of the companion crops and their subsequent yields, were also assessed each season to determine the effect of the different tree species on them. Fractional light interception was assessed during the maize growing seasons and the fraction of light reaching the canopy of the understorey maize crop and the fraction intercepted by it were assessed four times in each season. Measurements were made using a quantum sensor and a ceptometer (Accupar). Soil water measurements were recorded using a neutron probe throughout the study period at intervals of every 2 weeks during the rainy period and every 3 three weeks during the dry period.

Root trenching to determine tree and crop root distribution in the soil profile was done during August-November 1998 cropping season.

3.2. Site Description

3.2.1 Location and Topography

The study was conducted at Kifu Forest Research Station (latitude 0^0 48' N, longitude 32^0 46' E, elevation 1,250 m asl) in Mukono district in Central Uganda. It is 27 km east of Kampala, the capital of Uganda (figure 3.1). The terrain in the surrounding area is composed of small hills with low-lying areas covered by swamps. The altitude range varies from 1,158 to 1,300 m asl.

3.2.2 Climate and Vegetation

Kifu is within the bimodal rainfall area of East Africa. The "long rains" last from March to May and the "short rains" from August to November. The long rains yield the most water [Jameson and McCallum 1970]. The mean annual rainfall in the area is about 1240 mm. The long dry season from December to March is much more severe than the short dry season from June to July, but there is rarely a month without some rainfall. Figure 3.2 shows monthly rainfall distribution for Kifu for the period 1996 -1998. The annual rainfall was 1266mm in 1996, 1812 mm in 1997 and 1592 mm in 1998. Temperatures in the area are constant and high all year round. The high temperatures result in high evaporation rates but monthly rainfall usually exceeds evaporation in both rainy seasons [Jameson and McCallum 1970]. The mean annual minimum and maximum temperatures for the area are 12^0 and 29^0C respectively. Figures 3.3 shows the mean minimum and maximum monthly temperatures for Kifu for 1997 and 1998. The mean minimum and maximum annual temperatures for these years were 20.8 and 25.2^0 C for 1997 and 20.1 and 25.2^0 C for 1998. Data were not available for 1996 and for the months of January, February and March in 1997. The vegetation in the area comprises of remnants of high tropical forests, eucalyptus woodlots and bushes and grassland. Vast swamps transverse the area, often covered with papyrus reeds (*Cyperus papyrus*).

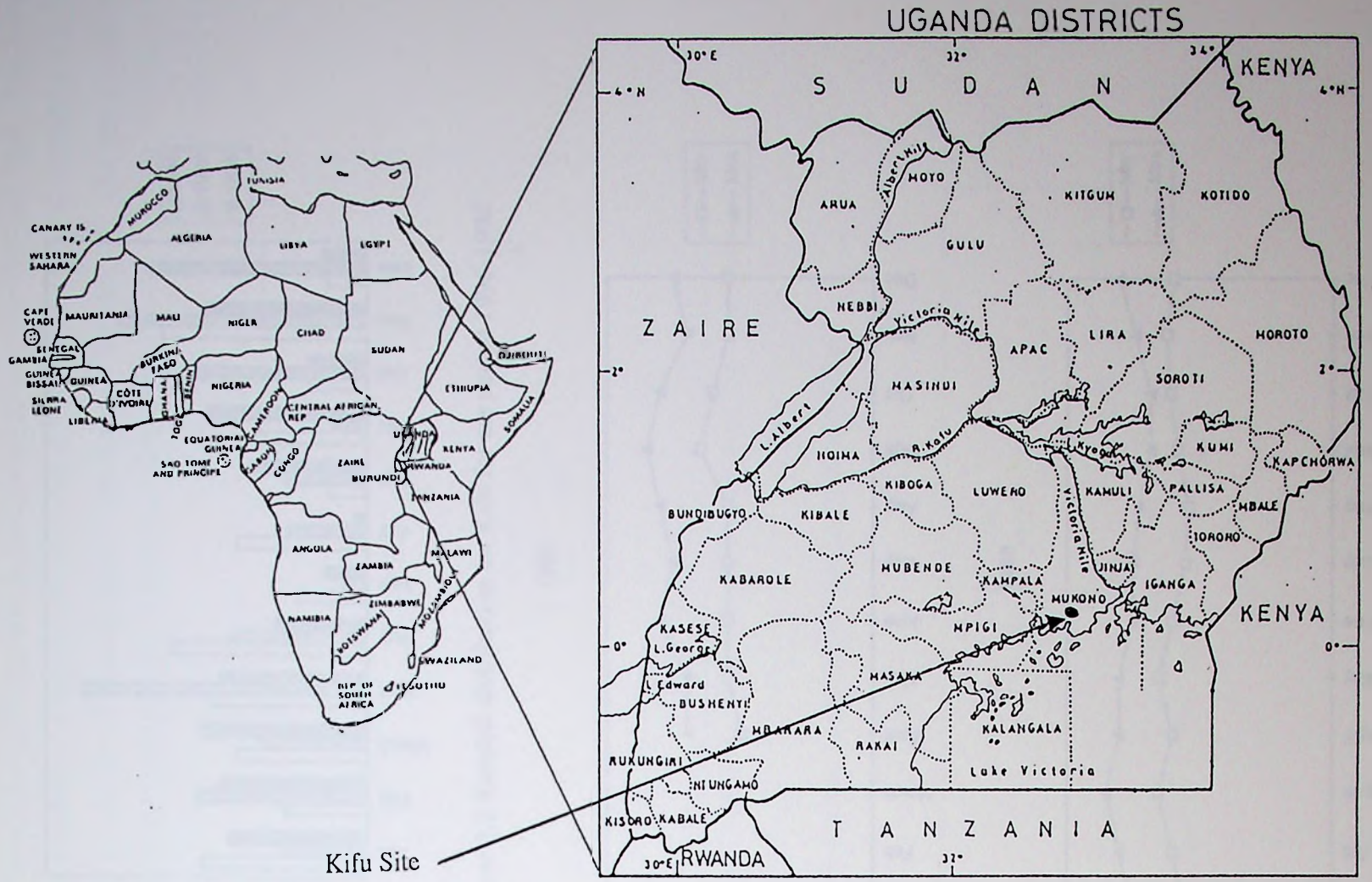


Figure 3.1 Location of Kifu experimental site in Uganda

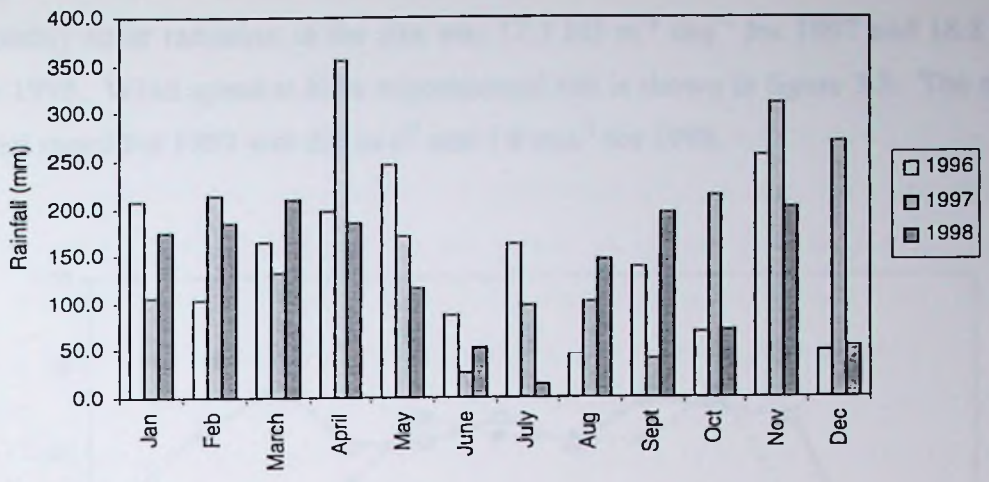


Figure 3.2 Rainfall distribution for Kifu for the period 1996-1998

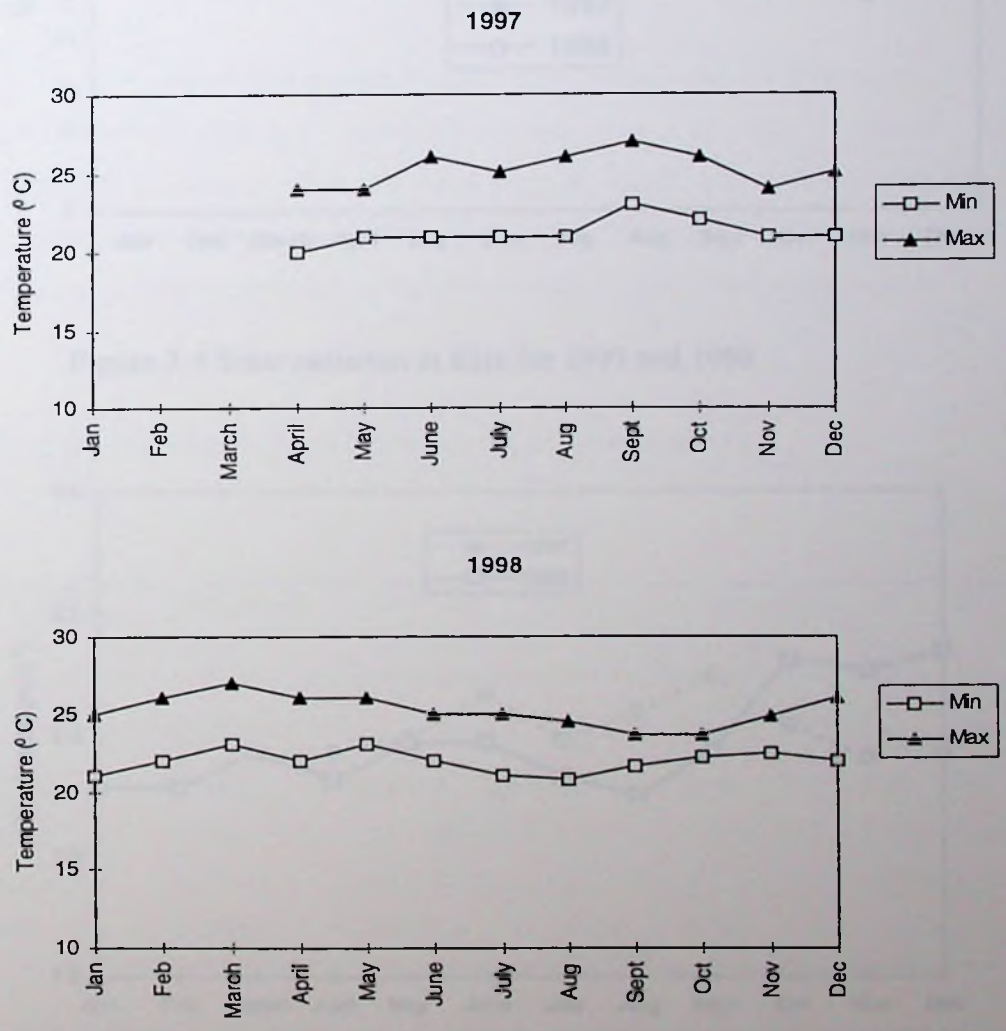


Figure 3.3 Minimum and maximum monthly temperatures at Kifu for 1997 and 1998.

Figure 3.4 below shows the incident solar radiation for Kifu for 1997 and 1998. The mean monthly solar radiation at the site was 17.7 MJ m^{-2} day^{-1} for 1997 and 18.8 MJ m^{-2} day^{-1} for 1998. Wind speed at Kifu experimental site is shown in figure 3.5. The mean monthly wind speed for 1997 was 2.0 m s^{-1} and 1.9 m s^{-1} for 1998.

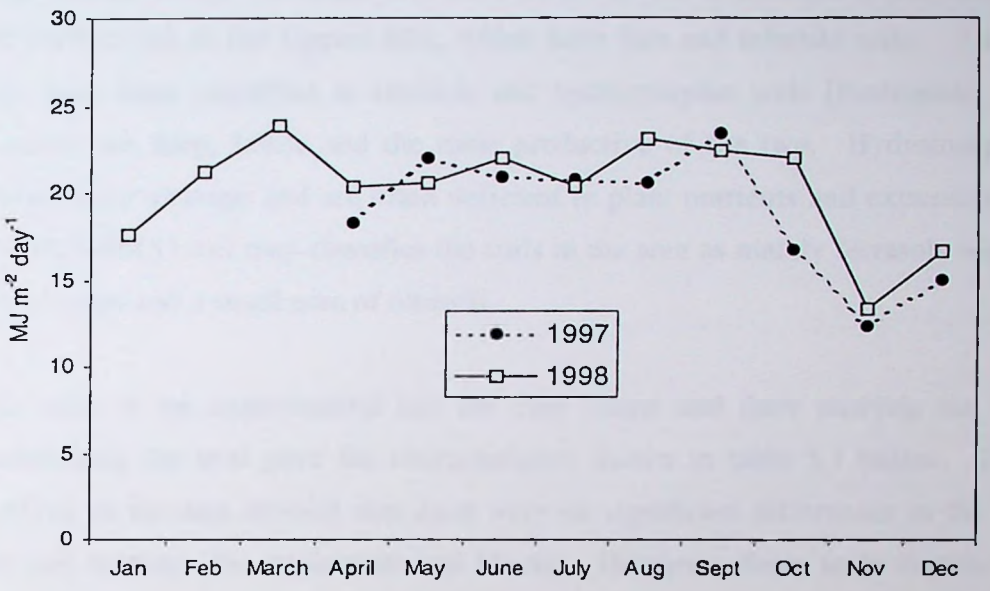


Figure 3.4 Solar radiation at Kifu for 1997 and 1998

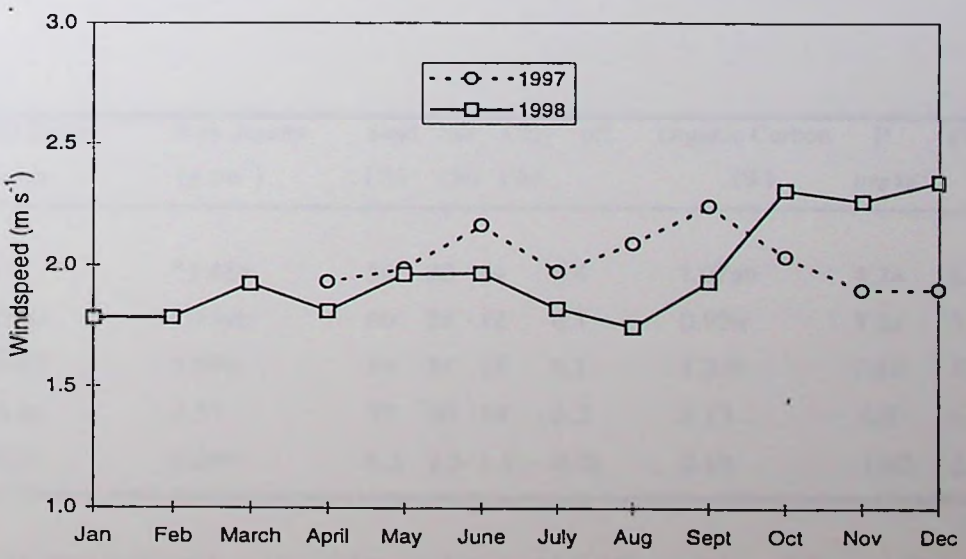


Figure 3.5 Monthly mean wind speed at Kifu for 1997 and 1998

3.2.3 Soils

The area is set in the crystalline basement complex characterized by metamorphosed granites and the soils originate from quaternary alluvial and lacustrine deposits [Water Department, 1996]. Geologically, the area is an eroded pene-plain with remnants of the old surface left as flat topped hills, which have thin and infertile soils. The soils in the area have been classified as ferrisols and hydromorphic soils [Radwanski, 1960]. The ferrisols are deep, fertile and the most productive of the two. Hydromorphic soils are found in the swamps and are often deficient in plant nutrients and extremely acidic. The FAO/UNESCO soil map classifies the soils in the area as mainly ferrasols with gleysols in the swamps and a small area of nitosols.

The soils at the experimental site are clay loams and their analysis six months after establishing the trial gave the characteristics shown in table 3.1 below. The statistical analysis of the data showed that there were no significant differences in the properties of the soil between the treatments and blocks. However, there were significant ($p<0.05$) differences between soil depths in bulk density, organic carbon and soil P.

Table 3.1 Characteristics of the soil at the experimental site

Soil depth (cm)	Bulk density ($g\ cm^{-3}$)	Sand (%)	Silt (%)	Clay (%)	pH	Organic Carbon (%)	P ($mg\ kg^{-1}$)	Ca	Mg	K
								($cmol_c\ kg^{-1}$)		
0-15	*1.48a	56	30	14	6.4	1.07ab	4.2a	6.4	1.4	0.31
15-30	1.53ab	60	28	12	6.1	0.95a	3.2a	5.3	1.4	0.23
30-45	1.69b	54	31	15	6.1	1.37b	7.1b	7.6	1.7	0.43
Mean	1.57	57	30	14	6.2	1.13	4.8	6.4	1.5	0.32
SED	0.089	6.2	2.3	1.5	0.28	0.19	1.02	2.1	0.15	0.09

* Figures in the same column that are followed by different letters differ significantly at $p<0.05$.

3.3. Description of the Tree species

The tree species that were used in the trial are briefly described in the following paragraphs.

Alnus acuminata (H.B. & K.) is a fast-growing deciduous or semi-deciduous tree that grows up to 30 m tall and a stem diameter of 50 cm at 30 years of age. The crown is rounded to pyramidal with its roots being lateral and extended rather than deep and confined [NFTA 1990]. It grows in cool tropical highland regions with abundant rainfall [FAO 1986]. Its altitudinal range is 1200-3800 m, mean annual temperature 4 to 27° c and mean annual rainfall 1000 to 3000 mm. It prefers deep-well drained soils and can grow in soils with pH as low as 4.5. It is native to Latin America. The symbiosis between *A. acuminata* and *Franki alni* enables the root system of the tree to fix atmospheric nitrogen. When inter-planted with pasture grasses *A. acuminata* has been found to improve forage production up to 7-fold [NFTA 1990]. Its other positive effects are the supply of organic matter and the control of soil moisture due to its fairly dense shade.

Casuarina equisetifolia (L.) is an evergreen tree that grows 6 to 35 m tall and up to 100 cm stem diameter, with a finely branched and open crown. The crown is initially conical but tends to flatten with age. The tree trunk is straight, cylindrical and usually branchless up to 10 m. It occurs naturally in tropical and sub-tropical coastlines but its natural range is semi-arid to sub-humid climates [National Academy of Sciences 1984; Doran and Turnbull 1997]. The altitudinal range for species is from 0 to 1400 m, mean annual temperature 10-35° c and the mean annual rainfall 200-3500 mm. The species prefers well-drained soils mainly sand and sand loams [MacDicken 1994]. Root nodules containing *Frankia* enable the tree to fix atmospheric nitrogen. The tree possesses proteoid roots and forms associations with vesicular arbuscular mycorrhizae. Due to fast growth, high productivity and properties that enhance soil fertility, *C. equisetifolia* shows promise as an agroforesty species for arid, semi-arid and sub-humid areas [Webb *et al* 1984]. In trials in India, citrus trees grown beneath *C. equisetifolia* grew larger than in pure stands [MacDicken 1994].

Grevillea robusta (A. Cunn. Ex R.Br.) is a deciduous medium-sized to large tree which grows up to 12-25 m tall and up to 80 cm in diameter. The crown is conical and fairly open, with branches projecting upward [National Academy of sciences 1981]. The tree

trunk is straight, and branchless up to 15 m. It occurs naturally in Australia and has been introduced into sub-tropical highland regions of the world and widely planted in Africa [Harwood 1992]. In its natural range, the species is semi-deciduous, shedding most of its leaves in the dry season. Its altitudinal range is 0-2300 m, mean annual rainfall 600-1700 mm and the mean annual temperatures vary from 14-23 to 25-31°c. The species establishes well in alluvial soils but prefers loam soil. *G. robusta* is moderate to fast growing attaining annual height and diameter increments of 2 m and 2 cm $year^{-1}$ respectively when planted on farms [Harwood 1994]. It re-grows well after pruning and pollarding, which are carried out repeatedly to provide wood products and to regulate shading of under-storey crops. The relatively open canopy of *G. robusta* makes it suitable for inter-planting with crops. The deep rooting system of the species causes little interference with shallow-rooted crops and therefore has been successfully been inter-cropped with various agricultural crops.

Maesopsis eminii (Engl.) is a leafy, semi-deciduous tree, which grows up to 10-30 m in height with a clear bole of up to 10 m. The branches are horizontal and the crown is dense and flat when young but more rounded with age [Eggling 1940]. It is a species of moist forests and secondary re-growth and is native to various parts of Africa including Uganda. Altitudinal range is 700-1500 m, mean annual temperatures 22-27°c and mean annual rainfall is 1200-1300 mm. It tolerates a wide range of site conditions but grows best on deep, moist and fertile sandy loam soils. Because of its dense canopy, *M. eminii* has been used as a shade tree for coffee in Uganda, cocoa in the Democratic Republic of Congo and cardamom plantations in Southern India. It is also commonly retained in home-gardens for shade. The leaves are *M. eminii* are used as fodder and due to its fast growth, it is widely planted for firewood [National Academy of Sciences 1983]. In the past the species has been used in taungya systems in Ghana, Kenya and Uganda.

Markhamia lutea (Benth.) K. Schum. is an upright evergreen tree that grows to 10-15 m high, with a narrow irregular crown and deep long tap root. It is found in the Lake basins and highland areas of East Africa. Its altitudinal range is 900-2000 m, mean annual temperature 12-17°c and mean annual rainfall of 800-2000 mm. The tree prefers red loam soil but can tolerate well drained, heavy acidic clay soils [Noad and Birnie 1989]. *M. lutea* grows fast in good forest soil and plants can attain growth rates of more than 2 m $year^{-1}$. The trees can be pruned and pollarded to reduce shading and can be coppiced when they are 1.7 m in height.

3.4 Experimental Design and Field Layout

The experiment was planted on land that had been cropped for several years with annual crops such as beans and sweet potatoes (*Ipomea batatus*) and perennial crops such as cassava (*Manihot esculenta*) and bananas (*Musa spp.*). Previously, the experimental site was part of Kifu natural tropical forest. Prior to the establishment of the experiment, a cover crop of maize was grown at the site during the long rains of 1994. A detailed soil depth analysis of the site was done before the planting of the cover crop. On the basis of the growth of the cover crop and the soil depth analysis, blocking of the site was done. A randomized complete block design with four replicates was used in the trial. There were six treatments in the trial, five of which were planted with trees, while the sixth was planted with a sole crop as shown below:-

1. *Alnus acuminata* + Crop
2 *Casuarina equisetifolia* + Crop
3 *Grevillea robusta* + Crop
4 *Maesopsis eminii* + Crop
5 *Markhamia lutea* + Crop
6 Sole Crop (Control)

The experiment had a total of 24 plots, with the tree plots measuring 25 m long and 30 m wide and the sole crop plots measuring 15 m long and 30 m wide. The layout of the experiment in the field is shown in figure 3.6. Every season, the whole experimental area was planted with crops including the guard areas (open spaces in figure 3.6), which were left out due to shallow soils, hence not representative of site.

3.5. Tree Establishment and Assessments

3.5.1 Establishment and Management

Four-month old potted seedlings were used to establish the trees in September 1995. Each tree plot had a line of trees planted in the middle length wise at a spacing of 1 m and the tree lines were oriented in a north-south direction. Each tree plot had 24 trees planted in it (plate 3.1). Any seedlings that died during the first and second cropping seasons were replaced to maintain the same number of trees per plot. The species planted in the trial and

the origin of the seeds is shown in table 3.2 below. Every season and prior to the planting of the crops, side pruning of the tree branches to a third of the total tree height, was done for all the tree species. This was done to reduce the amount of shade cast on the under-storey crop, as farmers would normally do in their fields. The prunings were weighed and removed from the site.

Table 3.2 Tree species evaluated in the study and geo-physical characteristics of the locations for the source of seed

Species	Provenance	Latitude	Longitude	Altitude (m)	Rainfall (mm)
A. acuminata	Siguampar, Sacatepezuez (Guatemala)	90° 48'S	14° 35'W	1900	1400
C. equisetifolia	Dheradun (India)	78° 15'N	30° 15'E	640	800
G. robusta	Altenango, Sacatepezuez (Guatemala)	90° 40'S	14° 30'W	1350	1100
M. eminii	Ikulwe, Iganga (Uganda)	0° 50'N	35° 50'E	1200	1200
M. lutea	Seeta, Mukono (Uganda)	0° 23'N	32° 40'E	1300	1250

3.5.2 Tree Assessments

The survival of the tree seedlings was recorded at end of the first growing season, but tree heights, stem diameters, crown heights and diameters were measured yearly at the beginning of every growing season. During the assessments, only the central twenty trees in each plot were measured and the mean growth rates for the tree species estimated. Diameter tapes were used for measuring stem diameter at breast height (DBH), while crown diameters and tree heights were measured using demarcated long poles. Both total tree height (from the base to the tip of the tree) and stem heights (from base to the first branch) were assessed during the study. Crown height was determined by measuring from the base of the crown to the tip of the tree, while crown diameter was determined by taking two measurements at the maximum and minimum diameters to get an average value.

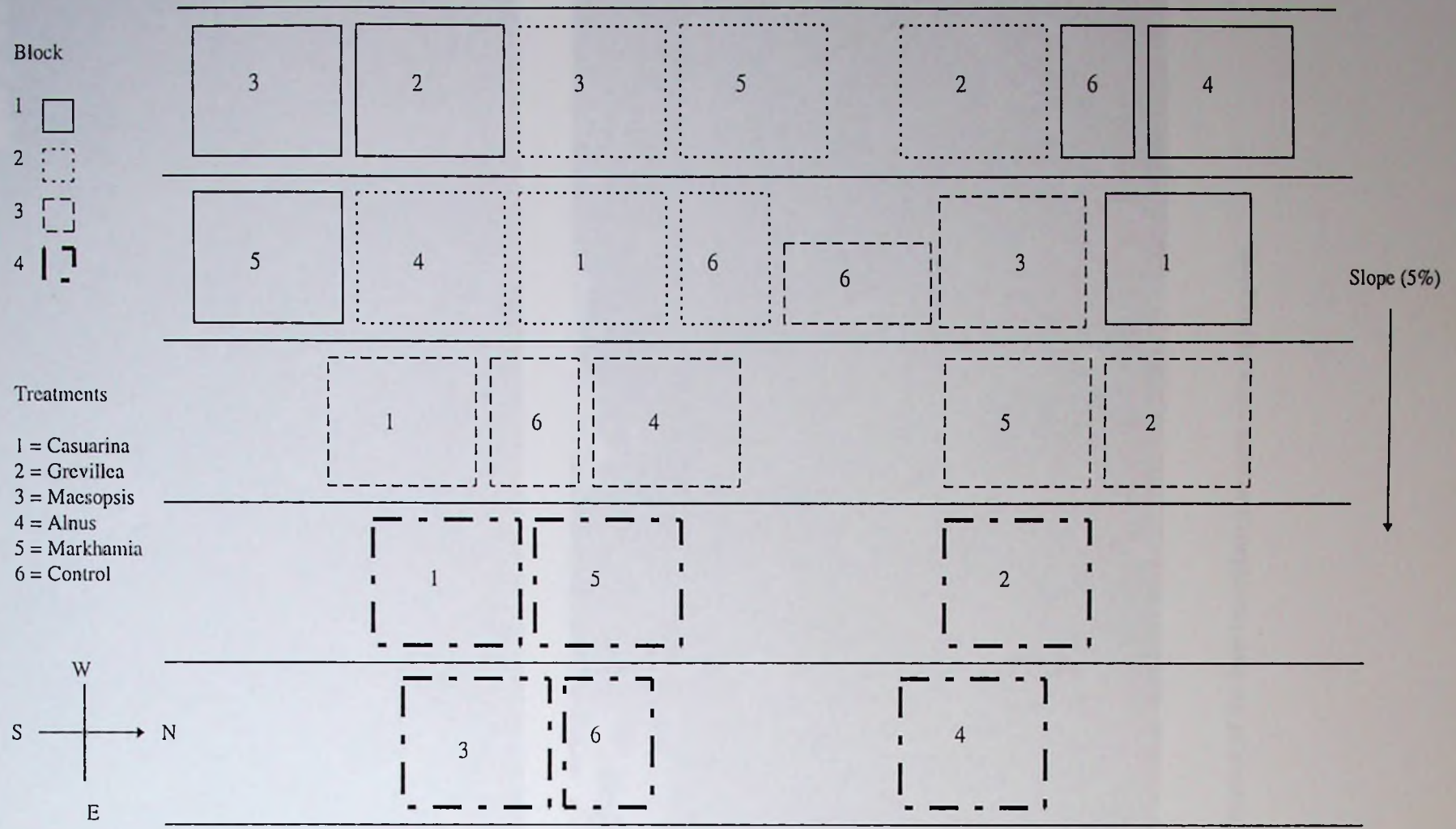


Figure 3.4 Layout of the experiment in the field



Plate 3.1 Position of the tree line relative to crop rows in the plots

3.6. Crop Agronomy and Assessments

3.6.1 Establishment and Management

Two crops, maize (*Zea mays*) and beans (*Phaseolus vulgaris*), were grown in the trial in rotation for three years (1996-1998) as shown in table 3.3. The maize crop was grown during the long rains (March-May) of every year except for the short rains of August - November 1998. In all cases, maize variety Longe 1, was planted at a spacing of 75 cm between rows and 30 cm within rows on both sides of the tree lines (plate 3.1). Weeding was done twice every season by hand hoe. Fertilizers, the equivalent of 200 kg of Single Super Phosphate (SSP) ha^{-1} and the equivalent of 100 kg NPK (25:5:5) ha^{-1}, were applied at each cropping season in order to eliminate nutrient deficiencies at the site. All plots, tree and sole maize, received 0.02 kg m^{-2} of SSP and 0.01 kg m^{-2} of NPK at the time of first weeding (14 days after crop emergence). The maize crop was thinned to one plant per hill when the plants were 10 cm tall, to give a plant population of 44,000 plants ha^{-1}. Termite damage to the crop and the trees, especially *Grevillea* that proved susceptible, was controlled using Dursban 4 (25% *Ethyl aminophosphate*) by applying a mixture of 10 ml of dursban in 1 litre of water around the stem base of each individual tree.

Beans were grown during the short rains of August-November each year, except in 1998 when maize was grown instead. They were grown twice, that is, during August-November 1996 and August-November 1997 cropping seasons. They were planted at a spacing of 50 cm between rows and 10 cm within rows using a seed rate of 60 kg ha^{-1}. Variety K132 was used in both seasons. Weeding was also done twice every season by hand hoe. There were 120 and 90 days in the March-May and August-November growing seasons respectively.

3.6.2 Crop growth and yield assessments

Both crops were assessed for biomass and grain yield production each season (table 3.4). At each assessment a sample, from 10 m length of row, was taken from each row and fresh weights of the samples obtained and then separated into stover and cobs in the case of maize, and stover and grain in the case of beans. They were then re-weighed separately. This was done on both sides of the tree line from row 1 nearest to the tree line, to row 18,

which was furthest away. For determining dry matter, sub-samples of five plants each were taken from rows 1, 5, 10 and 18. The sub-samples were air dried and re-weighed. A known weight of the air-dried material was cut into pieces and oven dried at 65^0 C to a constant weight. Dry matter production in each treatment was estimated by multiplying the fresh weight of total biomass with the ratio of oven-dried weight to fresh weight.

For grain yield estimation, the grain was separated from the cobs or stover and their air-dry weights recorded. A sub-sample of 200 g was then weighed and oven-dried at the same temperature. Appropriate ratios were then used to convert fresh biomass and grain yields to dry matter production per unit area (kg m^{-2}). The same sampling procedure was used when estimating the bean yields. Mean biomass and grain yields were then calculated for each plot on row by row basis. However, during March-May and August -November 1996 cropping seasons, quadrants (3x3m) of maize and bean crop samples, were taken from the middle of each plot from both sides of the tree line for biomass and grain yield assessments. This was done because at this stage, the trees were small and had no visible effect on crop growth and yield.

Maize height growth was also assessed during the study. Assessments were made in all the four cropping seasons when maize was grown. In all cases, height measurements were done at crop anthesis. At each assessment, 20 plants per row were selected from the middle of the plot and their heights measured. This was done on crop rows from both sides of tree line. The average height for each row was then obtained by taking the average of the 40 plants from each plot.

Leaf area index (LAI) of maize was estimated in March-May 1997, March-May 1998 and August-November 1998, by taking three maize plants each from rows 1, 10 and 18 in each plot from both sides of the tree line. For each plant, the total number of leaves was determined and individual leaves were then measured for length and width (maximum width). The area for each leaf was obtained by multiplying its length by its width and the value obtained was then multiplied by the empirically determined leaf area constant for maize (0.73) [McKee 1964]. The LAI was then obtained by multiplying the leaf area by the number of leaves per plant and the number of plants per square metre. The LAI was then estimated on row by row basis for each treatment.

Table 3.3. Summary of the treatments (tree/crop combinations) used in the trial from 1996 to 1998.

Year	Season	Tree/Crop combination
1996	March – May (120 days)	Trees + Maize
	August – November (90 days)	Trees + Beans
1997	March – May (120 days)	Trees + Maize
	August – November (90)	Trees + Beans
1998	March – May (120 days)	Trees + Maize
	August – November (90 days)	Trees + Maize

Table 3.4. The periods of crop and light interception measurements

Growing Season	Parameter	Time of measurement (Days after planting, DAP)
March-May 1996	- Maize height growth	80
	- Maize biomass	80
	- Maize yields	120
August-November 1996	- Bean yields	90
March-May 1997	- Maize height growth	80
	- Maize biomass	80
	- Maize yields	120
	-Light interception	40, 50, 80, 100
August-November 1997	- Bean yield assessment	80
March-May 1998	- Maize height growth	80
	- Maize biomass	80
	- Maize yields	120
	- Light interception	40, 50, 80, 100
August-November 1998	- Maize height growth	80
	- Maize biomass	80
	- Maize yields	120
	- Light interception	40, 50, 80, 100

3.7. Fractional Light Interception Measurements

To determine the shading effect of the upperstorey trees on the understorey crops, light interception measurements were done during the three cropping seasons of March-May 1997, March-May 1998 and August-November 1998 when maize had been planted in the trial. The fraction of incoming photosynthetically active radiation (PAR) incident on the maize crop and the fraction intercepted by the maize canopy were measured during these seasons.

The fraction of intercepted photosynthetically active radiation was measured periodically (table 3.3) during the three seasons using a ceptometer (Accupar, Model PAR-80) to measure the average PAR at ground level and a quantum sensor (Sky Instruments) to provide a contemperaneous measure of the incoming PAR immediately above the maize canopy (plate 3.2a). In the tree plots PAR measurements were taken along a transect consisting of pegs inserted in the ground. It ran across the middle of the plot passing in between trees 10 and 11 (middle of plot). Within the maize rows the pegs were located in between two maize plants and light measurements were always made at this point in each row during the season. During the measurements, the Accupar was held at 10 cm above the ground and its probe was inserted beneath the maize plants. It was positioned such that its midpoint was located along the maize row. The quantum sensor, attached to the Accupar and mounted on a pole, was held above the maize canopy. Measurements were made in rows 1, 2, 3, 4, 6, 9, 12 and 15 on both sides of the tree line at each occassion.

Measurements were made between 12.00 h and 14.00 h at each measurement occasion. A second quantum sensor located at a meteorological station 100 m away from the trial provided a continuous record of the amount of solar radiation incident on the land surface. The above and below maize canopy measurements were then used to determine fractional light interception by the maize crop (Intercepted PAR = 1 - (PAR below canopy/ PAR above canopy)). The fraction of incident photosynthetically active radiation reaching the maize crop canopy and the fraction intercepted by it, were then calculated for each treatment on row by row basis.



Plate 3.2a Measurement of light interception in the field



Plate 3.2b Location of rain gauges in a tree plot

3.8. Soil Water Measurements

3.8.1 Soil Water Content Measurements

A neutron probe moisture meter (Troxler, Model 4300) was used to monitor soil water changes in the different treatments during the study. The instrument is based on the principle that fast neutrons released by a radioactive source are slowed down by collisions with hydrogen nuclei and hence can be used to measure soil water. The slow neutrons can be detected by boron trifluoride (BF_3) detector and the count displayed is directly related to the soil moisture content. The neutron probe was calibrated to determine the relationship between the rate of detection of slow neutrons and the volumetric water content of the soil (see section 3.8.1.1).

To facilitate measurements, six aluminum access tubes were installed in each tree plot at distances of 1.12, 3.14, 4.8, 6.2, 9.6 and 13.2 m away from the tree lines (plate 3.3a). These distances corresponded to distances halfway between maize rows 1 & 2, 4 & 5, 6 & 7, 8 & 9, 12 & 13 and 17 & 18. Two blocks (1 and 3) had access tubes installed on the upper side of the tree line, while the other blocks (2 and 4) had them installed on the lower side. Installing access tubes on both sides would have made measurements difficult because this would take more than one day to measure all the tubes. More access tubes were located close to the trees in order to monitor water use by the trees more precisely. Only four access tubes were installed in the control plots at even distances across their widths. A total of 136 access tubes were installed in the trial. An auger of 5 cm diameter and 3 m length, was used to make holes to a maximum depth of 2 m. To minimize soil disturbance, a heavy metal steel plate with a hole in the middle, was placed on the ground at the location where the drilling was to take place. The auger was placed in the centre of the plate through the hole and a heavy metal hammer was used to drive it into the soil. Aluminum access tubes, sealed with wooden corks at the bottom, with 5-cm diameter, were carefully installed into the hole leaving 10 cm above the ground surface. After installation, the tubes were covered with metal caps to prevent rain and heat affecting the neutron counts.

Soil moisture content was measured at 0.15 m depth intervals to a depth of 1.65 m. Measurements were made every 14 days, beginning at 8.00 h each time (plate 3.3b). Water drum standard measurements, which were used in water content calculations, were

made prior to each field measurement session. Soil bulk density determination, which is needed for estimating soil water content, was done as described under Neutron probe calibration (Section 3.8.1.1). Changes in soil water content were then calculated for each soil depth and distance for each tree species. Based on the soil profile water contents for the various treatments, the total amount of water stored was calculated and the total daily water losses/gains derived.

Near-surface changes in soil water content were measured using the Theta probe (Delta T Devices, Cambridge). The probe has two steel prongs, which are inserted into the soil to a depth of 5 to 10 cm. Once calibrated against gravimetric measurements, it offers a very rapid means of measuring surface soil water content. The Theta probe measures volumetric soil moisture content by the well-established method of responding to changes in the apparent dielectric constant. These changes are converted into a voltage that is proportional to soil moisture content. A volumetric water content of 0 cm^3 cm^{-3} corresponds to a completely dry soil and pure water gives a reading of 1.0 cm^3 cm^{-3}. There is a linear correlation between the square root of the dielectric constant ($\sqrt{\varepsilon}$) and the volumetric moisture constant (θ) expressed as:-

$$\sqrt{\varepsilon} = a_0 + a_1 * \theta \qquad (3.1)$$

and hence volumetric water content is given by the equation:-

$$\theta = \frac{[(1 + 4.52V) - a_0]}{a_1} \qquad (3.2)$$

where a_0 and a_1 are constants that are determined during calibration and V is the Theta probe output. The relationship between Theta probe output (V) and the square root of dielectric constant is given by a linear relationship expressed as:-

$$\sqrt{\varepsilon} = 1 + 4.52V \qquad (3.3)$$



Plate 3.3a Location of access tubes relative to the tree line in a plot



Plate 3.3b Measurement of water uptake in the field

3.8.1.1 Neutron Probe Calibration

Neutron probe measurements were calibrated by concurrently measuring gravimetric soil water content whilst taking neutron probe readings. This was done three times during the August-November 1998 cropping season. This was done at six locations in the experiment outside the plots where extra access tubes had been installed. The first calibration was done when the soil was very dry, the second when the soil was moderately wet and the third when the soil around these tubes had been wetted until it reached field capacity.

Four neutron probe counts were taken at each depth and a mean probe count established. Undisturbed soil samples were then collected using rings (5x5 cm, 98.2 cm^3) at 15 cm intervals down the soil profile to a depth of 1.8 m. A shelf was then cut into a wall of the trench at each depth and leveled with a knife. A ring with a metallic cap was placed on the shelf and hammered gently vertically into the soil until the top of the ring was flush with the soil surface. The ring was then carefully excavated, excess soil removed with the knife and both sides of the ring sealed with plastic caps.

In the laboratory, the rings were weighed, then oven dried at 105^0 C to constant weight to determine the gravimetric water content. Linear regressions between the volumetric water contents and the ratios between the neutron probe soil counts and water counts produced calibration coefficients. Neutron probe measurements were converted to volumetric water contents (θ) by:

$$\theta = m\,(R/R_w) + n \qquad (3.4)$$

where R is the neutron probe count in the soil at a given depth, R_w is the neutron probe count in water, and m and n are the slope and intercept of the calibration coefficients.

3.8.1.2 Theta Probe Calibration

To determine the coefficients a_0 and a_1 for soil at Kifu, Theta Probe readings were taken on two separate occasions, when the soil was very dry and when it was damp. Four readings were taken when the soil was completely dry (i.e. when $\theta = 0$) to give $\sqrt{\varepsilon_0}$ which is equal to a_0 using the equation:-

$$\sqrt{\varepsilon} = a_0 + a_1 * \theta \qquad (3.5)$$

Another set of four readings was taken from a damp soil and the volumetric water contents of these samples were determined from gravimetric measurements of the water content of soil cores with known volume. Equation 3.3 was used to calculate $\sqrt{\varepsilon_w}$ and a_1 was determined using the equation:-

$$a_1 = [\sqrt{\varepsilon_w} - \sqrt{\varepsilon_0}] / \theta_w \qquad (3.6)$$

The values obtained for the two constants were then used in equation 3.2 to convert Theta probe readings to soil water content values.

3.8.2. Direct Evaporation from soil

Soil evaporation measurements were made in the *Maesopsis* plots in two replicates during the August-November 1998 growing season when a maize crop had been planted. Measurements were taken five times during the season, at 20, 35, 45, 58 and 75 DAP. Microlysimeters (160 mm in diameter and 100 mm deep) described in detail by Jackson and Wallace [1999] were installed in these plots at two positions on both sides of the tree line. The first set of two microlysimeters was located close to the tree, with the first one located between plants within row 1 and the second between rows 1 and 2 (plate 3.4a). The second pair was located far away from the tree line, with the first located in between plants in row 14 and the second located in between rows 14 and 15 (plate 3.4a). Another pair of microlysimeters was set up in a bare plot (plate 3.4b). Measurements were taken twice each day between 7.00 and 8.00 h in the morning and between 17.00 and 18.00 h in the evening. This was done at intervals of one, two, three, four, six and eight days after a rainfall event. Microlysimeters were weighed to an accuracy of ± 0.01 g, giving a resolution of 0.005 mm.

At alternate measurement times, the Accupar and the external sensor were left at the three locations for the whole day. This was in order to estimate the amount of incident radiation at these locations at the time of these measurements. Also during the excavating of the soil samples, theta probe measurements (four) were taken close to where the soil cores were

taken. The average of these readings gave an estimate of the water content of the soil at the time of evaporation measurement.

3.8.3. Rainfall Interception

Rainfall interception by the tree canopies was assessed for *Maesopsis* and *Casuarina*. This was done in blocks 1 and 2 during the March-May and August-November 1998 cropping seasons. Six rainfall gauges were installed in each plot with three on each side of the tree line (plate 3.2b). The first rain gauge was located between the tree line and row 1, the second one between rows 2 and 3 and the third between rows 5 and 6.

In one of the *Casuarina* plots, a fourth rain gauge was installed in between rows 16 and 17. This gauge was far away from the influence of the trees hence would give an estimate of rainfall intercepted by the sole maize crop. Rainfall was also monitored at the meteorological site close to the experiment. This measurement gave an estimate of how much rainfall was received without being intercepted by both the trees and the crop. At all times, measurements were made after a rainfall event at 9.00 h in the morning.

3.9. Root Distribution

The root trenching method was used to assess the distribution of tree and maize crop roots [Bohm 1979]. This was done once during the August-November 1998 cropping season. Trenches were dug two weeks after the maize crop had tasseled. A trench was dug between two trees at the edge of the tree plots and 2 m metres from the edge of the control plots. The trenches were 6 m long on either side of the tree line, 1 m wide and 2 m deep. The trenches cut across eight rows of maize on either side of the tree line. After digging the pits, the walls were softened with a light spray of water and then smoothened with a sharp knife. The cut root ends were then exposed using foreceps and needles. A wooden frame measuring 30 x 30 cm, with a 10 x 10 cm grid, was then used to map the root distribution down the soil profile and away from the trees. The number of roots (visible) in each 30x30 cm grid were counted and recorded. Both the tree and the maize crop roots were counted. The tree and maize roots were easily distinguishable, for example *Maesopsis* roots were black while the *Markahmia* dark brown compared to the white roots of maize. The assessment was done in two blocks (1 and 2) for all the tree species.



Plate 3.4a Location of the microlysimeters in a cropped plot

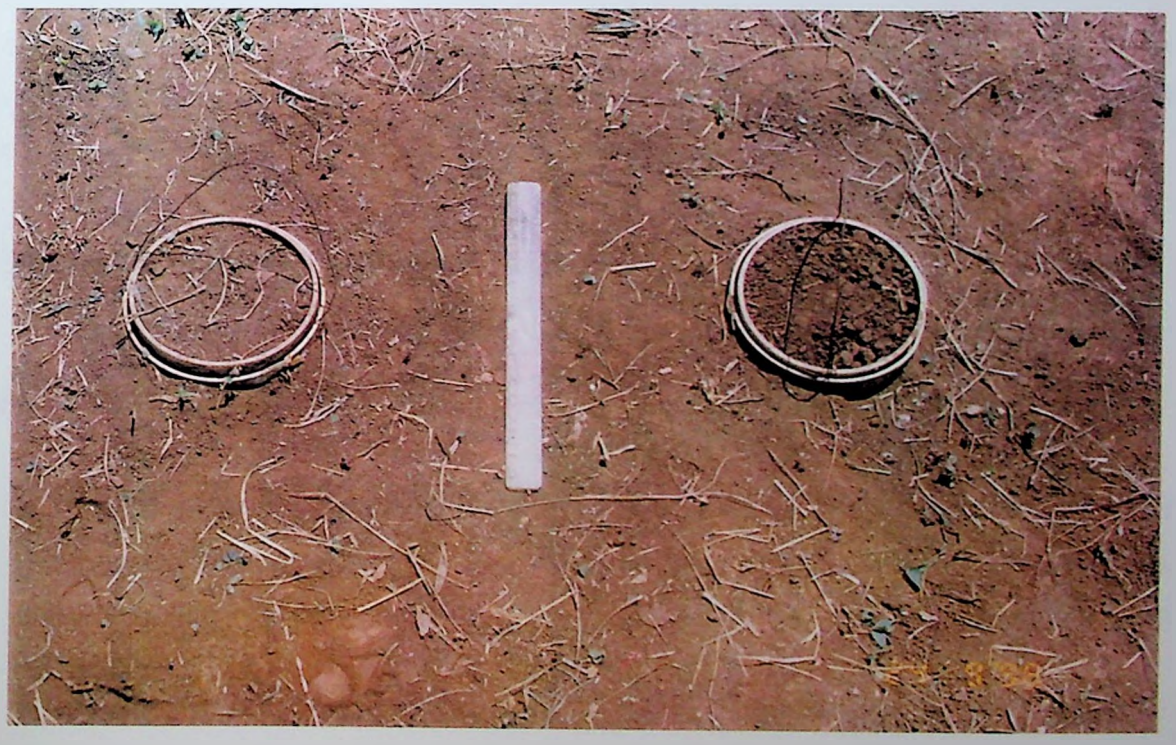


Plate 3.4b Microlysimeters located in bare ground

3.10 Meteorological Data

During the study period, daily rainfall, temperatures (daily minimum and maximum), relative humidity, wind speed and solar radiation for the site were monitored. A meteorological station set up at the site (about 100 m from the experiment) was used for monitoring these meteorological parameters during the study period. Pan evaporation records were not recorded at the site but were obtained from Makerere University Research Institute Kabanyolo, which is located about 10 km away from Kifu at a similar altitude.

The amount of rainfall received at the site during the study period was monitored using an ordinary rain gauge that was installed at the meteorological station. After every rainfall event, measurements of the amount of rainfall received was done at 9.00 h in the morning. Daily rainfall amounts were recorded and these were then converted to monthly totals. Daily minimum and maximum temperatures and relative humidity were measured using the wet and dry bulb thermometer that had been set up in a Stevenson's screen at 2 m height. The readings were also made daily at 9.00 h. Mean monthly minimum and maximum temperatures were derived from the daily readings. Solar radiation was measured using a quantum sensor (mounted onto a two-metre pole) connected to a data logger that was programmed to give integrated hourly average readings each day. The data was downloaded to a computer once every two weeks for the whole duration of the study.

3.11 Data Management and Analysis

3.11.1 Data Management

All tree, crop, light and root data were entered and stored in Microsoft Excel 97 spreadsheets, while the water data were organized in Microsoft Access 98 database. Summaries of the data were made in these computer packages and later exported to SAS for analyses.

3.10.2 Data Analysis

Tree, crop, light interception, water uptake and root distribution data were analyzed using SAS 6.12. The tree data were analyzed assuming a randomized complete block design. Because crop rows were within plots, the measuremnt of crop growth and yield, light, water and roots were treated as split-plots within main plots. Being a split-plot design, there is supposed to be constant variance across rows and constant correlation between rows. However, this was not the case in this experiment because rows close to the trees had low yields, hence low variance, compared to rows further way from the trees. In addition, rows that were close together were more correlated than those further apart. Due to these reasons, a modified form of analysis (Repeated Measures Analysis of Variance) was used in data analyses because it takes into account these problems. This form of analysis is used in cases where repeated measurements are made over time, or in this case, repeated measurements in rows that have fixed distances relative to the tree lines. Treatment differences between rows in a treatment or between treatments for a given row were separated using the LSD test [Cochran and Cox 1957].

CHAPTER FOUR

TREE AND CROP GROWTH ANALYSES

4.1 Introduction

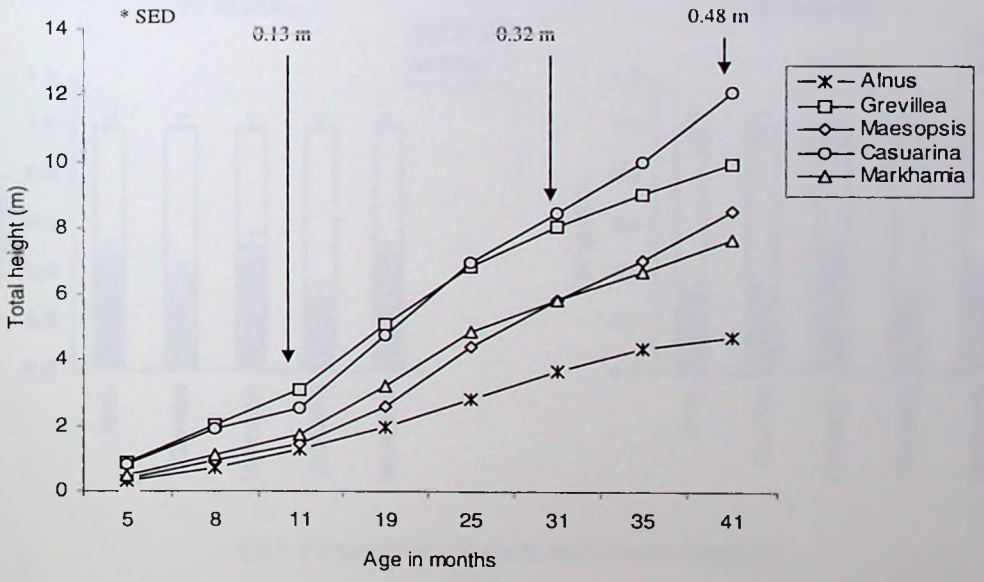
Crop yields under the trees in this agroforestry system may be unaffected during the early years of tree growth, but could increase or decrease when the trees grow large, depending on the tree species. Any positive influence of the trees on crop yields would not be expected for many years [Poschen 1986; Rhoades 1997] because trees modify the soil environment and microclimate slowly. However, there are reports where the positive effects of trees on crops are noted within a few years [Peden *et al* 1993; Chirko *et al* 1996a; Akyeampong *et al* 1999]. On the other hand, the negative effect of trees in this system due to competition for growth resources of water and light can be noted within a few years [Ralhan *et al* 1992; Okorio *et al* 1994; Akyeampong *et al* 1995]. The aim of this Chapter was to assess the effect of different upper-storey trees on the growth and yield of the associated crops from 1996 to 1998.

Results for tree growth, crop growth and yield are presented in the Chapter, while the methods used for collecting tree and crop data were presented in Chapter 3 (sections 3.4.2 and 3.5.2 respectively). Tree data are presented in section 4.2.1 and include tree survival, tree height, stem diameter growth and crown development of the tree species. Section 4.2.2 presents data on the growth and yield of maize for four cropping seasons and includes data on maize height growth, biomass production, grain yields and leaf area index. Data on bean biomass and grain yield production for two cropping seasons are presented in section 4.2.3, while section 4.3 discusses the current results in relation to results from other studies. The Chapter concludes by giving a summary (section 4.4) on the effect of the tree species on crop growth and yield.

4.2 Results

4.2.1 Tree growth

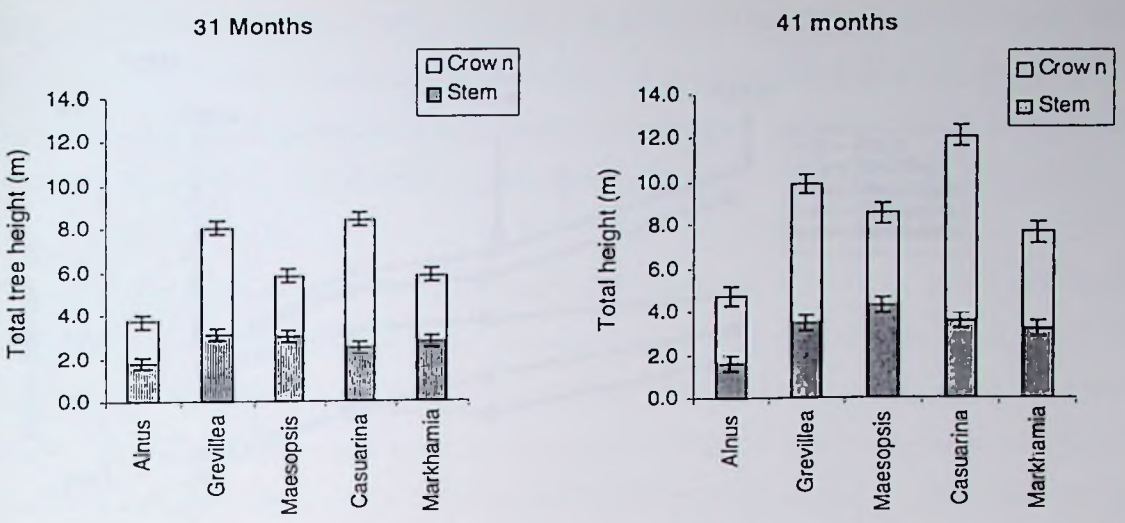
Tree survival was more than 95% for all the species, except *Alnus* that had a lower survival rate of 75%. There were significant ($p<0.001$) differences in height between the tree species 11 months after planting (figure 4.1). These differences became more significant ($p<0.0001$) as the trees grew bigger up to the age of 41 months. At this age, the height of *Casuarina* (12.2 m) was significantly more than that of *Grevillea* (9.8 m), which in turn grew significantly taller than *Maesopsis* (8.5 m) and *Markhamia* (7.7 m). However, there was no significant difference in height growth between the latter two species. *Alnus* had the least growth attaining a height growth of only 4.7 m.



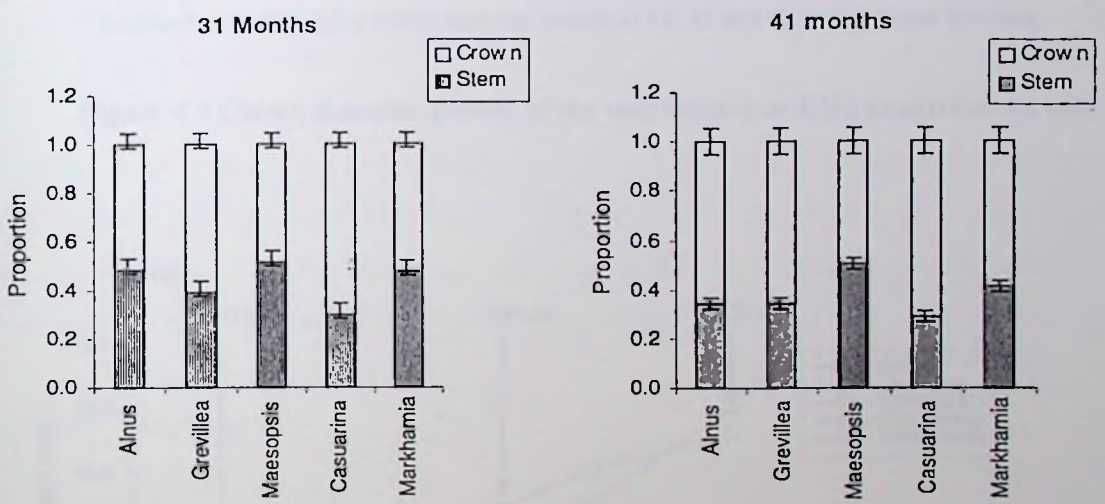
* Standard error difference (SED) between species at 11, 31 and 41 months after planting

Figure 4.1 Total tree heights of the species at Kifu experimental site.

When the proportion of the stem to canopy height was considered, the species had significant ($p<0.001$) differences at 31 and 41 months of growth (figure 4.2). At 41 months, *Casuarina* and *Grevillea* had significantly higher ($p<0.001$) canopy proportions,



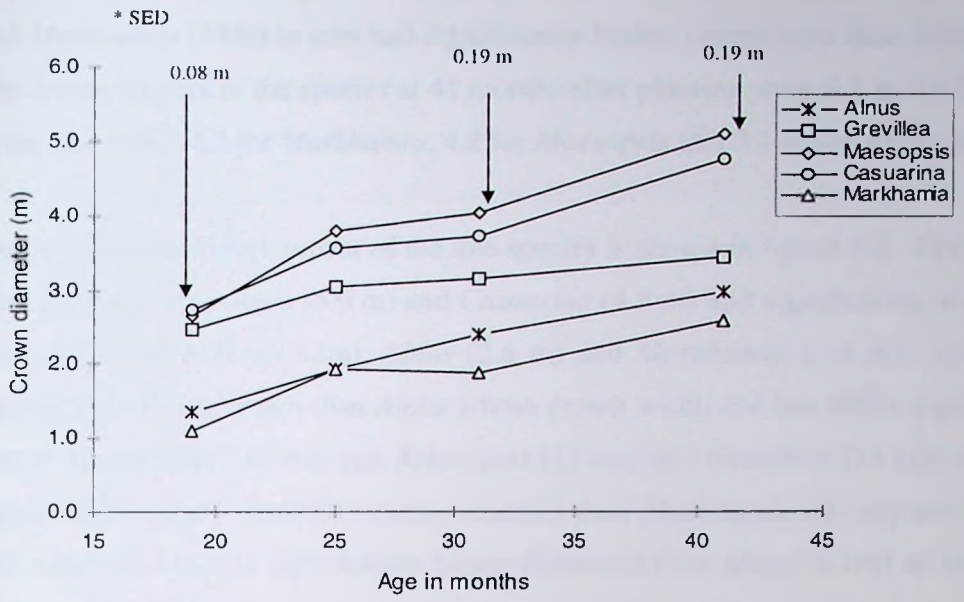
(A). Stem and crown lengths



(B). Proportion of stem and crown lengths

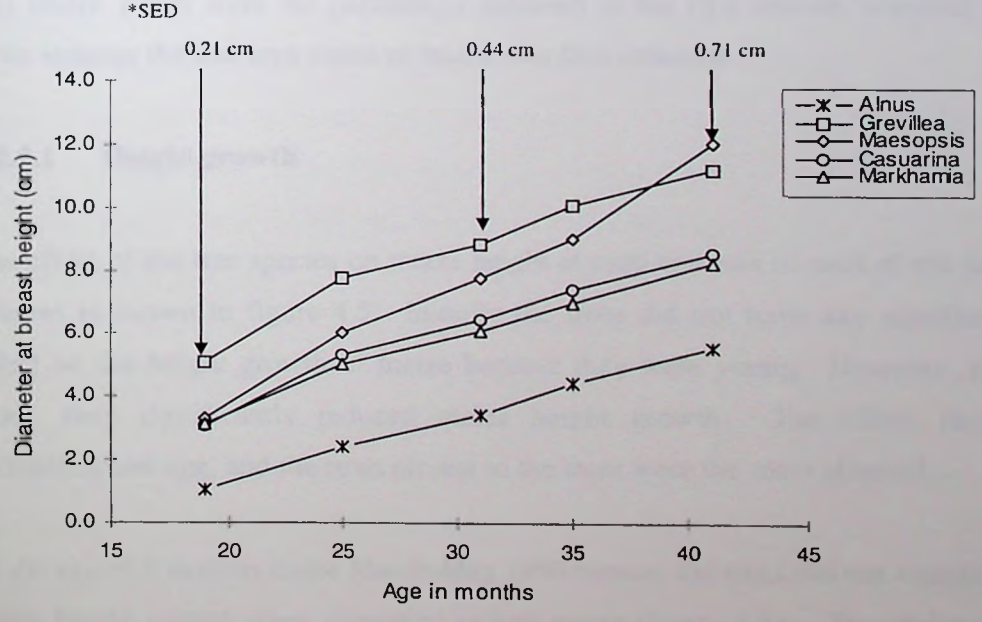
* Bars represent SE

Figure 4.2. Stem and crown lengths (A) and their relative proportions to total height (B) of different tree species at 31 and 41 months after planting in the field.



* Standard error difference (SED) between species at 19, 31 and 41 months after planting

Figure 4.3 Crown diameter growth of the tree species at Kifu experimental site



* Standard error difference (SED) between species at 19, 31 and 41 months after planting

Figure 4.4 Stem diameter growth of the tree species at Kifu experimental site

70% and 65% respectively, when compared to the other species (figure 4.2b). *Alnus* (54%) and *Markhamia* (53%) in turn had significantly higher proportions than *Maesopsis* (40%). The crown heights of the species at 41 months after planting were 8.5 m for *Casuarina*, 6.5 m for *Grevillea*, 4.5 for *Markhamia*, 4.2 for *Maesopsis* and 3.1 m for *Alnus* (figure 4.2a).

Canopy diameter development of the tree species is shown in figure 4.3. Forty-one months after planting, *Maesopsis* (5.0 m) and *Casuarina* (4.8 m) had significantly wider ($p<0.001$) crowns than *Grevillea* (3.2m), *Alnus* (2.6 m) and *Markhamia* (2.4 m). *Grevillea* had a significantly wider crown than *Alnus* whose crown width did not differ significantly from that of *Markhamia*. At this age, *Maesopsis* (12 cm) and *Grevillea* (11 cm) had developed significantly bigger ($p<0.001$) stem diameters than *Markhamia* (8 cm) and *Casuarina* (8 cm) which in turn had significantly bigger diameters than *Alnus* (6 cm) as shown in figure 4.4.

4.2.2 Maize Growth and Yield

A maize crop was grown in the four seasons of March-May 1996, March-May 1997, March-May 1998 and August-November 1998. Maize height growth, biomass production and maize yields were the parameters assessed in the first season, whereas in the other three seasons the leaf area index of maize was also assessed.

4.2.2.1 Height growth

The effect of the tree species on maize height at crop anthesis in each of the four cropping seasons is shown in figure 4.5. Initially the trees did not have any significant negative effect on the height growth of maize because they were young. However, as they grew older, they significantly reduced maize height growth. The effect increased with increasing tree age, and the rows closest to the trees were the most affected.

At the age of 8 months in the March-May 1996 season, the trees did not significantly affect maize height growth when compared to sole maize (figure 4.5a). The maize plants in the tree plots (average 219 cm) grew as tall as those in the sole maize plots (224 cm). However, at the age of 20 months (March-May 1997 season), there were significant differences ($p<0.001$) between the tree species in their effect on maize height when

compared to sole maize (225 cm) as shown in figure 4.5b. *Maesopsis* significantly reduced maize height growth more than all the other species by 37% and 27% for distances of 0.8 and 1.5 m (rows 1 to 2) from the tree line (table 4.1). *Casuarina* significantly reduced height growth (27%) more than *Grevillea* (16%), *Markhamia* (12%) and *Alnus* (8%) at 0.8 m distance (row 1). There were no significant differences in maize height growth for the latter three species for distances of 1.5 and 2.3 m (rows 2 and 3).

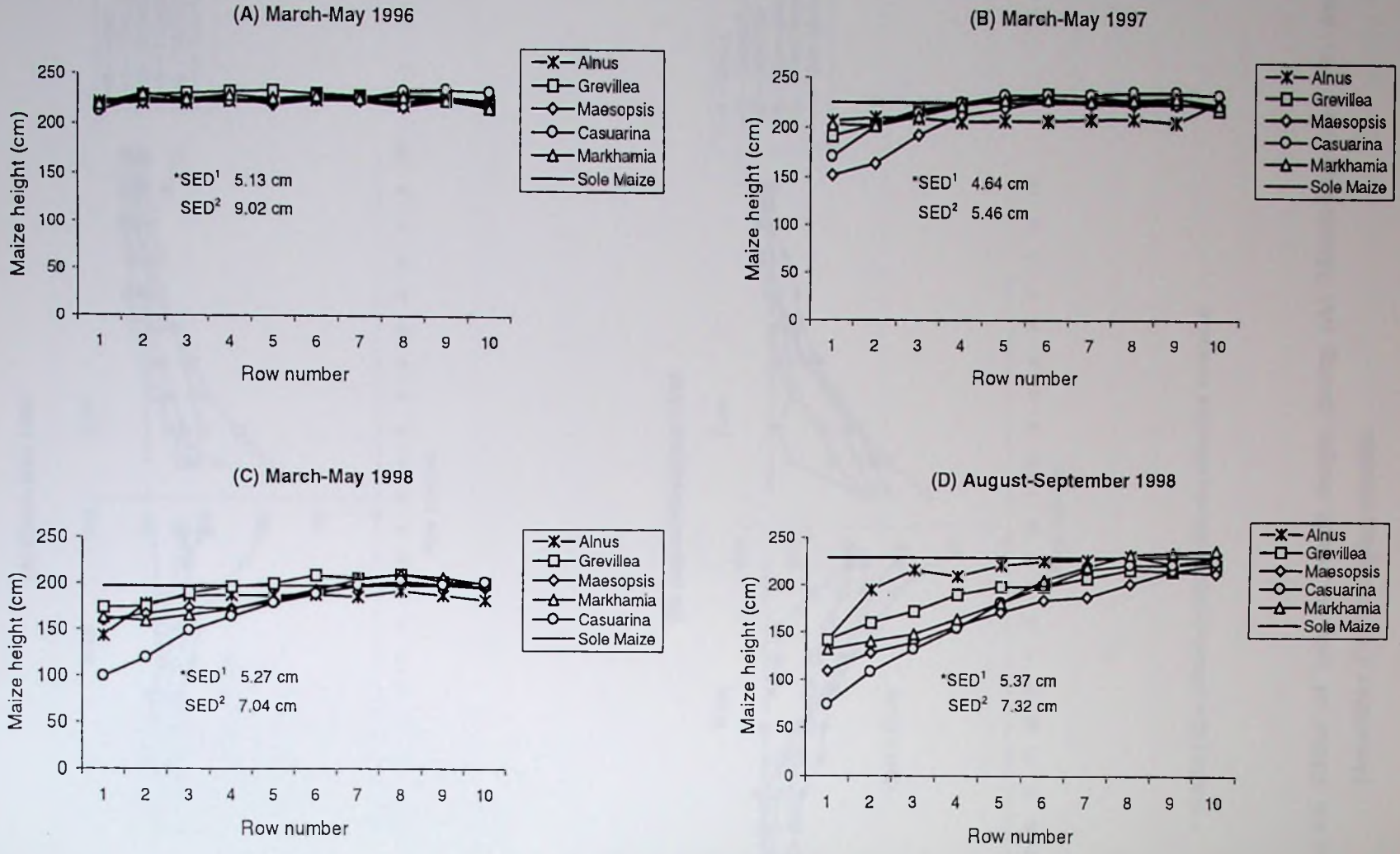
When the trees were 32 months old (March-May 1998 season), there were highly significant differences ($p<0.001$) between the species in their effect on maize height (figure 4.5c). The effect extended up to a distance of 3 m (row 4) from the tree lines. In this season, *Casuarina* significantly reduced maize height growth more than the other species by 50, 40 and 25% for 0.8 to 2.3 m (rows 1- 3) respectively, when compared to the height of sole maize (199 cm) as shown in table 4.1. There were no significant differences in maize height reduction between *Markhamia* (21 and 19%), *Maesopsis* (19 and 15%), *Grevillea* (15 and 14%) and *Alnus* (25 and 9%) for 0.8 and 1.5 m (rows 1 and 2), while for 2.3 m distance (row 3) *Markhamia* (18%), *Maesopsis* (11%) and *Grevillea* (8%) reduced maize height more than *Alnus* (0%). *Casuarina* (17%) and *Markhamia (15%)* significantly reduced maize height more than *Grevillea* (4%) and *Alnus* (0%) at 3.0 m distance (row 4).

During the August-November 1998 cropping season, the effect of the trees on maize height was more pronounced and the differences more significant ($p<0.0001$). The trees by now were 41 months old and their effect had reached 4.5 m away from the trees (row 6) as shown in figure 4.5d. *Casuarina* significantly reduced maize height growth more than all the other species when compared to sole maize (229 cm). It significantly reduced maize height (66 and 50%) more than all the other species for 0.8 and 1.5 m distance (rows 1 and 2) as shown in table 4.1. At 1.5 m distance (row 2), *Maesopsis* (36%) and *Markhamia* (38%) significantly reduced maize height more than *Alnus* (14%), but had a similar effect as *Grevillea* (24%). At 3.0 and 4.5 m distance (rows 4 and 5), *Casuarina* (29 and 16%), *Maesopsis* (21 and 14%) and *Markhamia* (20 and 9%) significantly reduced maize height than *Alnus* (5 and 2%) but had the same effect as *Grevillea* (10 and 6%). There were no significant differences between the species on maize height at 4.5 m distance (row 6). Table 4.1 gives a summary of the percentage reduction in maize height by the tree species in the three seasons.

There were marginal significant differences ($p<0.002$ and $p<0.005$) in maize height between the eastern and western sides of the tree line in the *Maesopsis* plots in March-May and August-November 1998 cropping seasons respectively (figure 4.6). The maize plants on the east were significantly taller than those on the west, by 31 cm in the March-May season (figure 4.6a), and by 20 cm in the August-November season (figure 4.6b). Generally, the effect of the trees on the height of maize varied with distance from the tree line. *Alnus* had a very small effect, with only the row closest to the tree lines (about 1 m away) having plants whose heights were significantly reduced by the presence of the trees. The effect of *Grevillea* was apparent up to a distance of 2.3 m (3 rows) from the tree line, while *Casuarina*, *Maesopsis* and *Markhamia* significantly reduced the height growth of maize up to a distance of 4.5 m (row 5) from the tree lines during the last season.

Tables 4.1 Percentage maize height reduction, in relation to sole crop maize, by the tree species during the three cropping seasons

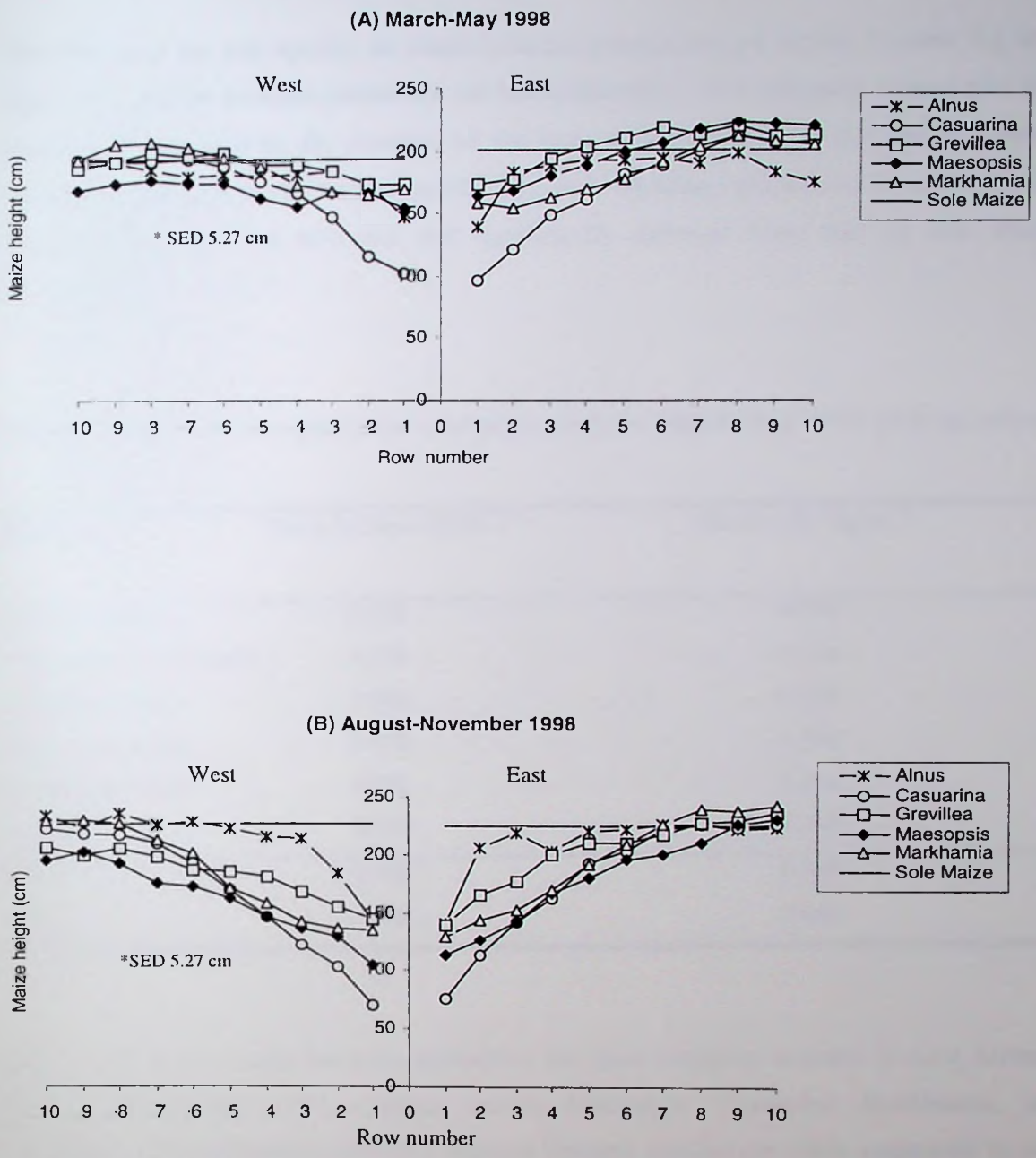
Season	Species	Percentage maize height reduction					
	Distance from tree (m)	*0.8*	*1.5*	*2.3*	*3.0*	*3.8*	*4.5*
March-May 1997	*Maesopsis*	37	27	15	0	0	0
	Casuarina	27	14	10	0	0	0
	Grevillea	16	14	8	0	0	0
	Markhamia	12	10	7	0	0	0
	Alnus	8	4	0	0	0	0
March-May 1998	*Casuarina*	50	40	25	17	0	0
	Markhamia	21	19	18	15	0	0
	Maesopsis	19	15	11	12	0	0
	Grevillea	15	14	8	4	0	0
	Alnus	25	9	0	0	0	0
August-Nov. 1998	*Casuarina*	66	50	39	29	16	6
	Maesopsis	45	36	30	21	14	11
	Markhamia	41	38	27	20	9	4
	Grevillea	33	24	19	10	6	5
	Alnus	37	14	8	5	2	0



SED¹ = Standard error difference (SED) between rows in a treatment

SED² = Standard error difference (SED) between treatments for a given row

Figure 4.5 Effect of line planted trees of different species on maize height at different distances from the tree row in the four seasons.



* Standard error difference (SED) between sides in a treatment

Figure 4.6 Effect of side on maize height during (A) March-May and (B) August-November 1998 cropping seasons.

4.2.2.2 Maize biomass production

The effects of the tree species on maize biomass production are shown in table 4.2 and figure 4.7. Maize biomass production for the March-May 1996 cropping season was not significantly affected by the presence of the trees as shown in table 4.2 below. Mean biomass production in the season was 0.77 kg m^{-2}. Biomass production from plots with trees (average 0.77 kg m^{-2}) was not significantly different from that of sole maize (0.79 kg m^{-2}).

Table 4.2 Maize biomass production and grain yields for March-May 1996 growing season

Species	Maize biomass (kg m^{-2})	Maize yield (kg m^{-2})
Alnus acuminata	0.734	0.360
Casuarina equisetifolia	0.732	0.324
Grevillea robusta	0.786	0.348
Maesopsis eminii	0.752	0.332
Markhamia lutea	0.822	0.364
Control	0.786	0.348
Mean	0.768	0.340
SED	0.098	0.041

Figure 4.7 shows maize biomass production for three cropping seasons at final harvest. During March-May 1997 cropping season, *Maesopsis, Casuarina Markhamia*, and *Grevillea* all significantly ($p<0.001$) reduced biomass production when compared to sole maize (1.10 kg m^{-2}). The effect of the trees extended up to a distance of 3m from the tree line (row 4) as shown in figure 4.7a. *Maesopsis* (65, 54 and 34%) significantly reduced maize biomass production more than all the other species at distances of 0.8 to 2.3 m (rows 1 to 3) (table 4.3). *Casuarina* (52%) and *Grevillea* (49%) significantly reduced maize biomass production more than *Markhamia* (41%), which in turn was more suppressive than *Alnus* (17%) at 0.8 m distance (row 1) from the tree line. At 1.5 m (row2), *Casuarina* (38%) and *Markhamia* (35%) significantly reduced maize biomass more than *Grevillea*

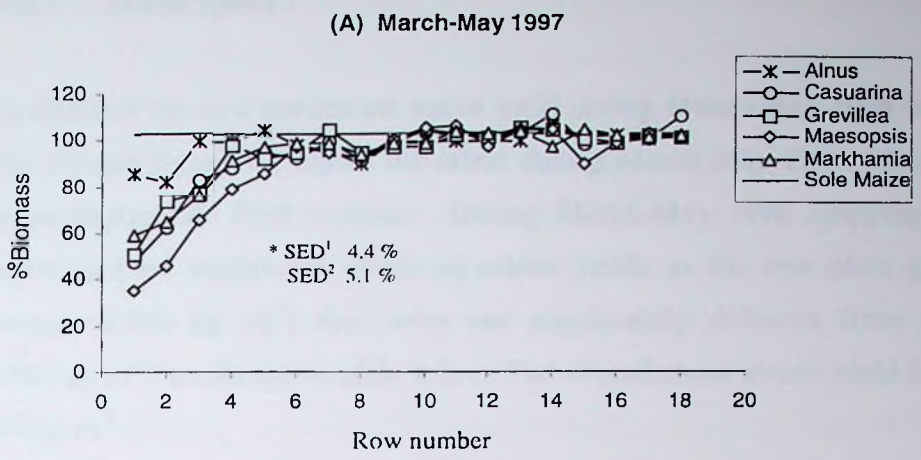
(26%) and *Alnus* (14%). At a distance of 3.0 m (row 4), *Maesopsis* significantly reduced maize biomass more than all the other species.

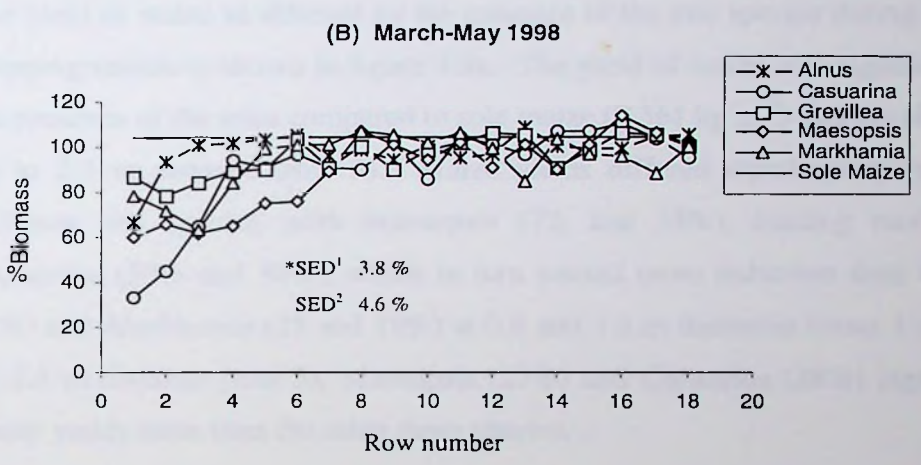
Maize biomass production during March-May1998 cropping season is shown in figure 4.7b. All the tree species significantly reduced ($p<0.001$) biomass production when compared to sole maize (1.01 kg m^{-2}) and the effect extended up to a distance of 4.5 m (row 5). *Casuarina* significantly reduced maize biomass (57, 52, 47 and 31%) more than all the other species from 0.8 to 3.0 m distance (rows 1 to 4) (table 4.3). *Maesopsis* (34, 34, 28 and 22%) and *Markhamia* (29, 29, 29 and 18%) were more suppressive than *Grevillea* (22, 22 12 and 7%) and *Alnus* (27, 15, 10 and 4%) for distances of 0.8 to 3.0 m (rows 1 to 4). *Casuarina* and *Maesopsis* were more suppressive than the other species at 3.8 m (row 5), while the effect of *Maesopsis* extended up to 4.5 m from the tree line (row 6).

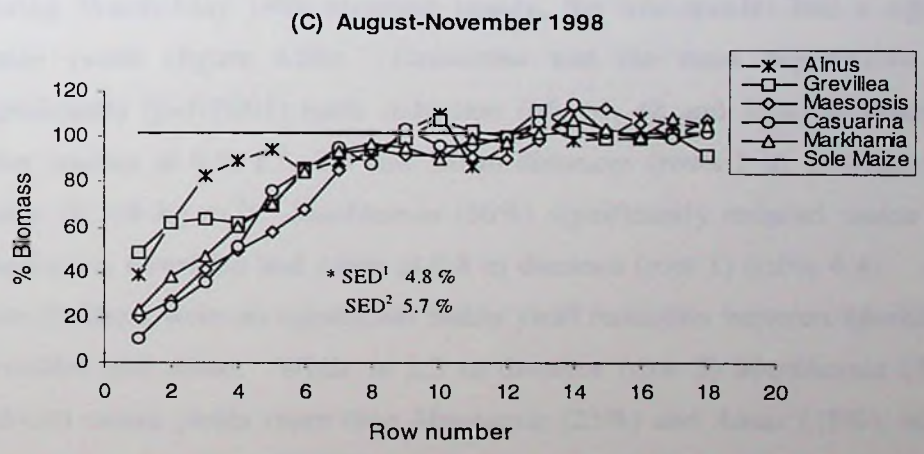
The effect of the tree species on maize biomass production for August-November 1998 cropping season is shown in figure 4.7c. During this season, *Casuarina, Maesopsis* and *Markhamia* significantly reduced ($p<0.0001$) maize biomass production more than *Grevillea* and *Alnus* when compared to sole maize (1.25 kg m^{-2}), with the effect extending up to 4.5 m distance (row 6). *Casuarina* (77, 67, 66, 51%) significantly reduced maize biomass production at 0.8, 1.5, 2.3 and 3.0 m(rows 1, 2, 3, 4) more than *Maesopsis* (67, 51, 46 and 36%) and *Markhamia* (61, 61, 52 and 37%). *Markhamia* on the other hand significantly reduced biomass production more than *Maesopsis* at 1.5 and 2.3 m (rows 2 and 3) but not at 0.8, 3.0 and 3.8 m distances (rows 1, 4 and 5) (table 4.3). *Grevillea* significantly reduced maize biomass production than *Alnus* for all rows except at 0.8 m (row 1).

Tables 4.3 Percentage maize biomass reduction, relative to sole crop maize, by the tree species during the three cropping seasons.

Season	Species	Percentage biomass reduction					
	Distance from tree (m)	*0.8*	*1.5*	*2.3*	*3.0*	*3.8*	*4.5*
March-May 1997	*Maesopsis*	65	54	34	21	0	0
	Casuarina	52	38	17	12	0	0
	Grevillea	49	26	23	2	0	0
	Markhamia	41	35	24	9	0	0
	Alnus	17	14	1	1	0	0
March-May 1998	*Casuarina*	57	52	47	31	20	0
	Markhamia	29	29	29	18	8	0
	Maesopsis	34	34	28	22	16	10
	Grevillea	22	22	12	7	7	0
	Alnus	27	15	10	4	4	0
August-Nov. 1998	*Casuarina*	77	67	66	51	34	28
	Maesopsis	67	51	46	36	27	20
	Markhamia	61	61	52	37	29	19
	Grevillea	46	43	32	22	20	14
	Alnus	46	29	14	6	2	1







* Standard error difference (SED^1) between rows in treatment

Standard error difference (SED^2) between treatments for row

Figure 4.7. The effect of line planted trees of different species on maize biomass production at different distances from the tree row in three seasons. Biomass is expressed as % of the biomass of sole maize.

4.2.2.3 Maize yields

The effect of the tree species on maize yield during March-May 1996 season is shown in table 4.2 and figure 4.8 shows the effect during March-May 1997, March-May 1998 and August-September 1998 seasons. During March-May 1996 cropping season, the tree species had no significant effect on maize yields as the tree plots gave maize yields (average 0.346 kg m^{-2}) that were not significantly different from sole maize plots (0.348 kg m^{-2}) as shown in table 4.2. The overall mean maize yield for the season was 0.34 kg m^{-2}.

The yield of maize as affected by the presence of the tree species during March-May 1997 cropping season is shown in figure 4.8a. The yield of maize was significantly reduced by the presence of the trees compared to sole maize (0.361 kg m^{-2}) and the effect was apparent up to 2.3 m distance (row 3). Maize yields differed significantly ($p<0.0001$) among different tree species, with *Maesopsis* (72, and 58%), causing more reduction than *Casuarina* (50% and 38%), which in turn caused more reduction than *Grevillea* (29 and 19%) and *Markhamia* (25 and 19%) at 0.8 and 1.5 m distances (rows 1 and 2) (table 4.4). At 2.3 m distance (row 3), Maesopsis (25%) and Casuarina (28%) significantly reduced maize yields more than the other three species.

During March-May 1998 cropping season, the tree species had a significant effect on maize yields (figure 4.8b). *Casuarina* was the most suppressive species, causing significantly ($p<0.0001$) more reduction (66, 64, 48 and 35%) in maize yields than any other species at 0.8, 1.5, 2.3 and 3.0 m distances (rows 1 to 4) when compared to sole maize (0.328 kg m^{-2}). *Markhamia* (56%) significantly reduced maize yields more than *Maesopsis*, *Grevillea* and *Alnus* at 0.8 m distance (row 1) (table 4.4). At 1.5 m distance (row 2), there were no significant maize yield reduction between *Markhamia, Maesopsis, Grevillea* and *Alnus*. While at 2.3 m distance (row 3) *Markhamia* (36%) significantly reduced maize yields more than *Maesopsis* (23%) and *Alnus* (18%), which in turn were suppressive than *Grevillea* (7%). *Markhamia* and *Maesopsis* significantly reduced maize yields than *Grevillea* and *Alnus* at 3.0 and 3.8 m distances (rows 4 and 5).

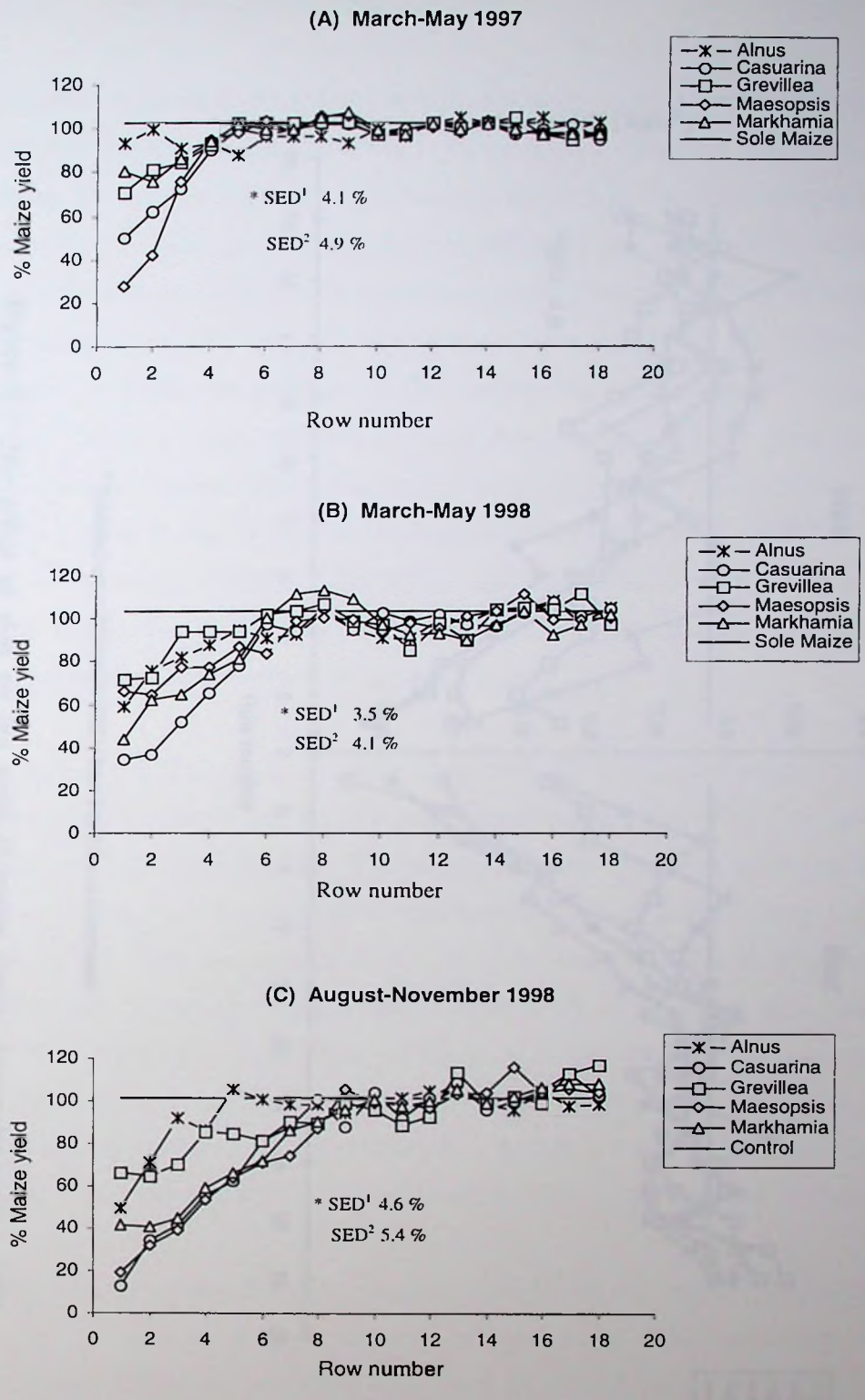
Figure 4.8c shows the effect of the trees on maize yields during August-November 1998 cropping season. The effect of the trees on maize yields was more pronounced in this season than in the previous seasons when compared to the sole maize yields

(0.342 kg m^{-2}). The differences due to the presence of the tree species were highly significant ($p<0.0001$). The most suppressive species were *Casuarina, Maesopsis* and *Markhamia*. At 0.8 m distance (row 1), the maize plants in association with *Casuarina* yielded significantly lower (88% reduction) than with *Maesopsis* (81%) which in turn produced lower yields than with *Markhamia* (59%). *Grevillea* (46%) and *Alnus* (34%) had the least effect in this row, but the former had lower yields than the latter. For the other rows, *Casuarina, Maesopsis* and *Markhamia* had significantly lower yields than *Grevillea* and *Alnus* (table 4.4). *Grevillea* in turn had significantly lower yields than *Alnus* only at 0.8 m distance (row 1). Table 4.4 below summarizes the percentage maize yield reduction by the tree species during the three cropping seasons.

There was a marginal significant difference ($p<0.07$) in maize yields between the eastern and western sides of the tree line in the *Maesopsis* treatments during the August-November 1998 growing season. Maize yields on the east were significantly higher than those in the west by 0.072 kg m^{-2} (figure 4.9).

Table 4.4 Percentage reduction in maize yield, relative to sole crop maize, by the tree species during the three cropping seasons.

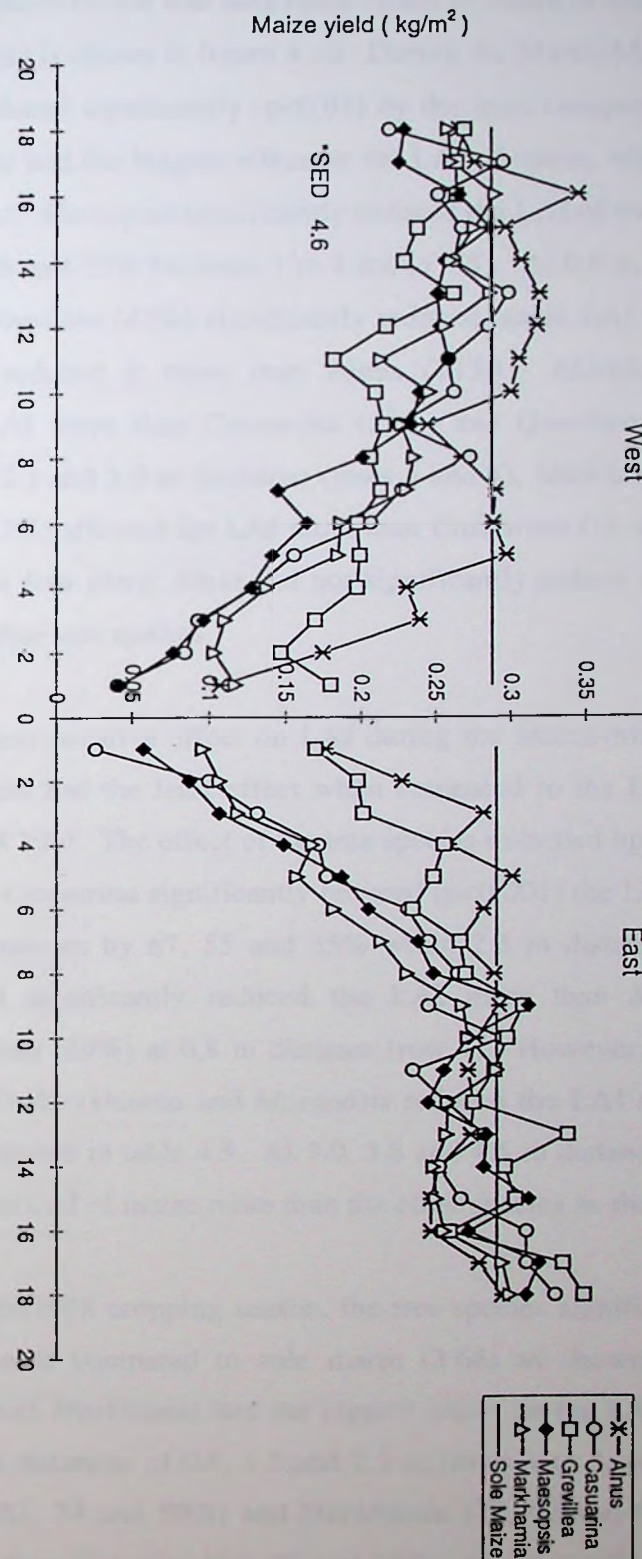
Season	Species	Percentage maize yield reduction					
	Distance from tree (m)	*0.8*	*1.5*	*2.3*	*3.0*	*3.8*	*4.5*
March-May 1997	*Maesopsis*	72	58	25	0	0	0
	Casuarina	50	38	28	0	0	0
	Grevillea	29	19	8	0	0	0
	Markhamia	19	25	14	0	0	0
	Alnus	7	10	7	1	0	0
March-May 1998	*Casuarina*	66	64	48	35	22	0
	Markhamia	56	38	36	26	19	0
	Maesopsis	34	35	23	23	14	0
	Grevillea	28	28	7	6	6	0
	Alnus	42	25	18	12	10	0
August-Nov. 1998	*Casuarina*	88	66	58	44	38	18
	Maesopsis	81	68	61	47	36	29
	Markhamia	59	59	55	41	33	28
	Grevillea	46	43	32	22	20	14
	Alnus	34	35	30	14	15	18



* Standard error difference (SED^1) between rows in treatment

Standard error difference (SED^2) between treatments for row

Figure 4.8 Maize yields in association with different species measured at different distances from the tree rows in three seasons. Yields of each specified row were averaged over two sides of the tree line, and expressed as a percentage of the sole crop (control).



* Standard error difference (SED) between sides in a treatment

Figure 4.9 The effect of side on the yield of maize during August-November 1998 cropping season.

4.2.2.4 Leaf Area Index (LAI) of Maize

The effect of the tree species on the leaf area index (LAI) of maize at crop anthesis during the three cropping seasons is shown in figure 4.10. During the March-May 1997 cropping season, the LAI was reduced significantly ($p<0.01$) by the trees compared to that of sole maize (3.47). *Maesopsis* had the biggest effect on the LAI of maize, while *Alnus* had the least effect (figure 4.10a). *Maesopsis* significantly reduced the LAI of maize more than all the species by 63, 65, 46 and 25% for rows 1 to 4 (table 4.5). At 0.8 m distance (row 1), *Casuarina* (49%) and *Grevillea* (47%) significantly reduced maize LAI more *Markhamia* (38%) which in turn reduced it more than Alnus (17%). *Markhamia* (43%) had significantly reduced LAI more than *Casuarina* (29%) and *Grevillea* (33%) at 1.5 m distance (row 2), but at 2.3 and 3.0 m distances (rows 3 and 4), *Markhamia* (35 and 19%) and *Grevillea* (29 and 21%) affected the LAI more than *Casuarina* (19 and 7%) as shown in table 4.5. For all the four rows, *Alnus* did not significantly reduce the LAI of maize when compared to the other tree species.

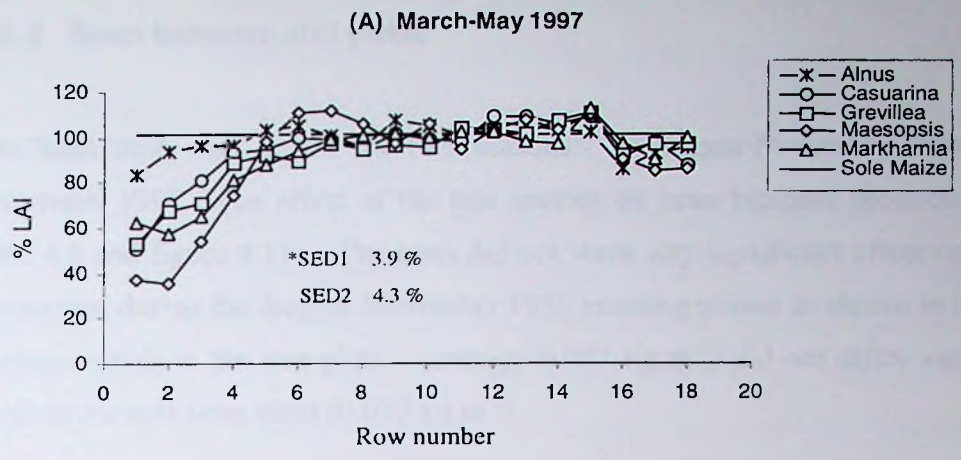
Casuarina had the biggest negative effect on LAI during the March-May 1998 cropping season, while *Alnus* again had the least effect when compared to the LAI of sole maize which was 3.26 (figure 4.10b). The effect of the tree species extended up to 4.5 m distance from the trees (row 6). *Casuarina* significantly reduced ($p<0.001$) the LAI of maize more than all the other tree species by 67, 55 and 35% wthin 2.3 m distance (rows 1 to 3). *Markhamia* (36%) had significantly reduced the LAI more than *Maesopsis* (24%), *Grevillea* (28%) and *Alnus* (29%) at 0.8 m distance (row 1). However, at 1.5 and 2.3 m distances (rows 2 and 3), *Markhamia* and *Maesopsis* reduced the LAI significantly more *Grevillea* and *Alnus* as shown in table 4.5. At 3.0, 3.8 and 4.5 m distances (rows 4, 5 and 6) *Maesopsis* reduced the LAI of maize more than the other species as shown in table 4.5.

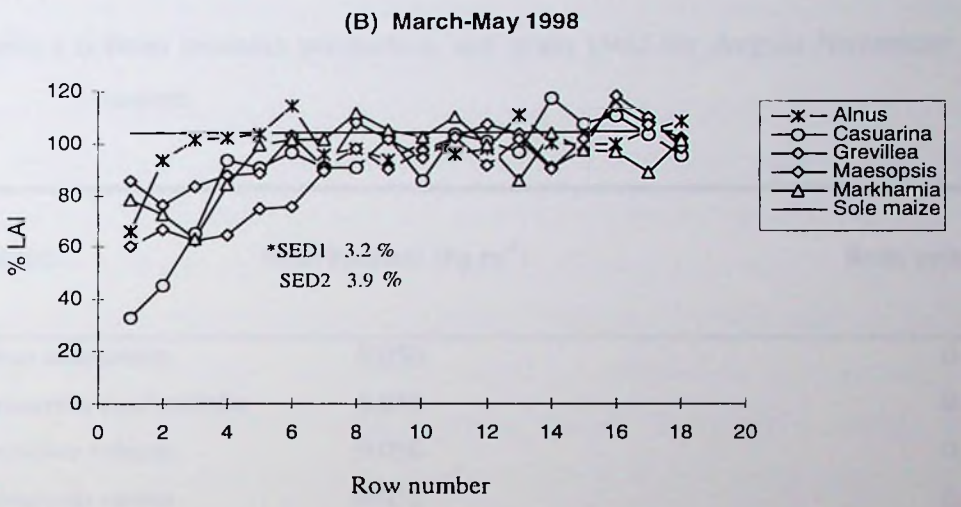
During August-November1998 cropping season, the tree species significantly ($p<0.0001$) reduced the LAI of maize compared to sole maize (3.68) as shown in figure 4.10c. *Casuarina, Maesopsis* and *Markhamia* had the biggest effect on the LAI of maize, while *Alnus* had the least. At distances of 0.8, 1.5 and 2.3 m (rows 1 to 3), *Casuarina* (89, 76 and 64%), *Maesopsis* (81, 74 and 59%) and *Markhamia* (77, 62 and 54%) significantly reduced the LAI more than *Grevillea* (51, 38 and 36%) and *Alnus* (61, 38 and 17%) as shown in figure 4.10c and table 4.5. But at 3.8 and 4.5 m distances (rows 5 and 6), *Maesopsis* (44 and 34%) reduced the LAI of maize more than *Casuarina* (24 and 15%),

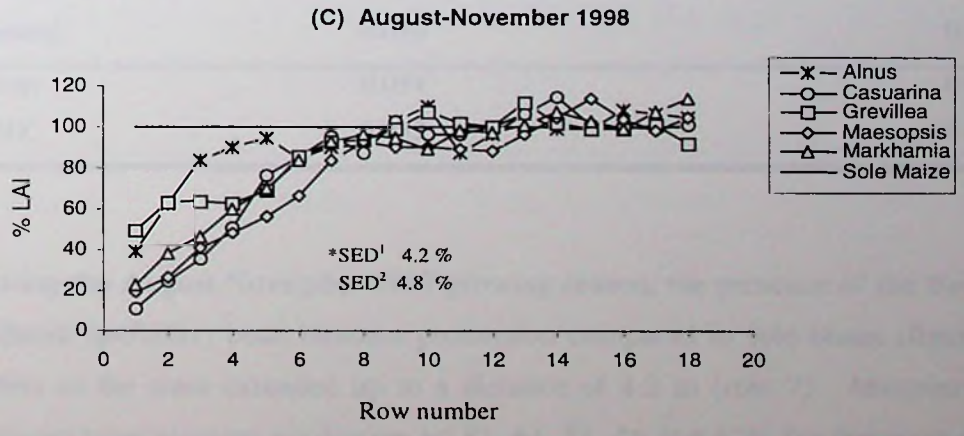
Markhamia (30 and 17%) and *Grevillea* (31 and 14%) which in turn reduced it more than *Alnus* (5 and 15%). The percentage reduction on the LAI of maize by the tree species during the three seasons is shown in table 4.5 below.

Tables 4.5 Percentage reduction on the LAI of maize, relative to sole crop maize, by the tree species during the three cropping seasons.

Season	Species	Percentage LAI reduction					
	Distance from tree (m)	*0.8*	*1.5*	*2.3*	*3.0*	*3.8*	*4.5*
March-May 1997	*Maesopsis*	63	65	46	25	2	0
	Casuarina	49	29	19	7	5	0
	Grevillea	47	33	29	21	8	11
	Markhamia	38	43	35	19	12	6
	Alnus	17	6	3	3	0	0
March-May 1998	*Casuarina*	67	55	35	6	9	3
	Maesopsis	40	33	38	35	25	24
	Markhamia	22	28	36	16	1	0
	Grevillea	14	23	17	12	11	0
	Alnus	34	7	0	0	0	0
August-Nov. 1998	*Casuarina*	89	76	64	49	24	15
	Maesopsis	81	74	59	52	44	34
	Markhamia	77	62	54	40	30	17
	Grevillea	51	38	36	38	31	14
	Alnus	61	38	17	10	5	15







* Standard error difference (SED^1) between rows in treatment

* Standard error difference (SED^2) between treatments for row

Figure 4.10. Effect of line planted trees of different species on the LAI of maize at different distances from the tree row in three seasons. LAI in association with trees is expressed as % of LAI of sole maize.

4.2.3 Bean biomass and yields

The bean crop was grown for two seasons:- in August-November 1996 and August-November 1997. The effect of the tree species on bean biomass production is shown in table 4.6 and figure 4.11a. The trees did not show any significant effect on bean biomass production during the August-November 1996 growing season as shown in table 4.6. Bean biomass yields in the tree plots (average 0.057 kg m^{-2}) did not differ significantly from those in the sole bean plots (0.059 kg m^{-2}).

Table 4.6 Bean biomass production and grain yield for August-November 1996 cropping season

Species	Bean biomass (kg m^{-2})	Bean yield (kg m^{-2})
Alnus acuminata	0.050	0.020
Casuarina equisetifolia	0.050	0.024
Grevillea robusta	0.056	0.028
Maesopsis eminii	0.052	0.020
Markhamia lutea	0.056	0.024
Control	0.059	0.022
Mean	0.054	0.024
SED	0.032	0.021

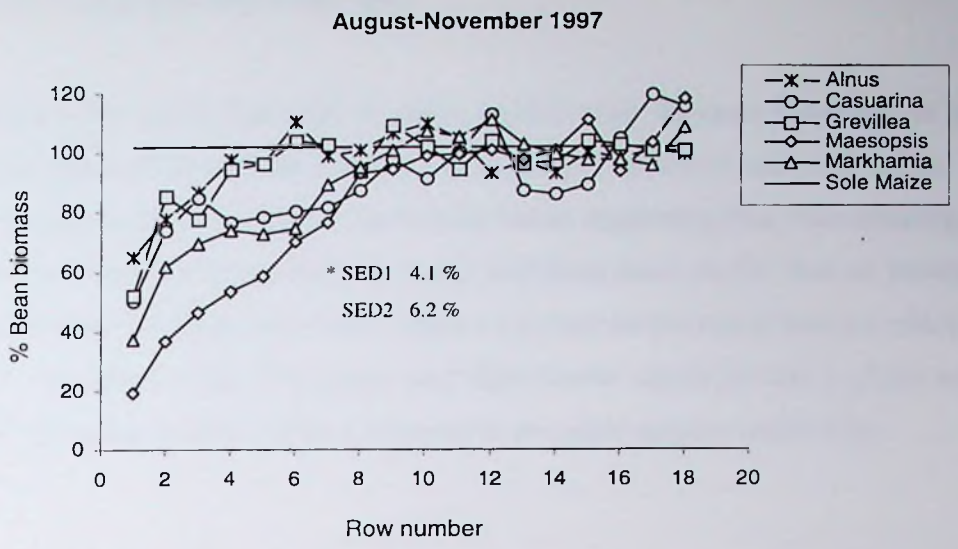
During the August-November 1997 growing season, the presence of the trees significantly reduced ($p<0.001$) bean biomass production compared to sole beans (figure 4.11a). The effect of the tress extended up to a distance of 4.2 m (row 7). *Maesopsis* significantly reduced bean biomass production by 81, 64, 54, 46 and 42% for distances from 0.6 to 3.0 m (rows 1 to 5) when compared to sole beans (table 4.7). However, its effect on bean biomass production for distances of 3.6 to 4.2 m (rows 6 and 7) (30 and 24%) was not significantly different from that of *Casuarina* (20 and 18%) and *Markhamia* (25 and 11%). *Markhamia* (63, 38 and 30%) significantly reduced bean biomass more than *Casuarina* (50, 26 and 15%) and *Grevillea* (48, 14 and 22%) and *Alnus* (32, 22 and 14%) up to 1.8 m

(rows 1 to 3). At distances of 2.4, 3.0, 3.6 and 4.2 m (4, 5, 6 and 7), *Casuarina* and *Markhamia* significantly reduced bean biomass more than *Grevillea* and *Alnus*, but the latter two had a similar effect on bean biomass production as shown in table 4.7

The effects of the tree species on bean yields during August-November 1996 and August-November 1997 cropping seasons are shown in table 4.6 and figure 4.11b respectively. The trees did not affect bean yields (average 0.024 kg m^{-2}) during August-November 1996 cropping season when compared to sole beans which were 0.022 kg m^{-2} (table 4.6). However, by the August-November 1997 season, the trees had significantly reduced ($p<0.001$) bean yields when compared to sole beans as shown in figure 4.11b. The effect extended up to a distance of 4.2 m (row 7). *Maesopsis* significantly reduced bean yields (83, 67, 53, 52 and 47%) more than *Markhamia* (69, 49, 37, 31 and 31%), which in turn reduced bean yields more than the other species for distances from 0.8 to 3.0 m (rows 1 to 5) (table 4.7). *Casuarina* and *Grevillea* had significantly reduced bean yields more than *Alnus* at 0.6 m distance (row 1), but the three species had similar yields at 1.2, 1.8 and 2.4 m (rows 2, 3 and 4). At 3.0, 3.6 and 4.2 m (rows 5, 6 and 7), *Casuarina* significantly reduced bean yields more than *Grevillea* and *Alnus*, which had similar effects in these rows. Table 4.7 below summarises percentage reduction in bean biomass and yield by the trees in August-November 1997 cropping season. There was a slightly greater effect on yield than on biomass, implying a slight reduction in the harvest index close to the trees.

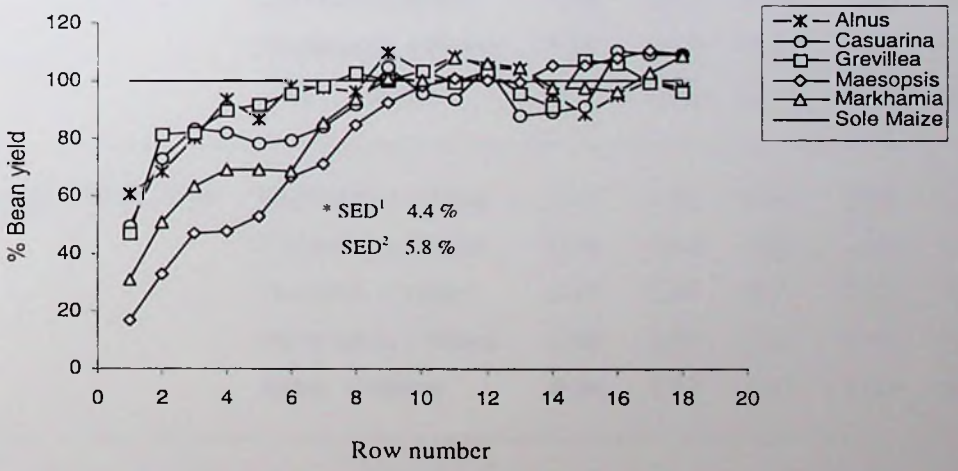
Table 4.7 Percentage reduction on bean biomass and grain yield, relative to sole crop maize, by the tree species in August-November 1997 season

Parameter	Species	Percentage reduction in bean biomass and yield Distance from tree (m)						
		0.6	*1.2*	*1.8*	*2.4*	*3.0*	*3.6*	*4.2*
Bean biomass	*Maesopsis*	81	64	54	46	42	30	24
	Markhamia	63	38	30	26	27	25	11
	Casuarina	50	26	15	23	22	20	18
	Grevillea	48	14	22	6	4	0	0
	Alnus	32	22	14	3	4	0	0
Bean yield	*Maesopsis*	83	67	53	52	47	33	29
	Markhamia	69	49	37	31	31	32	15
	Casuarina	50	27	17	18	22	20	16
	Grevillea	53	19	18	11	8	5	2
	Alnus	40	32	20	6	13	2	3



* Standard error difference (SED^1) between rows in treatment
Standard error difference (SED^2) between treatments for row

Figure 4.11a Effect of line planted trees of different species on bean biomass production at different distances from the tree row in August-November 1997 season. Biomass in association with trees is expressed as % of the biomass of pure bean crop.



* Standard error difference (SED^1) between rows in treatment
Standard error difference (SED^2) between treatments for row

Figure 4.11b. Bean yields in association with different species measured at different distances from the tree rows in August-November 1997 season. Yields in association with tree species are expressed as % of sole bean yields.

4.2.3 Crop Harvest Index (HI)

The harvest index, the ratio of grain yield to total biomass produced, of both maize and beans associated with the various tree species is shown in table 4.8 below. In both crops, there was slight reduction in the harvest index suggesting that inter-planting the crops with the trees had a greater effect on maize and bean grain yields than on biomass production. *Maesopsis* and *Casuarina* had a slight reduction on the maize harvest index for those rows near the trees, while *Maesopsis* and *Markhamia* similarly had a slight reduction on the harvest index of beans when compared to the other species (table 4.8).

Table 4.8. The harvest index (HI) of maize and beans associated with different tree species

Season	Tree/Crop combination	Harvest Index					
		Distance from tree (m)					
		0.8	1.5	2.3	3.0	3.8	4.5
March – May 1997	Maesopsis + Beans	0.25	0.28	0.29	0.34	0.37	0.38
	Casuarina + Beans	0.32	0.35	0.36	0.37	0.37	0.38
	Grevillea + Beans	0.34	0.35	0.36	0.38	0.37	0.37
	Markhamia + Beans	0.26	0.30	0.32	0.36	0.38	0.38
	Alnus + Beans	0.35	0.36	0.38	0.37	0.39	0.37
March – May 1998	Maesopsis + Maize	0.45	0.45	0.47	0.45	0.46	0.45
	Casuarina + Maize	0.36	0.34	0.40	0.40	0.41	0.43
	Grevillea + Maize	0.45	0.45	0.47	0.45	0.46	0.45
	Markhamia + Maize	0.46	0.40	0.41	0.40	0.41	0.43
	Alnus + Maize	0.36	0.42	0.41	0.44	0.45	0.43
August – Nov. 1998	Maesopsis + Maize	0.29	0.33	0.36	0.41	0.42	0.44
	Casuarina + Maize	0.23	0.39	0.43	0.46	0.44	0.46
	Grevillea + Maize	0.45	0.46	0.42	0.45	0.44	0.45
	Markhamia + Maize	0.46	0.44	0.40	0.41	0.43	0.47
	Alnus + Maize	0.42	0.45	0.49	0.42	0.49	0.46

4.3 Discussion

The results presented in this Chapter show that the growth and yield of both maize and beans were significantly reduced by the presence of the trees, with the effect varying according to species. Initially (2nd year) *Maesopsis* was the most competitive tree species, but later (3rd year) *Casuarina* became the most competitive. The competitive effect of the trees on crops extended progressively from 1 m distance from the tree line in the second year of tree growth, to 5 m in the third year. This indicates that trees become more competitive to the associated crops as they grow large. The results also indicate that fast growing trees with wide crowns such as *Casuarina* and *Maesopsis* were more competitive than slow growing trees with narrow crowns such as *Alnus* and *Markhamia*. This was not the case with *Grevillea* that was fast growing but less competitive than *Markhamia* which was slow growing. Similar observations on the negative effect of trees on crops have been reported in boundary/upper-storey tree planting agroforestry in a similar environment [Mwihomeke 1990; Okorio *et al* 1994; Akyeampong *et al* 1995]. The same observations have been made in semi-arid environments [Malik and Sharma 1990; Puri and Bangarwa 1992; Khybri *et al* 1992; Ralhan *et al* 1992; Singh *et al* 1993; ICRAF 1996].

There are few data in the literature on this type of agroforestry system in sub-humid environments with which to compare the present results. However, crop yield reductions caused by the competitive effect of the trees observed in the study are in agreement with most results where trees have been grown together with crops. In some studies, however, tree species such *Alnus acuminata* [Peden *et al* 1993], *Paulownia* spp. [Chirko *et al* 1996a], *Erythrina poepigiana* [Akyeampong *et al* 1995] and *Grevillea robusta* [Akyeampong *et al* 1999] have been found to significantly increase the yield of the associated crops when grown as upper-storey and /or boundary tree plantings.

A study carried out in a nearby site in Uganda [Okorio *et al* 1994] reported crop yield reductions by *Maesopsis* (60%), *Markhamia* (38%) and *Casuarina* (39%) which are comparable to those reported here. The trees in that study were of the same age (3 years) as those in the present study. Maize yield reductions in this study by these species were found to be 58% for *Maesopsis*, 49% for *Markhamia* and 59% for *Casuarina*. Decreases in bean yields for the species were 60, 43 and 27% for *Maesopsis*, *Markhamia* and *Casuarina* respectively. *Alnus acuminata* increased crop yields by 19% [Peden *et al* 1993] but in the present study it decreased maize yields by 26% and beans by 23 %. It is not

clear why this contradiction on the effect of *Alnus* on the associated crops, although Peden *et al* [1993] suggest that the yield increases observed could be due to improved soil fertility brought about by nitrogen fixation by the tree. *Grevillea* has been reported to have little or no negative effect on the yields of associated crops [Evans 1990; Mwihomeke 1992; Spiers and Stewart 1992] and in some cases increases crop yields [Akyeampong *et al* 1999]. In the present study, *Grevillea* decreased maize yields by 33% and beans by 22% when compared to sole crop plots. Nevertheless, these decreases were significantly smaller than those of *Casuarina*, *Maesopsis* and *Markhamia*. Similarly, bean yield reductions of 29 to 42% by *Grevillea* and 7 to 35% by *Markhamia,* have been reported in the highlands of Burundi [Akyeampong *et al* 1995]. Maize yields in this study were found to be higher on the eastern side of the *Maesopsis* tree line than on the western side in this study. This could have resulted from the big shade cast by the species that shelters maize plants on the eastern side at the time of the day when temperatures are high. The shading reduces soil evaporation and hence improves water use and photosynthesis by these plants. Similarly, increased wheat yields on the eastern side of a *Paulownia* tree line [Chirko *et al* 1996b] and increased millet yields on the eastern side of unpruned *Leuceana leucocephala* hedge [Corlett *et al* 1992b] have been reported. Both reports attribute these differences to varying levels of tree shade which influences crop growth and yield.

Several workers attribute decreases in crop yields in this agroforestry system to competition for light and water. However, these factors were not assessed in most of these studies, for example light [Okorio *et al* 1994] and water [Mwihomeke 1990]. In studies where they were assessed, indirect methods were used such as root exclusion in the case of competition for water [Okorio *et al* 1994; Akyeampong *et al* 1999]. Increases in crop yields due to the presence of trees in this agroforestry system, have been attributed to improved soil fertility by the trees [Peden *et al* 1993], favorable micro-climate provided by the trees [Akyeampong *et al* 1999] or complementarity in water use between the trees and crops [Howard *et al* 1995].

4.4 Summary

Tree survival and growth at the experimental site were good, except for *Alnus* that exhibited poor survival and the least growth rate. Tree survival was 100% for *Maesopsis*, *Casuarina* and *Markhamia*, 95% for *Grevillea* and 75% for *Alnus*. The tree species exhibited varying rates of growth with *Grevillea, Casuarina* and *Maesopsis* performing better than *Markhamia* and *Alnus*. *Casuarina* (12.2 m) and *Grevillea* (9.8 m) grew tallest, while *Maesopsis* (12.0 cm) and *Grevillea* (11.0 cm) had the biggest stem diameters. *Maesopsis* (5.0 m) and *Casuarina* (4.8 m) had the biggest tree crowns, while *Casuarina* (6.5 m) and *Grevillea* (4.5 m) had the tallest crowns.

The presence of the trees affected the growth and yield of the associated crops, with the effect increasing, as the trees grew bigger. The crop rows closest to the tree lines were the most affected and the effect extended up to a distance of 4.5 m from the tree line (row 6) in the last season (August-November 1998). The most competitive tree species were *Maesopsis, Casuarina* and *Markhamia,* while *Alnus* and *Grevillea* were the least competitive species, with *Alnus* affecting only the crop row nearest to the tree lines. *Maesopsis* was the most competitive species in the second year (March-May and August-November 1997 cropping seasons), but in the third year (March-May and August-November 1998 cropping seasons) *Casuarina* became the most competitive species. The effect of *Maesopsis* extended further away from the tree lines compared to that of the other species. The average maize yield reductions by the tree species for the August-November 1998 season up to a distance of 4.5 m from the tree line (rows 1 to 6) were 59, 58, 49, 33 and 25% for *Casuarina*, *Maesopsis*, *Markhamia*, *Grevillea* and *Alnus* respectively. Corresponding values for maize height reductions by the tree species were 40, 29, 27, 18 and 13%, while reductions in the LAI of maize by the tree species were 61, 62, 53, 39 and 26% respectively. Bean yield reductions by the tree species up to 4.2 m distance from the tree line (rows 1 to 7) during August-November 1997 cropping season were 60, 43, 27, 22 and 23 for *Maesopsis*, *Markhamia*, *Casuarina*, *Grevillea* and *Alnus* respectively.

CHAPTER FIVE

LIGHT INTERCEPTION

5.1 Introduction

The interception and utilization of light limits dry matter production by actively growing plants, and the success and survival of individuals in mixtures depends on how they intercept, compete for and respond to light [Ludlow 1978]. Therefore, competition for light occurs when the presence of one plant reduces the net photosynthesis of another by reducing the amount of radiant energy it receives.

In boundary/upper-storey tree planting agroforestry systems, the crop is shorter and hence at a competitive disadvantage relative to the trees. Because the canopies are separated vertically, the relationship can be analyzed as a permanent shading of the crop by the tree [Ong *et al* 1996]. Detailed measurements of PAR interception are, therefore, essential to understand the influence of the dominant tree component on light use, growth and productivity of under-storey crop. The aims of this Chapter were: -

- to measure the fraction of incident PAR reaching the crop, and the fraction that was intercepted by the crop canopy,
- to determine whether reduced crop growth and yield close to the trees were attributable to shading alone, and
- to develop a simple model for predicting the effect of tree shading on the fraction of PAR incident on the crop canopy.

The Chapter presents the results on light interception by the maize crop as influenced by the presence of the trees during March-May 1997, March-May 1998 and August-November 1998 cropping seasons. The materials and methods used in the measurement of the fraction of PAR reaching the maize canopy and the fraction intercepted by its foliage have been described in Chapter 3, section 3.6. The fraction of incoming PAR incident on the canopy of the maize crop as influenced by tree shading is presented in sub-section 5.2.1, while the fraction of PAR that was intercepted by the crop foliage is presented in sub-section 5.2.2. Section 5.3 presents the aims and objectives of the modeling process,

the methodology used and the results of the modeling process. Sections 5.4 presents the results of the study in relation to crop growth and yield presented in Chapter 4 and other related studies. A summary is given at the end of the chapter in section 5.5.

5.2 Results of Field Measurements

5.2.1 Fraction of incoming PAR incident on the maize canopy

The fraction of the incoming PAR that was incident on the maize canopy during the three cropping seasons is shown in figure 5.1. During March-May 1997 cropping season (figure 5.1a), the species significantly ($p<0.01$) reduced the fraction of the incoming PAR reaching the under-storey maize crop when compared to sole maize. *Maesopsis* (83%) and *Grevillea* (75%) significantly reduced the fraction of PAR reaching the crop more than *Casuarina* (61%) which in turn reduced it more than *Markhamia* (29%) to 0.8 m from the tree (row 1) as shown in figure 5.1a and table 5.1. *Alnus* had no effect at this distance. At 1.5 m distance (row 2), *Maesopsis* (56%) significantly reduced the PAR fraction more than *Grevillea* (29%) and *Casuarina* (23%). *Markhamia* (5%) and *Alnus* (5%) had very little effect up to this distance.

The tree species significantly reduced ($p<0.001$) the fraction of the incoming PAR reaching the crop canopy compared to sole maize during March-May 1998 cropping season as shown in figure 5.1b. The effect was observed up to a distance of 3.0 m (row 4). From 0.8 to 3.0 m distance (rows 1 to 4), *Maesopsis* (82, 75, 57 and 42%) significantly reduced the fraction of PAR more than *Grevillea* (56, 43, 28 and 20%), *Casuarina* (54, 42, 29 and 20%) and *Markhamia* (52, 33, 23 and 12%) (figure 5.1b and table 5.1). There were no significant differences for these distances (rows) between the latter three species. *Alnus* had the least effect, except for 0.8 m distance (row 1) where it was as suppressive as the other species (57%).

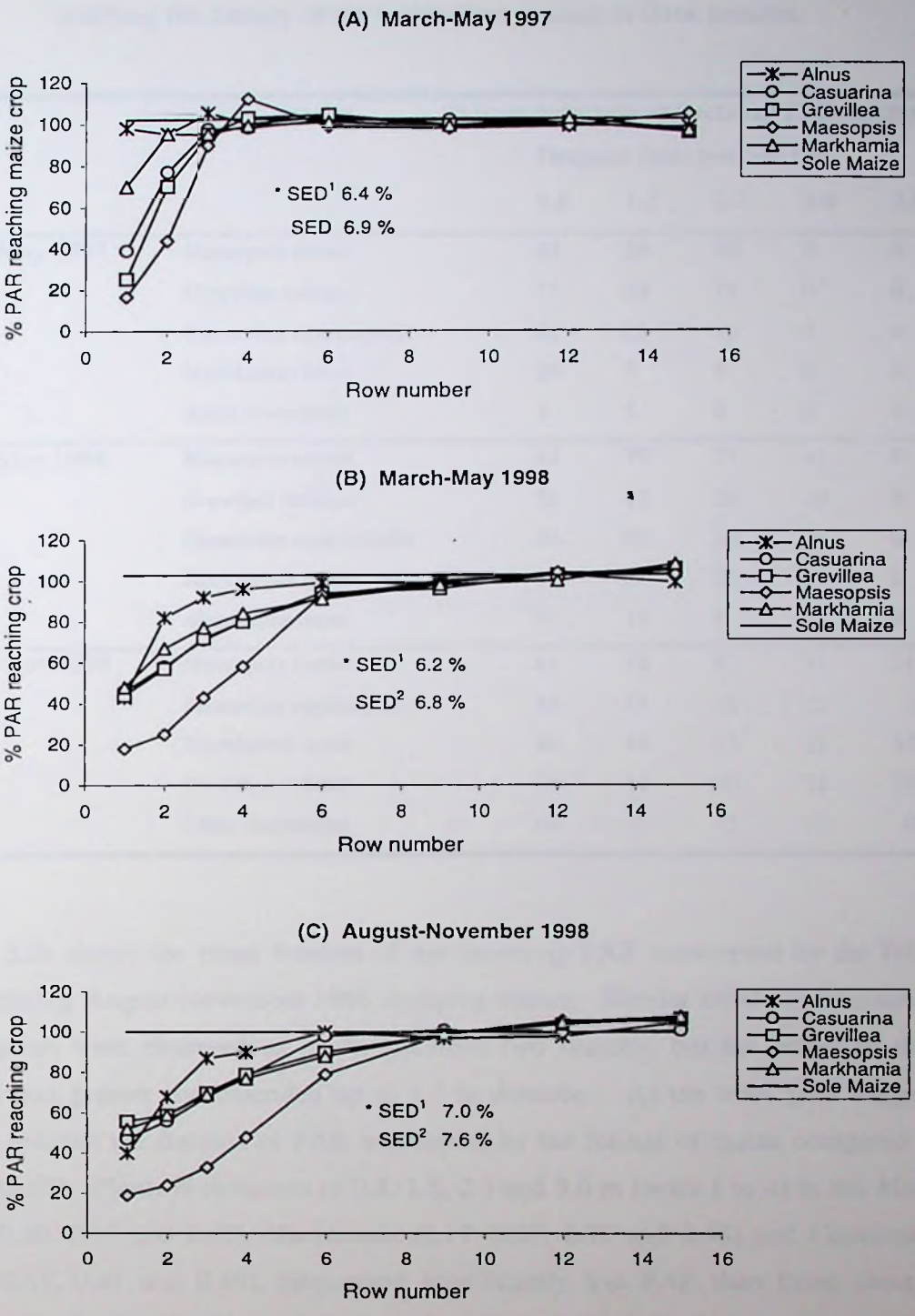
Figure 5.1c shows the effect of the tree species on the fraction PAR reaching the crop canopy during August-November 1998 cropping season. The effect of the trees was highly significant ($p<0.0001$) in this season and it was apparent up to 4.5 m distance from the trees (row 6) (figure 5.1c and table 5.1). The effect was similar to that of the previous seasons. *Maesopsis* (81, 76, 67, 52, 21 and 8%) significantly reducing the fraction of incoming PAR reaching the canopy of the crop more than the other species when

compared to sole maize at distances of 0.8, 1.5, 2.3, 3.0, 3.8 and 4.5 m (rows 1 to 6). *Alnus* (60%) significantly reduced the fraction of PAR more than *Markhamia* (48%) and *Grevillea* (44%) at 0.8 m distance (row 1), but had a smaller effect than these species at distances of 1.5, 2.3, 3.0 and 4.5 m (rows 2, 3, 4 and 6). There were no significant differences between *Casuarina* (53, 44, 32 and 22%), *Markhamia* (48, 41, 31 and 23%) and *Grevillea* (44, 41, 30 and 21%) up to 3.0 m distance (rows 1 to 4). Table 5.1 shows percentage reduction in the fraction of the incoming PAR that reached the canopy of the under-storey maize crop during the three cropping seasons.

5.2.2 Fraction of PAR intercepted by the foliage of the maize crop

The mean fraction of the incoming PAR that was intercepted by the maize crop during the three cropping seasons is shown in figure 5.2. During March-May 1997 cropping season (figure 5.2a), the mean fraction of PAR intercepted by the foliage of the maize crop was significantly lower in the tree plots at 0.8 and 1.5 m distances (rows 1 and 2) when compared to sole maize (0.65). Maize plants in the *Maesopsis* (0.2, 0.41), *Casuarina* (0.34, 0.57) and *Grevillea* (0.28, 0.54) plots intercepted significantly less PAR than those in the *Markhamia* (0.42, 0.64) and *Alnus* (0.63, 0.60) for these distances (rows) (figure 5.2a).

Mean fractional PAR interception by the foliage of the maize crop during March-May 1998 cropping season is shown in figure 5.2b. Maize plants at distances of up to 3.0 m (rows 1 to 4) in the tree plots significantly ($p< 0.001$) intercepted less radiation than those in sole maize (0.57). *Maesopsis* (0.16, 0.28, 0.38 and 0.47) and *Casuarina* (0.23, 0.33, 0.41 and 0.50) plots intercepted significantly less PAR than those in the *Markhamia* (0.28, 0.43, 0.46 and 0.46) and *Grevillea* plots (0.33, 0.44, 0.52 and 0.53) at these distances. The mean fraction of PAR intercepted by plants at 1.5, 2.3 and 3.0 m (rows 2, 3 and 4) in the *Alnus* plot (0.52, 0.51, 0.53) were not significantly different from that of sole maize except at 0.8 m distance (row 1) (0.30). Average mean fractional PAR interception upto 3.0 m distance (four rows) were 0.32, 0.37, 0.41, 0.46 and 0.47 for *Maesopsis*, *Casuarina*, *Markhamia*, *Grevillea* and *Alnus* respectively.



*SED¹ between rows in treatment

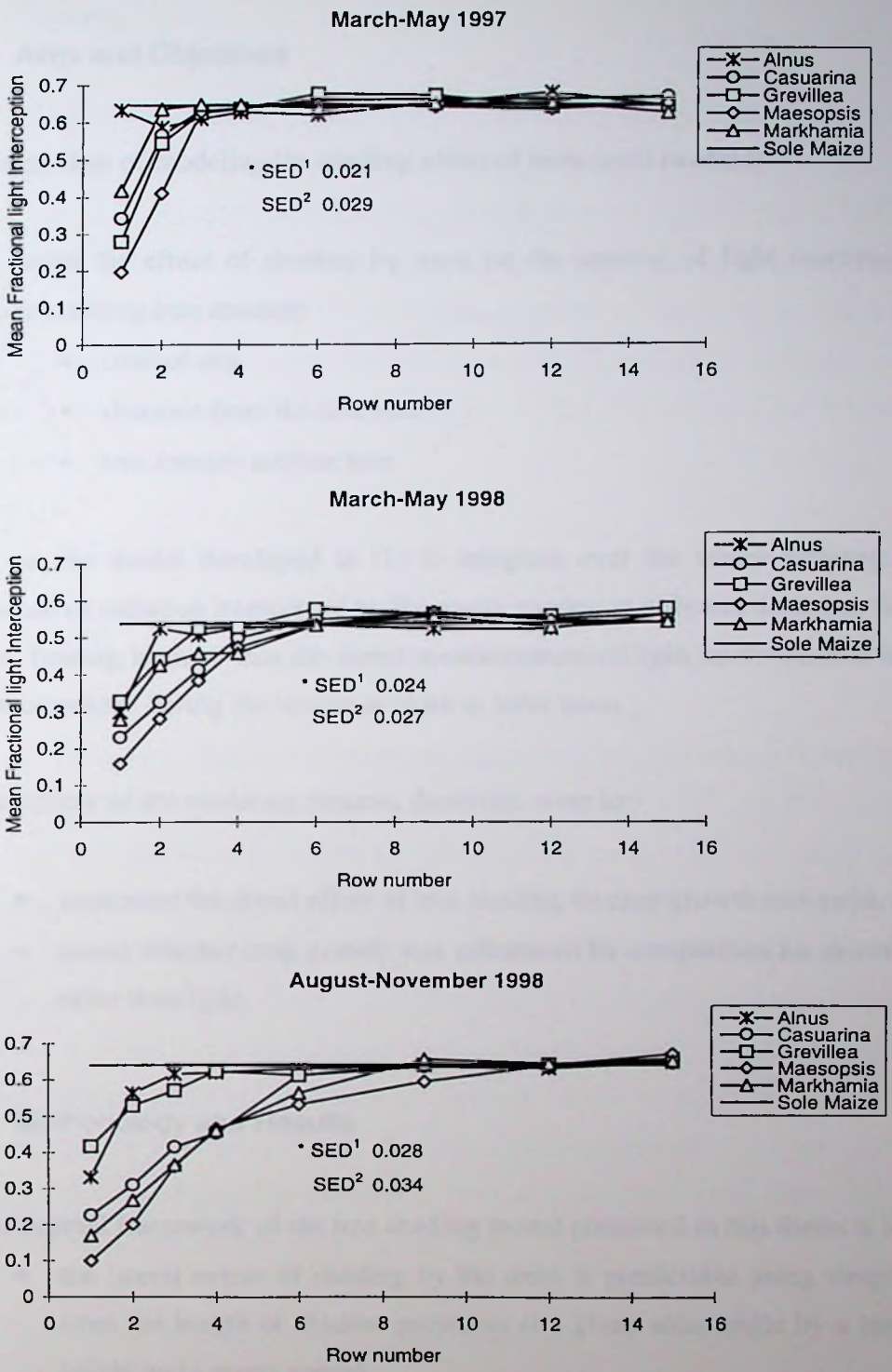
SED² between treatments for row

Figure 5.1 Effect of the tree species on the fraction of the incoming PAR reaching the maize crop for (A) March-May 1997, (B) March-May 1998 and (C) August-November 1998 cropping seasons.

Table 5.1 Percentage reduction, compared to sole maize, in the fraction of incoming PAR reaching the canopy of the under-storey maize in three seasons.

Season	Species	Percent reduction of fractional PAR reaching crop					
		Distance from tree line (m)					
		0.8	1.5	2.3	3.0	3.8	4.5
March-May 1997	*Maesopsis eminii*	83	56	10	0	0	0
	Grevillea robusta	75	29	15	0	0	0
	Casuarina equisetifolia	61	23	12	0	0	0
	Markhamia lutea	29	5	5	0	0	0
	Alnus acuminata	3	5	0	0	0	0
March-May 1998	*Maesopsis eminii*	82	75	57	42	0	0
	Grevillea robusta	56	43	28	20	0	0
	Casuarina equisetifolia	54	42	29	20	0	0
	Markhamia lutea	52	33	23	16	0	0
	Alnus acuminata	57	18	8	4	0	0
August-Nov.1998	*Maesopsis eminii*	81	76	67	52	21	8
	Casuarina equisetifolia	53	44	32	22	2	1
	Markhamia lutea	48	41	31	23	12	0
	Grevillea robusta	44	41	30	21	10	3
	Alnus acuminata	60	32	13	10	0	0

Figure 5.2c shows the mean fraction of the incoming PAR intercepted by the foliage of maize during August-November 1998 cropping season. Similar trends in fractional PAR interception were observed as in the previous two seasons, but the effect of the trees species was greater and extended up to 4.5 m distance. As the trees grew bigger, they further reduced the fraction of PAR intercepted by the foliage of maize compared to sole maize (0.65). Plants at distances of 0.8, 1.5, 2.3 and 3.0 m (rows 1 to 4) in the *Maesopsis* (0.10, 0.20, 0.36 and 0.47), *Markhamia* (0.17, 0.27, 0.37 and 0.46) and *Casuarina* plots (0.23, 0.31, 0.41 and 0.45), intercepted significantly less PAR than those close to the *Grevillea* (0.42, 0.53, 0.57 and 0.62) and *Alnus* plots (0.33, 0.56, 0.62, and 0.62). At 0.8 m (row 1), plants in *Alnus* plots (0.30) intercepted significantly less PAR than those in the *Grevillea* plots (0.33). Average interception values for these distances (rows) were 0.28, 0.32, 0.35, 0.54 and 0.53 for *Maesopsis*, *Markhamia*, *Casuarina*, *Grevillea* and *Alnus* respectively. The effect of the trees gradually extended from 1.5 m distance (row 2) in March-May 1997 to 4.5 m distance (row 6) in August-November 1998.



* Standard error difference (SED^1) between rows in treatment

Standard error difference (SED^2) between treatments for row

Figure 5.2 Mean fractional light interception by maize foliage (average of 4 measurements) for (A)March-May 1997, (B) March-May 1998 and (C) August-November 1998 cropping seasons. Light interception by the maize foliage is expressed relative to the light incident on the maize canopy.

5.3 Modeling the Shading effect of Trees

5.3.1 Aims and Objectives

The major aims of modeling the shading effect of trees were twofold: -

1. to model the effect of shading by trees on the amount of light reaching the maize canopy, taking into account:-
    - time of day
    - distance from the tree line
    - tree canopy architecture

2. to use the model developed in (1) to integrate over the maize growing season the amount of radiation intercepted by the maize canopy at different distances from the tree line, bearing in mind that the direct measurements of light interception were made on few occasions during the season at close to solar noon.

The objectives of the modeling process, therefore, were to:-

- determine the direct effect of tree shading on crop growth and yield, and
- assess whether crop growth was influenced by competition for growth resources other than light.

5.3.2 Methodology and Results

The conceptual framework of the tree shading model presented in this thesis is as follows:-

- the lateral extent of shading by the trees is predictable using simple geometry from the length of shadow projected at a given solar angle by a tree of known height and canopy spread.
- within the shadow of the tree, the fraction of incident radiation that penetrates the tree canopy at a given fraction of the shadow length remains constant, irrespective of time of day or time during the maize growing season.

5.3.2.1 The effect of Diurnal Variation in shadow length on the extent of Crop Shading

The length of shadow cast by the tree line (i.e. the lateral extent of shading) depends on the solar angle and the geometry of the tree. The approximate geometries of the canopies of the tree species in this study at 41 months after planting are shown in figure 5.3, where it is seen that the species vary widely in terms of tree height and in terms of the shape and lateral spread of the tree crown. The simplest approach to modeling the length of shadow cast by the tree line is to assume that the spread of the canopy is negligible, and that the tree line is in effect a thin "wall" of height H. In this case the furthest extent of shading from the tree line (S) is given by

$$H = S / tan\ \alpha \qquad (5.1)$$

where α is the solar angle which depends on latitude, altitude, time of day and time of year.

Figure 5.1 provides a data set for each tree species that enables estimation of the values of S based on fraction light interception made at close to solar noon. Based on these data, an estimate of the effective tree height for each species can be obtained using equation 5.1, taking appropriate values for S (from figure 5.1) and α. Figure 5.4 shows the relationship between the effective tree height calculated in this way and the measured height of the tree. Also shown is the 1:1 line. It can be seen that most of the points lie close to (but slightly above) the 1:1 line, suggesting a slight bias towards overestimating tree height. This is expected because equation 5.1 takes no account of the effect of the spread of the tree crown on the length of shadow cast. It is notable that *Maesopsis* is the species where there is the greatest overestimate of tree height, which is consistent with *Maesopsis* having the greatest lateral spread of tree crown (figure 5.3).

Figure 5.5 shows the influence of time of day on the extent of tree shading that is calculated using equation 5.1 based on the effective tree height (H) and the diurnal variation in solar angle. Predictions are shown for the three maize growing seasons, where it is seen that the lateral extent of shade increases from season to season, as the trees grow taller. The differences between the tree species in the lateral extent of shade become most marked at low solar angles, where there was a two-fold range of shadow length between the shortest tree (*Alnus*) and the much taller *Grevillea*, *Maesopsis* and *Casuarina*.

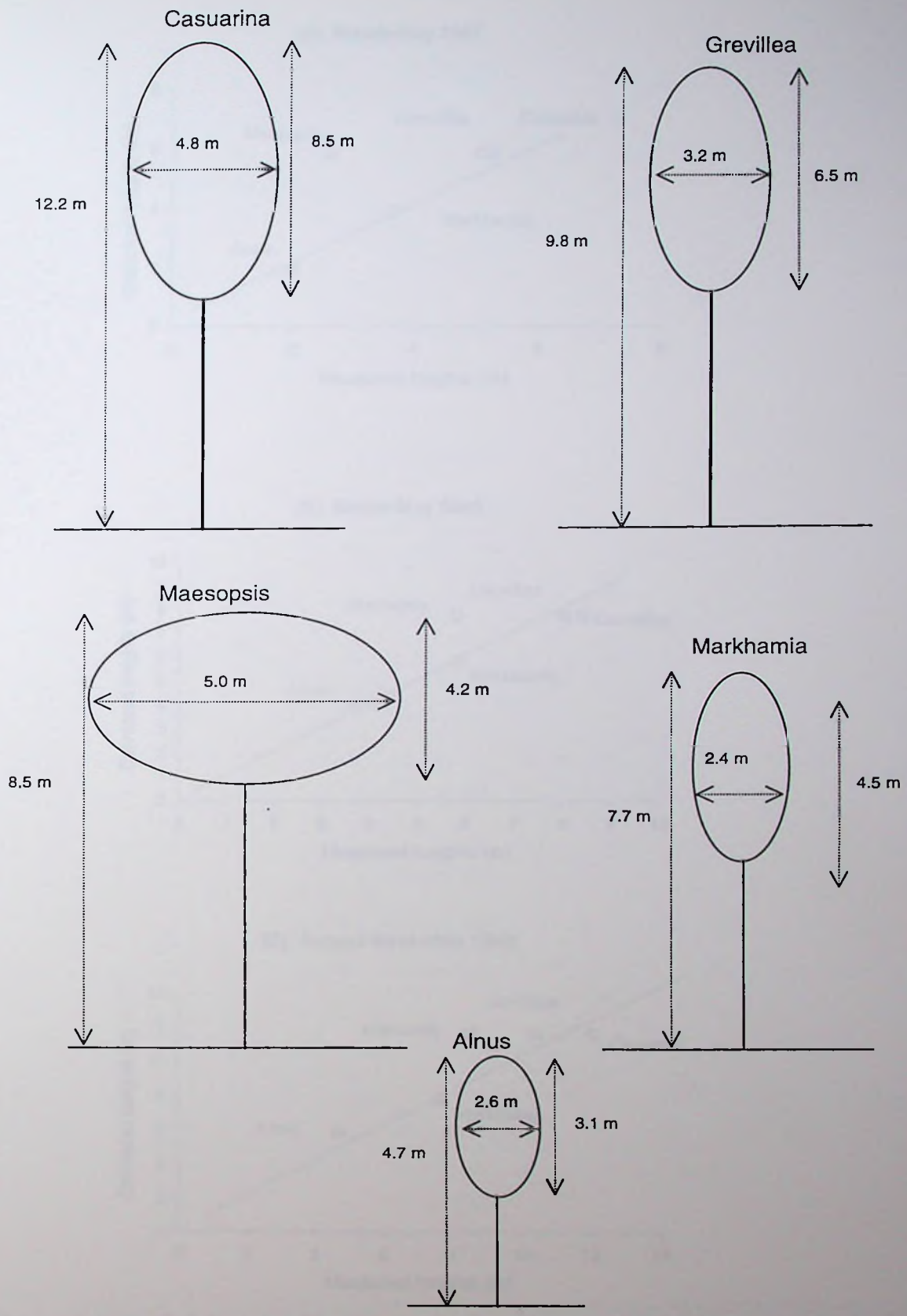


Figure 5.3. The dimensions, heights and canopy size, of the trees used in the modeling process.

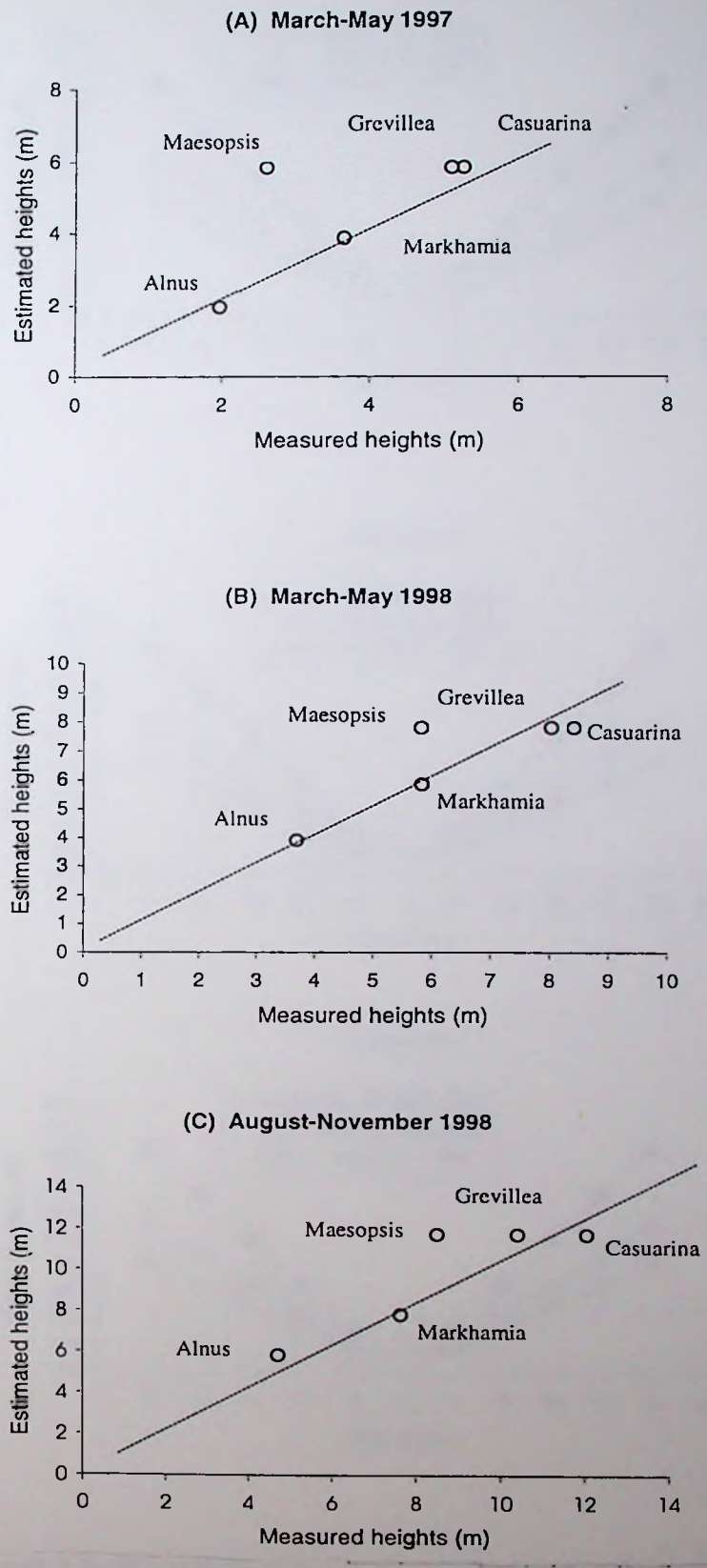
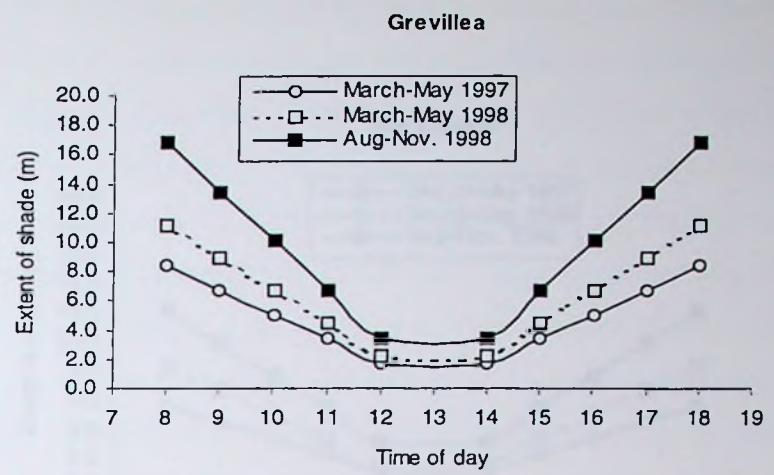
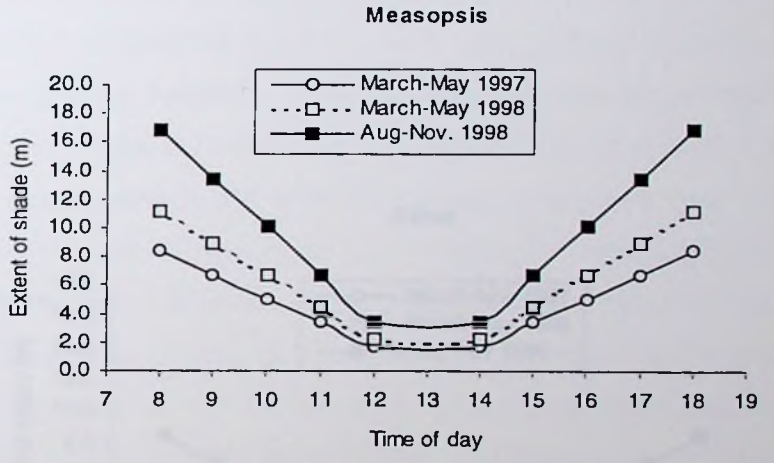


Figure 5.4. Estimated tree heights plotted against measured tree heights for tree species during (A) March-May 1997, (B) March-May 1998 and (C) August-November 1998 seasons.





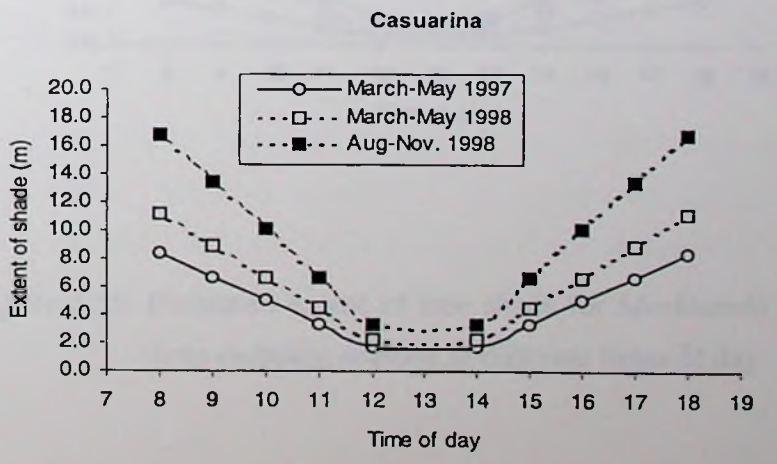


Figure 5.5a Estimated extent of tree shade for *Grevillea*, *Maesopsis* and *Casuarina* during the three cropping seasons at different times of day.

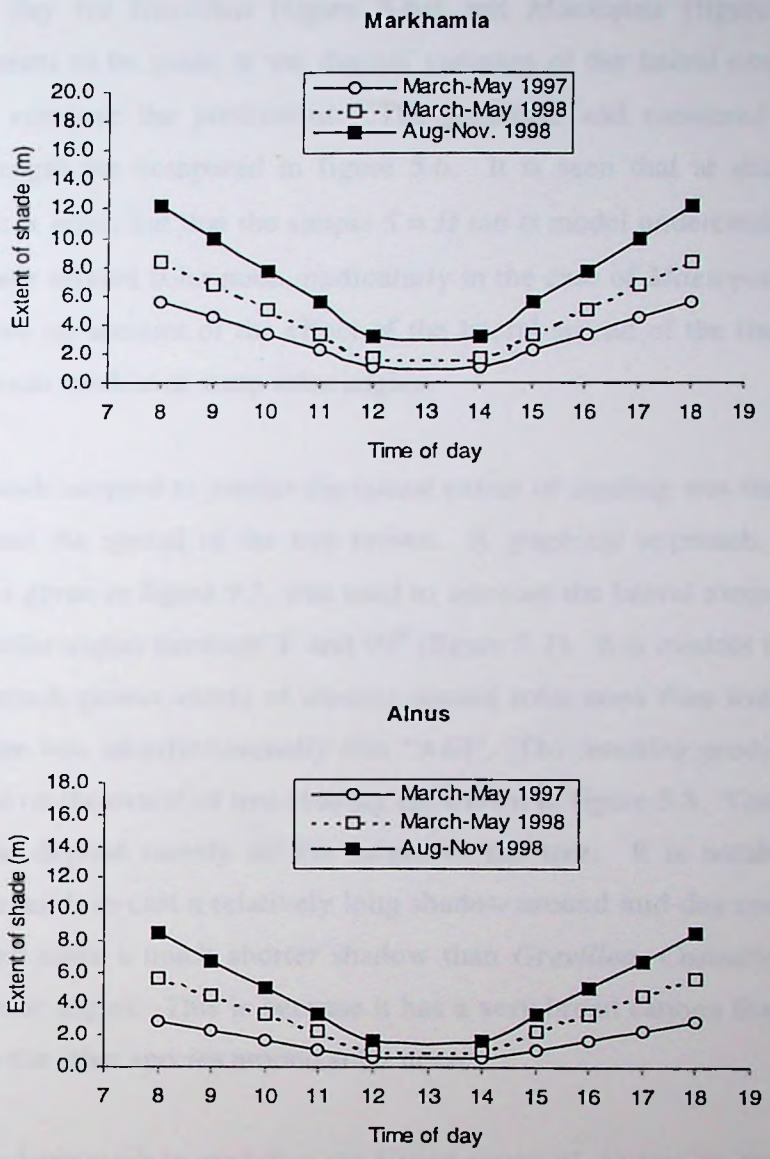
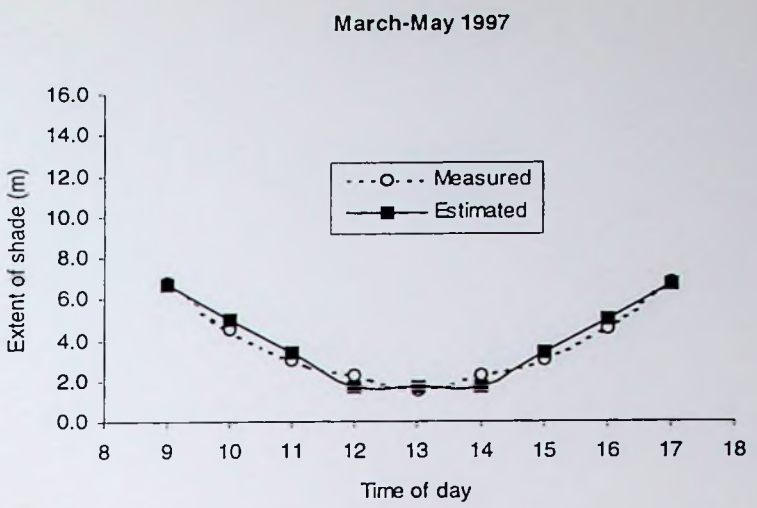


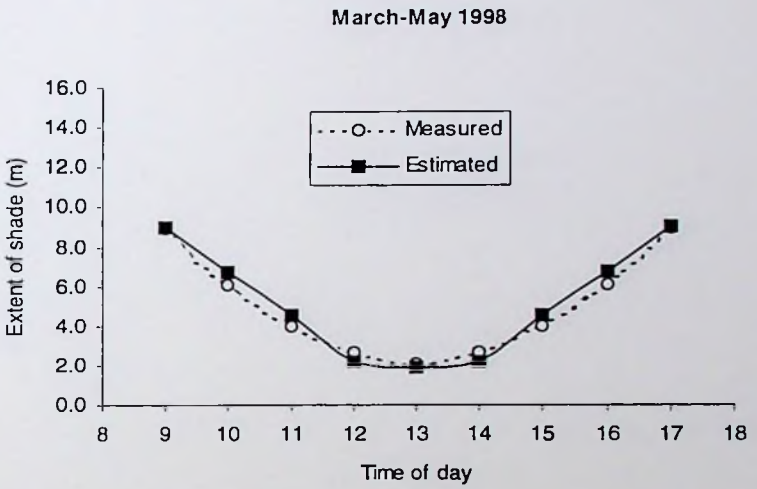
Figure 5.5b. Estimated extent of tree shade for *Markhamia* and *Alnus* during the three cropping seasons at different times of day

To verify the predictions made in figure 5.5, measurements for fractional light penetration through the tree canopy at different distances from the tree line were made at different times of day for *Grevillea* (figure 5.6a) and *Maesopsis* (figure 5.6b). This enabled measurements to be made of the diurnal variation of the lateral extent of tree shade with which to compare the predictions. The predicted and measured diurnal variations in shadow length are compared in figure 5.6. It is seen that at shallow solar angles the agreement is good, but that the simple $S = H \tan \alpha$ model underestimates the lateral extent of tree shade around solar noon, particularly in the case of *Maesopsis*. This is because the model takes no account of the effect of the lateral spread of the tree crown, the effect of which is most marked at steep solar angles.

The approach adopted to predict the lateral extent of shading was therefore refined to take into account the spread of the tree crown. A graphical approach, based on the canopy geometries given in figure 5.3, was used to estimate the lateral extent of tree shading for a range of solar angles between 0^0 and 90^0 (figure 5.7). It is evident that this approach will predict a much greater extent of shading around solar noon than would be made assuming the tree line was an infinitesimally thin "wall". The resulting predictions of the effect of solar angle on the extent of tree shading are shown in figure 5.8. This produces a family of curves that depend mainly on the height of the tree. It is notable that the curve for *Maesopsis* tends to cast a relatively long shadow around mid-day compared with the other species, but casts a much shorter shadow than *Grevillea*, *Casuarina* and *Markhamia* at shallow solar angles. This is because it has a very broad canopy that casts a long shadow relative to the other species around solar noon.

This refined approach to modeling the lateral extent of shading by the tree line was used in the analysis which follows, of the effect of tree shading on light intercepted by the maize under-storey. Figure 5.9 shows the performance of this refined model of shadow length, as judged from comparison of the lateral extent of tree shade with the measurements made around solar noon which shows that the predictions were generally within 0.5 m of the observations.





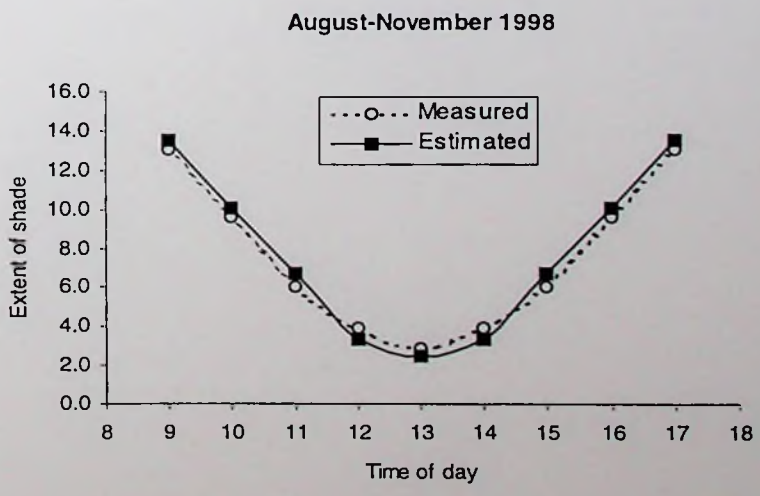


Figure 5.6a Measured and estimated extent of *Grevillea* tree shade for (A) March-May 1997, (B) March-May 1998 and (C) August-November 1998 cropping seasons.

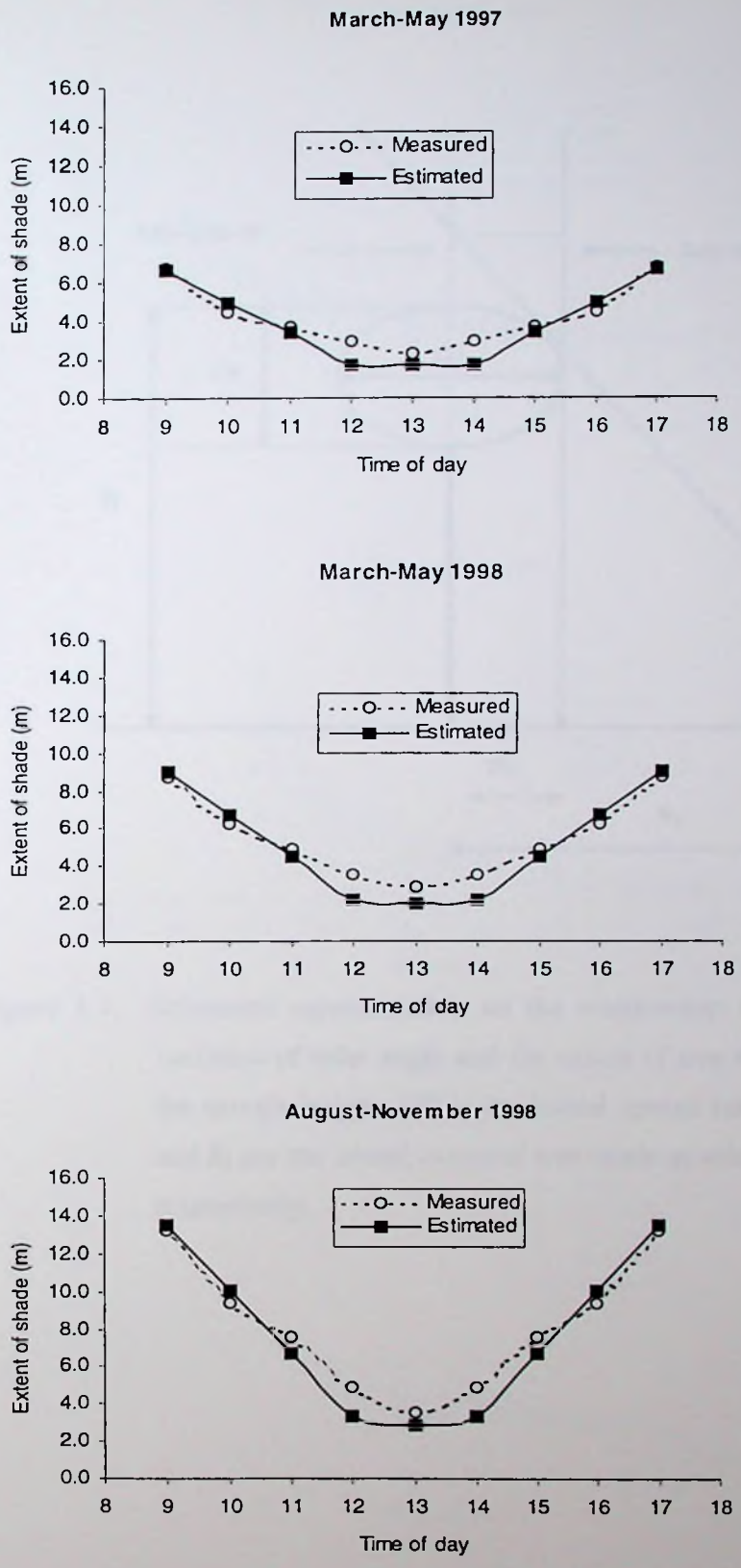


Figure 5.6b Measured and estimated extent of *Maesopsis* tree shade for (A) March-May 1997, (B) March-May 1998 and (C) August-November 1998 cropping seasons.

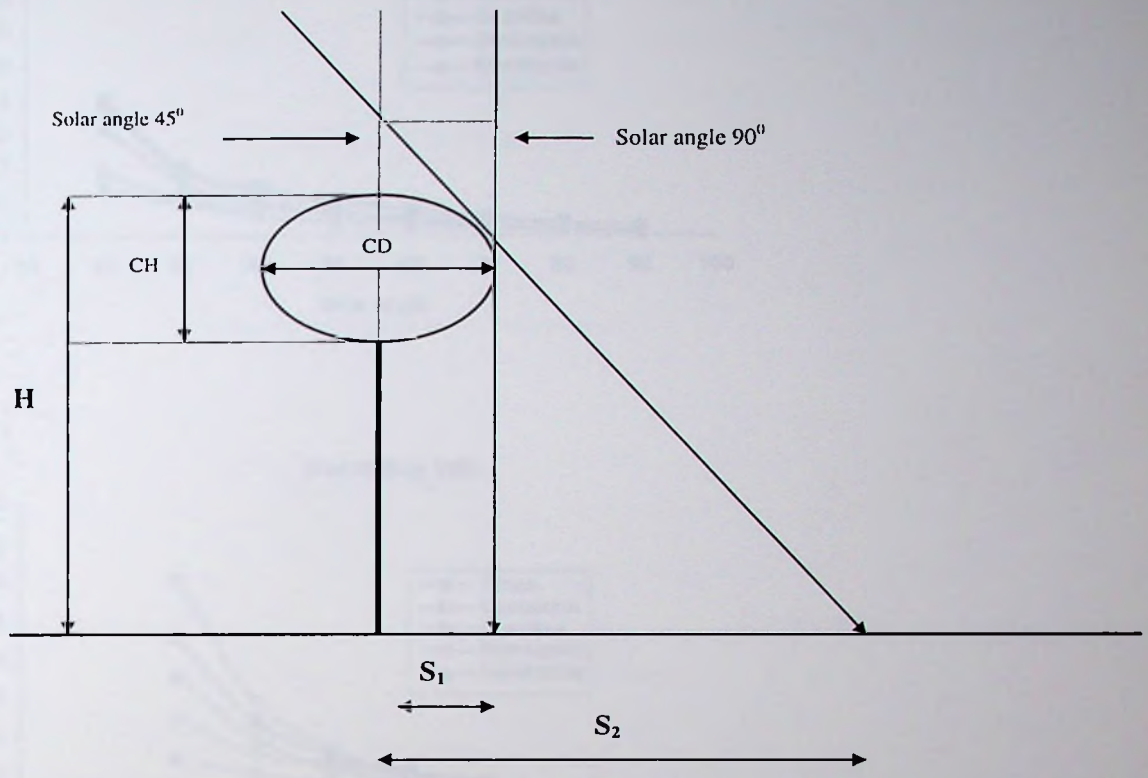


Figure 5.7. Schematic representation on the relationship between canopy size, diurnal variation of solar angle and the extent of tree shade. *H* is tree height, *CH* is the canopy height, *CD* is the lateral spread (diameter) of the canopy and S_1 and S_2 are the lateral extent of tree shade at solar angles of 90^0 and 45^0 respectively.

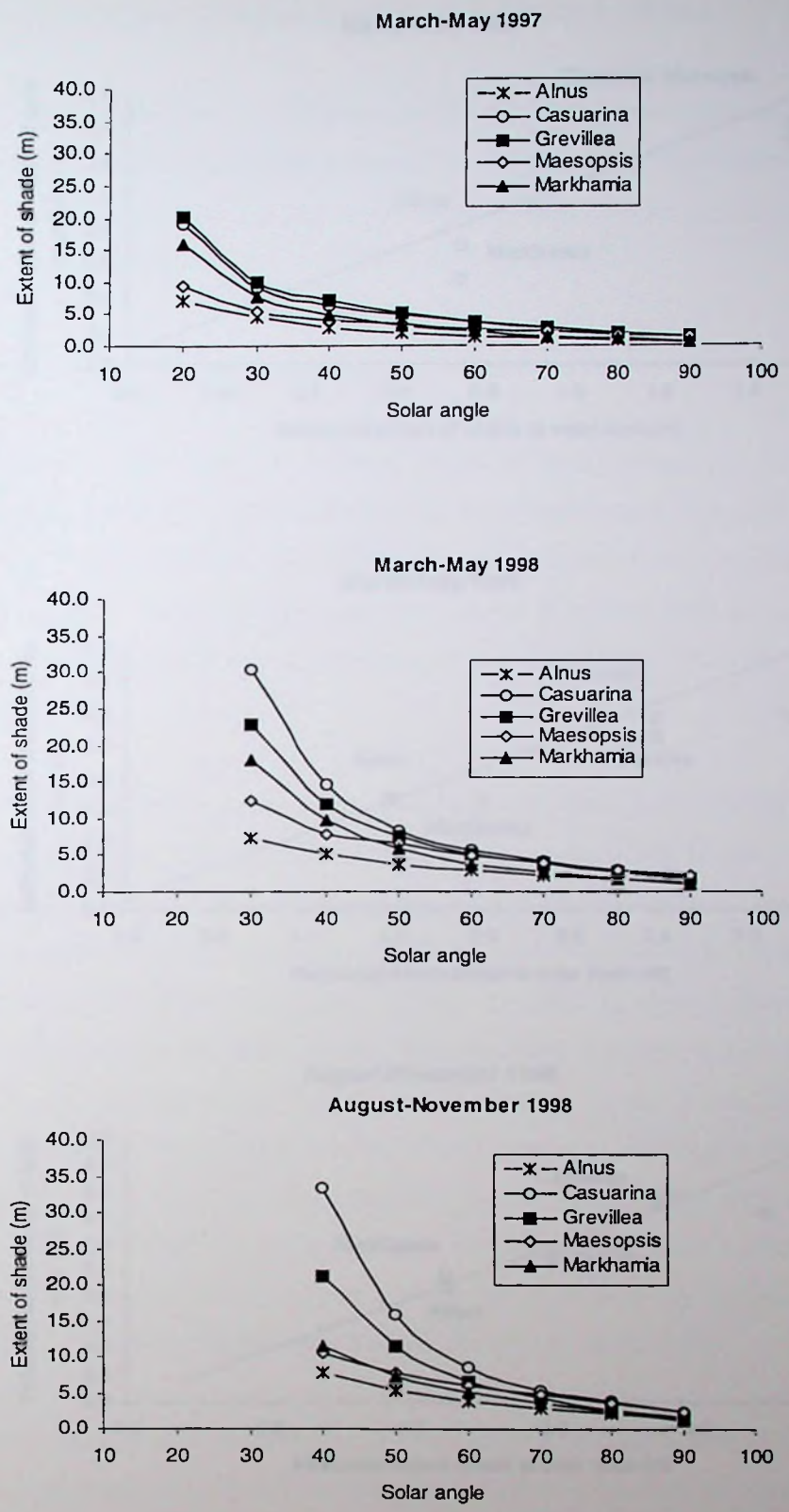


Figure 5.8 Modeled extent of tree shade for the species based on tree height and crown dimensions for (A) March-May 1997, (B) March-May 1998 and August-November 1998 cropping seasons.

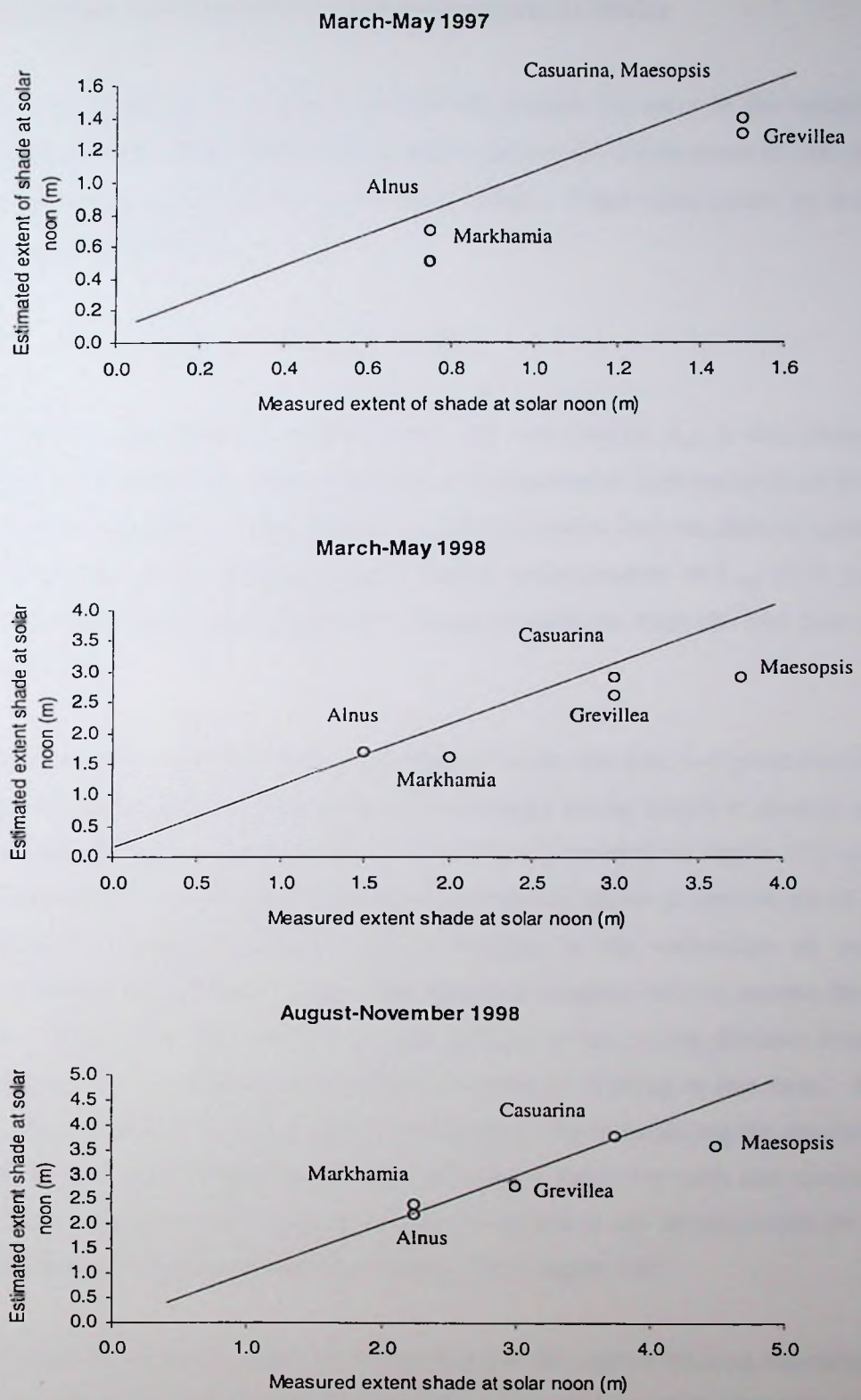


Figure 5.9 Measured extent of tree shade plotted against estimated extent of tree shade at solar noon for (A) March-May 1997, (B) March-May1998 and August-November 1998 cropping seasons. The line shown in the graphs is 1:1 line.

5.3.2.2 Diurnal variation in Light Interception by Maize

Having established a model to predict the diurnal variation in the lateral extent of tree shade, the next stage of the analysis was to predict the implications for the diurnal variation in light interception by the under-storey maize. Light interception by the maize canopy (S_{maize}) is given by:-

$$S_{maize} = I_o * f_{crop} * (1 - f_{tree}) \quad (5.2)$$

where I_o is the radiation incident above the tree canopy, f_{tree} is the fraction of I_o that is intercepted by the tree canopy and f_{crop} is the fraction of light incident on the maize canopy that is intercepted by maize foliage. f_{crop} is assumed to have no diurnal variation, but varies through the maize growing season. Direct measurements of f_{crop} were made at 4 times during each season and depended strongly on distance from the tree line as illustrated in figure 5.2.

The value of $(1-f_{tree})$ for maize rows shaded by the tree line is expected to depend strongly on solar angle, because of the effect of solar angle on the length of shadow cast by the tree. However, routine measurements of $(1-f_{tree})$ (as presented in figure 5.1) were only made close to solar noon, and there is need to predict the values at other times of day in order to account for diurnal variation in tree shading in the estimation of cumulative light interception by the maize crop. The approach adopted was to assume that at any given time of day, the value of $(1-f_{tree})$ was constant at any given distance from the tree line expressed as a fraction of the maximum extent of shading at that time. In other words, replotting the data for $(1-f_{tree})$ shown in figure 5.1 by normalizing the distance from the tree line by the lateral extent of shading, provides a curve for each tree species. This curve enables prediction of $(1-f_{tree})$ at any time of day and at any distance from the tree line given knowledge of the lateral extent of shading (from figure 5.8).

Polynomial equations (table 5.1) were fitted to the curves relating measured values of $(1-f_{tree})$ to distance from the tree line expressed as a function of the maximum extent of shade at the time of day that $(1-f_{tree})$ was measured. The polynomials were used to predict, for each row of maize, how $(1-f_{tree})$ varies with time of day. The next step was to calculate effective mean daily values of $(1-f_{tree})$ which will be denoted as $(\overline{f}_{tree})$ for each maize row for the purpose of estimating daily S_{maize} using equation 5.2.

Table 5.1. Polynomial equations used to estimate the variation of (1-f_{tree}) with distance from the tree line for each tree species during the three cropping seasons.

Species	Equation	R^2
	March-May 1997 cropping season	
Maesopsis	*$Y = 0.0112X^3 - 0.1326X^2 + 0.5348X + 0.2914$	0.999
Casuarina	$Y = 0.0112X^3 - 0.1326X^2 + 0.5348X + 0.2914$	0.999
Grevillea	$Y = 0.0112X^3 - 0.1326X^2 + 0.5348X + 0.2914$	0.999
Markhamia	$Y = 0.0033X^3 - 0.0589X^2 + 0.3565X + 0.2914$	0.999
Alnus	$Y = 0.0004X^3 - 0.0147X^2 + 0.1783X + 0.2914$	0.999
	March-May 1998 cropping season	
Maesopsis	$Y = 0.0595X^4 - 0.7942X^3 + 1.6917X^2 - 0.3747X + 0.1907$	0.998
Casuarina	$Y = 0.0091X^4 - 0.0278X^3 - 0.1324X^2 + 0.6436X + 0.3043$	0.999
Grevillea	$Y = 0.0264X^4 - 0.1299X^3 + 0.0253X^2 + 0.5985X + 0.2885$	0.998
Markhamia	$Y = 0.0236X^5 - 0.2289X^4 + 0.8591X^3 - 1.6049X^2 + 1.6264X + 0.1617$	0.999
Alnus	$Y = 0.0336X^4 + 0.3629X^3 - 1.3863X^2 + 2.2641X - 0.3965$	0.998
	August-November1998 cropping season	
Maesopsis	$Y = 0.1824X^5 + 1.3896X^4 - 3.8983X^3 + 4.622X^2 - 1.4859X + 0.3322$	0.999
Casuarina	$Y = - 0.2779X^6 + 1.8784X^5 - 4.5215X^4 - 4.5908X^3 - 1.9876X^2 + 0.9476X + 0.3483$	0.999
Grevillea	$Y = 0.3684X^6 - 2.8613X^5 + 8.5932X^4 - 12.545X^3 + 8.9634X^2 - 2.3778X + 0.7587$	0.999
Markhamia	$Y = 0.2265X^6 - 1.7023X^5 + 4.9126X^4 - 6.8365X^3 + 4.5329X^2 - 0.8107X + 0.557$	1.000
Alnus	$Y = - 0.0047X^6 + 0.0721X^5 - 0.4401X^4 + 1.3756X^3 - 2.4301X^2 + 2.4718X - 0.2027$	0.995

* where Y is the value of (1- f_{tree}) and X is the distance from the tree line expressed as a function of the maximum extent of shade at the time of day that Y was measured.

This is done by calculating a weighted daily average of ($1-f_{tree}$) according to the fraction of daily radiation incident at each hour of the day, that is,

$$\overline{f}_{tree} = \sum_{h=0}^{h=24} f_{tree,hour} * f_{I,hour} \qquad (5.3)$$

where f_I is the fraction of daily radiation that is incident in each hour of the day. An estimate of $f_{I,hour}$ was obtained using hourly radiation records over the season to establish an empirical relationship between $f_{I,hour}$ and hour of day (figure 5.10). Figure 5.11 shows, for each species, how f_{tree} varied with distance from the tree line. Comparison with the values measured close to solar noon (figure 5.1) shows that $\overline{f}_{tree}$ extends further from the tree line, because account is taken of times at day when longer shadows are cast. However, the comparisons between species are similar to that noted in the discussion of figure 5.1.

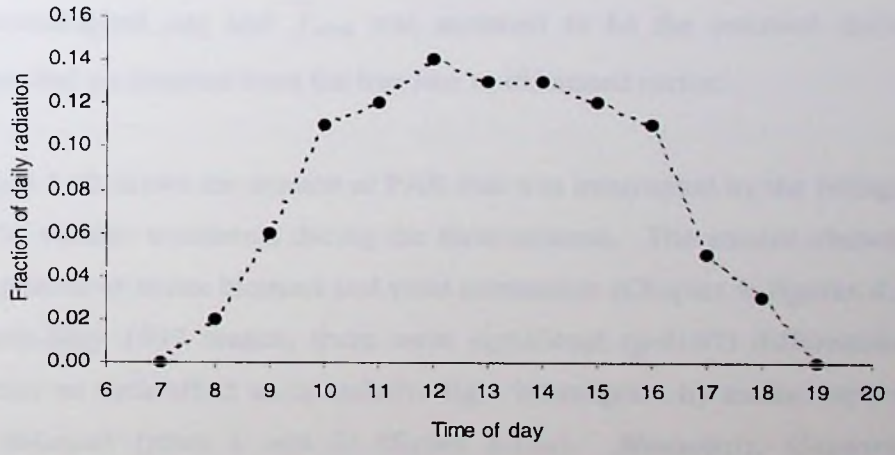


Figure 5.10. The relationship between fraction of daily radiation and hour of day

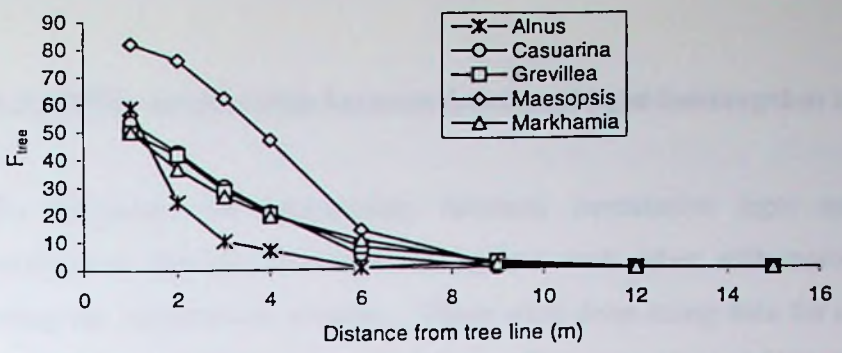


Figure 5.11. The variation of f_{tree} as a function of distance from the tree line.

Since $\overline{f}_{tree}$ for each row of maize (seasonal average, assumed constant) and f_{crop} (4 values at different times during each growing season) for each row of maize are known, cumulative light interception by maize each season is given by

$$S_{maize} = \sum_{n=0}^{N} f_{crop} * (1 - f_{tree}) * Io \qquad (5.4)$$

where f_{crop} was assumed to increase daily, as estimated by linear interpolation between the measurements made on 4 occasions (40, 50, 80 and 100 DAP), and assuming that $f_{crop} = 0$ at 10 days after planting. I_o was obtained from the daily integral radiation receipts at the meteorological site and $\overline{f}_{tree}$ was assumed to be the constant during the season and depended on distance from the tree line as discussed earlier.

Figure 5.12 shows the amount of PAR that was intercepted by the foliage of the maize crop in the various treatments during the three seasons. The pattern shown closely resembles the pattern of maize biomass and yield production (Chapter 4, figures 4.7 and 4.8). During March-May 1997 season, there were significant ($p<0.05$) differences between the tree species on their effect on cumulative light interception by maize, especially at 0.8 and 1.5 m distances (rows 1 and 2) (figure 5.12a). *Maesopsis*, *Casuarina*, *Grevillea* and *Markhamia* had a more significant effect than *Alnus*. The differences were more significant ($p<0.0001$) during the last two seasons. *Maesopsis* and *Casuarina* significantly reduced cumulative PAR intercepted more than *Grevillea* and *Markhamia*, which in turn had a more significant effect than *Alnus* in March-May 1998 season for 0.8 to 4.5 m distances (rows 1 to 6) (figure 5.12b). During August-November 1998 season, *Casuarina*, *Maesopsis* and *Markhamia* significantly reduced the amount of cumulative PAR that was intercepted by the maize crop more than *Grevillea* and *Alnus* (figure 5.12c).

5.3.2.3 The relationship between fractional light interception and biomass production

To determine the relationship between cumulative light interception and biomass production, the two were plotted against each other with cumulative light interception being the independent variable. These were done using data for crop rows 1, 2, 3, 6, 9, 12 and 15 for each tree species. Light use efficiency values (LUE) (biomass produced divided by the cumulative light intercepted) for each species were then plotted as a function of distance from the tree line. The LUE values give an indication of the effect of tree shading on the efficiency of biomass production.

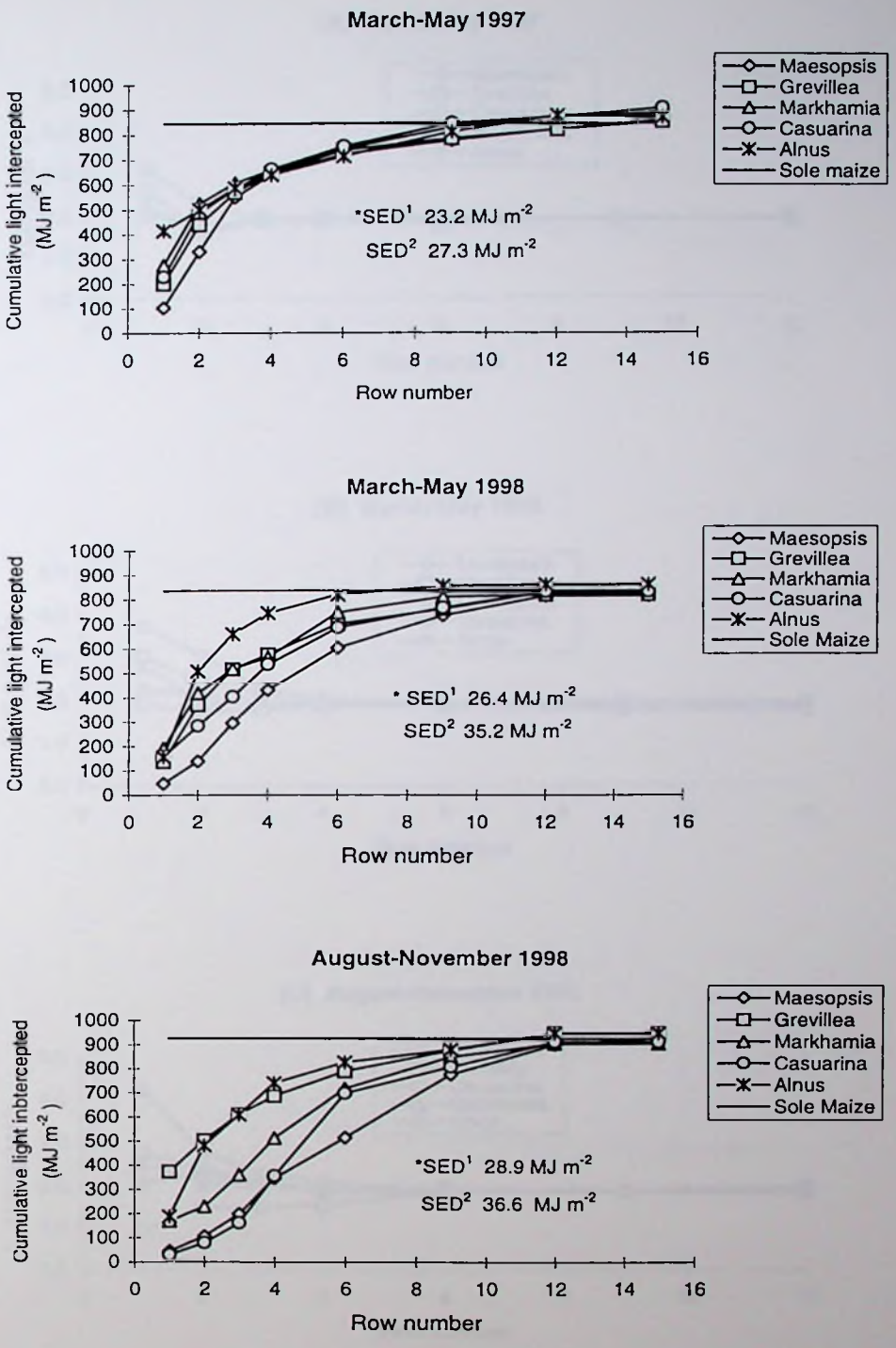
Figure 5.13 shows the light use efficiencies (LUE) of the maize crop under the various treatments as affected by distance from the tree lines. In March-May 1997 cropping season (figure5.13a), the plants at 0.8 m distance (row 1) for all the species had significantly ($p<0.05$) higher LUE values than those in other rows. This suggests that these plants produced more biomass for every unit of light they intercepted compared to those plants in rows further away from the tree lines. The differences were more significant ($p<0.001$) during March-May 1998 cropping season, by which time the effect had reached 1.5 m from the tree line (row 2) (figure 5.13b). The plants at 0.8 and 1.5 m (rows 1 and 2) in the *Casuarina* plots had LUE values that did not significantly differ from those of plants in rows that were further away from the trees. The effect of *Maesopsis* was highly significant when compared to that of the other species during the season. In the last season, plants at 0.8, 1.5 and 2.3 m from the trees (rows 1 to 3) in the *Maesopsis* plots had significantly higher LUE values when compared to those in rows further away from the tree line (figure 5.13c). This was also true for plants in the *Alnus* plots for the same rows. In the *Grevillea* plots there were no significant differences in the LUE values between the plants in all the rows. However, in the *Casuarina* and *Markhamia* plots, the plants at 0.8 m distance (row 1) had significantly lower LUE values than those in rows further away from the tree line. This implies that these plants used more light to produce a given amount of biomass.

A possible explanation of the apparent increase in maize LUE close to the tree lines is that the mean light intensity incident on the maize canopy was lower, which is expected to increase LUE because of the curvilinear nature of the photosynthetic light response curve. A second possibility is that shading by the trees reduces the temperature of the maize canopy, which might have implications for the rates of both photosynthesis and respiration.

In either case, these effects would be expected to be related to the degree of shading by the tree canopy, which has been assessed in terms of $(1-f_{tree})$. If this hypothesis were correct, then apparent differences in LUE beneath the different tree species would be expected to reflect the differences between the species in $(1-f_{tree})$. If this is so, then plotting LUE of maize against $(1-f_{tree})$, taking data from all tree species/row combinations, should produce a graph in which LUE increases with decreasing $(1-f_{tree})$(figure 5.14) and in which the data from the different tree species fall onto the same line.

Figure 5.14 shows that a large proportion of the differences between the species evident in figure 5.13 has been accounted for. For example, the very high LUE at 0.8 m distance (row 1) for *Maesopsis* in the third season can be attributed to the exceptionally low value of $(1-f_{tree})$ by comparison with the other species. This suggests that the direct or indirect effects of shading are a major factor explaining the apparent variation in LUE. However, not all of the variation in LUE is explained by taking account of $(1-f_{tree})$. For example, the low LUE of maize growing close to the *Casuarina* tree line is inconsistent with the value of $(1-f_{tree})$, implying that some other factor (such as water stress arising from competition from *Casuarina* roots) might be the factor influencing LUE.

Alternatively, it should be borne in mind that the estimates of LUE are based on a very crude model for estimating light interception by the maize crop. If for any reason this approach has tended to systematically underestimate light interception by the maize growing within the shade of the trees, then this will result in an overestimation of LUE close to the tree line. One possibility is that the procedure used to estimate the radiation incident on the maize canopy close to the trees does not allow for the possibility that the maize growing very close to the trees might be hardly shaded at low solar angles because of light passing beneath the tree crown. Also, the light transmission model used makes no attempt to partition between direct and diffuse radiation. However, the measurements of $(1-f_{tree})$ were made on days with typical cloud cover (i.e. partial shade), and measurements used in the analysis were average of 4 different days. It is reasonable to assume that the seasonal average values of $(1-f_{tree})$ were representative.



* Standard error difference (SED^1) between rows in treatment

Standard error difference (SED^2) between treatments for row

Figure 5.12. Cumulative PAR intercepted by maize in association with different upper storey trees during (A) March-May 1997, (B) March-May 1998 and (C) August-November 1998 cropping seasons.

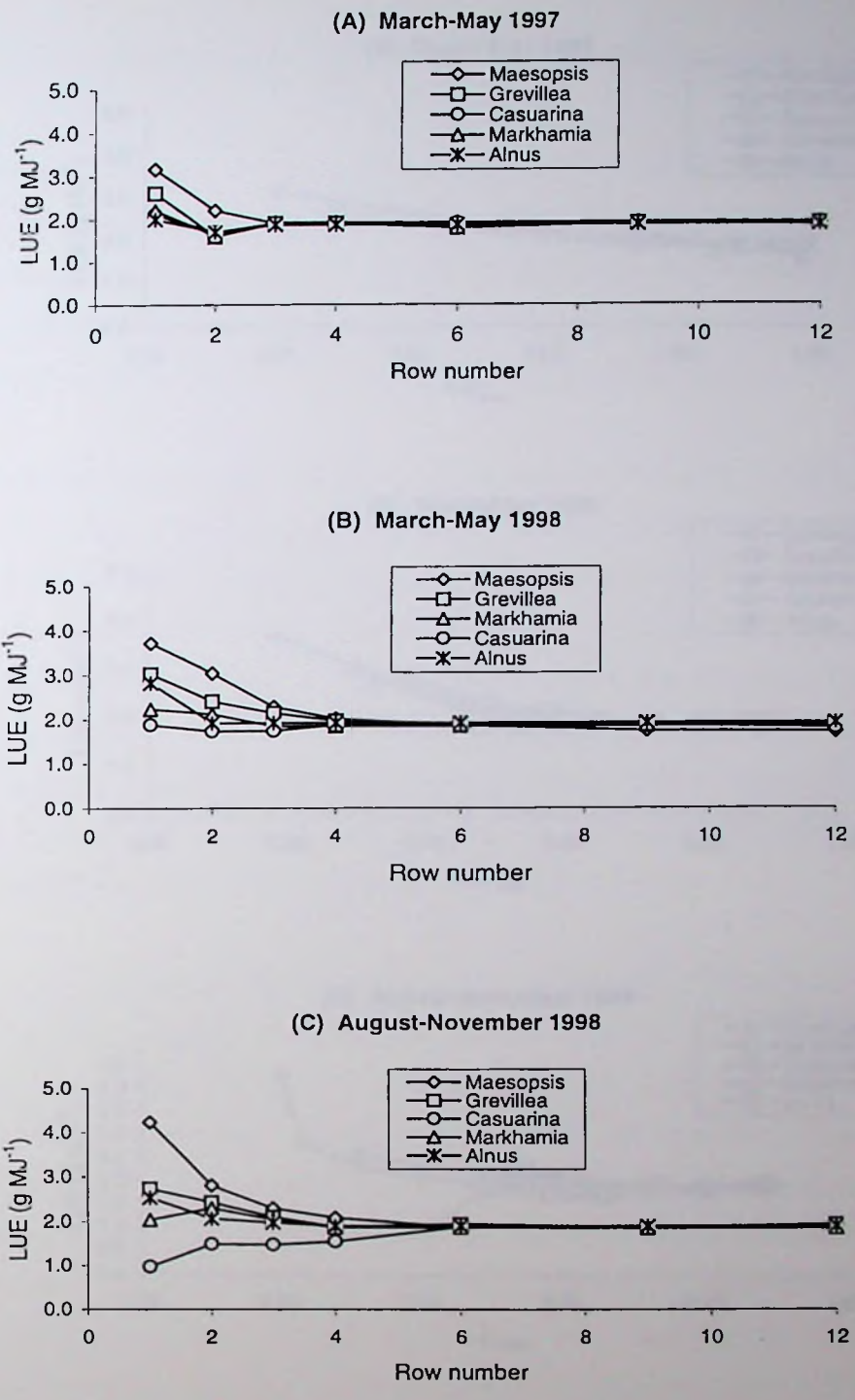


Figure 5.13 Light use efficiencies (LUE) of maize in association with different tree species as a function of distance from the tree lines during (A) March-May 1997, (B) March-May 1998 and (C) August-November 1998 cropping seasons.

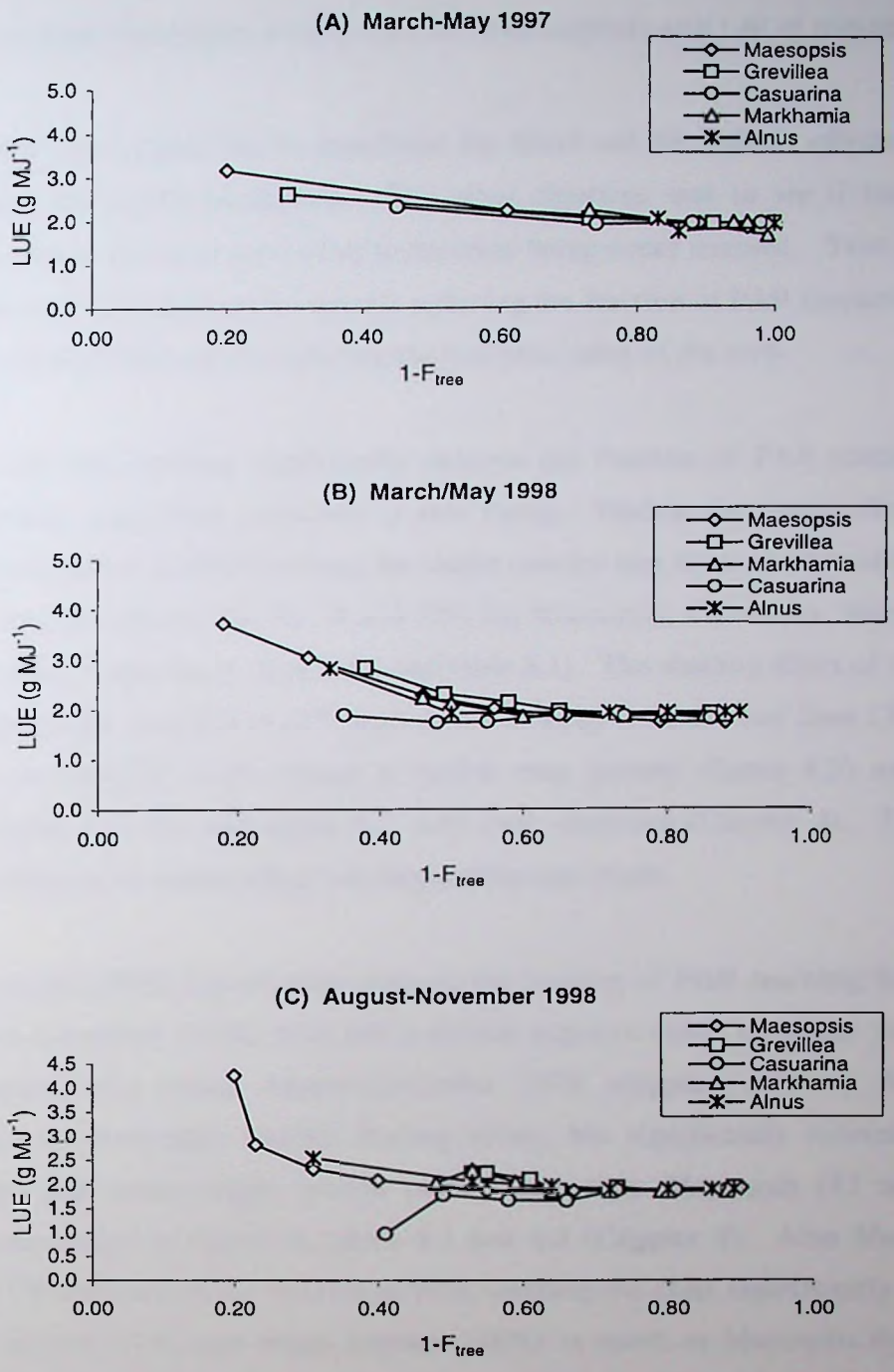


Figure 5.14 Light use efficiencies (LUE) of maize associated with different tree species as a function of ($1-f_{tree}$) values during (A) March-May 1997, (B) March-May 1998 and (C) August-November 1998 cropping seasons.

5.4 Discussion

5.4.1 Effect of tree shading on fractional PAR interception and LAI of maize

The major aim of this chapter was to determine the direct and the indirect effects of tree shading on crop dry matter production. The other objective was to see if there was evidence of the maize plants in rows close to the trees being water stressed. Tree shading affects crop dry matter production by directly reducing the fraction of PAR incident on the under-storey crop and indirectly by reducing the leaf area index of the crop.

Results show that tree shading significantly reduced the fraction of PAR reaching the under-storey maize crop when compared to sole maize. During the August-November 1998 season, the fraction of PAR reaching the maize canopy was reduced on average (5 m distance from tree line) by 69, 38, 36, 34 and 23% for *Maesopsis*, *Casuarina*, *Markhamia*, *Grevillea* and *Alnus* respectively (figure 5.1 and table 5.1). The shading effect of the trees extended progressively from 0.8 m (2nd year) to 4.5 m away from the tree lines (3rd year). This distance corresponds to the extent to which crop growth (figure 4.5) and yield reductions (figures 4.7, 4.8, and tables 4.3, 4.4) were observed (Chapter 4). The only exception was *Maesopsis* whose effect was beyond the tree shade.

Although *Maesopsis* (59%) significantly reduced the fraction of PAR reaching the maize crop more than *Casuarina* (31%), both had a similar negative effect on maize yields (58 and 59% respectively) during August-November 1998 cropping season. Similarly *Casuarina* had a significantly smaller shading effect, but significantly reduced maize biomass (59%) and maize height growth (40%) more than *Maesopsis* (45 and 29% reductions respectively) as shown in tables 4.1 and 4.3 (Chapter 4). Also *Markhamia* which had a 31% reduction in the fraction of PAR reaching the crop, significantly reduced maize height growth (27%) and maize biomass (48%) as much as *Maesopsis* that had a significantly bigger shading effect. For *Grevillea* and *Alnus*, reduction in crop growth and yield matched the reduction in the fraction of PAR reaching the under-storey maize crop.

The fraction of PAR that was intercepted by the foliage of the maize crop associated with the different trees varied according to species (figure5.2). Mean fractional light interception during August-November 1998 season for the first six rows (4.5 m distance from the tree lines) were 0.28 for *Maesopsis*, 0.35 for *Casuarina*, 0.32 for *Markhamia*,

0.53 for *Grevillea* and 0.53 for *Alnus*. Maize plants in sole maize had mean fractional light interception of 0.63. It appears that maize plants in rows close to the *Maesopsis* tree line intercepted the smallest fraction of incident PAR because the species allowed a very small fraction of the incident PAR to reach the under-storey maize.

Tree shading also significantly reduced the LAI of maize and the effect varied according to species and distance from the tree line (figure 4.10 and table 4.5). The LAI of maize was greatly reduced by *Casuarina*, *Maesopsis* and *Markhamia* in the last season (August-November 1998) on average (4.5 m distance from trees) by 60, 62 and 53% respectively. The reduction in the fraction of PAR reaching the under-storey maize crop was proportional to the reduction in LAI for *Maesopsis* (59% and 60%), *Grevillea* (30% and 39%) and *Alnus* (23% and 26%). However, for *Casuarina* and *Markhamia*, the reduction in LAI (61% and 53% respectively) was twice as much as the reduction in the fraction of PAR reaching the maize crop (31 and 31% respectively). This seems to suggest that maize plants close to the *Casuarina* and *Markhamia* tree lines had water stress, which reduced their LAI much more than would be expected if shading was the only factor influencing LAI of maize. This resulted in very low fractional PAR interception values (0.35 and 0.32 respectively) in these plots. This clearly shows that for these two species, tree shading alone was not responsible for reduction in LAI.

The direct (reduction in fraction of PAR) and indirect effects (reduction in LAI) of tree shading as shown above resulted in mean maize biomass reductions of 53, 41, 43, 29 and 20% for *Casuarina*, *Maesopsis*, *Markhamia*, *Grevillea* and *Alnus* respectively. It also resulted in mean maize yield reductions of 59, 59, 49, 33 and 26% by the species respectively. These results suggest that tree shading was partly responsible for the observed reduction in maize growth and yield, especially for *Casuarina* and *Markhamia*. The presence of the upper-storey trees significantly reduced the amount of radiant energy that the maize crop received. This reduced net photosynthesis of the shaded maize plants leading to lower growth and reduced yields [Ludlow 1978].

There are very few reports in the literature with which to compare the present results on the effect of tree shading on the under-storey maize. Most of the reports show that tree shading reduces the incident radiation reaching the under-storey crops. This results in decreased yields of the associated crops. Both the reduction on the fraction of PAR

reaching the crops and the resulting decreased yields reported in this study are within those reported in the literature.

Chirko *et al* [1996b] found wheat yields to be higher on the eastern side of *Paulownia* trees than on the western side. This was attributed to more radiation (9.5% higher) reaching the under-storey wheat on the eastern than on the western side. Reduced grass biomass production within 2 m radius of *Poplar* trees was caused by reduced radiation reaching the under-storey grass (49%) compared to the open [Zhang 1996]. Unpruned pigeon pea shaded under-storey crops by 46 to 57% [Daniel *et al* 1991], while *Robinia pseudoacacia* imposed serious competition on inter-planted maize, with the fraction of PAR reaching the maize crop ranging from 22 to 25% compared to sole maize [Ssekabembe *et al* 1997]. Similarly, unpruned *Gliricidia sepium*, *Acacia auriculiformis* and *Acacia mangium* reduced light incidence to under-storey crops by 53 to 59%, thereby causing reduction in crop yields. Other reports in the literature attribute reduced crop yields of the associated crops to shading by the trees but no measurements on light interception were done [Okorio *et al* 1994; Akyeampong *et al* 1995,1999]. There are also no reports in the above studies on the effect of tree shading on the LAI of the under-storey crops, especially maize, with which to compare the present results.

5.5.2 Effect of tree height and canopy size on crop shading

The results show that the field measurements were in good agreement with the modeling results. This was true for the measured and modeled tree heights of *Casuarina*, *Markhamia*, *Grevillea* and *Alnus* in all the three seasons. However, the height of *Maesopsis* was over estimated in all the seasons. This was mainly because of the shape of its crown, which is more broad than tall resulting in a flat topped canopy. Similarly, the measured and modeled extent of tree shading by the tree species at different times of the day were found to be in agreement for all the species except *Maesopsis* whose extent of tree shade was under-estimated due to the over estimation of its height. Inclusion of the lateral extent of tree canopy in the model improved the predictions of the lateral extent of tree shade, especially for *Maesopsis*. These results confirm earlier reports that crown shape or size has a strong influence on the spatial distribution of tree shade [Kuuluvainen and Pukkala 1987]. They also show that the shaded area of a narrow crown is smaller and

more concentrated around the tree (e.g. *Markhamia* and *Alnus*) than the shaded area caused by a broad crown (e.g. *Maesopsis*) [Pukkala *et al* 1993].

While most models of light interception, for example ERIN model(Evaporation and Radiation Interception by Neighbouring species) [Wallace 1997], use only canopy height for estimating light interception by plant canopies, both canopy width and height were used in modeling the shading effect of trees in this study. The results have demonstrated that both attributes of canopy size (height and width) determine the degree of tree shading. As far as I am aware, this approach has not been used before but as these results show, the inclusion of crown spread as a parameter in such models would improve the accuracy of predictions by these models of light interception by plant canopies. Trees with similar canopy heights but with different canopy spread can be used to assess the level of tree shading. In general, the modeled shading effect of trees show that tall trees (*Casuarina*, *Grevillea*) or trees with wide canopies (*Maesopsis* and *Casuarina*) have significantly bigger shading effects on the under-storey crops than short trees or trees with narrow canopies. At solar noon, trees with wide canopies have the biggest shading effect but before or after this time, canopy height seems to greatly influence tree shading more than canopy width.

5.4.3 Relationship between Cumulative Light Interception and Biomass produced

During the modeling process, tree canopy spread and height were used to determine the shading effect of the trees during the course of the day. These daily values were summed (from 10 days after sowing up to crop anthesis) in order to estimate cumulative light interception by the maize crop for the three cropping seasons. There were significant and positive correlations between the fraction of PAR intercepted by the foliage of maize crop and the biomass it produced in the different maize/tree associations. The light use efficiency values (LUE) obtained from this relationship varied according to species suggesting that different species affect crop growth differently. Tree species with big shading effects such as *Maesopsis* and *Grevillea,* increased the LUE of maize plants in rows that were shaded by the trees. Under shade, LUE is expected to increase, especially during that time of the day when temperatures are high. At this time, shaded plants do not reach their light saturation points hence their stomata remain open are therefore able to photosynthesize while those plants in open would have closed their stomata.

Consequently, shaded plants produce more biomass for a given amount of radiation received compared to the unshaded plants.

Despite being shaded, the plants in rows close to the *Casuarina* trees had lower LUE values (figure 5.12c) compared to the plants in the open. This implies that shading had no positive effect on LUE of these plants. This tends to suggest that the plants were probably water stressed as tree shading is supposed to have increased their LUE values. There are no reports on the LUE of maize under tree shade, but the values in this study ranged from 1.0 g MJ^{-1} for plants under *Casuarina* shade to 4.2 g MJ^{-1} for those under *Maesopsis* shade. The LUE value in sole maize averaged 2 g MJ^{-1}. Other results report LUE values of sole maize to range from 2.0 to 3.5 g MJ^{-1} [Andrade *et al* 1992, 1993; Fountier and Andrieu 1999]. The present values are on the lower side of this range, probably due to differences in the climatic conditions under which the various studies were done. Large variations in LUE values have also been attributed to different definitions of LUE [Charles-Edwards 1982; Ong *et al* 1996]. Despite this variations, light use efficiency has become a useful component in modeling because it allows the maximum growth and yield potential of a specific crop in a given environment to be assessed [Muchow *et al* 1990; Amir and Sinclair 1991a].

5.5 Summary

The presence of the trees significantly reduced the fraction of incoming PAR that was incident on the canopy of the under-storey maize crop. Overall, light availability to the under-storey maize was lowest in rows that were closest to the tree lines and highest in those further away. It also varied according to tree species and the effect was observed up to a distance of 5 m from the tree lines in the last season (August-November 1998). The tree species significantly reduced the mean fraction of PAR incident on the first five maize rows in this season when compared to sole maize by 59, 31, 31, 29 and 23% for *Maesopsis*, *Casuarina*, *Markhamia*, *Grevillea* and *Alnus* respectively.

A similar trend was observed for the fraction of PAR that was intercepted by the maize crop, with crop rows closest to the tree lines intercepting less radiation than those further away. Fractional light interception by maize plants in the proximity of the trees decreased over the seasons, as the trees grew taller. The plants in rows closest to the *Maesopsis*,

than those close to *Grevillea* and *Alnus* tree lines. The effect of the trees extended up to a distance of 5 m by the August–November 1998 cropping season. Mean fractional PAR interception during March-May 1998 season for rows 1 to 4 was 0.32, 0.37, 0.41 and 0.47 for *Maesopsis*, *Casuarina*, *Markhamia*, *Grevillea* and *Alnus* respectively. During the August-November 1998 season, mean fractional PAR interception for rows 1 to 5 were 0.28, 0.32, 0.35, 0.54 and 0.53 for *Maesopsis*, *Markhamia*, *Casuarina*, *Grevillea* and *Alnus* respectively.

The lateral extent of tree shading can be predicted from knowledge of tree height and the height and spread of the tree canopy. *Maesopsis*, *Grevillea* and *Casuarina* had significantly bigger shading effects than *Markhamia* and *Alnus* in all the three seasons. The modeled and the measured extent of *Grevillea* shade were in good agreement, while the extent of *Maesopsis* shade was under estimated especially between 12.00 and 14.00 hours. The modeling results show that tall trees (*Casuarina, Grevillea*) or trees with wide canopies (*Maesopsis, Casuarina*) have a significantly bigger shading effects on crops than short trees or trees with narrow canopies. At solar noon (13.00 hr) when the sun is overhead, trees with wide canopies have the biggest shading effect but before or after this time, canopy height seems to greatly influence tree shading more than canopy width.

The simple model based on the height of the trees and canopy height, overestimated tree height for species with wide canopies (*Maesopsis*), but fairly accurately predicted the heights of trees with narrow (*Alnus, Markhamia*) or conical canopies (*Casuarina*). Similarly the modeled extent of tree shade was fairly accurate for all the species except *Maesopsis* (March-May and August November 1998 seasons) which was under estimated. The accuracy of the predictions on the lateral extent of tree shading was improved by including the lateral spread of tree canopies in the model.

The relationship between the amount of the incoming PAR intercepted by the maize crop and the biomass it produced showed a significant positive correlation. For every unit increase in the amount of light intercepted by the crop, there was a corresponding increase in the quantity of biomass produced. This was true for all the treatments except for *Casuarina* and the correlations were significant ($p<0.001$). Light use efficiency (LUE) values showed that plants under shade produced more biomass for every unit of light intercepted (high LUE values) compared to plants in the open in the *Maesopsis*, *Alnus*, *Grevillea* and *Markhamia* plots. The LUE values ranged from 1.0 g MJ^{-1} for plants under

Casuarina shade to 4.2 g MJ^{-1} for plants under *Maesopsis* shade. However, during August-November 1998 season, the shaded plants in the *Casuarina* plot produced less biomass for every unit of light intercepted, meaning that they had lower LUE values compared to plants in the open. This suggests that other factors other than tree shading affected LUE values under *Casuarina* shade and to some extent under *Markhamia* shade.

CHAPTER SIX

TREE AND CROP ROOT DISTRIBUTION

6.1 Introduction

Minimizing resource competition between trees and crops whilst maximizing the use of available resources is central to improving yields and benefits in agroforestry [Cannell *et al* 1996]. Knowledge on the spatial distribution and density of tree and crop roots in the soil profile is necessary in designing appropriate agroforestry systems [Oldeman 1983]. Therefore, determining the spatial distribution of tree and crop root systems is a preliminary step towards gauging complementarity or the competitive capacity of the tree or crop in an agroforestry system [Caldwell 1987]. The aims of this Chapter were to determine the spatial distribution and density of tree and crop roots at crop anthesis, and to investigate the potential for resource competition between the tree and maize root systems.

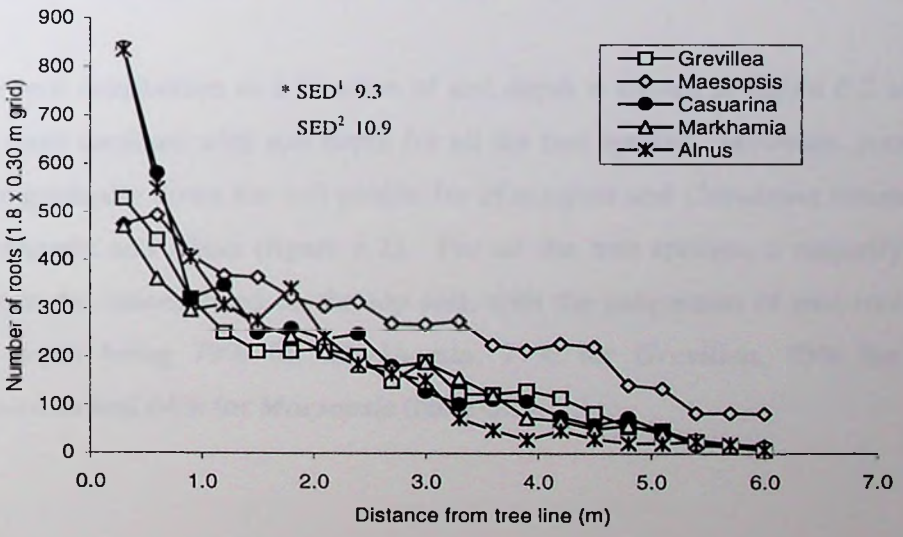
The Chapter presents results on the distribution of tree and maize crop roots during August-November 1998 cropping season. The materials and methods that were used for sampling and processing the tree and crop roots have been described in Chapter 3, Section 3.8. The vertical and horizontal distribution of the tree and maize roots are presented in Section 6.2. Sub-section 6.2.1 describes tree root distribution, while Sub-section 6.2.2 describes the distribution of maize roots as influenced the presence of the trees. The results are discussed (Section 6.3) in light of crop growth and yield observed in Chapter 4. The results are also discussed in relation to water uptake by both the trees and crops (Chapter 7). The last section, Section 6.4, gives a summary of the results and conclusions on the Chapter.

6.2 Results

6.2.1 Tree Root Distribution

6.2.1.1 Root distribution with distance from the tree line

The distribution of tree roots as a function of distance from the tree lines is shown in figure 6.1. The total number of roots, summed over 6m distance x 1.8 m depth, for each species were:- 5,268 for *Maesopsis*, 3,997 for *Casuarina*, 3,772 for Alnus, 3,441 for *Grevillea* and 3,331 for *Markhamia*. Tree root densities declined with increasing distance from the tree lines for all species, with *Alnus* (56%) and *Casuarina* (52%) having about half their roots within 1.2 m from the tree line (table 6.1). *Maesopsis* and to some extent *Grevillea* and *Markhamia* had a more uniform spread of roots out from the tree line. The mean number of roots within 2.4 m from the tree line were 83 % of the total for *Alnus*, 77 % for *Casuarina*, 70% for *Markhamia*, 69% for *Grevillea* and 58% for *Maesopsis* (table 6.1).



* SED¹ between distances for species

SED² between species for given distance

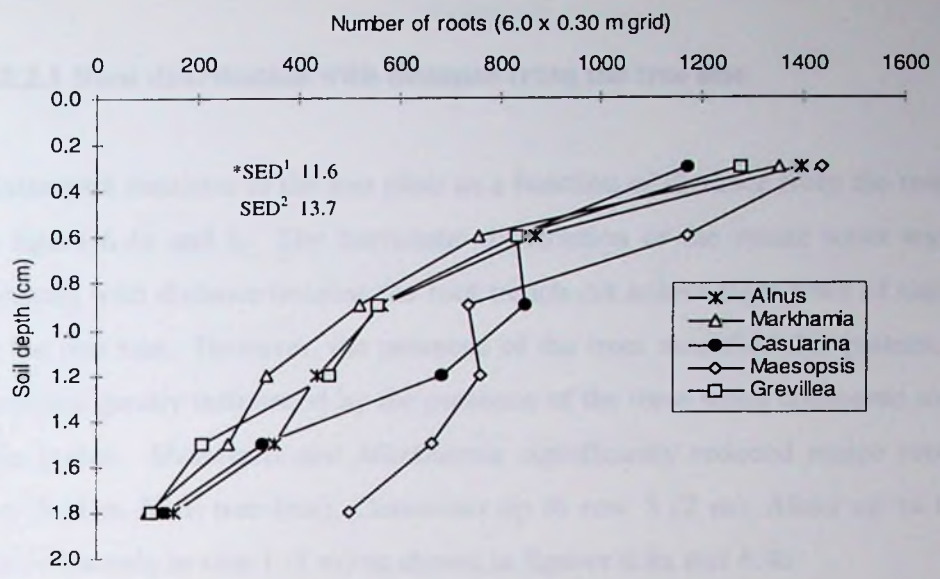
Figure 6.1 Tree root distribution as a function of distance from the tree line

Table 6.1 Proportion of tree roots as a function of distance from the tree lines to a depth of 1.8 m

Distance (m)	Percentage (%) of roots				
	Grevillea	*Maesopsis*	*Casuarina*	*Markhamia*	*Alnus*
0.00 – 1.20	44.8	33.2	52.2	43.2	55.6
1.20 – 2.40	24.3	24.7	24.8	27.0	27.7
2.40 – 3.60	17.0	19.6	13.0	19.3	11.5
3.60 – 4.40	11.1	15.2	7.8	7.4	3.3
4.80– 6.00	2.8	7.3	2.2	3.1	1.9
Total	3,441	5,268	3,997	3,331	3,772

6.2.1.2 Root distribution down the soil profile

Tree root distribution as a function of soil depth is shown in figure 6.2 and table 6.2. The tree roots declined with soil depth for all the tree species. However, root density declined more gradually down the soil profile for *Maesopsis* and *Casuarina* compared to *Grevillea*, *Markhamia* and *Alnus* (figure 6.2). For all the tree species, a majority of the tree roots seem to be concentrated on the top soil, with the proportion of tree roots within 0-90 cm soil depth being 79% for *Markhamia*, 77% for *Grevillea*, 75% for *Alnus*, 71% for *Casuarina* and 64% for *Maesopsis* (table 6.2).



* SED¹ between distances for species

SED² between species for given distance

Figure 6.2 Tree root distribution as a function of soil depth, averaged over 0-6 m from the tree line

Table 6.2 Proportion of tree roots as a function of soil depth to a distance of 6 m from tree line

Depth (m)	Percentage (%) of roots				
	Grevillea	*Maesopsis*	*Casuarina*	*Markhamia*	*Alnus*
0.00 – 0.30	37.0	27.2	29.2	40.6	37.1
0.30 – 0.60	24.2	22.3	20.9	22.7	23.0
0.60 – 0.90	16.2	14.0	21.2	15.7	15.0
0.90 – 1.20	13.5	14.4	17.1	10.1	11.6
1.20 – 1.50	6.0	12.6	8.2	7.9	9.3
1.50 – 1.80	3.1	9.5	3.3	3.0	4.0
Total	3,441	5,268	3,997	3,331	3,772

6.2.2 Maize root distribution

6.2.2.1 Root distribution with distance from the tree line

Maize root densities in the tree plots as a function of distance from the tree lines are shown in figure 6.4a and b. The horizontal distribution of the maize roots was expected to be constant with distance because the root trench cut across eight rows of maize on either side of the tree line. However, the presence of the trees modified this pattern, with maize root densities greatly influenced by the presence of the trees when compared to root densities in sole maize. *Maesopsis* and *Markhamia* significantly reduced maize root densities up to row 5 (4 m from tree line), *Casuarina* up to row 3 (2 m), *Alnus* up to row 2 (2 m) and *Grevillea* only in row 1 (1 m) as shown in figures 6.4a and 6.4b.

When the distance at which maize biomass (figure 4.7c, Chapter 4, section 4.3.2) starts to decline, is plotted against the distance at which the number of maize roots in the tree plots equal that of sole maize (figure 6.4a, b), a significant positive correlation ($R^2 = 0.8$) was obtained (figure 6.3).

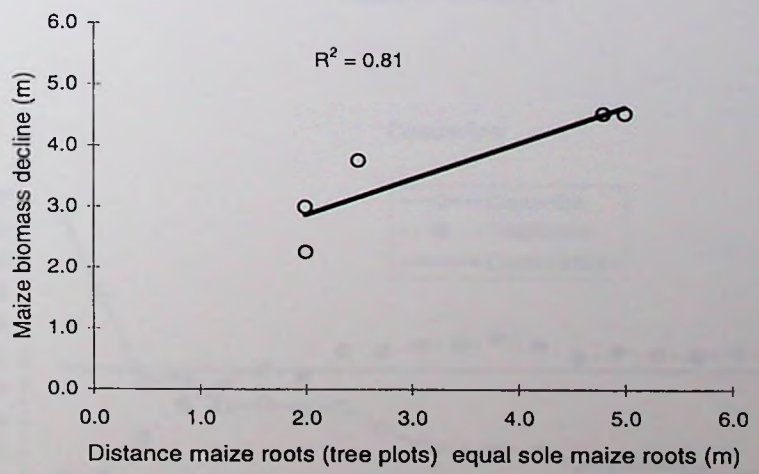
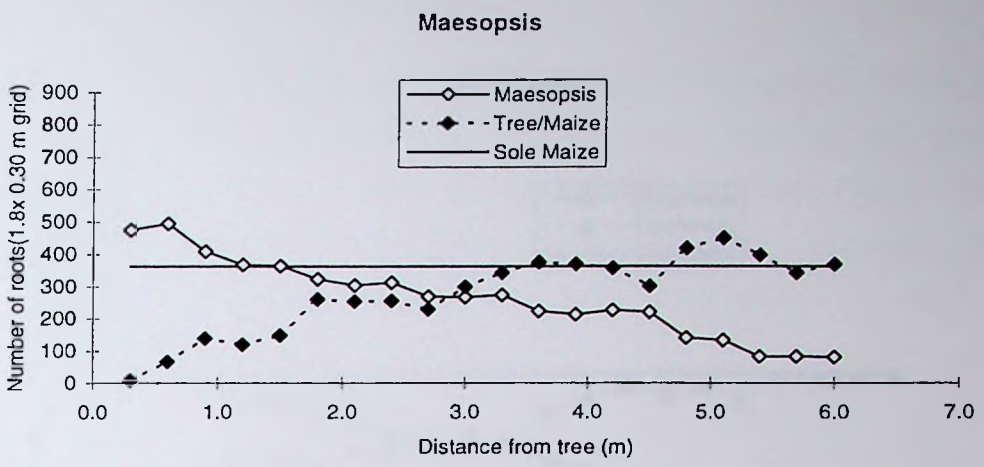
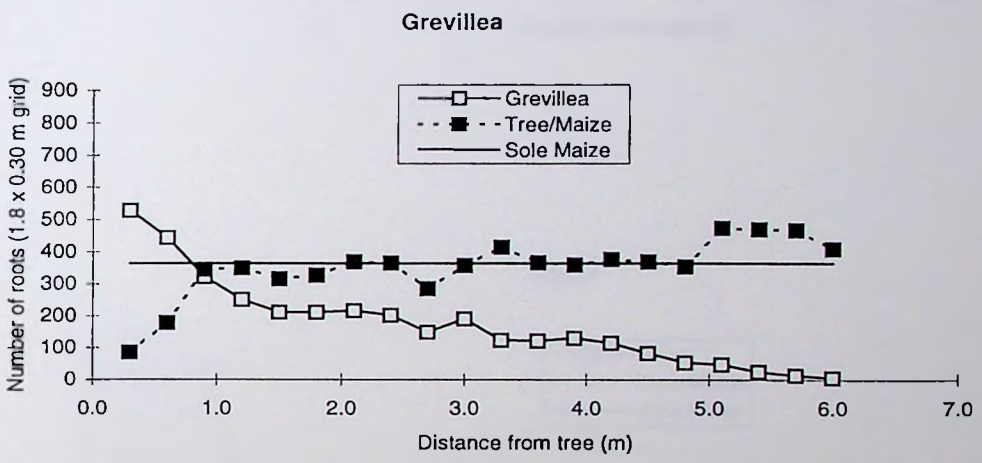


Figure 6.3 Relationship between the distance at which maize biomass declines and the distance at which maize roots in tree plots equal those in sole maize





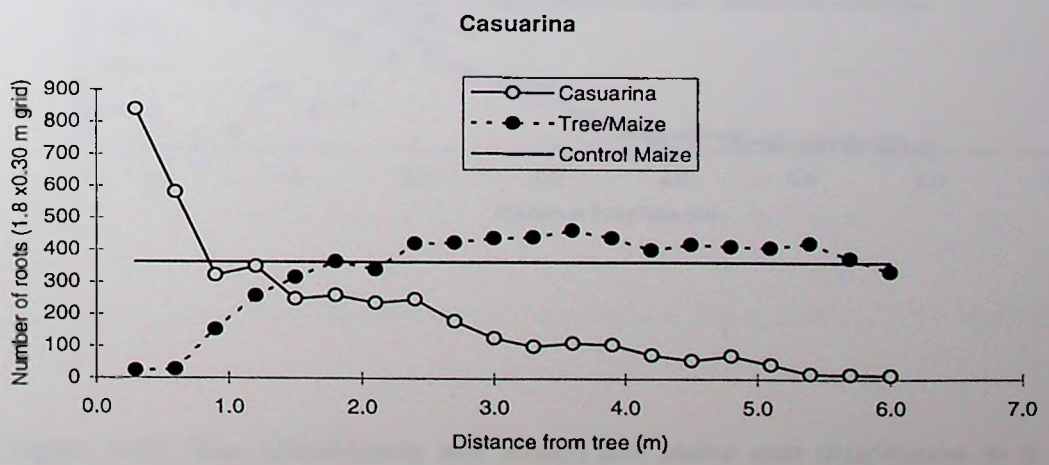


Figure 6.4a. Tree (*Maesopsis*, *Grevillea*, *Casuarina*) and maize root distribution as a function of distance from the tree line

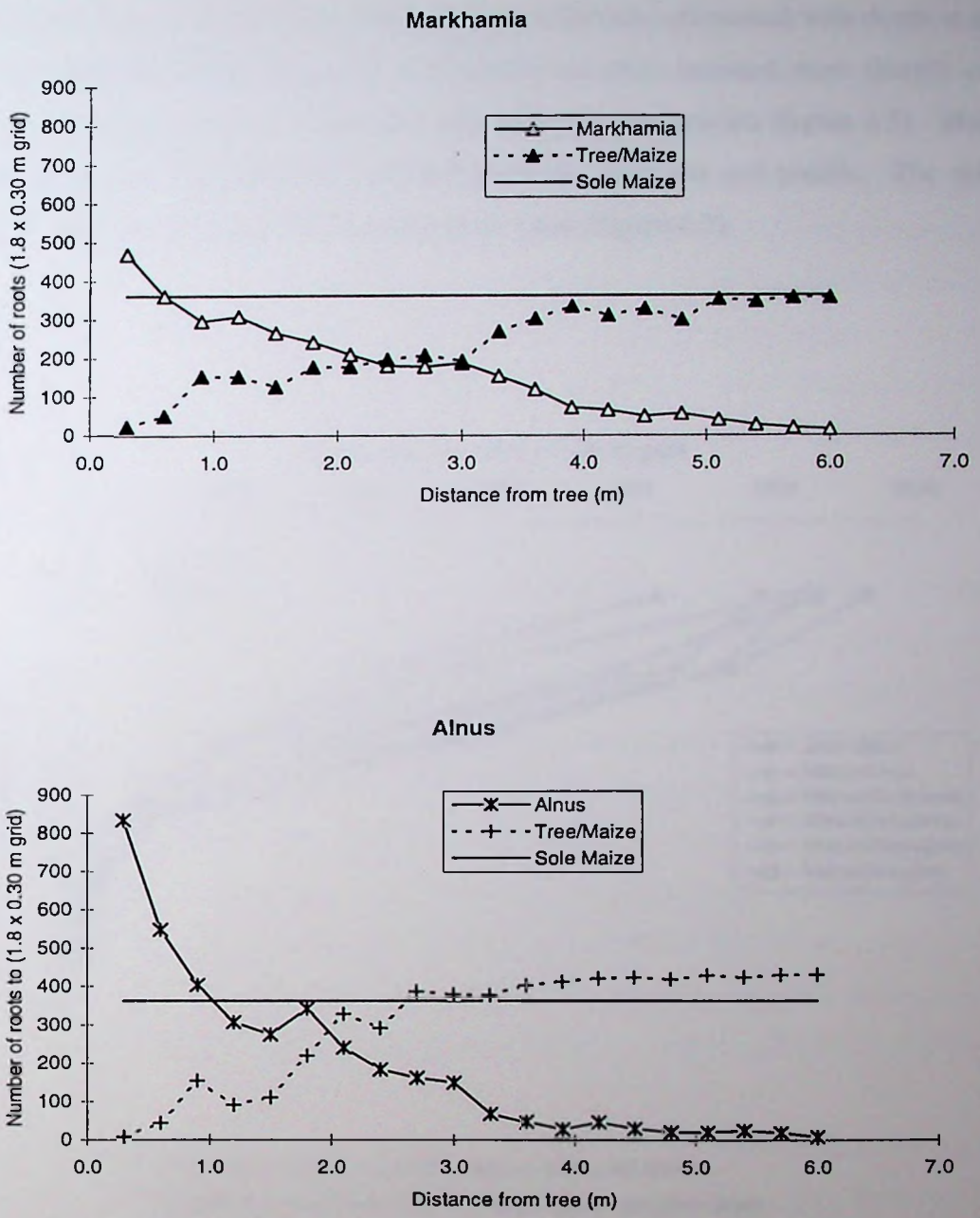
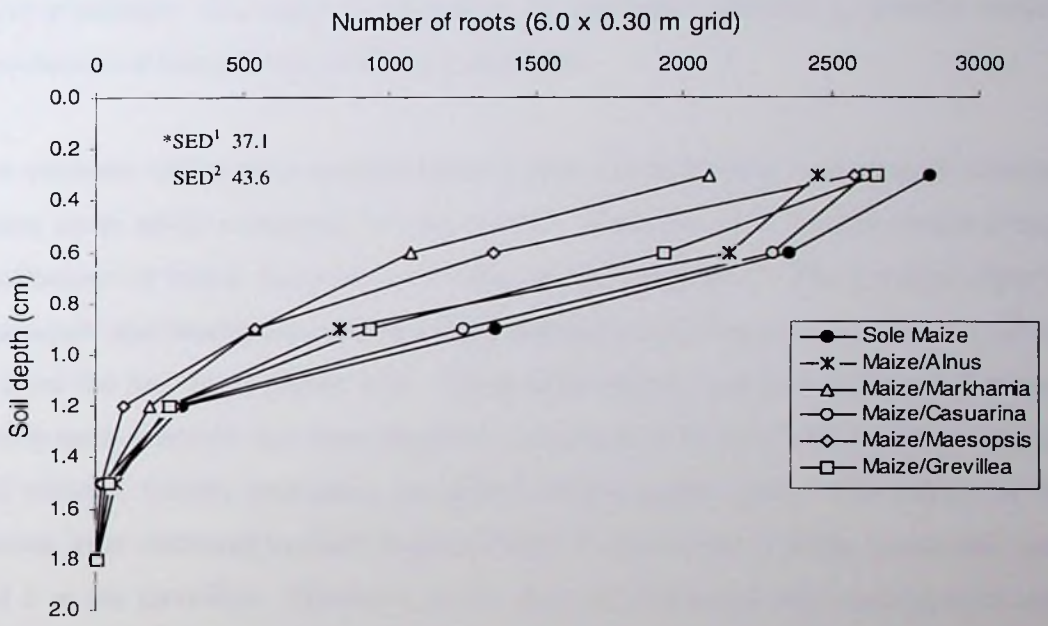


Figure 6.4b. Tree (*Markhamia* and *Alnus*) and maize root distribution as a function of distance from the tree line

6.2.2.2 Root distribution down the soil profile

As was the case with the tree species, maize root densities decreased with depth in all cases but the densities in the *Maesopsis* and *Markhamia* plots declined more sharply with soil depth than when grown in association with the other tree species (figure 6.5). Maize root densities in the other tree plots declined gradually down the soil profile. The maximum rooting depth for maize at this site was about 1.6 m (figure 6.5)



* Standard error difference (SED^1) between depths for species
Standard error difference (SED^2) between species for given depth

Figure 6.5 Maize root distribution (in tree plots and sole maize) as a function of soil depth

6.3 Discussion

The tree species exhibited different patterns of root development. The root system of *Maesopsis* spread furthest out from the tree line as well as down the soil profile, while the *Casuarina* root system was confined around the trees but spread down the soil profile. The root system of *Markhamia* was spread out from the trees, with roots concentrated in the topsoil. *Grevillea* had its roots spread out from the tree but the density was much lower, while *Alnus* had its roots concentrated around the tree. The root densities of both the tree species and maize reported here are generally low. This is mainly because very fine roots (<0.1 mm) would have been missed during the sampling process. However, because the same procedure was used in sampling all the root systems, a general trend in the distribution of tree and crop roots was obtained.

The presence of the trees greatly reduced both the horizontal and vertical distribution of maize roots when compared to sole maize. The tree roots greatly reduced the lateral distribution of maize roots in rows close to the tree lines. The greatest effect was by *Maesopsis* and *Markhamia* which greatly reduced maize roots up to a distance of 4 m (row 5) from the tree lines (figure 6.3). Since both species had root densities that spread out evenly away from the tree lines (figure 6.1 and table 6.1), their root systems occupied a big soil volume, thereby restricting the growth of the maize roots. The effects of the other species were restricted to short distances from the tree lines, 2 m for *Casuarina* and *Alnus*, and 1 m for *Grevillea*. However, in the case of *Casuarina*, the roots spread out evenly down the soil profile despite being restricted to a few metres away from the tree line.

Maize root distribution down the soil profile was also greatly influenced by the presence of tree roots when compared to sole maize (figure 6.5). The maize roots in the *Markhamia* and *Maesopsis* plots were significantly ($p<0.01$) reduced by the presence of tree roots when compared to sole maize. This was mainly because the *Maesopsis* tree roots were evenly spread down the soil profile (figure 6.2), while in the *Markhamia* plots the tree roots occupied most of the topsoil. The maize roots were therefore, restricted in their development by the growth of the tree roots. *Grevillea*, *Alnus* and *Casuarina* least affected maize root distribution with depth. *Alnus* and *Grevillea* had roots that were confined to within a short distance of the tree lines, hence occupying a smaller soil volume. Although the *Grevillea* roots was spread out from the tree line, they were confined to the topsoil and

their density was also smaller than that of the other species.

It is worth noting that the distance to which tree roots significantly reduced maize roots (figure 6.1) is similar to the distance where maize biomass and yield start to decline (figures 4.7 and 4.8). This was especially true for *Maesopsis* and *Markhamia*. This indicates that the tree and maize roots were competing for growth resources especially water, since nutrient deficiencies in the trial had been minimized by the application of fertilizers.

Reduced crop root density or length due to the presence of tree roots potentially decreased the ability of maize roots [Livesley 1999], sorghum roots [Jones and Sinclair 1996] and grass roots [Eastham and Rose 1990] to compete for growth resources. Odhiambo [1999] reported a 50% reduction in maize root length by roots of a line of *Grevillea* trees in a semi-arid environment of Machakos, Kenya. This seems to have been the case in this study for *Maesopsis* and *Markhamia* tree species. However, this assumes that the ability of a plant to compete for nutrients and water from the same soil volume is proportional to the density of its fine roots [Bowen 1985]. There are other factors such as root diameter, mycorrhizal infection or suberization [Schroth and Zech 1995] that also influence nutrient or water uptake by plants. Tree root systems are able to restrict the growth of crop roots because by the time the crop is planted, they are already established, and hence have an advantage in water and nutrient uptake [Van Noordwijk *et al* 1996]

These results are in agreement with most studies that have shown that the rooting density of most agroforestry trees coincide with those of crops [Jonsson *et al* 1988; Dhyani *et al* 1990; Ruhigwa *et al* 1992; Odhiambo 1999; Livesley 1999]. This means both root systems occupy the same soil volume, and are therefore bound to compete for growth resources of water and nutrients. The results also show that both the tree and maize root densities decline with distance from the plant and with soil depth [Van Noordwijk *et al* 1996]. These findings are in contrast to Paulownia/wheat inter-cropping systems where the tree roots occupy soil layers below the crop-rooting zone [Zhu Zsao-Hua *et al* 1986; Chirko *et al* 1996b]. Complementarity in fine root distribution between the tree and crop, is probably the main reason for the success of this inter-cropping system.

6.4 Summary

The tree species exhibited different patterns of root development. *Maesopsis* root system spread out from the tree line as well as down the soil profile, while the *Casuarina* root system was confined around the tree line but spread down the soil profile. The root system of *Markhamia* was spread out from the tree line with roots concentrated on the topsoil. *Grevillea* had its roots spread out from the tree but the density was much lower, while *Alnus* had its roots concentrated around the tree.

Tree root densities decreased with increasing distance from the tree line and with soil depth. However, the rate of decrease varied between species. The mean number of roots within 2.4 m from the tree line were:- 83% for *Alnus,* 77% for *Casuarina,* 70% for *Markhamia,* 69% for *Grevillea* and 58% for *Maesopsis.* The majority of tree roots seem to be concentrated on the top 90 cm of the soil. The proportion of tree roots found within this soil depth were: - 79% for *Markhamia*, 77% for *Grevillea*, 75% for *Alnus*, 71% for *Casuarina* and 64% for *Maesopsis.*

The horizontal distribution of maize roots was constant in sole maize plots because the root trench cut across eight rows of maize. However, the presence of the trees modified this pattern, with the species having different effects. *Maesopsis* and *Markhamia* significantly ($p<0.01$) reduced maize root density up to row 5 (4 m distance), *Casuarina* and *Alnus* up to row 3 (2 m distance), and *Grevillea* only row 1 (1 m distance). Maize root densities down the soil profile were also significantly reduced by the presence of tree roots. The densities in the *Maesopsis* and *Markhamia* plots declining sharply down the soil profile. The maize root densities in the other plots declined gradually down the soil profile.

Maesopsis and *Markhamia* significantly reduced maize root distribution in the soil profile more than *Casuarina*. *Grevillea* and *Alnus* had the least effect on the growth and development of the maize roots.

CHAPTER SEVEN

WATER USE BY TREES AND CROPS

7.1 Introduction

Agroforestry systems offer the opportunity for spatial and temporal complementarity in water use, resulting in improved exploitation of available soil water relative to sole crops [Ong *et al* 1996]. The introduction of trees into farming systems increases water use because trees utilize water outside the crop-rooting zone and also outside the crop-growing season [Huda and Ong 1989]. It is theoretically possible that the inclusion of trees or shrubs on cropland may improve rainfall use efficiency either directly by using more rain through transpiration or indirectly by improved transpiration efficiency (more dry matter produced per unit of water used) [Brenner 1996]. The former effect could be achieved by either spatial or temporal complementarity in water use by the tree and crop, and the latter by modifying the plant microclimate [Wallace 1996]. Trees reduce water losses and therefore increase the availability of soil moisture by providing shade, reducing windspeed, increase infiltration by reducing rainfall intensity at the soil surface and improving soil structure [Budelman 1989; Torquebiau and Kwesiga 1996; Young 1997]. The loss of water through drainage may be the hydrological term most easily modified by the introduction of trees [Wallace *et al* 1995].

The presence of trees on cropland invariably increases water use, but overall productivity will only increase if the beneficial effects of trees compensate for the negative effects of competition for water, light and nutrients on crop yield [Cannell *et al* 1996]. Competition for water in agroforestry systems can occur when the root systems of the tree and crop overlap [Van Noordwijk and Purnomoshidhi 1995] and when water supply is limiting. The aims of the research presented in this Chapter were to measure water losses by the different tree/crop combinations compared to sole crops, and to determine water use by the different tree/crop combinations.

The materials and methods that were used for determining water use between the tree and crops were described in Chapter 3, Section 3.7. Results on seasonal water loss and water-use by trees and maize crop during the three cropping seasons of March-May 1997, March-May 1998 and August-November 1998 are presented in Section 7.2. Sub-sections 7.2.1 and 7.2.2 give results on seasonal water loss and soil water depletion down the soil profile by the different tree/crop combinations respectively. A crude attempt to partition water use between the maize crop and the different tree species is shown in sub-section 7.2.3. Data on direct evaporation from the soil surface beneath the tree and crop canopies and bare soil are presented in sub-section 7.2.4. Section 7.3 discusses the results in relation to the rooting patterns of both the trees and maize presented in Chapter 6. The results are also discussed in relation to the observations of crop growth and yield discussed in Chapter 4. Section 7.4 summarizes the research findings and the discussion on the Chapter.

7.2 Results

7.2.1 Seasonal Soil Water Loss

Figure 7.1 shows the seasonal water loss through drainage and evaporation by the different tree species grown in association with maize during March-May 1997, March-May 1998 and August-November 1998 cropping seasons. Seasonal water loss was estimated from the difference between precipitation and the change in water storage in the soil profile. It is assumed in this analysis that there is negligible run-off, and negligible uptake by roots below the depth of soil water measurement. There were no significant differences in total water loss between the different tree species during March-May 1997 cropping season as a function of distance from the tree line (figure 7.1a). Neither were there any differences between water loss from the tree plots and sole maize as shown in figure 7.1a.

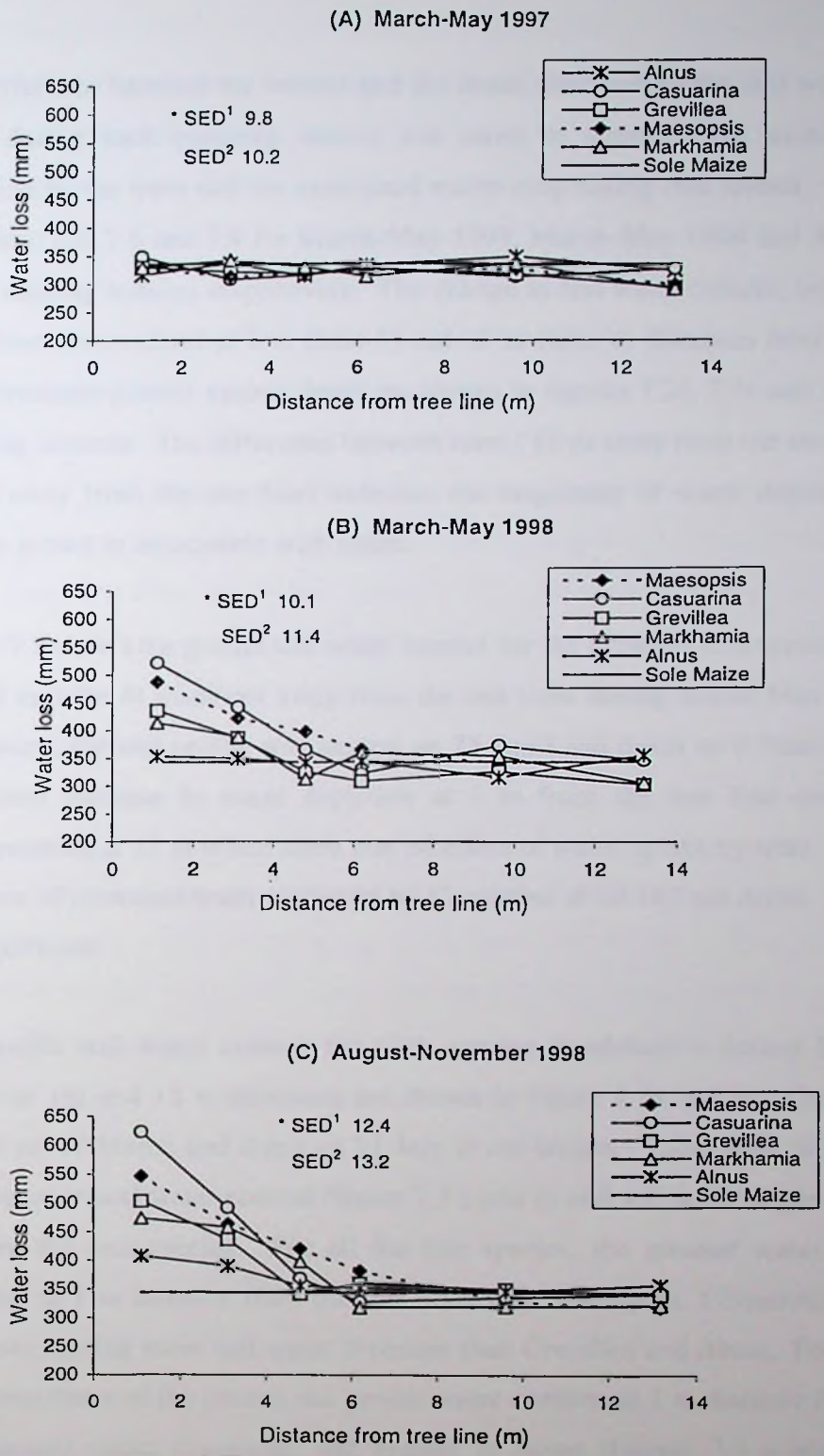
Total water loss for March-May 1998 cropping season as a function of distance from the tree lines is shown in figure 7.1b. The tree plots lost significantly ($p<0.01$) more water than sole maize. Within the tree species, *Casuarina* and *Maesopsis* had significantly higher water losses than *Markhamia* and *Grevillea* to a distance of 3 m from the tree lines. *Maesopsis* had significantly bigger losses than the other species at 5 m distance from the tree lines. Beyond 5 m from the tree line, there was no apparent increase in water use attributable to water uptake by trees. *Alnus* plots lost the least water during the season.

During the August-November 1998 season, the effect of the tree species on soil water loss was even more significant ($p<0.001$) than in the earlier seasons as shown in figure 7.1c. All the tree plots lost more water during the season than sole maize, with *Casuarina* losing significantly more water than *Maesopsis* which in turn lost more water than *Grevillea* and *Markhamia* within 3 m distance from the tree lines. At this distance, *Alnus* lost the least amount of water. In the *Maesopsis* plots, water losses were significant at 6 m distance from the tree lines. Beyond 6 m from the tree line, the water losses from all the plots were similar. The effect of distance from the tree line on water loss is evidence of water uptake by the trees and the magnitude and the lateral extent of the effect varied according to species.

Table 7.1 below shows the plot averages of seasonal water loss by the various treatments during the three cropping seasons calculated assuming that each neutron probe access tube was representative of the area extending up to the mid-point between the adjacent access tubes. Data presented in figure 7.1 show the seasonal water losses in the soil profile at the location of individual access tubes, while the data presented in table 7.1 is the average water loss for all tubes in each plot. This takes into account the size of the plots. Water losses in the tree plots increased from season to season, reflecting the increase in tree size, while water losses from sole maize plots were almost similar for the three seasons. In the last season (August-November 1998) water loss values ranged from 590 mm in sole maize plots to 698 mm in the *Casuarina* plots (table 7.1)

Table 7.1 Plot averages of seasonal water loss (mm) by the various treatments during the three cropping seasons

Species	March-May 1997	March-May 1998	August-November 1998
Sole Maize	532	586	590
Alnus	542	582	630
Markhamia	544	602	640
Grevillea	532	620	662
Maesopsis	534	664	682
Casuarina	546	672	698



* Standard error difference (SED¹) between distances in treatment

Standard error difference (SED²) between treatments for given distance from tree line

Figure 7.1 Seasonal water loss by the different tree species associated with maize for (A) March-May 1997, (B) March-May 1998 and (C) August-November 1998 cropping seasons.

7.2.2 Soil Water Depletion down the Soil Profile

The difference between the wettest and the driest observed profile soil water contents with depth during each cropping season was taken to represent the maximum soil water depletion by the trees and the associated maize crop during that season. These are shown in figures 7.2, 7.3 and 7.4 for March-May 1997, March-May 1998 and August-November 1998 cropping seasons respectively. The change in soil water content, between the wettest and driest observations at 1 m (tube 1) and 13 m (tube 6) distances from the tree line, for each treatment plotted against depth are shown in figures 7.2c, 7.3c and 7.4c for the three cropping seasons. The difference between tube 1 (1 m away from the tree line) and tube 6 (13 m away from the tree line) indicates the magnitude of water depletion by each tree species grown in association with maize.

Figure 7.2 shows the profile soil water content for the different tree species at 1 m (tube 1) and 13 m (tube 6) distances away from the tree lines during March-May 1997 season. In this season, the soil profile was wettest on 25 April and driest on 8 June and there was no significant increase in water depletion at 1 m from the tree line compared with the measurements at 13 m where there was no effect of water uptake by trees. There was slight evidence of increased water depletion by *Casuarina* at 80-165 cm depth, although this was not significant.

The profile soil water content for each species combination during March-May 1998 season at 1m and 13 m distances are shown in figure 7.3a and b. The soil profile was wettest on 17 March and driest on 21 July in the season. There were significant ($p<0.05$) differences in soil water content (figure 7.3 a and b) and soil water depletion (figures 7.3c) between the tree species. For all the tree species, the greatest water content changes occurred at 1 m distance from the tree lines with *Maesopsis, Casuarina* and *Markhamia* tree plots, having more soil water depletion than *Grevillea* and *Alnus*. For both the wettest and driest times of the season, the profile water contents at 1 m distance from the tree lines were lowest under *Casuarina* and highest in Alnus (figures 7.3 a and b). *Casuarina* depleted most of the soil water at soil depths of 40-120 cm, while *Maesopsis* had the biggest water depletion at 60-160 cm soil depth (figure 7.3c). *Markhamia* on the other hand, had the greatest soil water depletion in the top soil (20-80 cm).

Figure 7.4a and b show the profile soil water content for the tree species during August-November 1998 season. The soil profiles were wettest by 1 September and driest by 28 November in the season. The shape of the vertical distribution of changes in soil water content observed during this season were similar to those observed in the previous season, but the changes were slightly greater. The greatest changes occurred at 1m distance for all the species, with *Casuarina*, *Markhamia* and *Maesopsis* showing the largest differences in water depletion between the tubes at 1 and 13 m distance (figures 7.4a and b). The smallest changes were observed under *Alnus* and *Grevillea.* The profile soil water contents for both the driest and wettest periods were lowest in *Casuarina* and *Markhamia* but higher were under *Maesopsis*, *Grevillea* and *Alnus*. There were no marked differences between the treatments in the soil water contents at 13m distance at either the wettest or the driest periods. *Casuarina*, *Markhamia* and *Maesopsis* significantly depleted more soil water than *Grevillea* and *Alnus* (figure 7.4c). Most of the extra soil water depletion associated with the trees took place at top layers of the soil profile (20-80 cm) for *Maesopsis* and *Markhamia,* while for *Casuarina* it took place at 40-120 cm soil depth. The increases in soil water depletion close to the tree line in the *Grevillea* and *Alnus* plots were small.

Table 7.2 below shows the maximum soil water depletion in the upper 1.8 m of the soil profile for various the treatments at 1 m from the tree line. Summing water content differences for the wettest and driest periods for each layer multiplied by the thickness of the respective layers gave the maximum soil water depletion values for each treatment. Maximum soil water depletion increased across seasons for the tree plots but remained almost constant for sole maize. In the last season (August-November 1998), values ranged from 100 mm for sole maize to 160 mm for the *Casuarina* plot (table 7.2).

Table 7.2 The maximum soil water depletion (mm) in the upper 1.8 m of the soil profile for the various treatments during the three cropping seasons.

Species	March-May 1997	March-May 1998	August-November 1998
Sole Maize	69	118	100
Alnus	68	97	84
Markhamia	66	134	133
Grevillea	70	141	148
Maesopsis	66	142	158
Casuarina	73	167	160

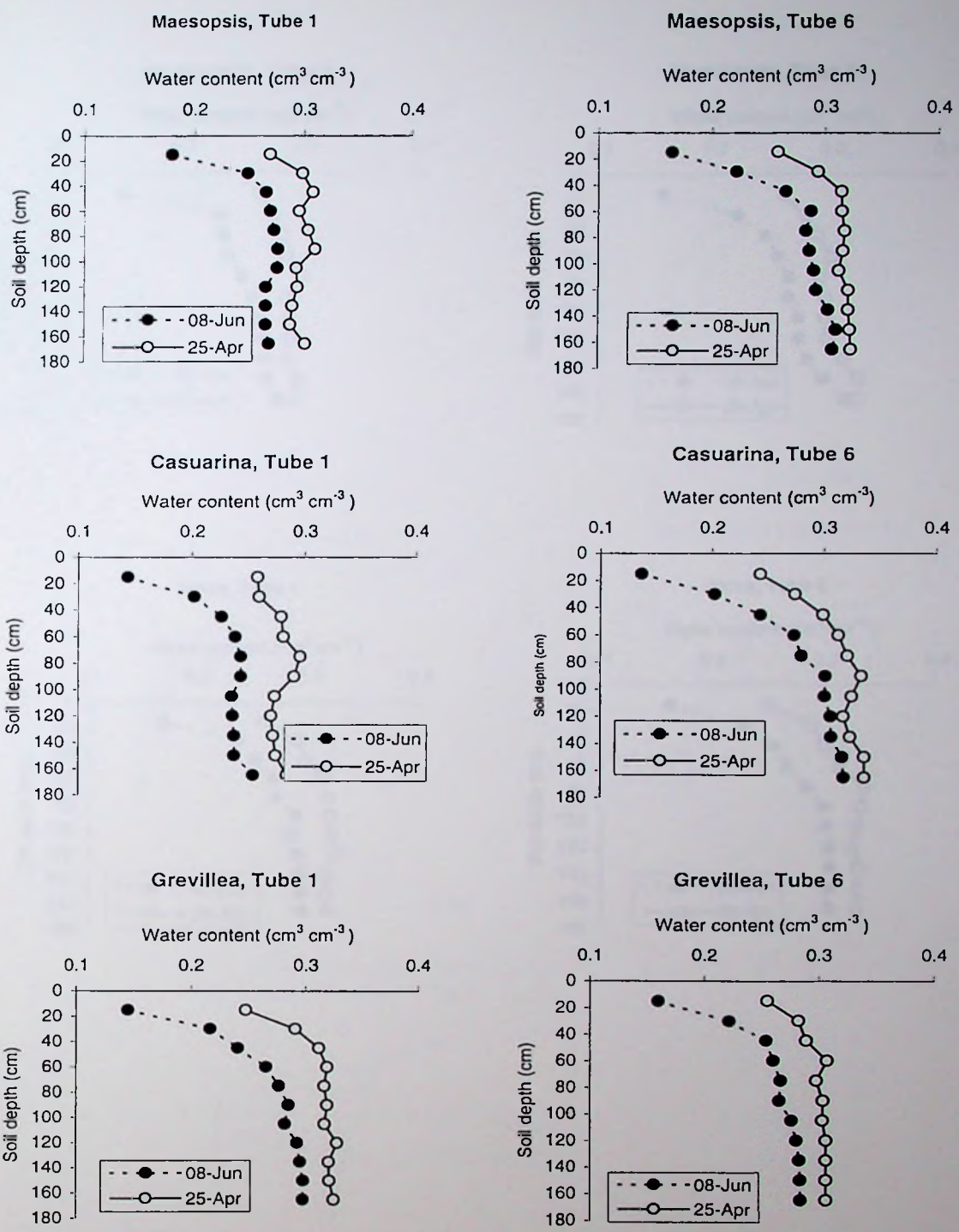


Figure 7.2a Soil water content for *Maesopsis*, *Casuarina* and *Grevillea* at 1 m (tube 1) and 13 m (tube 6) distances from the tree line when the profile wettest (25 April) and driest (8 June) during March-May 1997 cropping season.

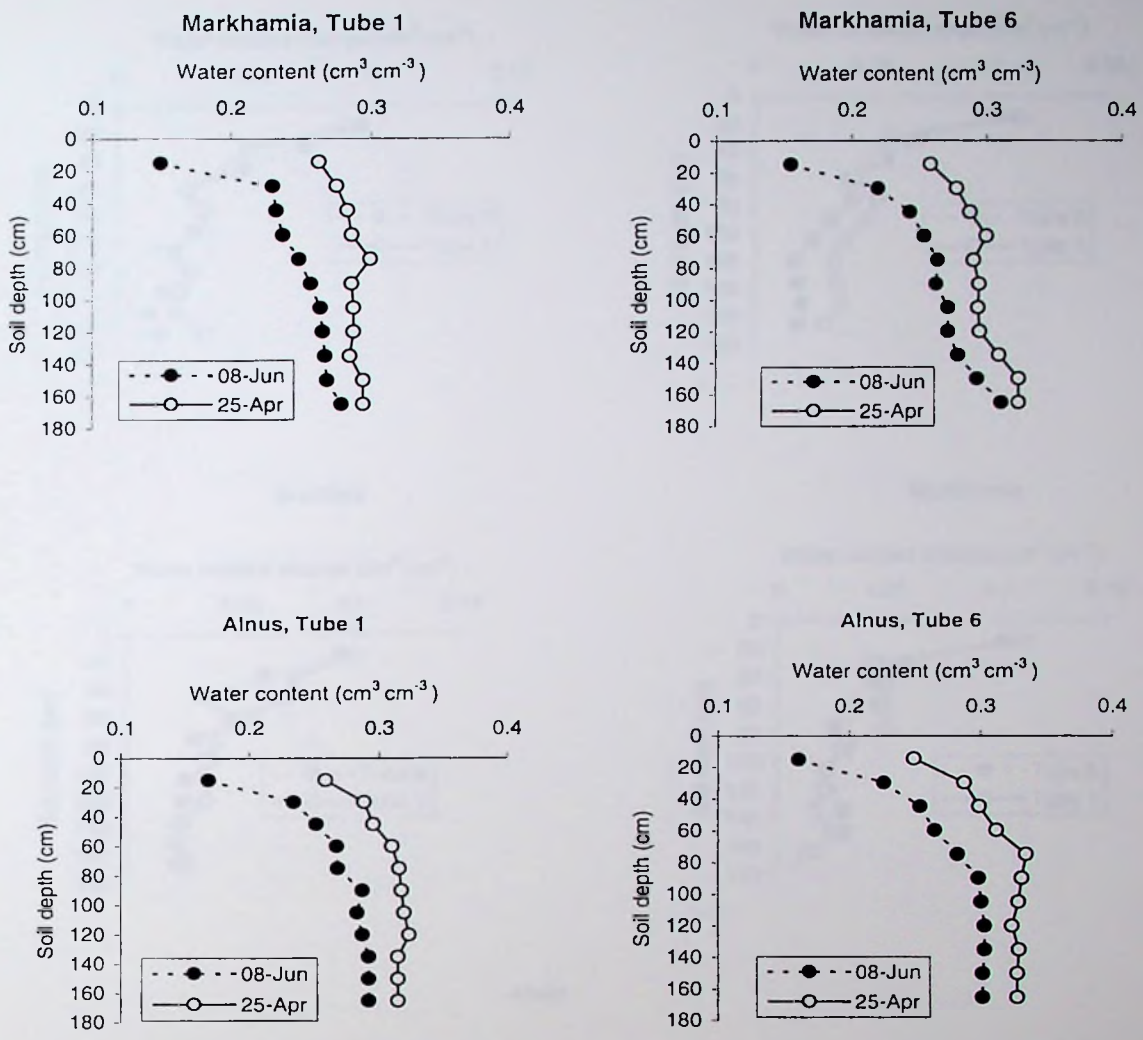


Figure 7.2b Soil water content for *Markhamia* and *Alnus* 1 m (tube 1) and 13 m (tube 6) distances from the tree line when the profile was wettest (25 April) and driest (8 June) during March-May 1997 cropping season.

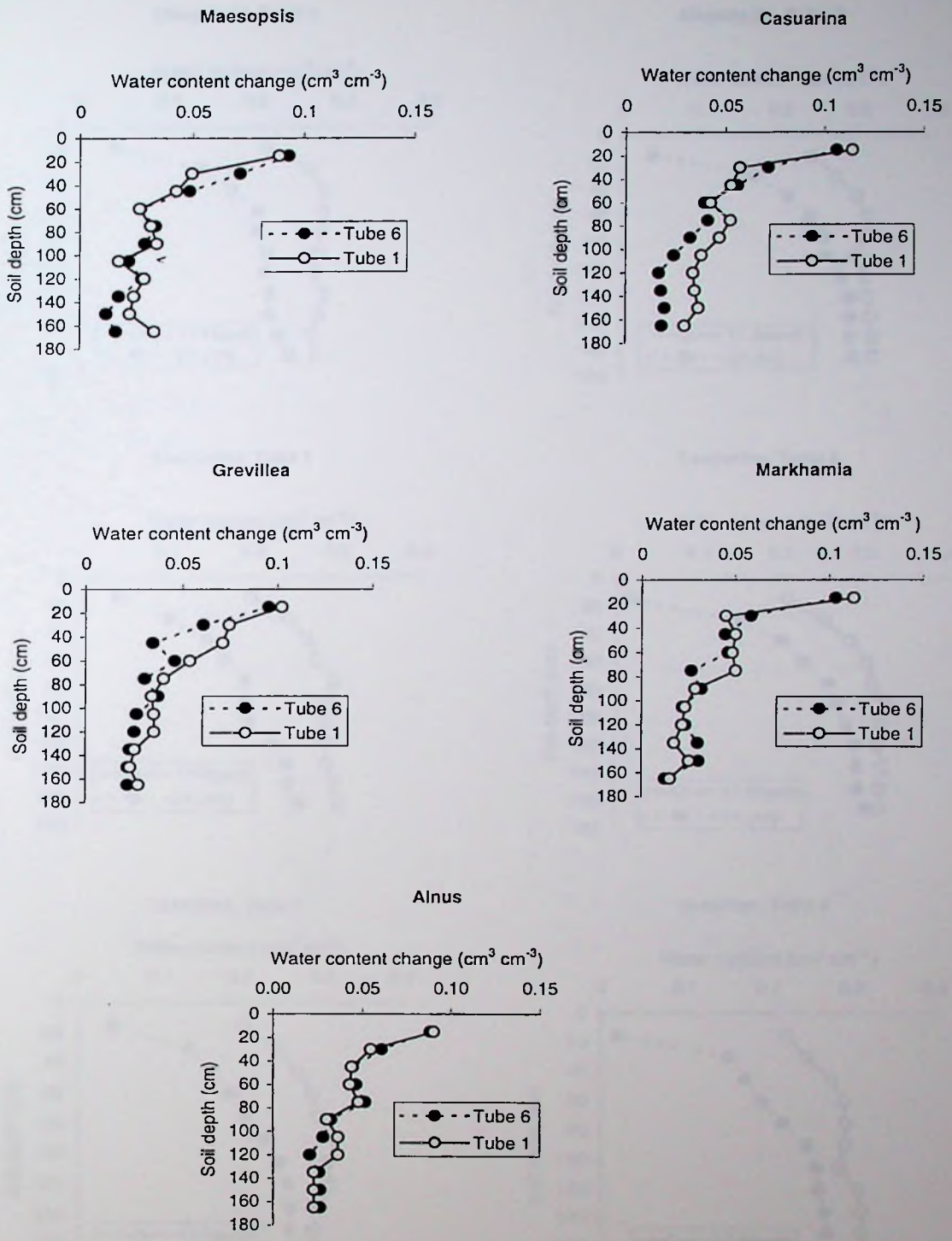


Figure 7.2c Soil water depletion by the tree species associated with maize during March-May 1997 cropping season.

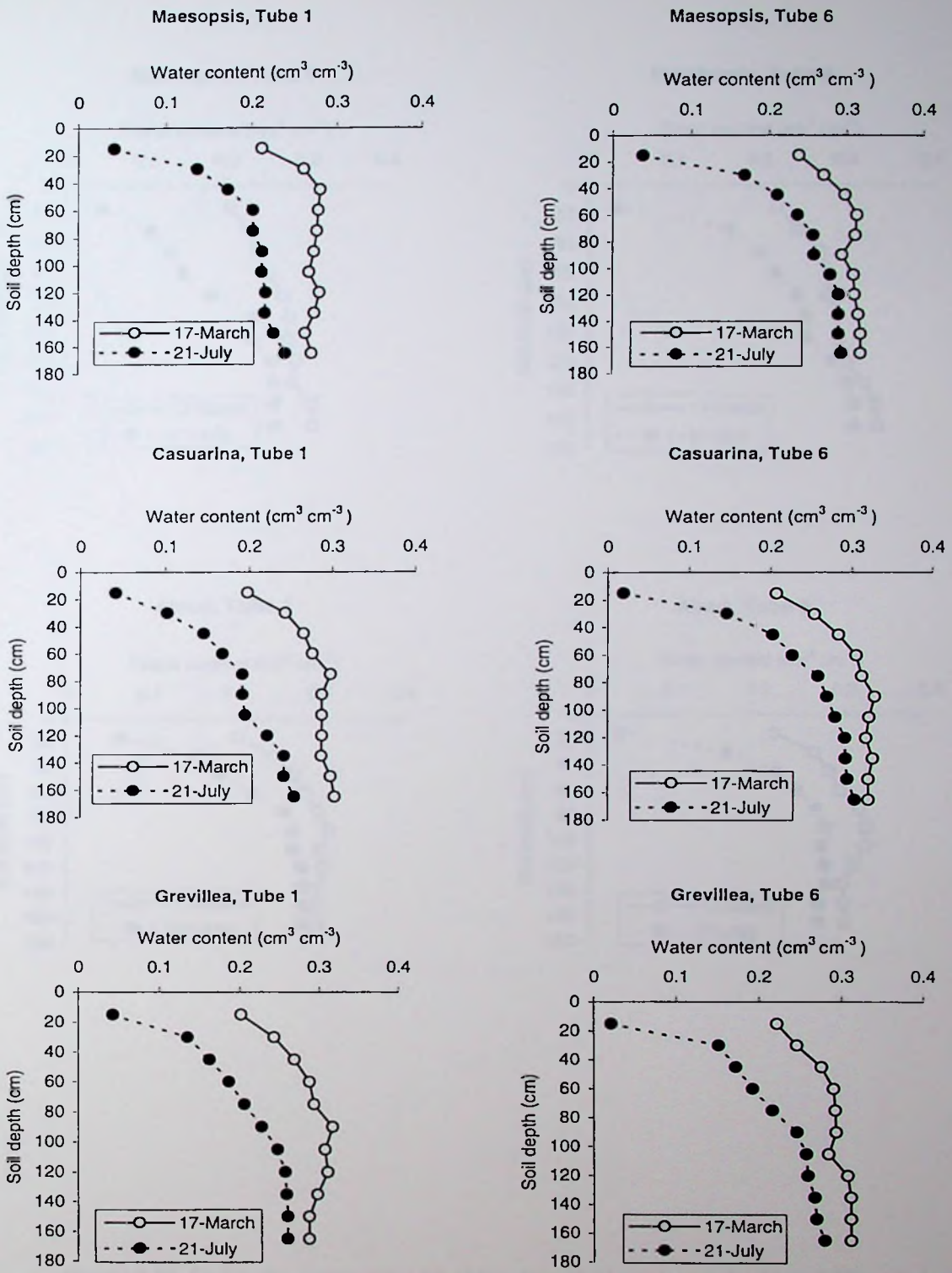


Figure 7.3a Soil water content for *Maesopsis*, *Casuarina* and *Grevillea* at 1 m (tube 1) and 13 m (tube 6) distances from the tree line when the profile was wettest (17 March) and driest (21 July) during March-May 1998 cropping season.

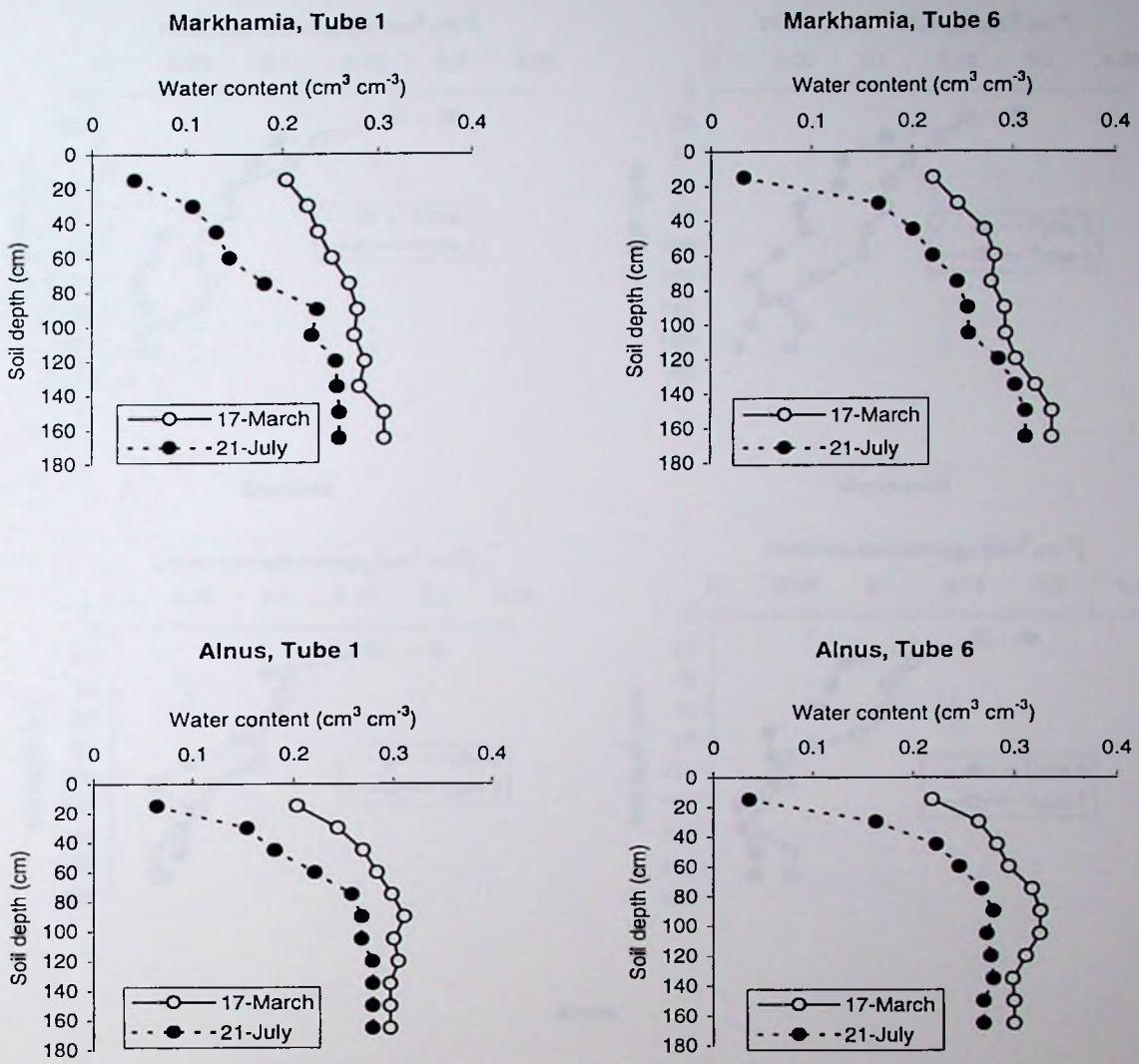


Figure 7.3b Soil water content for *Markhamia* and *Alnus* 1 m (tube 1) and 13 m (tube 6) distances from the tree line when the profile was wettest (17 March) and driest (21 July) during March-May 1998 cropping season.

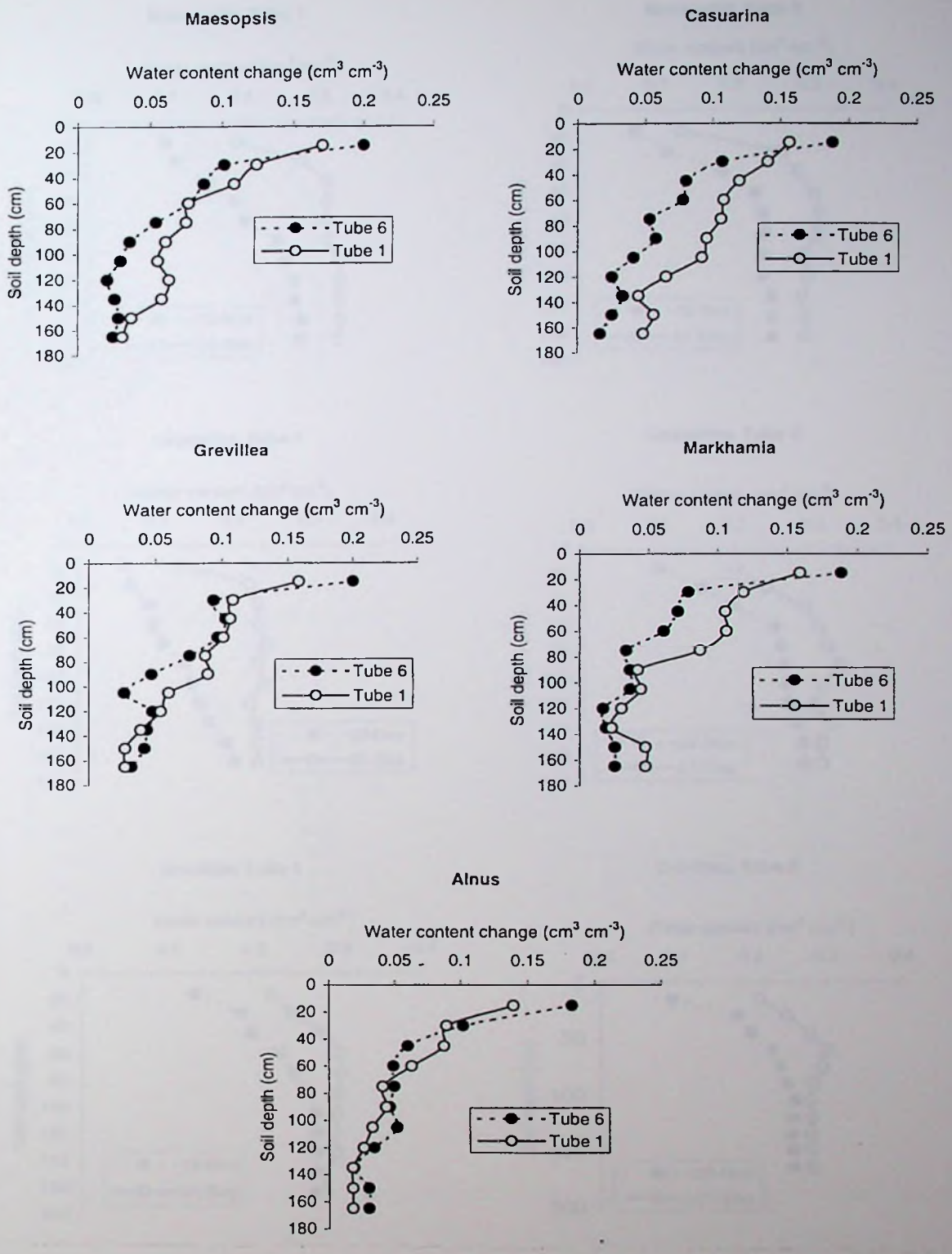


Figure 7.3c Soil water depletion by the tree species associated with maize during March-May 1998 cropping season.

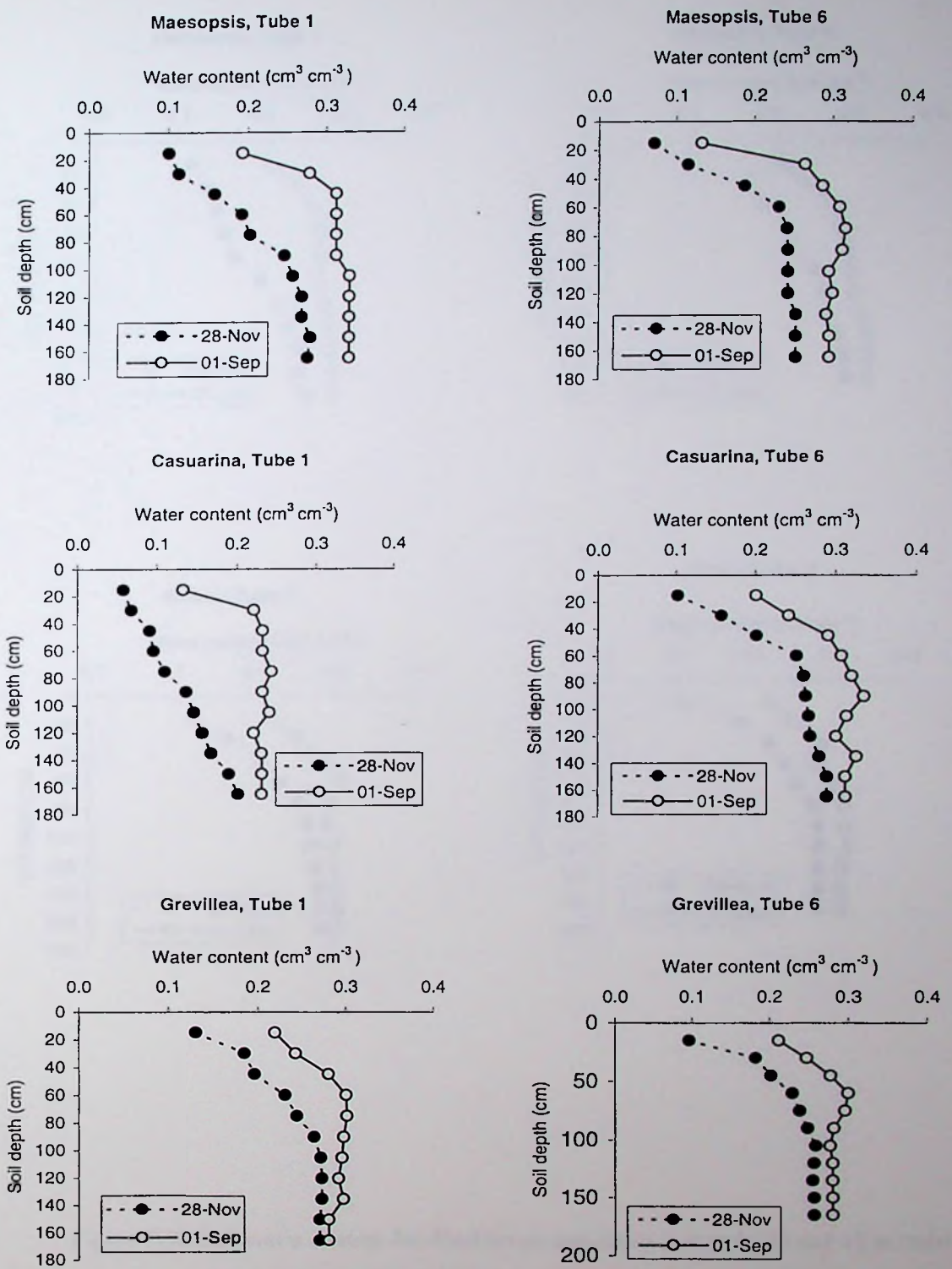


Figure 7.4a Soil water content for *Maesopsis*, *Casuarina* and *Grevillea* at 1 m (tube 1) and 13 m (tube 6) distances from the tree line when the profile was wettest (1 September) and driest (28 November) during August-November 1998 cropping season.

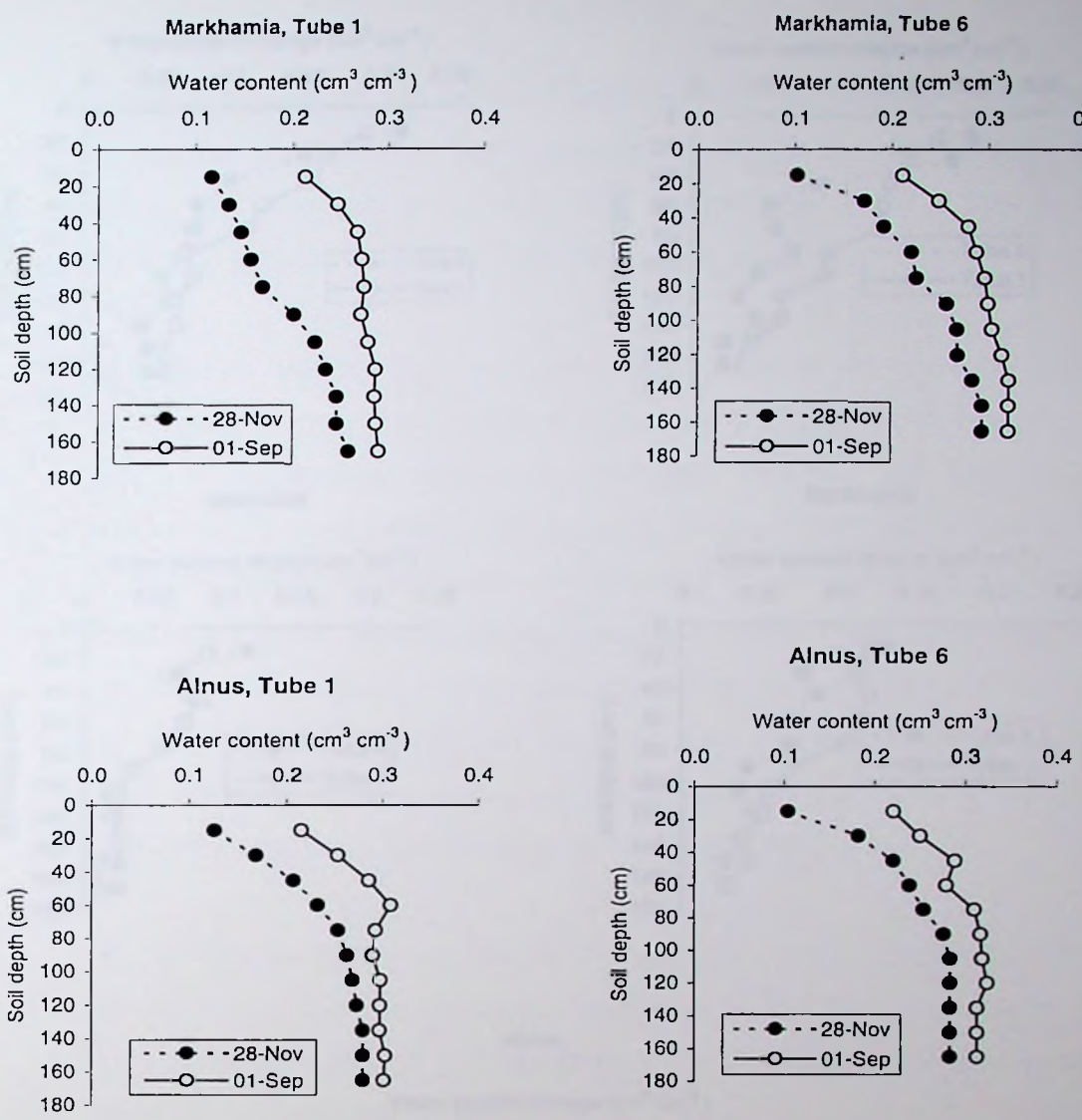


Figure 7.4b Soil water content for *Markhamia* and *Alnus* 1 m (tube 1) and 13 m (tube 6) distances from the tree line when the profile was wettest (1 September) and driest (28 November) during August-November 1998 cropping season.

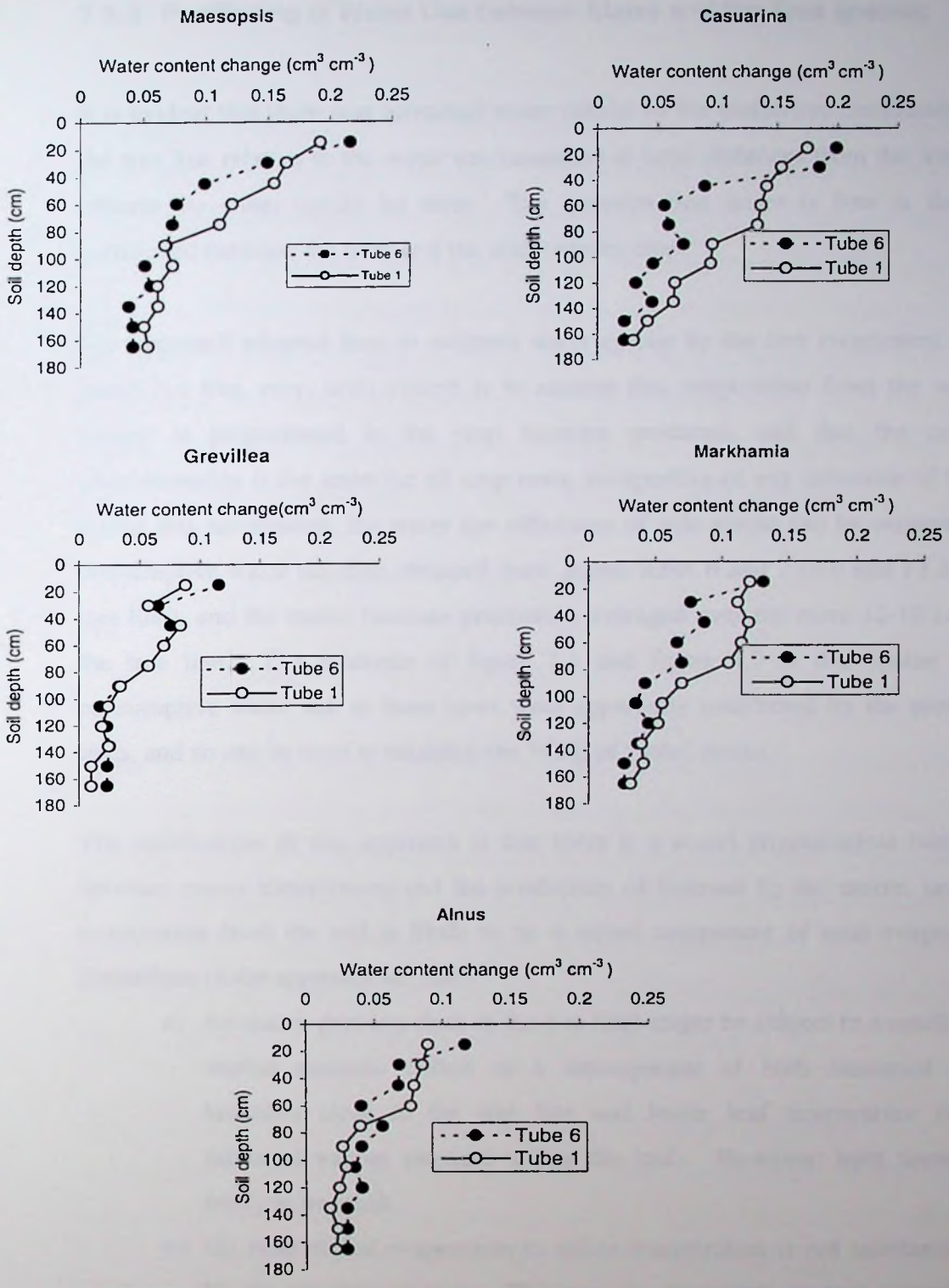


Figure 7.4c Soil water depletion by the tree species associated with maize during August-November 1998 cropping season.

7.2.3 Partitioning of Water Use between Maize and the Tree species

It is evident that there was increased water uptake by the maize/tree combinations close to the tree line relative to the water use measured at large distances from the tree line. This reflects the water uptake by trees. The question that arises is how is the water use partitioned between the trees and the under-storey crop?

The approach adopted here to estimate water uptake by the tree component of the three phase (i.e tree, crop, soil) system is to assume that evaporation from the soil and crop foliage is proportional to the crop biomass produced, and that the coefficient of proportionality is the same for all crop rows, irrespective of any influence of the tree line. Given this assumption, the water use efficiency of sole maize can be estimated from the consumptive water use data obtained from access tubes 6 and 7 (9.6 and 13.2 m from the tree line), and the maize biomass production averaged over the rows 12-18 (> 9 m) from the tree line. The evidence of figure 7.1 and figure 4.7 is that maize growth and consumptive water use in these rows were apparently unaffected by the presence of the trees, and so can be used to establish the WUE of "sole" maize.

The justification of this approach is that there is a sound physiological basis for a link between maize transpiration and the production of biomass by the maize, and that direct evaporation from the soil is likely to be a minor component of total evaporation. The limitations of the approach are that:-

a) the maize growing close to the tree lines might be subject to a smaller leaf-to-air vapour pressure deficit as a consequence of both increased atmospheric humidity close to the tree line and lower leaf temperature (hence lower saturated vapour pressure within the leaf). However, both these effects are likely to be small.

b) the ratio of soil evaporation to maize transpiration is not substantially affected by the presence of trees. This may be reasonable on two counts. First, soil evaporation is likely to be small relative to maize transpiration (evidence of which is presented later in section 7.2.4), and so any shift in the soil evaporation : maize transpiration will have a small effect on the maize WUE. Second, most soil evaporation is likely to occur during first-stage

(i.e energy limited) evaporation, and so will be reduced by tree shading in similar proportion to the reduction in maize transpiration.

To partition water use between the maize crop and the tree species, regressions were developed by plotting seasonal water losses with the corresponding biomass produced by maize as mentioned earlier. The data from the tree plots were pooled for these regressions (n = 40). This was done for March-May and August- November 1998 when there were significant differences between the tree species in water loss. By fitting regression lines that passed through the origin, regression equations were obtained which were then used to estimate the amount of water used by maize to produce a given amount of biomass (WUE). Equations 7.1 and 7.2 below were obtained and were used to calculate water use by the maize crop during March-May and August-November 1998 seasons.

$$B = 0.0018*W \qquad (R^2 = 0.94) \qquad 7.1$$

and

$$B = 0.0039*W \qquad (R^2 = 0.91) \qquad 7.2$$

where B was the biomass produced and W was the amount of water used by the maize crop. The approximately two-fold difference in maize water use efficiency was notable. This big difference in WUE between the two seasons could possibly be explained by the fact that the August-November 1998 season was more humid than the March-May 1998 season. WUE has been found to be inversely proportional to mean saturation deficit [Monteith 1988], implying that when the air is drier, plants use more water to produce a given amount of biomass compared to when the air is humid.

Figure 7.5a shows water use by the maize crop (derived from equation 7.1) as a function of distance from the tree lines for March-May 1998 season based on the values for the measured maize biomass. Corresponding water use by the tree species was obtained by subtracting maize water use from the total seasonal water loss (figure 7.1b). These values were then plotted against distance from the tree line to obtain figure 7.5b. Water use by the maize crop was significantly ($p<0.001$) lower under the trees up to a distance of 4 m from the tree line (figure 7.5a). Maize plants under *Casuarina* were the most affected followed by *Maesopsis* and *Markhamia*. The least effects were observed under *Grevillea* and *Alnus* tree species. The *Casuarina* trees used significantly more water than all the other tree

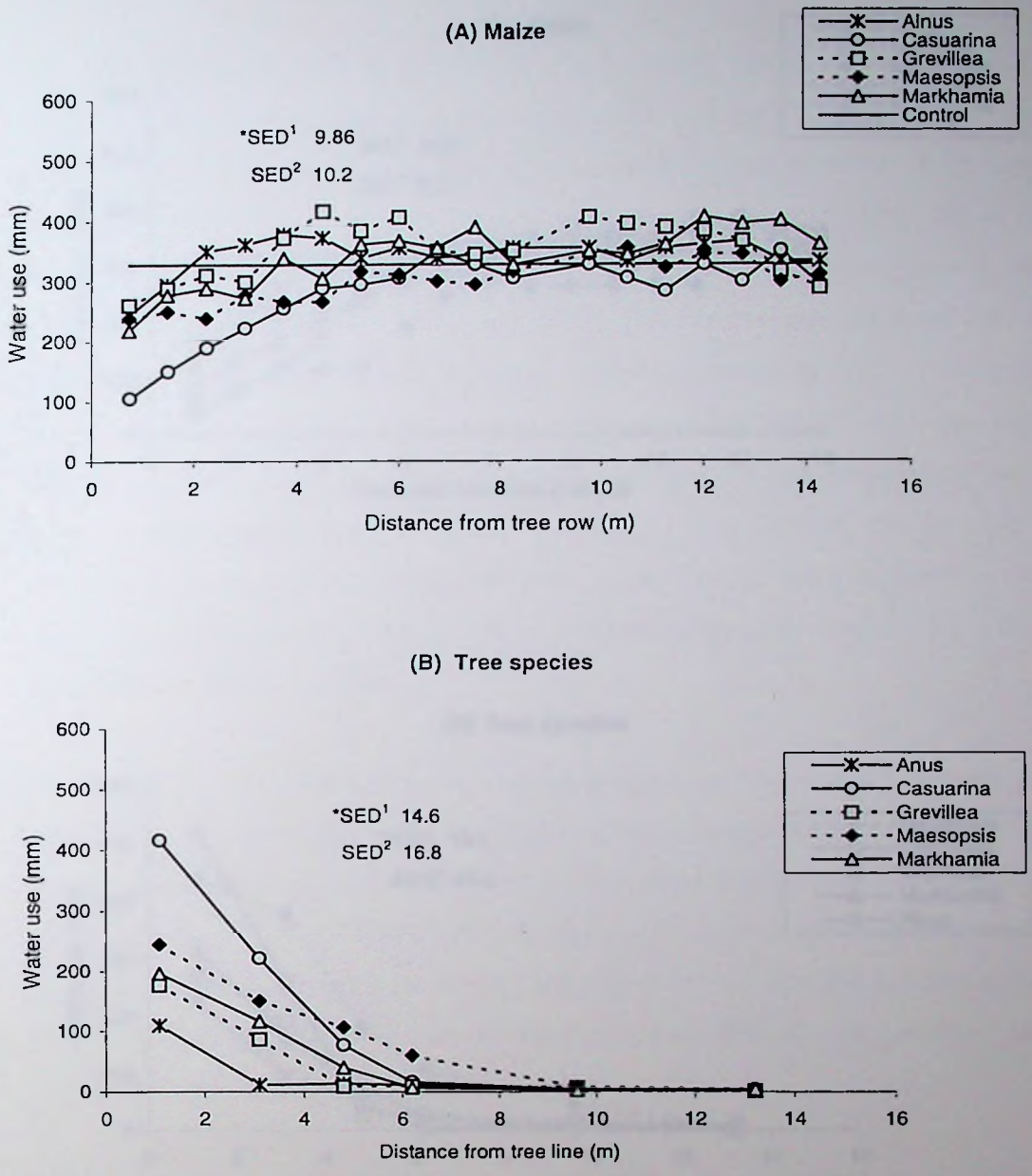
species up to 4 m distance as shown in figure 7.5b, followed by *Maesopsis* whose effect reached a distance of 6 m from the tree line. *Markhamia* and *Grevillea* had similar rates of water use, while *Alnus* used the least water.

Similar trends in water use were observed during the August-November 1998 cropping season for both the maize crop and the trees (figure 7.6). The effects were more significant ($p<0.001$), with *Casuarina* having the greatest reduction on maize water use followed by *Markhamia* and *Maesopsis*. *Grevillea* and *Alnus* again had the least effects (figure 7.6a). Tree water use followed the same pattern as in the previous season, with *Casuarina*, *Markhamia* and *Maesopsis* using significantly more water than the other two species (figure 7.6b). The effect of *Maesopsis* on water use was significant up to 6 m distance from the tree lines.

Table 7.3 shows the estimated amount of water used by individual trees during the two seasons based on data in figures 7.5 and 7.6. In both seasons, *Casuarina* and *Maesopsis* used more water than the other tree species. During March-May 1998 season, *Casuarina* and *Maesopsis* used 107 and 99 kg of water $tree^{-1}$ day^{-1} respectively. *Grevillea* and *Markhamia* used similar amounts of water, 89 kg of water $tree^{-1}$ day^{-1}, while *Alnus* used the least water (57 kg $tree^{-1}$ day^{-1}). In the next season, a similar pattern emerged but the amount of water used by individual trees increased (table 7.3). Water use increases were 35, 16, 26, 26 and 49% for *Maesopsis*, *Casuarina*, *Grevillea*, *Markhamia* and *Alnus* respectively. The high water use by *Casuarina* compared with the other species is consistent with the relatively low values for the LUE of maize grown within the influence of *Casuarina* compared with the other tree species (see figure 5.14).

Table 7.3 Water use by the tree species during March-May and August-November 1998 cropping seasons

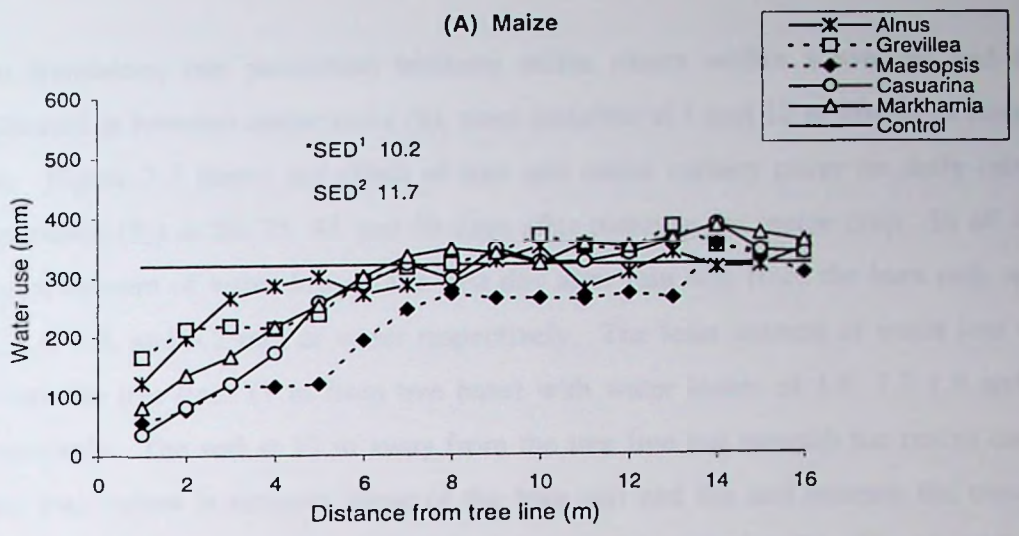
Season	Species	Water use (kg tree^{-1})	Water use (kg/tree/day)
March-May 1998	*Maesopsis*	10,920	99
	Casuarina	11,760	107
	Grevillea	9,840	89
	Markhamia	9,840	89
	Alnus	6,120	57
August-November 1998	*Maesopsis*	12,060	134
	Casuarina	11,160	124
	Grevillea	10,080	112
	Markhamia	10,170	113
	Alnus	7,650	85

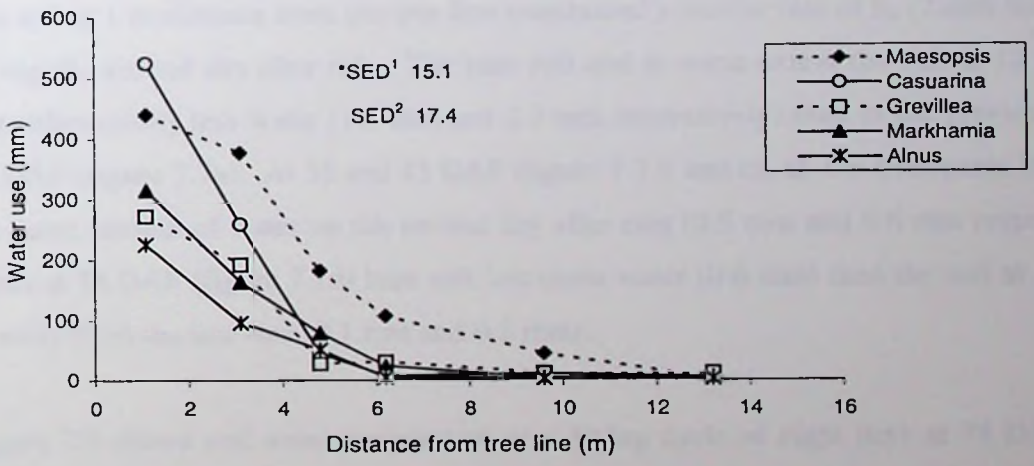


* SED¹ between distances in treatment

SED² between treatments for given distance

Figure 7.5 Water use by the maize crop (A) and the different tree species (B) during March-May 1998 cropping season.





* SED¹ between distances in treatment

SED² between treatments for given distance

Figure 7.6 Water use by the maize crop (A) and the different tree species (B) during August-November 1998 cropping season.

7.2.4 Soil Water Evaporation

Two lysimeters, one positioned between maize plants within a row (a) and the other positioned in between maize rows (b), were installed at 1 and 12 m distances from the tree lines. Figure 7.7 shows the effect of tree and maize canopy cover on daily rates of soil evaporation (E_s) at 20, 35, 45 and 58 days after planting the maize crop. In all cases, the greatest amount of water lost on the first day after rain was from the bare soil, which lost 5.5, 3.4, 3.8, and 3.2 mm of water respectively. The least amount of water lost was from beneath the tree lines (1 m from tree base) with water losses of 1.6, 1.2 1.8 and 1.1 mm respectively. The soil at 12 m away from the tree line but beneath the maize canopy had water loss values in between those of the bare soil and the soil beneath the trees. Water losses at this location were 3.2, 2.3, 2.6 and 2.1 mm for 20, 35, 45 and 58 DAP respectively. There were no differences in the amount of soil water lost between lysimeters located within the crop rows (a) and those in between the crop rows (b) for both 1 m and 12 m distances from the tree line.

The soil at 1 m distance from the tree line maintained a similar rate of E_s (2 mm water loss) during the second day after rain. The bare soil and to some extent the soil at 12 m away, lost substantially less water (1.8 mm and 2.3 mm respectively) than in the previous day at 20 DAP (figure 7.7a). At 35 and 45 DAP (figure 7.7 b and c), all the treatments lost about the same amount of water on the second day after rain (0.5 mm and 0.6 mm respectively), while at 58 DAP (figure 7.7d) bare soil lost more water (0.6 mm) than the soil at 1 and 12 m away from the tree line (0.1 mm and 0.1 mm).

Figure 7.8 shows soil water evaporation at a drying cycle of eight days at 75 DAP. The cumulative loss of water through evaporation from bare soil was 8.9 mm. Total E_s at 1 m from the base of the tree was 4.4 mm (49% of bare soil) and total E_s at 12 m from the base of the tree was 6.3 mm (71% of bare soil). Figure 7.9 shows soil water evaporation plotted against the inverse of the square root of the number of days after rain

Generally, total E_s was markedly reduced beneath the tree canopy (1 m distance) compared to under the maize canopy (12 m distance) and the bare soil. This could have been the result of tree shading which reduced the radiation load (3.8 MJ m^{-2}) on the soil beneath the

trees compared to 12 m away (8.2 MJ m^{-2}) and bare soil (12.8 MJ m^{-2}). The tree canopy might have also decreased the atmospheric vapor pressure deficit (D) and/or the wind speed beneath the tree, which lead to a reduction in E_s [Jackson and Wallace 1999].

Evaporation from the bare soil initially proceeded at the potential rate of E_o during the first phase (1-2 days) as shown in figure 7.9. After this period, the rate of soil evaporation reduced and was mainly determined by the hydraulic properties of the soil [Ritchie 1972]. Shading appears to have reduced evaporation rate during the the first phase of soil evaporation at both 1 and 12 m distances from the tree lines. The reduction was more marked under the tree canopy than under the maize canopy. This is mainly because first phase evaporation depends on E_o and hence the energy available at the soil surface. Second phase evaporation is dependent on the soil hydraulic properties and hence independent of shade. That is probably why the three curves tended to converge during this phase. The curves for the 1 m and 12 m distances from the tree lines were lower than that of the bare soil probably due to water abstraction by the tree and maize roots in these locations.

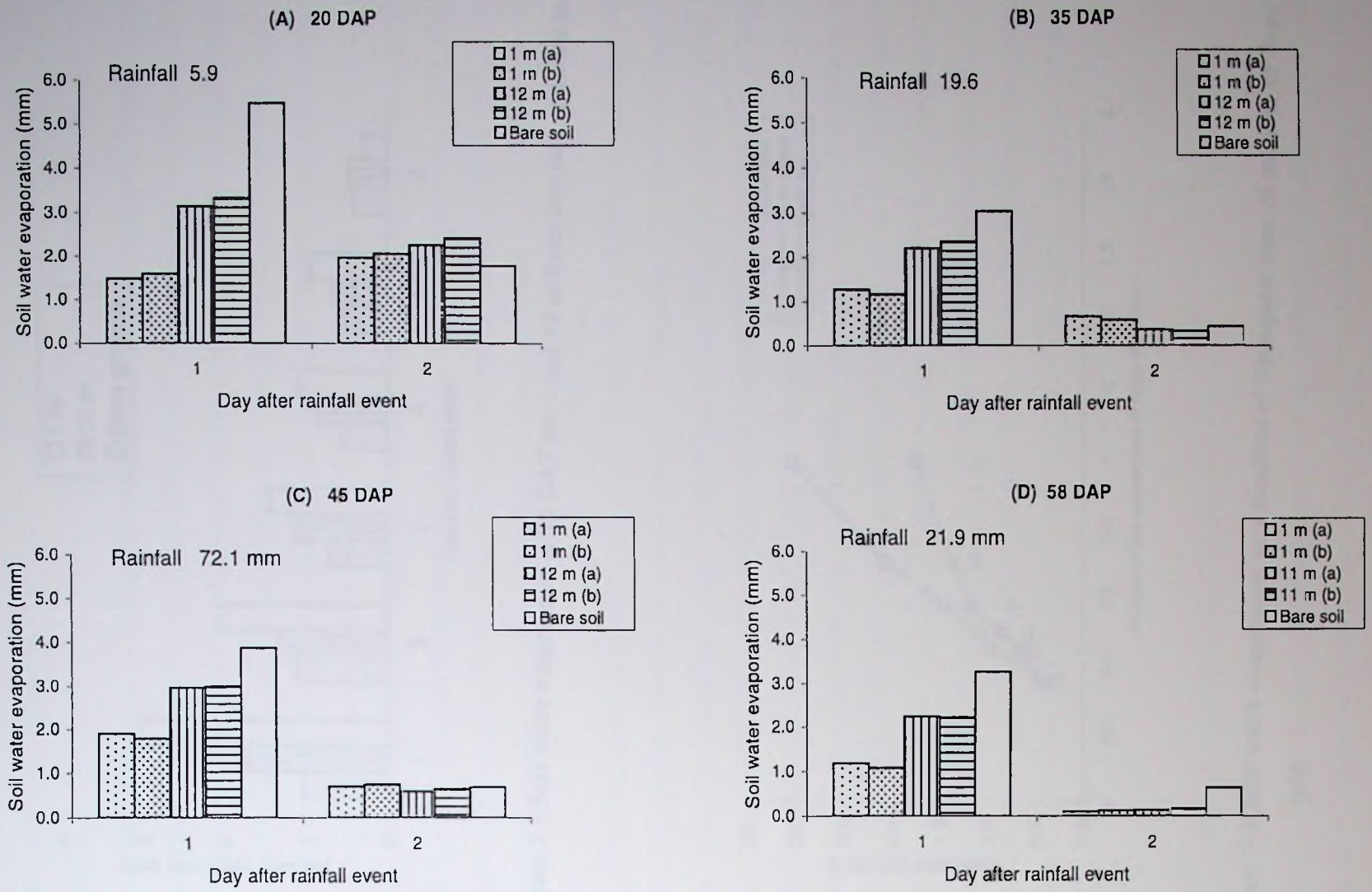


Figure 7.7 Soil water evaporation at 1 and 12 m from tree line and bare soil for (A) 20, (B) 35, (C) 45 and (D) 58 days after planting.

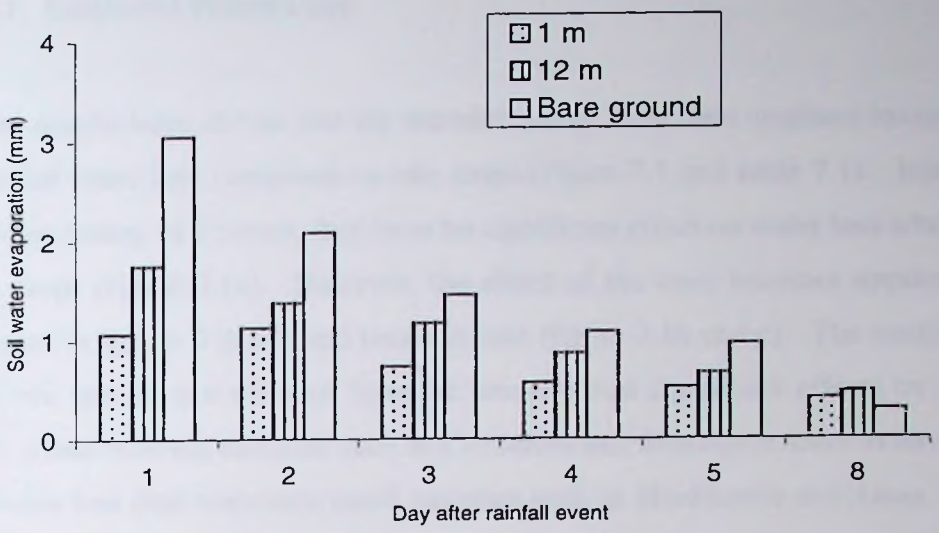


Figure 7.8 Soil water evaporation at 75 DAP for 1 and 12 m from tree line and bare soil

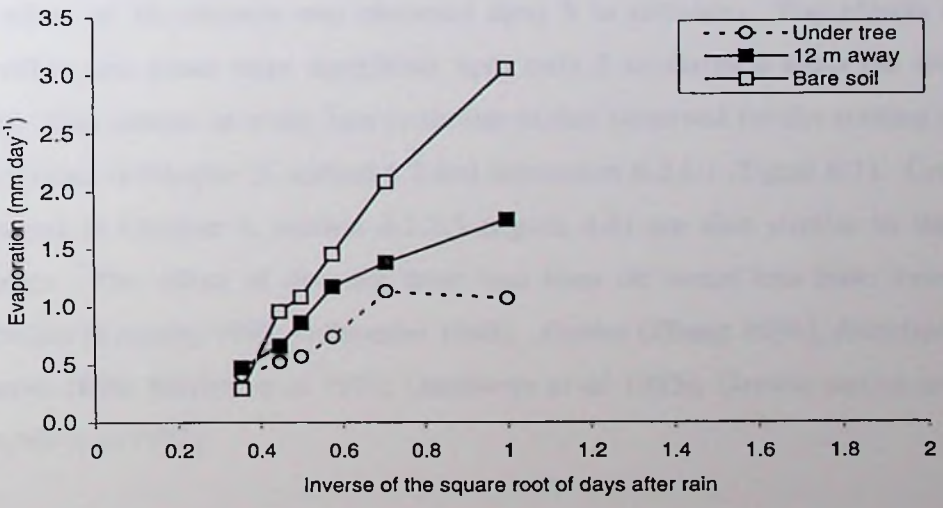


Figure 7.9 Soil water evaporation as a function of the square root of number of days after rain

7.3 Discussion

7.3.1 Seasonal Water Loss

These results have shown that the introduction of trees onto cropland invariably increases seasonal water loss compared to sole crops (figure 7.1 and table 7.1). Initially when the trees are young (< 2 years), they have no significant effect on water loss when compared to sole crops (figure 7.1a). However, the effect of the trees becomes apparent as the trees increase in age (> 2 years) and hence in size (figure 7.1b and c). The results also indicate that tree species and distance from the tree row had significant effects on seasonal water loss. Trees with big canopies such as *Casuarina* and *Maesopsis* seem to have larger effects on water loss than trees with small canopies such as *Markhamia* and *Alnus*. The effects of different tree species on water loss have been reported in other agroforestry trials [Eastham *et al* 1994; Yunusa *et al* 1995; Livesley 1999; Odhiambo 1999].

Water loss due to the presence of the trees decreased with increasing distance from the tree lines with species showing different effects. In the last season (August-November 1998), *Maesopsis* had a significant effect on water loss to 6 m distance from the tree line, while the effect of *Markhamia* was observed upto 5 m distance. The effects of *Casuarina*, *Grevillea* and *Alnus* were significant upto only 3 m distance from the tree row (figure 7.1c). This pattern in water loss is similar to that observed for the rooting patterns of the tree species in Chapter 5, section 6.2 and subsection 6.2.1.1 (figure 6.1). Crop yield trends observed in Chapter 4, section 4.2.2.3 (figure 4.8) are also similar to these water loss patterns. The effect of distance from tree lines on water loss have been reported for *Grevillea* [Livesley 1999; Odhiambo 1999], *Poplus* [Zhang 1996], *Eucalyptus* [Malik and Sharma 1990; Khybri *et al* 1992; Onyewotu *et al* 1995], *Grewia optiva* and *Morus alba* [Khybri *et al* 1992].

7.3.2 Soil Water depletion down the Soil profile

The tree species showed different patterns of water depletion down the soil profile at 1 m distance from the tree lines (figures 7.3c and 7.4c). The greatest water depletion in the soil profiles occurred under *Casuarina*, *Maesopsis* and *Markhamia*. The former two species

also had the greatest seasonal water losses from the soil profile. *Grevillea* and *Alnus* had the least effects on soil water depletion. The maximum soil water depletion in the upper 1.8 m of the soil profile varied from 100 mm in sole maize plots to 160 mm in the *Casuarina* plots during the August-November 1998 cropping season (table 7.2). *Markhamia* depleted soil water from the topsoil (20-80 cm), while *Casuarina* and *Maesopsis* depleted soil water to greater soil depths (30-160 cm). This pattern in water depletion with depth closely resembles the rooting patterns of the species (figure 6.2) presented in Chapter 6, section 6.2.1.2. *Markhamia* had most of its roots at the topsoil, while *Maesopsis* and *Casuarina* had their roots spread down the soil profile.

It is generally accepted that trees will preferentially abstract water from the topsoil when soil water is distributed uniformly [ICRAF 1994; Zhang 1996]. The patterns of water abstraction observed here could have been greatly influenced by the rooting patterns of the tree species. This is probably why *Maesopsis* and *Casuarina*, which had deep rooting systems, were able to abstract water from deeper soil layers compared to the other species. These species were, therefore, able to abstract water from the deep soil layers when the topsoil had dried out. The rate of water abstraction does not only depend on the available soil moisture but also on rooting depth and density, which determine the total volume of soil colonized by plant roots [Passioura 1993]. Zhang [1996] found the zone of maximum root water uptake moved progressively from shallower to deeper depths as the soil dried, and the amount of water taken up from any given layer depended on both the distribution of soil water and rooting density. When the soil profile was uniformly wet, water uptake mainly occurred in the surface layers, which had the highest root density. As the soil dried, the deeper soil layers, which were wetter than the surface layers, contributed more to total water uptake despite having lower rooting density. Livesley [1999] found that water abstraction by *Grevillea* trees was greater at the topsoil than at the deeper soil layers, while Howard *et al* [1997] found that *Grevillea* utilized water from below the crop rooting zone (> 60 cm depth). Odhiambo [1999], however, reports that *Grevillea* exclusively utilized water from deep horizons, but there was also an overlap in water use between *Grevillea* and maize in the topsoil.

7.3.3 Partitioning of Water Use between Maize and Tree species

Water use values for both the tree species and the maize crop reported in section 7.2.3 was a crude attempt to partition water use between the trees and maize. Several assumptions were made during the process as was mentioned in section 7.2.3. This therefore, means that the data on water use by maize and the tree species presented in this study can only be regarded as approximate. The values are, therefore, a reasonable first approximation of the true values of water use for the tree species and maize. Water use by the maize crop associated with the different tree species closely followed biomass production patterns observed in Chapter 4, section 4.2.2.2 (figure 4.7). Maize water use was significantly influenced by the presence of the trees with *Casuarina* significantly reducing maize water use upto 5 m distance from the tree lines when compared to sole maize (figures 7.5a and 7.6a). *Maesopsis* significantly affected water use by the maize upto 6 m distance from the tree lines, while *Markhamia* and *Grevillea* appeared to affect it upto 3 m distance. *Alnus* had the least effect on water use with the effect only reaching 2 m distance from the tree line.

Tree water use (figures 7.5b and 7.6b) closely resembles the seasonal water loss graphs (7.1b and c). This is not surprising because when estimating water use, drainage was assumed not to have taken place in all the plots. Water use was greatest under *Casuarina* and *Maesopsis*, with each individual tree using 134 and 124 kg of water day^{-1} respectively. They were followed by *Markhamia* and *Grevillea*, which used 112 and 113 kg of water $tree^{-1}$ day^{-1}. *Alnus* used the least amount of water, with each tree using only 85 kg of water day^{-1}. There are no data in the literature with which to compare water use by maize interplanted with upper-storey trees. However, there are reports that tree root competition for water greatly reduced soil water availability for successful crop establishment [Odhiambo 1999] and the subsequent reduction in yields of the associated crops [Malik and Sharma 1990; Khybri *et al* 1992; Odhiambo 1999].

7.3.4 Soil Water Evaporation

These results confirm the general hypothesis that soil evaporation is reduced when trees are incorporated into cropping systems. Loss of water from the soil surfaces through evaporation (E_s) is often a major component in soil water balance of most agricultural systems [Allen 1990]. In agroforestry systems, the added evaporation loss caused by the incorporation of trees into a cropping system might be compensated for, at least in part, by a reduction in soil evaporation due to changes in the microclimate beneath the trees [Jackson and Wallace 1999]. Reductions in E_s observed in this study could have been due to the shading effect of the tree and crop canopies, reduced input of water to the soil due to rainfall interception, and depletion of surface soil water due to root water abstraction [Allen 1990; Yunusa *et al* 1993; Daamen *et al* 1995; Wallace *et al* 1998]. These effects cannot easily be separated from the lysimeter data alone, however, an attempt has been made by Wallace *et al* [1998] using a simple model of the three processes involved. Soil evaporation rates have been found to change with soil type and rainfall frequency [Wallace *et al* 1998].

Jackson and Wallace [1999] studied direct evaporation from the soil (E_s) in an agroforestry system involving *Grevillea* in a semi-arid environment in Machakos, Kenya. E_s was found to vary according to the different shade regimes and as a function of proximity to trees. There was considerable influence of tree proximity on both daily and cumulative soil evaporation rates. The presence of the trees over bare soil reduced total seasonal E_s by 24%, compared to an 8% reduction in E_s by the maize crop. The maize crop was less effective in reducing E_s largely because of its shorter duration. They conclude that given the strong dependence of E_s on canopy cover, it is possible to postulate agroforestry management regimes, which reduce soil evaporation when the maize crop has recently emerged. Reductions in E_s by the tree and maize canopies, 51 and 29% respectively, reported here are much higher than those reported by Jackson and Wallace [1999] probably because they represent values from a single drying cycle of 8 days when the crop had fully matured with full LAI (75 DAP).

7.4 Summary

There were higher seasonal water losses from the tree plots than sole crop plots, especially during March-May and August-November 1998 cropping seasons. These high water losses from the trees were associated with greater soil water depletions than occurred in sole crop plots. *Casuarina* and *Maesopsis* had significantly higher water losses than *Grevillea* and *Markhamia*. *Alnus* lost the least water. The effect of *Maesopsis* extended upto 6 m distance from the tree line, while *Markhamia* had its effect upto 5 m. All the other species had their effect upto 3 m distance from the tree lines. The plot averages of seasonal water losses for the August-November 1998 season were 698, 682, 662, 640, 630 and 590 mm for *Casuarina*, *Maesopsis*, *Grevillea*, *Markhamia*, *Alnus* and sole maize respectively.

Soil water depletion down the soil profile by the tree species followed a similar pattern, with *Casuarina*, *Maesopsis* and *Markhamia* having the greatest effects. The least effects in soil water depletion were observed under *Grevillea* and *Alnus*. *Casuarina* and *Maesopsis* depleted soil water at soil depths of 40-160 cm, while *Markhamia* depleted soil water from the topsoil (20-80 cm). Maximum soil water depletion in the upper 1.8 m of the soil profile during August-November 1998 season were 160, 158, 148, 133, 84 and 100 mm for *Casuarina*, *Maesopsis*, *Grevillea*, *Markhamia*, *Alnus* and sole maize respectively.

Water use by the maize crop was significantly ($p<0.001$) reduced by the presence of the trees upto a distance of 5 m from the tree lines. *Casuarina* and *Maesopsis* had the greatest effects, followed by *Markhamia*. *Grevillea* and *Alnus* had the least effects. Water use by the trees decreased with increasing distance from the tree lines, and during August-November 1998 season, individual trees used 134, 124, 112, 113 and 85 kg of water day^{-1} for *Maesopsis*, *Casuarina*, *Grevillea*, *Markhamia* and *Alnus* respectively.

Total soil evaporation (E_s) was greatly reduced beneath the tree canopy compared to under the maize crop canopy and bare soil. Total E_s under the tree canopy was 49% of bare soil, while total E_s under the maize canopy was 71 % of bare soil.

CHAPTER EIGHT

GENERAL DISCUSSION AND CONCLUSIONS

8.1 Introduction

Comprehensive discussions on the research findings have been made in Chapters 4, 5, 6 and 7. The main purpose of this Chapter, therefore, is to discuss some of the most important points concerning the effects of trees on crop growth and yield which were a direct result of competition for light and water in this study. This is done in Sections 8.2 and 8.3, while section 8.4 presents an attempt to evaluate the biological advantage of tree/crop mixtures over sole crops and sole trees. The last part of the Chapter (section 8.5) gives a summary of the main conclusions reached, based on the results of the study.

8.2 Effect of trees on crops

The incorporation of trees into cropping systems may have either beneficial or detrimental effects on crop production. From the famer's perspective, the nature of this effect is of prime importance. Resource exploitation is the most direct way a tree can affect the associated crop by reducing the availability of a shared resource [Goldberg and Werner 1983; Connell 1990]. Generally resource uptake interactions have a negative effect on crop performance, but are unavoidable in simultaneous agroforestry systems such as upper-storey tree planting. Resource uptake by trees may be smaller than that of crops on a per unit biomass basis, but the amount of biomass growth and continuous tree resource uptake often leads to a negative effect on the crop and the shared resource environment [Goldberg 1990].

The results from this study have demonstrated that crop yields in close proximity to the trees are significantly reduced three years after tree establishment. The magnitude of the effect depends on the tree species and distance from the trees. The results also seem to suggest that there was little or no complementarity in light and water use between the different tree species and the associated maize and beans in this study. The trees and the

crops competed for growth resources. It therefore, appears that the management of the trees (mainly the canopies and roots) in this agroforestry system, seems to be the obvious way of minimizing this competition and hence improving the yield of the companion crops. Side pruning of tree branches [Kessler 1992; Tilander *et al* 1995] reduces competition for light and provides tree products such as fuel-wood and fodder in addition to enhanced fruit production in certain tree species [Timmer *et al* 1996]. Below ground competition for water in this agroforestry system can be reduced or minimized by periodically root pruning the trees prior to the planting of the companion crops. This can be achieved either by deep ploughing or by use of axes and hoes [Roger and Rao 1990; Rao *et al* 1990; van Roode 1992]. These management practices should allow the under-storey crop to establish and better compete for growth resources of light and water as the tree canopy and root system recover [Jones and Sinclair 1996]. However, certain tree species are sensitive to frequent pruning [Horst *et al* 1995], therefore research is required to establish the frequency and the ability of different tree species to survive and respond to heavy shoot and root pruning.

The competitive effects of trees tend to increase as the agroforestry system matures and produces a concomitant decrease in the yields of the associated crops [Srinivasan *et al* 1990]. Rao *et al* [1998] argue that inspite of large crop yield increases and decreases under the trees, the overall effect of the trees on crop yields in this agroforestry system could be small because, only a small proportion (about 10%) of the area is subjected to tree/crop interactions.

8.3 Competition for Light and Water

8.3.1 Competition for Light

Competition for light and water between the tree species and associated crops were both found be important in this study. Competition for light occurs when the presence of one plant reduces the net photosynthesis of another by reducing the amount of radiant energy it receives [Ludlow 1978]. In boundary/upper-storey tree planting agroforestry systems, the tree and crop canopies are separated vertically in space due to the differences in relative heights between the two components. Because the crop is shorter, it is permanently shaded by the tree. This implies that the fraction of PAR reaching the under-storey crop is reduced by the presence of the trees. This reduces the net photosynthesis of the shaded maize

plants leading to lower growth and reduced yields. Tree shading is expected to affect crop growth and yield only within the radius of the tree canopy. However, in the case of *Maesopsis*, crop growth and yield were significantly affected up to a distance of 6 m from the tree line, well beyond the radius of the tree canopy (2.5 m). This suggests that competition for water between the trees and the crop was responsible the observed reduced crop growth and yield beyond the influence of the tree shade. This was confirmed by the presence of *Maesopsis* tree roots beyond 6 m from the tree line. Maize root densities were also significantly reduced by the presence of *Maesopsis* tree roots up to 4 m distance from the tree line. Results on competition for light between the tree species and maize in this study are in agreement with results reported elsewhere [Daniel *et al* 1991; Chirko 1993; Miah *et al* 1995; Chirko *et al* 1996b; Zhang 1996; Ssekabembe *et al* 1997]. The fraction of PAR reaching the under-storey crops in these studies was reduced by 12 to 65% when compared to the open or sole cropped areas.

8.3.2 Competition for Water

In agroforestry systems, trees with deep rooting systems are expected to exploit soil moisture from greater depth than do arable or pasture crops, therefore making better use of available resources [Jarvis 1991; Ong *et al* 1996]. Complementarity between the spatial distribution of tree and crop root systems has been regarded as a primary requirement to maximize the use of soil resources such as water whilst minimizing the negative competitive effects below ground [van Noordwijk *et al* 1996]. This was not the case in this study as the trees and the associated crops had overlapping root systems, with the result that the established root systems of the trees greatly reduced the growth and water uptake capacity of the maize roots. Similar overlaps between the distribution of tree and crop root systems has been reported by other workers [Jonsson *et al* 1998; van Noordwijk *et al* 1991; Ruhigwa *et al* 1992]. However, some degree of complementarity has been observed in some cases [Eastham and Rose 1990; Tomlinson and Eason 1990; Chirko *et al* 1996b; van Noordwijk *et al* 1996; Huxley *et al* 1996; Zhang 1996]. In the latter case, the tree root systems have probably been displaced downwards after many years of concurrent growth with root systems of competitive crops or pasture [Anderson *et al* 1993]. Livesley [1999] observed that rapid growth and competitive activity of the maize root system appears to have forced better structural complementarity through the downward

displacement of the *Grevillea* root system. In this study, five seasons of continuous inter-cropping of trees with crops did not show any evidence of the displacement of tree roots by the crop roots. The root systems of all the tree species reduced the vertical and horizontal distribution of maize roots, with the effect varying according to species. This gave the tree roots a competitive advantage in water use observed in this study.

The trees exploited a greater proportion of the available soil water than the sole crops because of their well-developed root systems. Total seasonal water losses and water use were significantly higher in the tree plots than in the sole maize, but this declined with increasing distance from the tree lines. In addition, total seasonal water losses and tree water use increased over the seasons as the trees grew big and hence significantly affected water use by the associated maize crop. There was no evidence of deep-water uptake by the trees in this study as the tree species abstracted soil water from the top layers of the soil profile (20-120 cm). Direct evidence of water uptake by trees [Jackson *et al* 1997; Lott 1997; Howard *et al* 1997] indicate that trees preferentially abstract water from the topsoil when the soil is uniformly wet but abstract water from greater depths when the top soil has dried [Zhang 1996; Howard *et al* 1997].

In agroforestry systems, the added evaporation losses caused by the incorporation of trees into cropping systems might be compensated for, at least in part, by a reduction in soil evaporation due to changes in the microclimate beneath the trees [Jackson and Wallace 1999]. In this study, there was marked reduction in E_s beneath the *Maesopsis* tree canopies compared to the soil under the maize canopy and bare soil. Similar results have been reported for *Grevillea* in a semi-arid environment of Machakos, Kenya [Jackson and Wallace 1999]. The results of this study confirm the general hypothesis that soil evaporation is reduced when trees are incorporated into cropping systems. Given the strong dependence of E_s on canopy cover, Jackson and Wallace [1999] suggest agroforestry management regimes, which will reduce soil evaporation when the under-storey crop has just germinated. If the tree canopy was not pruned until several weeks into the crop growing season, an optimum reduction in total E_s might be achieved. The reduction in tree canopy later in the season would not expose completely bare soil, as the crop would have developed a seizable canopy. The reduced tree canopy would also reduce competition with the crop for light and water, increasing the chances of obtaining a reasonable crop yield. However, pruning trees when the crop is already established would probably cause

considerable damage to the under-storey crop, thereby negating the advantages of reduced E_s.

8.4 Is there an advantage of growing trees and crops as mixtures?

One of the main reasons why intercropping and agroforestry are practised is because mixtures have been found to be more productive than sole cropping [Ofori and Stern 1987; Ong and Black 1994]. The concept of Land Equivalent Ratio (LER) is the most widely accepted index for evaluating the effectiveness of all forms of mixed cropping relative to sole cropping [Willey 1979] and has been extended to agroforestry [Rao *et al* 1990, 1991]. LER is the ratio of the area under sole cropping to the area under intercropping or agroforestry that gives an equal amount of yield or resource used. When the LER = 1, there is no advantage to intercropping or agroforestry over sole cropping, but when when LER < 1, then more land is needed to produce a given yield or utilize a given resource by each component as an intercrop. Agroforestry or intercropping has an advantange over sole cropping when the LER > 1, implying that less land is needed to produce a given yield or utilize a given resource by each component in the mixture.

However, estimation of LER values for the tree/crop mixtures studied in this thesis are problematic, because there was no 'sole tree' treatment in the experimental design. Sole crop information is available, assuming that crops growing in rows 12 to 18 were at sufficient distance from the tree line to be beyond the influence of trees. In order to calculate LER values, there is therefore a need to make intestable assumptions about what would have been obtained by way of yield or resource use by a pure stand of the tree species in question. In the analysis which follows, this has been attempted in two ways. The first is from consideration of the water use by trees where the water use of the tree component of the mixture has been evaluated, and making use of the assumption that the amount of water used by trees grown in a sole stand would have been similar to potential evaporation. The second approach is based on consideration of the partitioning of light interception between the maize crop and tree canopies, and making use of the assumption that a dense stand of trees grown as a sole stand would have intercepted 100% of incident radiation.

Both these approaches are used below to make an assessment of the LER for the tree/crop

mixtures. Because of the progressively decreasing impact of trees on crop growth with increasing distance from the tree, the LER calculations have been calculated assuming different numbers of maize rows associated with each tree line. Trees were planted at 1 m spacing within the tree row. Hence a 'unit cell' of tree/crop mixture extending to encompass the first five maize rows has an area of 7.5 m^2, with corresponding figures of 15 and 22 m^2 for unit cells covering the first 10 and 15 maize rows respectively. LER calculations were made for each of these cell sizes.

The LER's based on water use were estimated as the ratio of water used by the tree/crop mixture (measured) to the predicted amount of water that would be used by a field which was divided between a sole stand of trees with complete ground cover and sole maize. The objective in this analysis was to allocate a fraction of the field (A_{tree}) to sole trees, which would give similar tree water use (and hence similar tree biomass production) to that obtained in the mixture. The LER calculations then assume that the remaining fraction of the field area ($A_{crop}=1-A_{tree}$) is devoted to sole maize, which has the same water use per unit land area as measured for the maize grown in rows 12 to 18 in the mixture. Seasonal water use by the individual trees in the mixtures is known (table 7.3). Hence the land area used by 'equivalent' trees in a sole stand was estimated by dividing the water use per tree in the mixture by the mean seasonal potential evaporation (mean daily potential evaporation x number of days). This equivalent land area per tree was divided by the 'unit cell' areas for each of the cases considered (e.g. by 7.5 m^2 for the case of a tree line with 5 rows of crop) to estimate the fraction of the field area that would need to be devoted to a stand of sole trees to give the same tree water use as in the mixture (A_{tree}). This calculation assumes that the sole trees would have been planted such that there was complete ground cover, and that a dense stand of trees would have used water at the potential evaporation rate. Water use by sole maize and sole trees grown in equivalent land proportions is given by:-

$$W_{sole\ crops} = (A_{trees} * E_o) + (A_{crop} * E_{crop}) \qquad (8.1)$$

where E_o is the potential evaporation for the season and E_{crop} is the seasonal water use by the sole crop (taken as the average seasonal water use measured in rows 12 to 18). The corresponding value for the water use in the mixture ($W_{mixture}$) was estimated as the mean of the total water use as measured for each of the rows within the unit cell in question. In cases of rows where there were

no access tubes, values were obtained by linear interpolation from between the nearest access tubes.

The land equivalent ratio calculated on the basis of water use is given by:

$$LER = W_{mixture} / W_{sole\ crops} \qquad (8.2)$$

The LER's derived from this approach during the two growing seasons are shown in table 8.1. based on mixtures with 5, 10 or 15 rows of maize grown either side of the tree line. The results indicate that growing *Maesopsis. Casuarina* and *Grevillea* (March–May 1998) and *Maesopsis* and *Grevillea* (August-November 1998) with crops, gave a marginal biological advantage over sole cropping in terms of water use. In both seasons, these mixtures had LER > 1.0 (table 8.1). *Markahmaia* and *Alnus* on the other hand, had LER values that were close to 1.0. implying that there was no advantage gained in terms of water use by growing these tree species in mixture with crops.

Table 8.1. Land equivalent ratios (LER) for the various tree species inter-planted with maize based on water use at varying distances from the tree line for two seasons.

Season	Tree/Crop Mixture	Land Equivalent Ratio (LER)		
		Distance from tree line (m)		
		3.8	7.5	11.3
March – May 1998	*Maesopsis* + Maize	1.27	1.25	1.09
	Casuarina + Maize	1.25	1.10	1.22
	Grevillea + Maize	1.18	1.13	1.11
	Markhamia + Maize	1.11	1.11	1.07
	Alnus + Maize	1.07	1.08	1.06
August-Nov.1998	*Maesopsis* + Maize	1.27	1.28	1.24
	Casuarina + Maize	1.06	1.03	1.05
	Grevillea + Maize	1.21	1.16	1.14
	Markhamia + Maize	1.19	1.21	1.14
	Alnus + Maize	1.05	1.06	1.06

The estimation of LER on the basis of water use has a number of rather uncertain assumptions, particularly with respect to the prediction of the water that would be used by a sole stand of trees. An alternative is to attempt to determine the LER for the various tree/crop combinations on the basis of light utilisation. In this approach, the mean yield of maize in the mixture for areas of 7.5, 15.0 and 22.0 m^2 (i.e. assuming 5, 10 or 15 rows of maize grown either side of the tree line) was calculated for each tree/crop combination. Mean yield for sole maize was obtained by taking the mean yields for rows 12-18, which were far away from the influence of trees. Therefore, the fraction of land area needed to grow sole maize to give the same yield as in the mixture A'_{crop} is given by:-

- A'_{crop} = (Mean maize yield $_{mixture}$) / (Mean maize yield $_{sole\ crop}$) (8.3)

The question then arises as to whether the remainder of the land if devoted to a pure stand of trees is likely to give tree yields greater or less than in mixture. The problem then is how to assess whether tree growth in sole tree stands would be greater or less than in the mixture. One possibility is to estimate whether a stand of sole trees grown on the remaining land area would intercept a different amount of light to that intercepted by trees growing in the mixture. The mean values of $(1-f_{tree})$ obtained from figure 5.1 represents the fraction of the radiation incident on the unit cell of the mixture that passes through the tree canopy for rows 1-5, 1-10 and 1-15 for each species. These values give the mean fraction of PAR that was incident on the maize crop for these maize rows. Subtracting this value from one gives an estimate of how much light was intercepted by the trees (f_{tree}). It is assumed that the LUE of the trees in the mixture and pure stand is the same. The assumption is reasonable if there are no stress effects on water use. This means that if the trees were grown as a sole crop at one side of the field, then the fraction of land area (assuming 100% light interception within sole crop) needed for growing trees in order for the tree light interception to be the same as in the mixture ($A'_{sole\ tree}$) is the same as mean f_{tree}. The land equivalent ratio is, therefore, given by:-

- LER = $(A'_{sole\ crop}) + (A'_{sole\ tree})$ (8.4)

Table 8.2. presents the LER values for the tree/crop combinations based on light utilization at different distances from the tree line for the two cropping seasons. The data show that during March-May 1998 season, there was no advantage gained by growing trees with

crops in terms of light utilization, because the LER values for all the species were < 1.0. However, during the August-November 1998 season, *Maesopsis* and *Grevillea* gave LER values > 1.0 (table 8.2), implying that there was an advantage in growing the species as mixtures rather than as sole crops. The other tree/crop combinations gave LER values of < 1.0 which suggests that there was no advantage gained by growing these tree species together with crops on light utilization.

Table 8.2. Land equivalent ratios (LER) for the various tree species inter-planted with maize based on light utilization at varying distances from the tree line for two cropping seasons.

Season	Tree/Crop Mixture	Land Equivalent Ratio (LER)		
		Distance from tree line (m)		
		3.8	7.5	11.3
March – May 1998	*Maesopsis* + Maize	0.95	0.92	0.95
	Casuarina + Maize	0.71	0.83	0.87
	Grevillea + Maize	0.98	0.96	0.97
	Markhamia + Maize	0.76	0.83	0.88
	Alnus + Maize	0.96	0.96	0.97
August-Nov.1998	*Maesopsis* + Maize	1.41	1.25	1.19
	Casuarina + Maize	0.87	0.95	1.05
	Grevillea + Maize	1.23	1.17	1.12
	Markhamia + Maize	1.01	1.09	1.06
	Alnus + Maize	0.97	0.93	0.93

It apparent from the LER values presented for both water and light utilization by the tree/crop mixtures at this stage of tree growth had only a marginal biological advantage on resource use over sole tree and sole maize systems. This is probably because the trees have not yet grown to a stage where they can significantly improve soil and the microclimate around them. Based on these results, the tree species that can be interplanted with crops in

order to have a biological advantage over sole cropping are *Maesopsis* and *Grevillea* as they gave LER > 1.0 (both seasons) for water use and LER > 1.0 (August-November 1998) for light utilization. All the other tree/crop combinations gave LER =< 1, signifying that there was no advantage gained in resource use by planting them with crops. LER values in other agroforestry systems have been found to be in the range of 1.17 to 2.36 [Singh *et al* 1990; Rao *et al* 1990, Corlett *et al* 1992]. The low LER values reported in this study compared to those quoted above can probably be due to that fact that this agroforestry system has not fully matured (only 3 years), so the long term effect of the trees on soil productivity and microclimate are not yet evident. Therefore, the assessment of the system on the basis of LER at a later time will probably give a clearer picture.

These conclusions LER have to be treated with caution, because of the assumptions made about the light and water use in sole stands of trees. Errors arising from these assumptions could lead to systematic errors in the LER calculations, so the absolute values of LER should be used with care. However, if the errors are largely systematic, then the relative values of LER between seasons and between treatments may be more reliable indicators of differences between seasons and tree species on the productivity of mixtures relative to equivalent sole crops.

8.5 Conclusions

The main conclusions drawn from the results of this study are:-

- The presence of the trees significantly reduced the growth and yield of the associated maize and beans three years after tree establishment. The effect varied depending on the species and the distance from the tree lines.

- The fraction of the incoming photosynthetically active radiation (PAR) that was incident on the under-storey maize crop was significantly reduced by the presence of the trees. The effect again depended on the tree species and the distance from the tree lines. Similarly, the mean fractional PAR intercepted by the under-storey maize was significantly reduced by the presence of the trees.

- The shading effects of the trees can accurately be modeled by using tree characteristics that strongly influence shading, those are tree height, canopy width and canopy height. The modeled shading effects of the trees showed that tall trees such as *Casuarina* or trees with wide crowns such as *Maesopsis* have significantly bigger shading effects on crops than short trees or trees with narrow canopies such as *Markhamia*.

- Most of the tree and crop roots, more than 70%, were found to be concentrated in the topsoil (0-90 cm). The tree species showed varying patterns of root development and the presence of tree roots significantly reduced maize root densities.

- Water uptake patterns by the tree species closely followed that of their rooting patterns. The tree plots significantly lost more water than sole crop plots and these high water losses from the trees were associated with greater soil water depletion than in sole crop plots. The trees significantly reduced water use by maize with the effect decreasing with increasing distance from the tree lines.

- Total soil evaporation (E_s) was greatly reduced beneath tree canopies compared to soil under maize the canopy and bare soil.

- Interplanting *Maesopsis*, *Grevillea* and *Casuarina* with crops, at this stage of development of this agroforestry system, had a marginal advantage over sole cropping in terms of water use.

- Interplanting *Maesopsis*, and *Grevillea* with crops, at this stage of development of this agroforestry system, had a marginal advantage over sole cropping in terms of light utilization.

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APPENDICES

APPENDIX A: - ANALYSIS OF TREE DATA

Table 1.1: Analysis of Tree heights

- **11 Months after Planting**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	3	0.27753	0.09251	2.55	0.104
Treatment	4	9.24320	2.31080	63.79	<.001
Residual	12	0.43470	0.03622		
Total	19	9.95543			

Tables of means

Grand mean 2.047

Block	1	2	3	4	
	2.112	2.205	1.955	1.914	
Treatment	Casuarina	Grevillea	Maesopis	Alnus	Markhamia
	2.547	3.114	1.467	1.331	1.774

Standard errors of differences of means

Table	Block	Treatment
rep.	5	4
d.f.	12	12
s.e.d.	0.1204	0.1346

- **31 Months after Planting**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	3	2.7089	0.9030	4.36	0.027
Treatmen	4	58.6958	14.6739	70.81	<.001
Residual	12	2.4869	0.2072		
Total	19	63.8915			

Tables of means

Grand mean 6.37

Block	1	2	3	4	
	6.65	6.72	6.30	5.79	
Treatment	Casuarina	Grevillea	Maesopsis	Alnus	Markhamia
	8.42	8.04	5.83	3.70	5.84

Standard errors of differences of means

Table	Block	Treatment
rep.	5	4
d.f.	12	12
s.e.d.	0.288	0.322

- **41 Months after Planting**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	3	3.5438	1.1813	2.60	0.101
Treatment	4	118.3882	29.5970	65.11	<.001
Residual	12	5.4548	0.4546		
Total	19	127.3868			

Tables of means

Grand mean 8.57

Block	1	2	3	4	
	9.03	8.89	8.42	7.96	
Treatment	Casuarina	Grevillea	Maesopsis	Alnus	Markhamia
	12.06	9.90	8.52	4.73	7.65

Standard errors of differences of means

Table	Block	Treatment
rep.	5	4
d.f.	12	12
s.e.d.	0.426	0.477

Table 1.2: Analysis of Tree Crown diameters (m)

- **31 Months after Planting**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	3	0.72210	0.24070	3.46	0.051
Treatment	4	12.56023	3.14006	45.14	<.001
Residual	12	0.83484	0.06957		
Total	19	14.11717			

Tables of means

Grand mean 3.077

Block	1	2	3	4	
	3.343	3.115	3.039	2.811	
Treatment	Casuarina	Grevillea	Maesopsis	Alnus	Markhamia
	3.718	3.170	4.113	2.389	1.994

Standard errors of differences of means

Table	Block	Treatment
rep.	5	4
d.f.	12	12
s.e.d.	0.1668	0.1865

- **41 Months after Planting**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	3	0.52365	0.17455	2.33	0.126
Treatment	4	19.52510	4.88127	65.20	<.001
Residual	12	0.89839	0.07487		
Total	19	20.94714			

Tables of means

Grand mean 3.756

Block	1	2	3	4	
	3.937	3.821	3.770	3.496	
Treatment	Casuarina	Grevillea	Maesopsis	Alnus	Markhamia
	4.745	3.421	5.083	2.949	2.582

Standard errors of differences of means

Table	Block	Treatment
rep.	5	4
d.f.	12	12
s.e.d.	0.1731	0.1935

Table 1.3: Analysis of Stem diameters

- **31 Months after Planting**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	3	4.7729	1.5910	4.16	0.031
Treatmen	4	57.4318	14.3580	37.51	<.001
Residual	12	4.5927	0.3827		
Total	19	66.7975			

Tables of means

Grand mean 6.60

Block	1	2	3	4
	7.17	6.88	6.49	5.86

Treatment	Casuarina	Grevillea	Maesopsis	Alnus	Markhamia
	6.51	8.82	7.78	3.82	6.06

Standard errors of differences of means

Table	Block	Treatment
rep.	5	4
d.f.	12	12
s.e.d.	0.391	0.437

- **41 Months after Planting**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	3	5.381	1.794	1.79	0.203
Treatment	4	90.970	22.742	22.69	<.001
Residual	12	12.026	1.002		
Total	19	108.377			

Tables of means

Grand mean 9.19

Block	1	2	3	4
	9.81	9.51	8.99	8.45

Treatment	Casuarina	Grevillea	Maesopsis	Alnus	Markhamia
	8.51	11.15	11.99	6.08	8.23

Standard errors of differences of means

Table	Block	Treatment
rep.	5	4
d.f.	12	12
s.e.d.	0.633	0.708

APPENDIX B:- ANALYSIS OF CROP DATA

Table 1.1: Analysis of Maize Height for March-May 1996 cropping season

Repeated Measures Analysis of Variance
Tests of Hypotheses for Between Subjects Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BLOCK	3	8464.78333333	2821.59444444	1.22	0.3300
TREAT	5	34067.27500000	6813.45500000	2.95	0.0405
BLOCK*TREAT	15	86894.64166667	5792.97611111	2.51	0.0326
SIDE	1	2050.13333333	2050.13333333	0.89	0.3583
TREAT*SIDE	5	19273.59166667	3854.71833333	1.67	0.1925
Error	18	41515.87500000	2306.43750000		

Univariate Tests of Hypotheses for Within Subject Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
Row	9	2910.41666667	323.37962963	3.07	0.0020	0.0254
Row*BLOCK	27	3445.13333333	127.59753086	1.21	0.2318	0.2976
Row*TREAT	45	8029.05833333	178.42351852	1.69	0.0093	0.0620
Row*BLOCK*TREAT	135	16680.19166667	123.55697531	1.17	0.1659	0.2667
Row*SIDE	9	3132.11666667	348.01296296	3.30	0.0010	0.0184
Row*TREAT*SIDE	45	7678.90833333	170.64240741	1.62	0.0158	0.0795
Error(Rows)	162	17072.37500000	105.38503086			

Greenhouse-Geisser Epsilon = 0.4078
Huynh-Feldt Epsilon = 1.3504

Least Squares Means

TREAT	Row1	Row2	Row3	Row4	Row5	Row6	Row7	Row8	Row9	Row10
Casuarina	213.25	225.88	222.25	222.25	222.38	228.75	226.00	233.50	235.00	233.00
Grevillea	217.86	228.38	230.63	232.50	233.63	230.50	228.63	229.13	228.63	220.38
Maesopsis	194.63	210.88	215.38	206.25	209.25	214.38	213.13	207.75	214.63	215.13
Alnus	210.25	210.50	208.50	203.13	206.00	204.50	207.13	209.13	207.13	204.25
Markhamia	219.13	230.25	224.75	229.00	225.25	228.50	225.88	227.88	224.25	216.88
Sole Maize	229.50	231.63	226.75	227.13	227.25	228.63	224.13	220.25	222.38	218.75

Table 1.2: Analysis of Maize Height for March-May 1997 cropping season

Repeated Measures Analysis of Variance
Tests of Hypotheses for Between Subjects Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BLOCK	3	23668.01341667	7889.33780556	18.94	0.0001
TREAT	5	19617.48541667	3923.49708333	9.42	0.0002
BLOCK*TREAT	15	54793.04008333	3652.86933889	8.77	0.0001
SIDE	1	4.96133333	4.96133333	0.01	0.9143
TREAT*SIDE	5	10447.48916667	2089.49783333	5.02	0.0047
Error	18	7497.87250000	416.54847222		

Univariate Tests of Hypotheses for Within Subject Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
Row	9	56277.39091667	6253.04343519	72.64	0.0001	0.0001
Row*BLOCK	27	5343.39158333	197.90339198	2.30	0.0008	0.0083
Row*TREAT	45	56575.33458333	1257.22965741	14.60	0.0001	0.0001
Row*BLOCK*TREAT	135	21441.77991667	158.82799938	1.85	0.0001	0.0028
Row*SIDE	9	855.57450000	95.06383333	1.10	0.3626	0.3638
Row*TREAT*SIDE	45	6595.71500000	146.57144444	1.70	0.0087	0.0365
Error(Rows)	162	13945.85750000	86.08554012			

Least Squares Means

TREAT	Row1	Row2	Row3	Row4	Row5	Row6	Row7	Row8	Row9	H1
Casuarina	170.88	201.33	214.73	224.68	232.76	233.73	233.05	235.74	236.23	232.88
Grevillea	191.46	203.05	217.69	223.86	228.26	233.56	231.74	227.36	226.29	218.84
Maesopsis	151.91	163.93	192.70	212.70	219.40	227.88	224.34	223.54	224.33	224.28
Alnus	206.46	209.94	209.75	205.99	207.22	207.49	208.94	209.49	206.25	227.04
Markhamia	203.38	201.91	210.98	222.70	227.93	228.99	226.90	228.84	230.18	223.84
Sole Maize	231.33	228.10	227.50	226.43	222.40	217.23	221.88	220.09	220.31	217.81

Table 1.3: Analysis of Maize Height for March-May 1998 cropping season

Repeated Measures Analysis of Variance
Tests of Hypotheses for Between Subjects Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BLOCK	3	29755.13972917	9918.37990972	10.08	0.0004
TREAT	5	41908.27818750	8381.65563750	8.52	0.0003
BLOCK*TREAT	15	32161.75239583	2144.11682639	2.18	0.0587
SIDE	1	12107.23852083	12107.23852083	12.30	0.0025
TREAT*SIDE	5	13812.89285417	2762.57857083	2.81	0.0480
Error	18	17712.77212500	984.04289583		

Univariate Tests of Hypotheses for Within Subject Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
Row	9	90712.2666	10079.14074	90.87	0.0001	0.0001
Row*BLOCK	27	6733.6225	249.3934282	2.25	0.0010	0.0147
Row*TREAT	45	75005.6886	1666.793082	15.03	0.0001	0.0001
Row*BLOCK*TREAT	135	27737.8915	205.4658634	1.85	0.0001	0.0048
Row*SIDE	9	4748.747520	527.6386134	4.76	0.0001	0.0013
Row*TREAT*SIDE	45	6426.769854	142.8171079	1.29	0.1298	0.2084
Error(HEIGHT)	162	17969.01412	110.91984028			

Greenhouse-Geisser Epsilon = 0.4794
Huynh-Feldt Epsilon = 1.6652

Least Squares Means

TREAT	Row1	Row2	Row3	Row4	Row5	Row6	Row7	Row8	Row9	Row10
Casuarina	99.46	119.13	148.64	163.95	178.71	187.98	197.03	202.36	198.63	201.18
Grevillea	173.88	175.29	189.34	196.40	199.86	208.39	205.18	209.68	201.65	200.09
Maesopsis	159.74	166.93	173.56	172.59	180.11	190.68	196.08	199.24	197.94	195.18
Alnus	143.56	178.03	186.73	187.28	187.01	187.68	185.23	191.53	187.01	181.83
Markhamia	163.03	159.34	165.26	172.03	183.13	192.86	203.41	209.73	206.41	199.55
Sole Maize	205.41	201.79	198.68	201.25	200.88	198.56	196.66	192.45	191.11	188.23

Table 1.4: Analysis of Maize Height for August-November 1998 cropping season

Repeated Measures Analysis of Variance
Tests of Hypotheses for Between Subjects Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BLOCK	3	11431.395500	3810.46516667	3.44	0.0390
TREAT	5	207861.113500	41572.22270000	37.52	0.0001
BLOCK*TREAT	15	32021.686000	2134.77906667	1.93	0.0929
SIDE	1	10974.881333	10974.88133333	9.91	0.0056
TREAT*SIDE	5	5922.5141666	1184.50283333	1.07	0.4097
Error	18	19941.500500	1107.86113889		

Univariate Tests of Hypotheses for Within Subject Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
Row	9	380536.1958	42281.7995370	366.94	0.0001	0.0001
Row*BLOCK	27	4138.9553	153.2946420	1.33	0.1422	0.2029
Row*TREAT	45	142499.8431	3166.6631815	27.48	0.0001	0.0001
Row*BLOCK*TREAT	135	25187.1157	186.5712272	1.62	0.0017	0.0152
Row*SIDE	9	2112.0486667	234.6720741	2.04	0.0384	0.0825
Row*TREAT*SIDE	45	6901.1083333	153.3579630	1.33	0.1016	0.1673
Error(Rows)	162	18667.0070000	115.2284383			

Least Squares Means

TREAT	Row1	Row2	Row3	Row4	Row5	Row6	Row7	Row8	Row9	Row10
Casuarina	73.60	107.938	131.94	154.50	181.04	197.98	215.64	221.19	220.90	224.08
Grevillea	141.93	160.013	172.49	190.05	198.14	198.89	207.35	216.49	214.16	220.75
Maesopsis	109.40	128.46	138.89	156.59	170.75	183.58	186.79	200.84	213.74	212.48
Alnus	142.23	195.24	216.20	208.98	221.03	224.78	225.54	230.38	221.75	227.91
Markhamia	132.20	139.59	147.79	164.29	181.04	204.79	218.70	232.41	233.58	235.54
Sole Maize	228.25	234.91	228.28	222.89	229.88	235.00	223.38	228.95	227.40	234.86

Table 2.1: Analysis of Maize Yields for March-May 1997 cropping season

Repeated Measures Analysis of Variance

Tests of Hypotheses for Between Subjects Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BLOCK	3	0.28573723	0.09524574	6.52	0.0035
TREAT	5	0.28918534	0.05783707	3.96	0.0134
BLOCK*TREAT	15	0.63568887	0.04237926	2.90	0.0169
SIDE	1	0.03010889	0.03010889	2.06	0.1682
TREAT*SIDE	5	0.15017469	0.03003494	2.06	0.1188
Error	18	0.26290636	0.01460591		

Univariate Tests of Hypotheses for Within Subject Effects

Source: ROWS

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
17	0.91024656	0.05354392	31.71	0.0001	0.0001

Source: ROWS*BLOCK

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
51	0.12589253	0.00246848	1.46	0.0285	0.1040

Source: ROWS*TREAT

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
85	0.77775471	0.00915006	5.42	0.0001	0.0001

Source: ROWS*BLOCK*TREAT

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
255	0.54865641	0.00215159	1.27	0.0213	0.0974

Source: ROWS*SIDE

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
17	0.04475566	0.00263269	1.56	0.0739	0.1544

Source: ROWS*TREAT*SIDE

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
85	0.14248624	0.00167631	0.99	0.5039	0.4903

Source: Error(ROWS)

DF	Type I SS	Mean Square
306	0.51674079	0.00168870

Greenhouse-Geisser Epsilon = 0.4079
Huynh-Feldt Epsilon = 1.7587

Least Squares Means

TREAT	Row1	Row2	Row3	Row4	Row5	Row6	Row7	Row8	Row 9
Casuarina	0.195	0.252	0.289	0.356	0.398	0.394	0.399	0.407	0.415
Grevillea	0.266	0.307	0.316	0.350	0.389	0.389	0.385	0.386	0.392
Maesopsis	0.103	0.154	0.269	0.340	0.351	0.371	0.351	0.378	0.380
Alnus	0.311	0.333	0.302	0.309	0.295	0.324	0.318	0.316	0.310
Markhamia	0.300	0.277	0.317	0.351	0.379	0.375	0.371	0.389	0.404
Sole Maize	0.375	0.369	0.376	0.358	0.367	0.343	0.348	0.357	0.347

TREAT	Row10	Row11	Row12	Row13	Row14	Row15	Row16	Row17	Row18
1	0.390	0.397	0.460	0.406	0.407	0.385	0.397	0.407	0.393
2	0.370	0.370	0.394	0.377	0.392	0.396	0.373	0.357	0.373
3	0.351	0.360	0.363	0.355	0.372	0.353	0.347	0.355	0.358
4	0.335	0.317	0.336	0.349	0.337	0.344	0.345	0.326	0.339
5	0.375	0.357	0.383	0.366	0.376	0.367	0.359	0.364	0.363
6	0.341	0.346	0.360	0.358	0.376	0.376	0.385	0.353	0.361

Table 2.2: Analysis of Maize yields for March-May 1998 cropping season

Repeated Measures Analysis of Variance
Tests of Hypotheses for Between Subjects Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BLOCK	3	0.87791035	0.29263678	29.18	0.0001
TREAT	5	0.17055913	0.03411183	3.40	0.0245
BLOCK*TREAT	15	0.37422478	0.02494832	2.49	0.0340
SIDE	1	0.01386403	0.01386403	1.38	0.2550
TREAT*SIDE	5	0.16046946	0.03209389	3.20	0.0306
Error	18	0.18050193	0.01002788		

Univariate Tests of Hypotheses for Within Subject Effects

Source: ROWS

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
17	0.36308913	0.02135818	17.92	0.0001	0.0001

Source: ROWS*BLOCK

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
51	0.10870498	0.00213147	1.79	0.0016	0.0340

Source: ROWS*TREAT

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
85	0.33665698	0.00396067	3.32	0.0001	0.0001

Source: ROWS*BLOCK*TREAT

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
255	0.46650671	0.00182944	1.53	0.0002	0.0155

Source: ROWS*SIDE

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
17	0.05810973	0.00341822	2.87	0.0002	0.0116

Source: ROWS*TREAT*SIDE

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
85	0.07935333	0.00093357	0.78	0.9101	0.7797

Source: Error(ROWS)

DF	Type I SS	Mean Square
306	0.36473875	0.00119196

Greenhouse-Geisser Epsilon = 0.3627
Huynh-Feldt Epsilon = 1.4612

Least Squares Means

TREAT	Row1	Row2	Row3	Row4	Row5	Row6	Row7	Row8	Row9
Casuarina	0.069	0.073	0.105	0.131	0.157	0.196	0.190	0.212	0.192
Grevillea	0.212	0.158	0.206	0.206	0.205	0.223	0.226	0.232	0.215
Maesopsis	0.138	0.135	0.161	0.161	0.181	0.175	0.207	0.210	0.209
Alnus	0.107	0.140	0.157	0.156	0.172	0.171	0.175	0.183	0.175
Markhamia	0.170	0.131	0.135	0.156	0.171	0.212	0.235	0.239	0.230
Sole Maize	0.212	0.221	0.200	0.211	0.199	0.189	0.193	0.186	0.172

TREAT	Row10	Row11	Row12	Row13	Row14	Row15	Row16	Row17	Row18
Casuarina	0.208	0.199	0.206	0.196	0.194	0.206	0.217	0.204	0.211
Grevillea	0.211	0.186	0.214	0.197	0.227	0.230	0.227	0.243	0.213
Maesopsis	0.197	0.206	0.200	0.212	0.217	0.233	0.208	0.208	0.210
Alnus	0.168	0.161	0.178	0.172	0.185	0.184	0.215	0.175	0.189
Markhamia	0.205	0.195	0.197	0.190	0.205	0.218	0.195	0.205	0.215
Sole Maize	0.181	0.172	0.184	0.196	0.192	0.192	0.219	0.205	0.212

Table 2.3: Analysis of Maize yields for August-November 1998 cropping season

Repeated Measures Analysis of Variance
Tests of Hypotheses for Between Subjects Effects

Source	F	Type I SS	Mean Square	F Value	Pr > F
BLOCK	3	0.01238013	0.00412671	0.07	0.8597
TREAT	5	0.87399676	0.17479935	2.95	0.0001
BLOCK*TREAT	15	0.88892192	0.05926146	3.60	0.0056
SIDE	1	0.05869715	0.05869715	3.57	0.0751
TREAT*SIDE	5	0.18286610	0.03657322	2.22	0.0967
Error	18	0.29612458	0.01645137		

Univariate Tests of Hypotheses for Within Subject Effects

Source: ROWS

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
17	2.30907998	0.13582823	65.00	0.0001	0.0001

Source: ROWS*BLOCK

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
51	0.20842365	0.00408674	1.96	0.0003	0.0101

Source: ROWS*TREAT

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
85	0.99222572	0.01167324	5.59	0.0001	0.0001

Source: ROWS*BLOCK*TREAT

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
255	0.66434724	0.00260528	1.25	0.0325	0.1091

Source: ROWS*SIDE

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
17	0.08733504	0.00513736	2.46	0.0012	0.0182

Source: ROWS*TREAT*SIDE

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
85	0.20775818	0.00244421	1.17	0.1715	0.2553

Source: Error(ROWS)

DF	Type I SS	Mean Square
306	0.63942845	0.00208964

Greenhouse-Geisser Epsilon = 0.4438
Huynh-Feldt Epsilon = 2.0261

Least Squares Means

TREAT	Row1	Row2	Row3	Row4	Row5	Row6	Row7	Row8	Row9
Casuarina	0.038	0.104	0.127	0.170	0.188	0.247	0.267	0.303	0.266
Grevillea	0.198	0.195	0.210	0.256	0.253	0.244	0.271	0.269	0.296
Maesopsis	0.056	0.093	0.109	0.156	0.186	0.209	0.216	0.254	0.308
Alnus	0.160	0.227	0.295	0.277	0.338	0.322	0.314	0.314	0.303
Markhamia	0.121	0.119	0.130	0.173	0.194	0.209	0.251	0.264	0.280
Sole Maize	0.329	0.335	0.325	0.312	0.334	0.316	0.307	0.297	0.327

TREAT	Row10	Row11	Row12	Row13	Row14	Row15	Row16	Row17	Row18
Casuarina	0.314	0.279	0.306	0.328	0.291	0.301	0.317	0.342	0.309
Grevillea	0.287	0.266	0.278	0.339	0.297	0.305	0.296	0.338	0.349
Maesopsis	0.289	0.291	0.282	0.302	0.304	0.338	0.303	0.307	0.304
Alnus	0.326	0.326	0.335	0.335	0.316	0.307	0.335	0.313	0.304
Markhamia	0.293	0.285	0.291	0.307	0.288	0.298	0.308	0.313	0.316
Sole Maize	0.343	0.316	0.300	0.337	0.329	0.322	0.345	0.319	0.366

APPENDIX C:- ANALYSIS OF LIGHT DATA

Table 1.1:- Analysis of Light Incident on the Maize canopy for March-May 1997

Repeated Measures Analysis of Variance
Tests of Hypotheses for Between Subjects Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BLOCK	3	0.32026250	0.10675417	3.79	0.0332
TREAT	5	0.85370417	0.17074083	6.06	0.0029
Error	15	0.42245000	0.02816333		

Univariate Tests of Hypotheses for Within Subject Effects

Source: ROWS

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
7	2.53738333	0.36248333	19.67	0.0001	0.0001

Source: ROWS*BLOCK

DF	Type I SS	Mean Square	F Value	Pr > F	**Adj Pr > F G - G**
21	0.85765417	0.04084067	2.22	0.0044	0.0486

Source: ROWS*TREAT

DF	Type I SS	Mean Square	F Value	Pr > F	**Adj Pr > F G - G**
35	3.73772917	0.10679226	5.79	0.0001	0.0001

Source: Error(ROWS)

DF	Type I SS	Mean Square
105	1.93538333	0.01843222

Greenhouse-Geisser Epsilon = 0.3708
Huynh-Feldt Epsilon = 0.6944

Least Squares Means

TREAT	Row1	Row2	Row3	Row4	Row6	Row9	Row12	Row15
Casuarina	0.370	0.793	0.885	0.948	1.020	0.990	1.038	0.950
Grevillea	0.390	1.045	1.093	1.200	1.100	0.978	1.003	0.925
Maesopsis	0.205	0.508	0.975	1.208	1.005	1.005	0.968	1.025
Alnus	1.080	1.120	1.118	1.008	1.003	0.990	1.005	1.002
Markhamia	0.975	1.075	0.983	1.030	0.990	1.028	1.000	0.975
Sole Maize	0.988	1.005	0.978	0.973	0.985	0.940	1.035	1.035

Table 1.2:- Analysis of Light Incident on the Maize canopy for March-May 1998

Repeated Measures Analysis of Variance
Tests of Hypotheses for Between Subjects Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BLOCK	3	0.28457083	0.09485694	2.01	0.1557
TREAT	5	1.76411042	0.35282208	7.48	0.0011
Error	15	0.70758542	0.04717236		

Univariate Tests of Hypotheses for Within Subject Effects

Source: ROWS

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
7	5.68146667	0.81163810	55.00	0.0001	0.0001

Source: ROWS*BLOCK

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
21	0.58805417	0.02800258	1.90	0.0182	0.0572

Source: ROWS*TREAT

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
35	3.82026458	0.10915042	7.40	0.0001	0.0001

Source: Error(ROWS)

DF	Type I SS	Mean Square
105	1.54953958	0.01475752

Greenhouse-Geisser Epsilon = 0.5402
Huynh-Feldt Epsilon = 1.1302

Least Squares Means

TREAT	Row1	Row2	Row3	Row4	Row6	Row9	Row12	Row15
Casuarina	0.46	0.58	0.71	0.80	0.92	1.00	1.03	1.05
Grevillea	0.44	0.57	0.72	0.80	0.94	0.96	1.03	1.06
Maesopsis	0.18	0.25	0.43	0.58	0.93	0.99	1.04	1.03
Alnus	0.43	0.82	0.92	0.96	0.99	0.99	1.03	0.99
Markhamia	0.48	0.67	0.77	0.84	0.91	0.98	1.00	1.08
Sole Maize	1.08	1.07	1.06	1.18	0.99	0.99	0.99	1.00

Table 1.3:- Analysis of Light Incident on the Maize canopy for August-November 1998

Repeated Measures Analysis of Variance
Tests of Hypotheses for Between Subjects Effects

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BLOCK	3	0.32457083	0.09485694	2.21	0.1557
TREAT	5	1.76411042	0.35282208	6.48	0.0011
Error	15	0.81758542	0.03717236		

Univariate Tests of Hypotheses for Within Subject Effects

Source: ROWS

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
7	5.68146667	0.81163810	55.00	0.0001	0.0001

Source: ROWS*BLOCK

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
21	0.58805417	0.02800258	1.90	0.0182	0.0572

Source: ROWS*TREAT

DF	Type I SS	Mean Square	F Value	Pr > F	Adj Pr > F G - G
35	3.82026458	0.10915042	7.40	0.0001	0.0001

Source: Error(ROWS)

DF	Type I SS	Mean Square
105	1.54953958	0.01475752

Greenhouse-Geisser Epsilon = 0.5402
Huynh-Feldt Epsilon = 1.1302

Least Squares Means

TREAT	Row1	Row2	Row3	Row4	Row6	Row9	Row12	Row15
Casuarina	0.47	0.56	0.68	0.78	0.98	1.01	1.00	1.01
Grevillea	0.56	0.59	0.70	0.79	0.90	0.99	1.04	1.07
Maesopsis	0.19	0.24	0.33	0.48	0.79	0.99	1.06	1.06
Alnus	0.40	0.68	0.87	0.90	1.00	0.97	0.98	1.05
Markhamia	0.52	0.59	0.69	0.77	0.88	0.99	1.05	1.08
Sole Maize	0.97	1.00	0.99	1.04	0.99	1.00	0.99	1.00