TREE ROOT DEVELOPMENT AND INTERACTIONS IN DRYLANDS: FOCUSING ON *MELIA VOLKENSII* WITH SOCIO-ECONOMIC EVALUATIONS.

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Declaration

This thesis is my own composition, the results presented are of investigations conducted by myself, work other than my own is clearly indicated by reference to the relevant workers or their publications. This work has not been presented in any previous applications for a higher degree.

Signed.......J Mulatya.......(candidate)

Date.......20.12.00.......

Statement

I certify that Jackson Mulatya spent 9 terms of full time research work under my supervision and has fulfilled the conditions of Ordinance No. 14 (University of Dundee) and is thus qualified to submit this thesis for the degree of Doctor of Philosophy.

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Date..

SUMMARY

Tree-crop competition is an important concern in agroforestry systems, and has been the subject of much attention by researchers in recent years. Farmers on the other hand, often seem to either ignore or accept competition and do little to manage it. In this thesis, I make the first attempt to reconcile farmers' practices and beliefs with experimental data, focusing on the economically important tree: *Melia volkensii* in drylands of Kenya. This tree is of particular interest because farmers' perceptions of its competivity appear at odds with researchers perceptions: farmers believe it does not compete with crops while researchers have found it competes.

After conducting a survey on farmers' fields in which it was confirmed *Melia volkensii* does not compete with crops, an experimental programme was conducted to investigate the causes of this discrepancy in perceptions. The study covered; Kitui, Embu, Kibwezi and Machakos sites. *Melia volkensii* provenances from these sites and *Melia* plant types used in tree establishment (seedlings and cuttings) were evaluated to examine whether the reported yield differences were as result of differences in root architecture between provenances or between plant types used by farmers.

The rainfall confounded the problem of tree-crop interactions; because extreme rainfall conditions were experienced during the study period. Excessive soil moisture occurred in the first season while rainfall failed in the second season. Competition was therefore evaluated when competition was occurring. Results highlights are as follows; competition index (CI) method was unable to predict tree competitiveness with crops in conditions where trees are planted closely. The CI values were highly variable within individuals of a particular *Melia* provenance or species and therefore found inconsistent and unreliable to predict tree competition with crops. Surprisingly, it was able to predict tree-crop competition where trees occurred in isolation. There were neither differences in root architecture between the *Melia volkensii* provenances nor were there difference in soil water or crop yields between provenances' plots. However, when root architecture of seedlings and cuttings were compared, cuttings tended to develop shallow roots than seedling plants and that roots which descended into the soil at deeper angles developed some secondary root branches which grew to the surface, thus making them competitive with crops.

Overall, the results support the view that *Melia volkensii* is competitive with crops in normal seasons. Isolated *Melia* trees on farmers' fields reduced crop yields beyond 15 m radius from trees. However, the value of the timber outweighs the value of the lost crop and farmers may chose to have *Melia* trees on the cropland whose value will compensate the lost yields and still benefit from other tree products e.g. fuelwood and fodder, or plant trees in separate plots e.g. fallow lands and maximize productivity of both components. *Melia* timber fetched >45% more cash than timber products of other species such as cypress and pines. Results suggest that when promoting the planting of *Melia*, seedlings should be used instead of cuttings as they have a less competitive root architecture, as seed germination is a problem this should be a priority research area for Kenya seed specialists.

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CHAPTER ONE

1 INTRODUCTION

1.1 Problems of farming in the semi-arid tropics

The productivity of agricultural systems in semi-arid environments is often severely constrained by the prevailing environmental conditions (Huxley, 1994; Vandenbelt, 1992). In such conditions, rainfall is low (400-1000 mm), unevenly distributed and varies greatly in intensity (McIntyre *et al.*, 1996). In addition, semi-arid areas experience high temperature and radiation resulting in rapid potential evapotranspiration (Allen, 1990). Annual rainfall is much lower than potential evapotranspiration (Jackson *et al.*, 1997), causing water stress in growing plants. The availability of soil water determines the plant growing periods and provides the greatest constraint to plant growth (Wallace *et al.*, 1990). Additional constraints such as availability of soil nutrients (Livesley *et al.*, 1997), eroded shallow soils and waterlogging (Pritchett and Fisher, 1987) may also limit plant growth.

The natural vegetation in semi-arid conditions is adapted to prevailing climatic and soil conditions. Generally, woodland, forests and grassland dominate the vegetation. The dominant plant species have developed morphological and physiological mechanisms to enable them survive under such resource-limited environments (Pritchett and Fisher, 1987). In agricultural systems, unless the introduced exotic species adapt themselves to these conditions, their water requirements might exceed the available soil water resulting in water stress and poor crop yields and depletion of soil moisture for neighbouring plants (Tilander *et al.*, 1995).

Cultivation of inappropriate agricultural food crops in semi-arid areas may lead to lower crop yields especially in sites where competition for soil moisture between various plant components is involved. Crop monocultures may leave the soil bare and unprotected for extended periods and when grown without proper soil management may deplete and impoverish the surface horizons which their shallow root systems colonise (Lott, 1998). To overcome the problems of land productivity associated with nutrient impoverishment, farmers in the past practiced shift and fallow cultivation. These methods are no longer possible because of the diminishing size of land holdings caused by settlement and land demarcations (Foley and Barnard, 1984).

A dryland agroforestry tradition, with raising of food crops together with trees and livestock on the same unit of land has existed for many decades (Vandenbelt, 1992). However, although tree growing in crop lands enhances soil fertility (Schroth, 1997), reduces soil erosion (Wallace *et al.*, 1995) and provides useful products, tree integration into cropping systems has not been fully backed by agricultural development policies except for fruit trees (Kerkhoff, 1990). Mahapatra and Paul (1997) attributed lack of such policies to historical land use development, rural poverty, community heterogeneity, shortage of land, conflict in land tenure systems and gender issues.

Management of natural resources in drylands is increasingly under population pressure (Cooper *et al.*, 1996), leading to changes in land use. It is estimated that populations in semi-arid parts of the tropics will increase by half in the next 50 years (Fischer and Heilig, 1996) and this increase will occur predominantly in developing countries. The demand for food and wood products may increase linearly with population growth (Scherr, 1991). In addition, clearing of large areas for cultivation in order to provide adequate yields and food security for increasing population will occur. To meet these challenges, improved land use practices and increased productivity on the limited cultivatable areas will be required. Farmers will be required to increase the number of trees and yet sustain agricultural crops within their restricted farmland by either using simultaneous or sequential agroforestry systems (Sanchez, 1995).

To overcome the above challenges, integrated land use systems where both trees and crops are managed in the same unit of land for improved land productivity are seriously needed. Integration of trees into farmer's fields is referred to as agroforestry which Burley (1983) redefined as;

' a collective term for land use systems that incorporate trees amongst agricultural crops and animals either sequentially or simultaneously to meet social and ecological objectives at the level of small holders or rural communities'.

Sequentially agroforestry systems involve practices such as fallow farming or shifting cultivation where trees and crops occupy the same land at different times. Simultaneous agroforestry systems include practices such as alley cropping, where trees and crops occupy land at the same time. In modern subsistence farming, both components (tree and crop) are integrated, managed and new technologies applied to improve the traditional practices (Sanchez, 1995). There are other advantages of growing trees together with crops. For instance, tree roots may pump up nutrients from deeper soil layers to the surface for crop use (Gregory, 1996) and the tree canopy can modify microclimatic conditions which might be beneficial for crop plant growth (Jonnson *et al.*, 1999; Ranganathan and De Wit, 1996).

Although agroforestry systems provide improved productivity and ecological benefits, other associated factors may have negative impacts on its applications, especially in simultaneous agroforestry systems. In simultaneous agroforestry systems where trees and crops are grown in close proximity, serious competition for natural resources might occur (Van Noordwijk *et al.*, 1994). Studies carried out at Machakos Research Station by Ong *et al.* (1992), indicated that intercropped *Senna spectabilis* trees intercepted 20% of seasonal rainfall and that the overall competition for resources between trees and crops led to a 46% maize yield reduction in plots with dispersed upper storey trees and 20% yield reduction in plots with hedgerow cropping.

1.2 Agricultural development and strategies in semi-arid tropics

As described earlier, agroforestry is an integrated process where biological productivity, environmental protection and resource conservation are realised in a single land use system (Ranganathan and De Wit, 1996). This is the only viable land use system that is able to sustain the production of both agricultural and wood products at household level in developing countries of semi-arid Africa.

Rocheleau *et al.* (1988) and Nair (1991) reviewed traditional agroforestry practices in the tropics. In summary, they identified traditional farming practices such as multi-storey home gardens, parkland farming of West Africa, multipurpose trees on cropland, shelter-belts and windbreaks, shift and fallow cultivation, pasture and range-lands, agrosilvopastoral systems for food and fodder banks and woody hedgerow intercropping for soil conservation, mulch and fodder. The combination of some of these practices into one system has been reported

(Nair, 1991; Rocheleau *et al*, 1988; Burley, 1983). For instance, in sub humid parts of east Africa the Chaga home gardens are a mixture of multi-storeyed and multipurpose trees in the boundary planting while agrosilvopastoral systems consist of fodder banks and shelter-belts within crop lands. In West Africa, parkland systems combine silvopastoral, multipurpose trees and cropping systems for improved productivity. Vandenbelt (1992) attributes the increased grass and crop productivity in parkland farming to the presence of *Faidherbia albida* which can provide mulch, recycle nutrients and provide beneficial shading. Such systems have been managed sustainably to provide products like wood, fodder, food and services such as soil conservation, environmental amelioration, replenishment of soil fertility and shading.

In Africa, it is estimated that 80 to 90 percent of rural areas will depend on these farming systems over the next 50 years (Sanchez, 1995). Matilla (1987) estimates that over 90 percent of the rural population will depend on fuelwood energy and unless integrated agroforestry systems are adapted to provide increased land productivity and diversity of products for the challenges of increased population, wood demand, land degradation and consequently poverty in the developing countries will increase.

In Kenya, arid and semi-arid lands (ASALs) represent 80% of total land area. The government has targeted these as priority areas for agricultural development and farm forestry (Government of Kenya Development Plans, 1995). In realisation that the limited gazetted forests could not meet wood demand for the increasing population (3.4 % annually) and that demand for more agricultural land is threatening these limited forest lands, the government has embarked on promoting farm forestry. Farm forestry is used to describe inclusion of trees for any reason within farmers' fields (Kenya Forestry Master Plan 1994). Kenya Forestry Master Plan (1994) proposes farm forestry as the only viable means of providing both food and wood products to rural households. The farmers will be encouraged to start group nurseries to augment the government's efforts in providing tree seedlings for those species in great demand within a particular area. Farmers will be required also to plant and manage trees on farms to meet their social and economic needs (The Kenya Forest Policy, 1999). They will be entirely responsible for their trees. Researchers will provide technologies on how farmers should combine trees and crops on-farms for improved productivity and forest extension officers will advise farmers on how to raise and tend trees.

The farm forestry approach had been tested in Kitui and Embu districts (KEFRI Annual Report, 1998). Identification of farmers' needs and constraints to farm forestry showed that farmers deliberately left high value trees in their farms during land clearing and often introduced others (exotics and high value indigenous) into their farming. A socio-economic survey carried out by Kaudia (1996) at Kitui farms on social forestry adoption indicated that farmers plant trees in their farms for various economic reasons but expansion of the most desired tree species on-farm was limited by seedling availability. Similarly, Kidundo (1997) conducted a survey at Embu farms on participatory tree planting techniques and identified lack of desired tree seedlings as the main constraint limiting expansion of farm forestry. However, the Embu survey results highlighted that farmers resorted to alternative methods of propagating tree-planting materials. For example, because of lack of seedlings, farmers were using transplanted wildlings and natural regeneration to propagate *Melia volkensii*.

With the above background, integration of trees into cropland will dominate dryland agroforestry in Kenya probably for more than 50 years (Sanchez, 1995). Furthermore, unless the current declining economic growth rate (projected at 4% annually for 2000-2005) was to attain the required 10% to spur economic growth (Kenya Forestry Master Plan, 1994), other economic opportunities such as employment or industrialization will not occur soon enough for farmers, who will continue to rely fully on subsistence agriculture. There is a need therefore to improve the social and economic welfare of farmers by expanding and improving the productivity of agroforestry practices continuously

1.3 Resource utilization in dryland agroforestry systems

In agroforestry systems, whenever plants are grown in close proximity with crops, they interact by sharing available resources (water, CO_2, light and nutrients) (Ong *et al.*, 1996). The component plant species of mixtures may impose different demands on the available resources. For instance, Rao *et al.* (1998) cautions that such species mixtures may result in resource competition, especially under resource-limited conditions. Vandermeer (1989) wrote that competition is more severe for similar species than different species, to the point where species with overlapping niches may be unable to coexist within the same community. Minimum competition is therefore achieved by growing tree species with differing resource requirements on the same area of land (Ong *et al.*, 1996).

Agroforestry species may use resources in a complementary manner between agroforestry components (Ong, 1995). Such complementarity describes positive associations of species that result in increased system productivity (Hooper, 1998). Cannell *et al.* (1996) state simply that complementarity in resource use in an agroforestry system occurs when trees acquire resources that crops could not acquire and that available resources must be used efficiently such that total productivity increases. This implies that complementarity may be manifested by either increased resource capture or improved resource use.

Trees with deep roots can potentially intercept nutrients leaching down soil profiles and also capture nutrients accumulated in subsoil below the rooting depth of annual crops (Livesley *et al.*, 1997; Van Noordwijk *et al*, 1996). Nutrients captured by trees from beneath the rooting zone of annual crops may be transferred to the soil surface in the form of leaf litter, roots, prunings of tree leaves and branches (Schroth, 1995). Previous studies have demonstrated the occurrence of complementarity. For example, Ong *et al.*, (1992) reported that hedgerow planting of *Leucaena leucocephala* extracted more water than sole crops and widely spaced trees in crop alleys extracted even more water than sole *Leucaena leucocephala*, suggesting that agroforestry systems were more effective in utilising available resources than either sole crop or tree planting systems. Similarly, Howard *et al.* (1997) describe *Grevillea robusta* as having great complementarity potential for intercropping systems because of its limited lateral roots that extracted only 20% of the trees' water requirement from the crop's rooting zone.

While appreciating the fact that complementarity has the potential to improve productivity in agroforestry systems as whole, recent studies (Odhiambo, 1999; Namirembe, 1999; Lott, 1998) highlight the fact that trees can out-compete crops for soil water and nutrients leading to greatly reduced crop yields in the overall system. The availability of the most limiting resource (particularly water) and how it is shared between trees and crops are more crucial in determining the complementarity of resource use. Such complementarity is determined by tree roots distribution and the degree of their interactions with that of roots (Hooper, 1998).

The contrasting results might have arisen due to rainfall variation or differences in soil fertility between sites during the times these trials were conducted. In semi-arid areas, good or poor rain seasons might give totally different yields in the same experiment at different times. For instance, Jonsson *et al.* (1999) reported higher millet yields under trees compared with crops in the open after receiving above average rains in Burkina Faso, but below average rains caused reduced crop yields in close proximity to trees (Rao *et al.*, 1998). Other studies (Jama *et al.*, 1995; Umaya, 1991) after incorporating lopped tree leaves as mulches reported greater crop productivity in hedgerow intercropping than in crop only plots. However, results of similar repeated trials indicated reduced yields when soil moisture was limiting (Rao *et al.*, 1998).

Who takes the lion's share of the resources, trees or crops? In agroforestry, established trees have a network of fine roots in place before the introduction of crops thus giving trees an added advantage over the crops in water and nutrient uptake (Schroth, 1999). Depending on the environmental conditions, species type and management regimes, tree root systems may develop either shallowly or deeply (Ong *et al.*, 1996). Consequently, such root structures may dictate the way resources are utilised in the soil profile. Van Noordwijk *et al.* (1995) suggest that competition for water and nutrients depends on relative distribution of fine roots of both trees and crops and that once tree roots share the same soil layers as food crops, competition for resources results. For example, Makonnen *et al.* (1999) showed that *Sesbania sesban* has shallow roots which caused reduced crop yields near the trees.

1.4 Agroforestry system components interactions

Interactions between the components of agroforestry systems are multi-faceted (Ong *et al.*, 1996) and occur in the above ground (light, rainfall, transpiration and temperature) and below ground (soil water, nutrients and organic matter) environments. These interactions between agroforestry components are further made complex by changing patterns of resource capture as the systems mature and interactions that occur between agroforestry components when trees are young are likely to change as trees mature. Furthermore there are other factors that influence differences in competition between trees with crops, such as differences attributed to tree origin or provenance.

While previous studies on tree-crop interaction reported interspecific differences between trees (Ong, 1996), there are also likely to be intra-specific differences between provenances. Provenance variation is an important component of tree improvement programmes (Greaves and Hughes, 1976), because tree growth of the same species obtained from different sites often differs. This is so because growth of introduced trees in any site will depend on their geographical source (Zobel and Talbert, 1984).

'Provenance is the geographic source or geographic area from which seed or planting material is obtained' (Zobel and Talbert, 1984).

Kenyan ASALs cover large areas, and rainfall amounts, temperatures and altitudes differ between localities, and provenance differences could be very important when selecting trees for agroforestry.

Altitudinal, edaphic and climatic conditions between different regions may differ significantly (Webb *et al.*, 1984). Plant growth characteristics are a product of genetic constituents and environmental conditions (Zobel and Talbert, 1984). Consequently, trees exhibit some characteristics to cope with these particular environmental conditions. For instance, Shepherd (1986) reported that trees from drier areas developed deep roots to capture water resources at soil water table. Based on provenance differences, the same species from wetter and higher parts of the drylands may perform better or worse than plants from drier and lower altitudes when planted in the same site. The acquired growth characteristics could be portrayed in rooting behaviour, stem form, leaf cover and stomata behaviour (Shepherd, 1986).

1.4.1 Above ground and below ground interactions between agroforestry systems components

The resource uptake by plants within agroforestry systems depends on environmental conditions above the ground such as temperature, radiation and relative humidity (Nobel, 1980; Kramer, 1980). Howard *et al.* (1997) report soil water as the most limiting resource in dryland agroforestry. Below ground interactions between trees and crops is therefore emphasized in this investigation.

Generally, above and below ground interactions between trees and crops depend on the stages of tree establishment. For instance, at a young age, light and rainfall interception are usually lower than when trees are mature (Jackson *et al.*, 1997). Mature established trees may develop extensive root networks which may deplete resources from large areas (Coutts, 1983). The balance of resource use between tree and crops depends on tree water use efficiency (Ong *et al.*, 1996), phenology (Passioura, 1988; Nobel. 1980), age and tree management. For instance, Cooper *et al.* (1987) report that the quantity of dry matter produced depends on the quantity of water capture (= transpired) and the efficiency with which water is used to produce dry matter.

For above ground competition, once trees are pruned or cut to lower heights e.g. hedgerow intercropping, light interception by tree canopy is reduced considerably. For example, Corlett *et al.* (1992) attributed the tremendous changes observed in crop yields to the management of tree canopy (pruning) by regulating light intensities reaching crops underneath. They observed 85% shading of adjacent crops by tree canopies which resulted into 2.2 t ha^{-1} reduction in millet yields relative to sole crop but once trees were pruned, crop yields doubled. Also, Howard *et al.* (1998) reported 30% yield loss due to 60% light interception by *Leucaena leucocephala* in hedgerow intercropping. While light can be very important, reduction in canopy area (either by leaf shedding or pruning) will also reduce tree water use and more recent studies, attribute much of these yield reductions to below ground competition for water and nutrients between trees and crops (McIntyre *et al.*, 1996; Namirembe, 1999).

Trees in agroforestry systems may contribute favourably to increased productivity by trapping more resources. For instance, intercepted runoff rainfall water by tree hedges and grass bands improved soil water recharging resulting in increased system productivity during the low rainfall seasons (Jackson *et al.*, 1997). In addition, tree shading and sheltering of crops from wind speed in agroforestry systems may modify microclimate below the canopy. For instance, Jonsson *et al.* (1999) reported that temperature reduction under parkland trees in Burkina Faso was enough to compensate for the negative effects of shade on pearl millet.

Below ground competition involves water and nutrient capture. The soil water capture by plants is influenced by soil structure and water content within the soil profile. For instance, soil water uptake by trees is conducted by capillary forces created between soil pores and leaf suction pressure (Russell, 1988). The distribution and the amount of pores within the soil structure determine the saturation soil water deficit. In addition, if soil water potential increases, water uptake by roots increases when atmospheric conditions are favourable. Furthermore soil structure in different sites may differ in organic matter, chemical and physical properties which may also change water holding and release capacities (Russell, 1988). Plant root systems will absorb water between soil field capacity and permanent wilting points, after that plants wilt (Jones, 1980). Between these points, plants regulate the use of the available soil water in contact with its roots in such a way that whenever soil water is greatly depleted, plants regulate some of the root and leaf processes and activities. For instance, Odhiambo (1999) reported greater root mortality of *Gliricidia sepium* within crop rooting zone during dry period and Namirembe (1999) reported loss of leaves in *Senna spectabilis* and lower transpiration rate when soil water became limiting.

Water use efficiency of plants changes when they are water stressed (Ong *et al.*, 1996) and the most sensitive stages occur at seedling establishment and crop anthesis (Howard *et al.*, 1997; Mooney, 1980). Interestingly, some dryland species shed their leaves to conserve water immediately drought sets in but flush new leaves before the rains start. Then, available soil moisture which is stored in soil profile is used by species that maintain greater leaf area during drought when other species shed theirs. However, the presence of many leaves does not automatically imply increased photosynthesis as some leaves may have reduced transpiration, but efficiency of water use and stomatal activity determine photosynthetic processes (Fisher, 1980).

For below ground competition, root distribution within the soil profile determines how below ground resources are utilised between trees and crops in simultaneous agroforestry systems (Schroth, 1997). Root distribution is therefore crucial in dryland agroforestry systems, where soil water is the main constraint to improved system productivity (Jackson and Wallace, 1999).

Roots do a lot for a plant. Thicker roots originating from the tree stem (proximal roots), help anchor the plant and contain transport tissues (Fitter, 1991). Thicker roots also hold distal or fine roots which absorb water and nutrients in place (Van Noordwijk *et al.*, 1995). If tree roots are shallow and occupy the same soil layers as food crops under the conditions of limited soil water, competition for water between trees and crops occurs. For instance, Odhiambo (1999) reported that soil water was less in the plots with trees than in control plots lacking trees suggesting that crop yield reductions were caused by competition for water between trees and crops.

An ecological perspective of roots is clearly understood by studying the morphology of root systems, described as root architecture (Fitter, 1991). The way thicker roots are structured in the soil profile indicate the areas of soil layers where most root activities occur (Fitter and Stickland, 1992). Knowledge of the architectural characteristics of root systems within plant types or species should enable us to understand the potential of different plants to compete with associated crops.

There are many root quantification methods. The methods do not all give the same information: some indicate root distribution, some root density and others give root dynamics. Some of the methods include; fractal characterization (Fitter and Stickland, 1992), minirhizotron (López *et al.*, 1996; Hendrick and Pregitzer, 1996), root architecture (Groot and Samouré, 1995; Coutts, 1983), root coring (Jonsson *et al.*, 1988) and trenching or profile mapping (Singh *et al.*, 1989). Reviews of the above root quantification methods (Van Noordwijk *et al.*, 1994) indicated that they are expensive and time consuming. Van Noordwijk and his colleagues however, suggested an alternative cheaper and quicker method to quantify tree roots to predict tree competition with crops; the competition index method (described in Chapters 2 and 4).

1.5 The Study

Farmers believe that *Melia* does not compete with crops as indicated in the previous studies (Kidundo, 1997; Tedd; 1997), but studies carried out at Machakos indicated that *Melia volkensii* competes with crops (ICRAF annual report, 1995). The Machakos study indicated that *Melia volkensii* was more competitive with crops compared to known competitive species such as *Senna spectabilis, Grevillea robusta* and *Gliricidia sepium* of the same age. So, the question arose, do these different perceptions of the competitivity of *Melia* arise from provenance differences (are farmers using less competitive provenances) or were there differences resulting from methods of propagation (farmers often use cuttings instead of seedlings to establish their trees). This study aims at answering these questions.

Maize (*Zea mays* L. var. Katumani) which was highly regarded by farmers as both food and cash crop was selected for this study. Furthermore, it was also chosen because earlier reports about *Melia* competition with crops were based on the maize yields (Tedd, 1997).

1.5.1 Aims and objectives

Because of farmers' interest in *Melia volkensii* and contrasting reports from farmers views and experimental data about its competitiveness with crops, the aim of this work was to evaluate impact of *Melia volkensii* on crop yields at different sites and how its root architecture develops and influences the use of below ground resources. This was done through comparing different provenances of *Melia* and comparing *Melia* with other agroforestry species. Furthermore the study attempts to reconcile farmers' knowledge and research results.

The specific objectives were to:

1. determine whether there are differences arising from intra and inter-specific tree competition with crops that are associated with the distribution of tree root systems;
2. evaluate the competition index (CI) method to predict effects of tree root system development on crop yields;
3. determine whether soil moisture content in the soil profile is closely related to root system structure;
4. establish whether root system architecture of stem cuttings, root cuttings and normal seedling differ;
5. find out whether phenologies and hence timing of water demand by *Melia volkensii* provenances differ;
6. establish whether the effects of crop yield reduction by *Melia volkensii* can be compensated for by income generation through timber production on average tree rotation;
7. carry out a socio-economic survey to verify whether farmers' perception on *Melia* farming and impact on crops differ at different sites.

1.5.2 Expected outputs

1. Quantification of the effects of *Melia volkensii* provenances on crop yields in Kenyan ASALs.
2. Assessment of whether *Melia volkensii* can be economically integrated into Kenyan agriculture.
3. Quantification of competitive effects of a range of tree species including *Melia volkensii* on crop yields.

4. Identification of the *Melia volkensii* plant type with inherent root structure development which is less competitive when grown with crops.

1.5.3 General outline of the thesis

This thesis consists of eight chapters. Chapter 1 introduces the study and gives its background, objectives, hypotheses and expected outputs. Chapter 2 covers the materials and methods used for various aspects of the study and describes the data analysis. In chapter 3, results of socio-economic survey of *Melia volkensii* in farming areas of Kitui and lower Embu are presented. Tree establishment, management, constraints and possible effects on crop yields within farmers fields were covered in the survey.

Chapters 4 and 5 deal with tree root system orientation, distribution and root architecture of tree species. In particular, Chapter 4 deals with evaluation of competition indices of different *Melia* provenances and tree species in order to predict their competitiveness with crops. Chapter 5 covers the root architecture of different plant types especially that of *Melia volkensii* raised through seedlings, root cuttings and stem cuttings and that of *Melia volkensii* provenances usually used during fields and on-farm tree planting.

Measurements of soil moisture content and tree and crop growth are covered in Chapters 6 and 7. Soil moisture content by neutron probe at specific distances from trees and at varying soil depth distances plus tree transpiration rates are covered in Chapter 6. Crop growth analysis, grain yields at various distances from trees and tree-crop interactions in the field station and in the farmers' fields are covered in Chapter 7. A general discussion and recommendations are presented in the last chapter (Chapter 8).

CHAPTER TWO

2. MATERIALS AND METHODS

2.0 INTRODUCTION

The socio-economic survey was carried out using structured questionnaires and field discussion with merchants, farmers and local forestry experts. The results were used with the results of experiments at Machakos (Ong *et al.*, 1999) in the planning of the field trials and on-farm experiments. The sites and trials are described in sections 2.1 and 2.2.

The techniques for measuring competition index, root architecture, soil moisture, sap flow, crop growth and yields are outlined in sections 2.3 and 2.4, and the methods used are described in more detail in sections 2.4.1 (competition index), 2.4.2 (root architecture), 2.5 (tree growth), 2.6 (crop growth), 2.6.3 (crop yield), 2.7.1 (soil moisture), 2.7.3 (sap flow) and pot experiment to evaluate the effect of tree litter fall on below canopy soils was carried out under nursery conditions is detailed in section 2.8.

The experimental layout and plan of measurements are detailed in Table 2.3 and data analysis procedures for different observations are detailed in section 2.10.

2.1 Site descriptions

The location of the four sites, Machakos, Kitui, Kibwezi, and Lower Embu (Mbeere) are indicated (Fig. 2.1.1). The Kibwezi site represented the lower altitude of *Melia volkensii*'s natural range, the Kitui was intermediate and Mbeere site represented the upper altitude of the study. The Machakos site had no *Melia* growing history and was used for comparing *Melia* provenances obtained from the other sites.
Generally, *Melia volkensii* occurs in eastern dry lands of Kenya at 37°36' E to 40°43' E.

The Machakos site is situated at 1°33' S, 37°14' E and elevation of 1600 m with soils described as lixisols (FAO-UNESCO, 1988) which range from weakly to moderately leached, well-drained, dark reddish brown, erodible and in some areas exceeding 2 m depth (Howard, 1997). At this site, 3 on-station trials were conducted. Trials 1, 2 and 3 consisted of a *Melia* provenance trial, a species comparison trial and a root structure comparison experiment between *Melia* seedlings, stem and root cuttings respectively (Table 2.2.1).

The Kitui sites are situated at 1°30'S, 38°50' E and elevation of 1300 to 1400 m above sea level (asl). The soils are excessively drained to well drained, dark reddish brown, sandy clay loam, of moderate fertility and in places shallow (Kenya Soil Survey, 1982). At this site, two trials were conducted: the species selection trial (trial 4) on the station and the on-farm trial 5 of the effect of isolated *Melia* trees on crop yields. In addition, a socio-economic survey on *Melia* establishment, management and constraints on farmers' fields was conducted in this area.

The Kibwezi site is at 2°20' S, 38°57' E and elevation of 1200 m asl, has sandy to clay loam, dark reddish brown, well drained and moderately deep soils (Joestzard and Schmidt, 1983). At this site, an on-farm evaluation of competition index (trial 6) was carried out.

The surveyed sites in Mbeere (formerly Lower Embu) district had annual rainfall ranging from 830 to 1260 mm. Mbeere lies at 0°45' S 37°45' E at 1400 to 1800 m asl. Soils are generally dark red to yellow red, and vary from stony loamy sand, to clay. At this site, a socio-economic survey was carried out as in the Kitui sites.

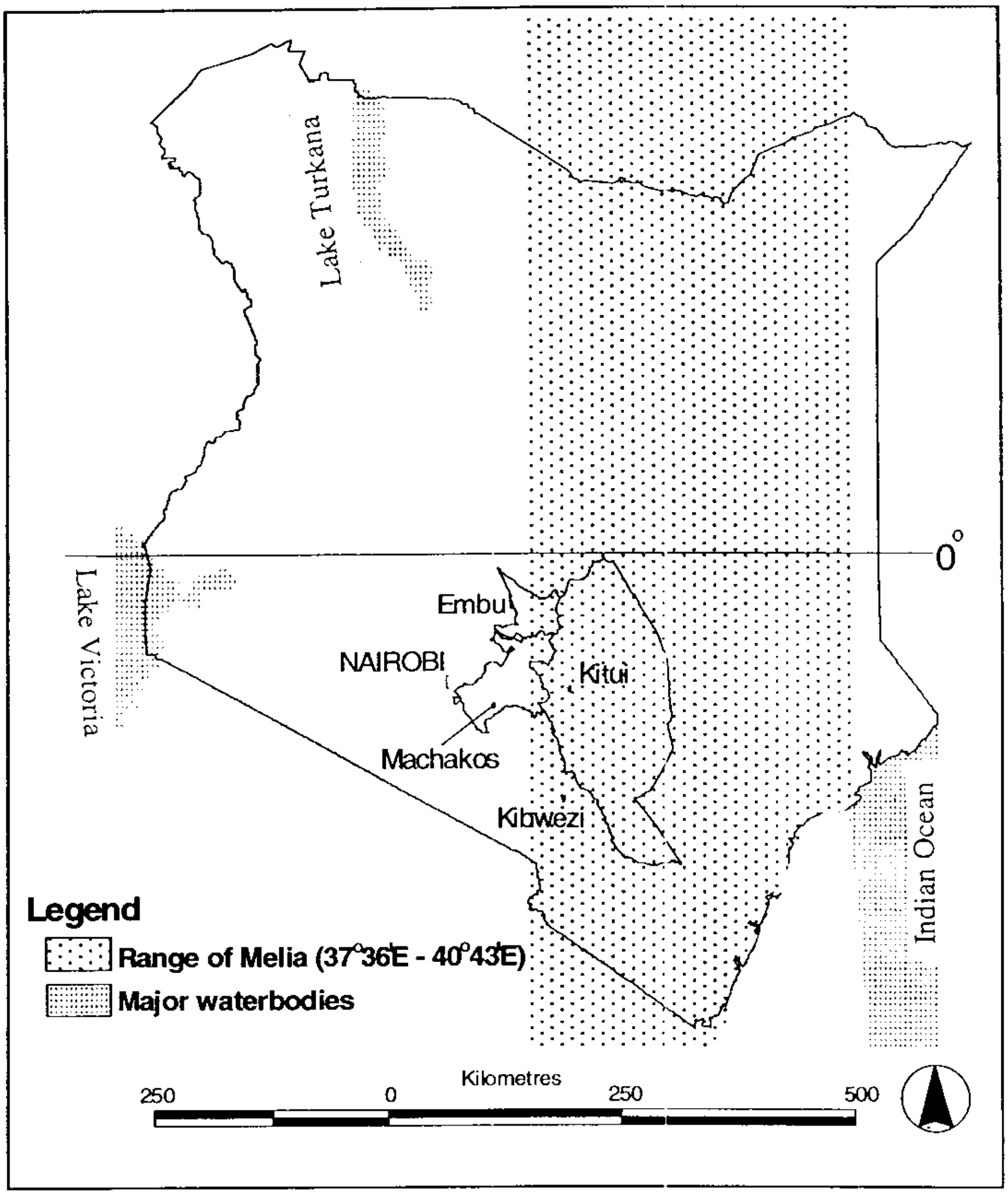


Figure 2.1.1 Map of Kenya indicating the four sites (Machakos, Embu/Mbeere, Kitui and Kibwezi) where this study was carried out.

2.2 Experimental layout

The trials covered in the study at each site and their rainfall and species and crop composition are summarised in Table 2.2.1.

At the Machakos site, where most of the activities were investigated, there were three trials. Trial 1 consisted of four *Melia volkensii* provenances originating from Kitui, Kibwezi, Siakago and Ishiara sites the environmental conditions of which are summarised in Table 2.2.2. Trial 2 consisted of four species (see Table 2.2.1). Trial 3 was planted with nursery raised seedlings, root and stem cuttings (plant types) generally used in *Melia* tree establishment.

Both trials 1 and 2 had trees planted at the centre of the plots in single rows at 1m spacing. The plots measured 20 x 30 m (provenance trial) and 40 x 40 m (species trial) (Fig. 2.2.1 and Fig. 2.2.2 respectively). There were 21 trees in each of *Melia volkensii* provenance plot and 51 tree per plot in the species trial. Each treatment had four replicates, laid out in a randomized block design, plus a control plot without trees in every block. The tree rows were orientated on an east to west axis to minimise shading over crops. This is because trees were tall and could cast substantial shading of crops if tree rows were planted in the orientation across the sun's direction.

The trees in each plot were managed as follows; side branches of *Melia volkensii* and *Grevillea robusta* were pruned to give clean boles and low branches of *Gliricidia sepium* and *Senna spectabilis* were pruned to reduce shading of crops. The *Melia volkensii* provenance trial site was slightly sloping from south-west to north-east (see design layout). The species trial site also had a slight gradient from east to west. Block randomization of both trials was laid along the gradient slope. Results of bean yields planted earlier in 1993 as cover crop before tree establishment was used to guide the way the plots were replicated by siting blocks in a such way that yield variation arising out of site bias due to the slope was overcome.

Trial 3 was planted in separate groups of 25 seedlings, 25 root cuttings and 5 stem cuttings (Fig. 2.2.3). Only five stem cuttings were planted because of problems with propagation. The trees were planted at 3 m x 3 m spacing and plant groups were at 5 m apart.

Table 2.2.1: Summary of site and experiment descriptions.

Trial	Site	Rainfall (mm/year)	Tree species	Tree age (years)	Cropped (yes or no)
1	Machakos	750	4 *Melia volkensii* provenances from: Kitui, Ishiara, Siakago, Kibwezi.	2, 3	yes
2	Machakos	750	4 species: *Melia volkensii, Senna spectabilis, Grevillea robusta, Gliricidia sepium.*	3, 4	yes
3	Machakos	750	*Melia volkensii* seedlings, root and stem cuttings.	1.5	no
4	Kitui	650	7 species: *Melia volkensii,* *Acacia polyacantha,* *Senna spectabilis,* *Grevillea robusta ,* *Senna siamea,* *Azadirachta indica,* *Eucalyptus camaldulensis.*	3	no
5	Kitui on-farm	650	*Melia volkensii*	3, 5, 7, 8	yes
6	Kibwezi on-farm	600	*Melia volkensii*	3, 5, 7	yes
7	ICRAF - Nursery	Hand watered	*Melia volkensii*- pot experiment	2 months	yes

Table 2.2.2: Characteristics of sites of origin of *Melia volkensii* provenances used in trial 1.

	Provenance			
Feature	Kitui	Kibwezi	Siakago	Ishiara
Elevation (m)	1200	1000	1400	1700
Latitude (S)	1° 29'	2 ° 20	0 ° 48'	0 ° 30'
Longitude (E)	37 ° 50'	38 ° 57'	37 °55'	37 ° 30'
Mean annual temperature (°C)	26.5	27.5	26.15	22.5
Mean annual rainfall (mm)	650	600	750	850
Soils	rhodic ferralsol	chromic luvisol	ferralic arenosol	ferralic luvisol

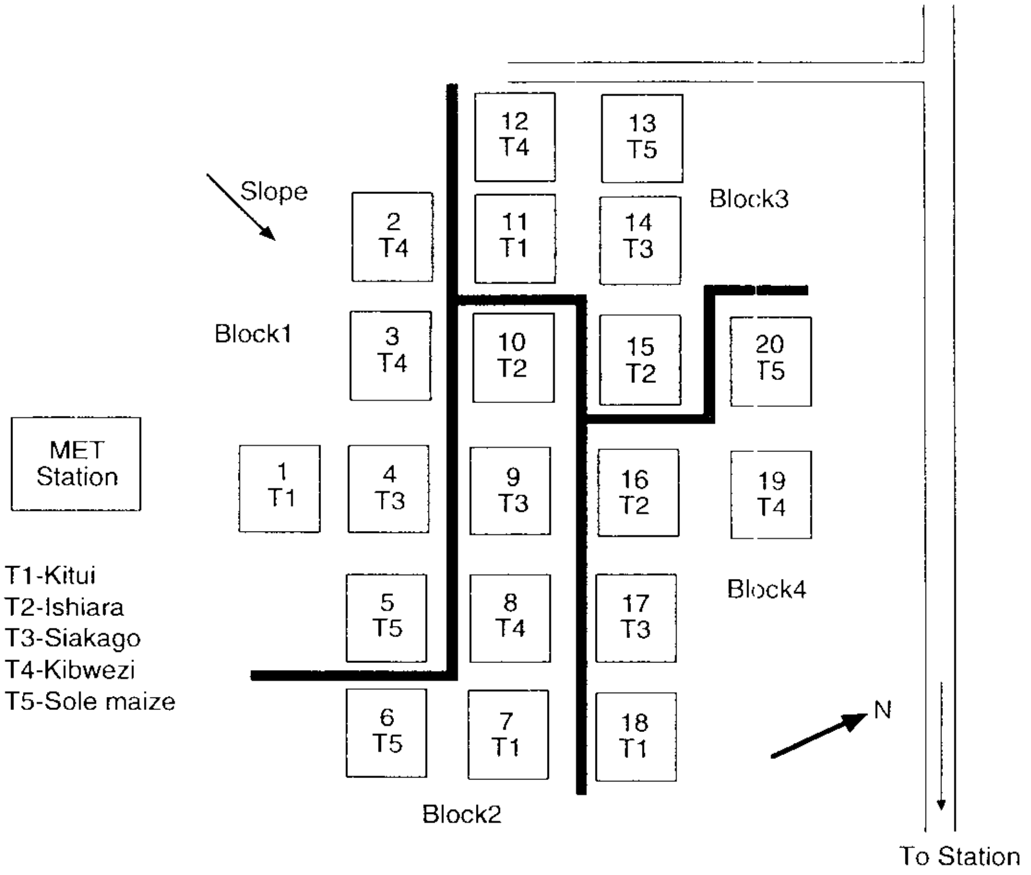
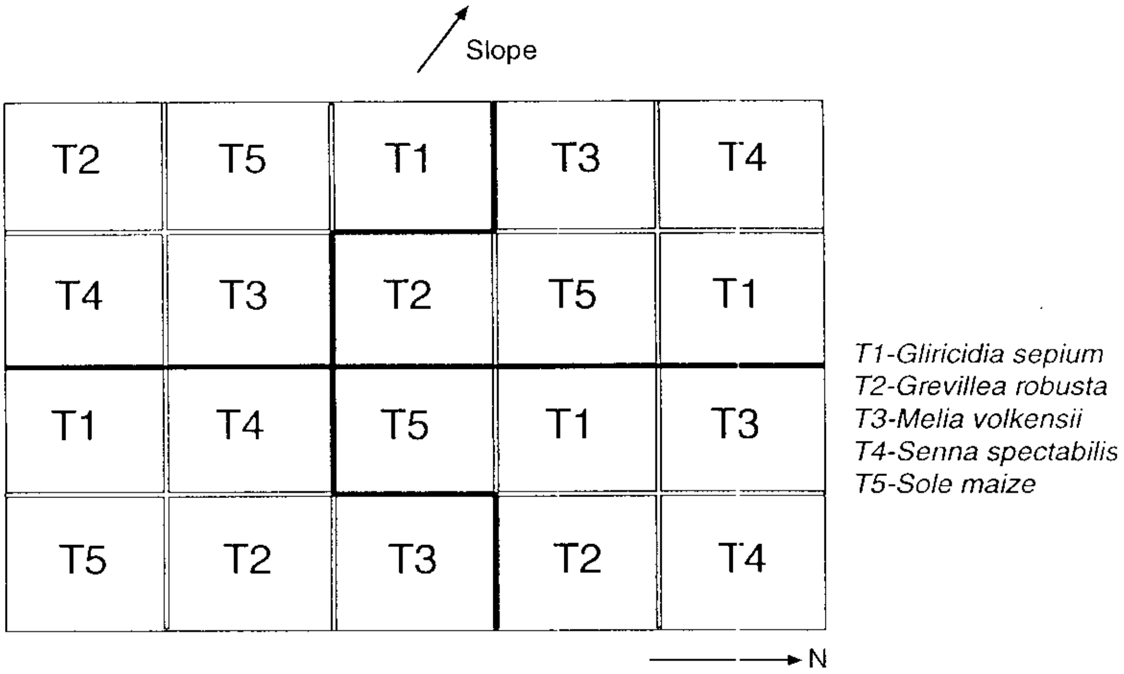


Figure 2.2.1 Experimental layout of trial 1 (*Melia volkensii* provenance trial) planted in April 1996 at ICRAF Machakos station.



T2	T5	T1	T3	T4
T4	T3	T2	T5	T1
T1	T4	T5	T1	T3
T5	T2	T3	T2	T4

T1-Gliricidia sepium
T2-Grevillea robusta
T3-Melia volkensii
T4-Senna spectabilis
T5-Sole maize

Figure 2.2.2 Experimental layout of trial 2 (tree species comparison trial) planted in November 1995 at ICRAF Machakos station. The bold lines indicate block boundaries

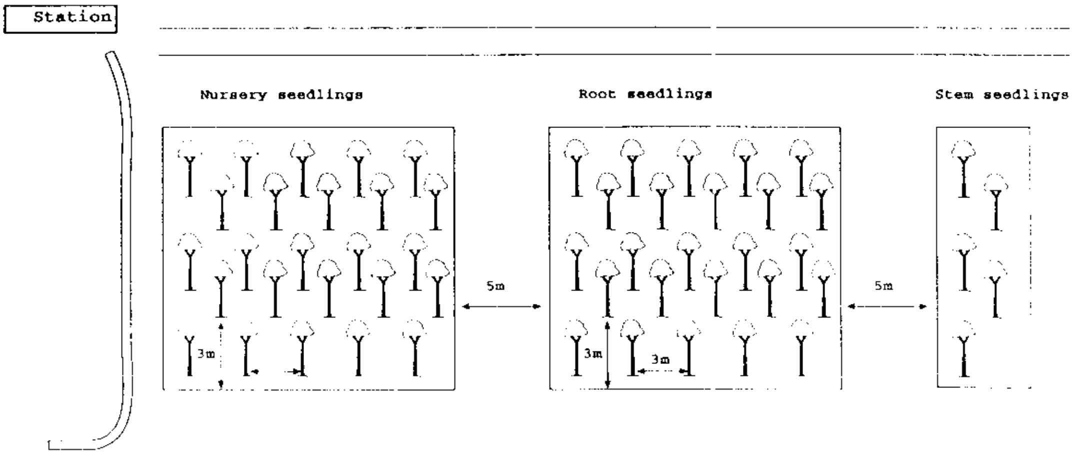


Figure 2.2.3 Field layout of trial 3 (*Melia volkensii* seedlings, root cutting and stem cuttings root architecture comparison trial) planted in November 1997 at ICRAF Machakos station.

At the Kitui site, the species selection trial 4 (Table 2.2.1) which was planted in 1995 at KEFRI Kitui station, like trial 1 and 2 was used to determine and compare competition indices between species. It was selected because it had many species, some of which also occurred in the Machakos trials. This provided an opportunity to validate the results from Machakos sites. Trial 4 had seven dryland agroforestry trees each replicated four times in a randomized block design (Fig 2.2.4). The species were planted in groups of 9 trees at 3 m x 3 m spacing per plot. The block layout followed the slope gradient in an east to west axis. No crops were planted.

In addition, ten isolated *Melia volkensii* trees were selected in farmers' fields and treated as trial 5 in this study (Table 2.2.1). Because of the need for small and bigger trees to capture effects of tree size, several farms with single trees were selected to allow crop yield measurements in the situation and direction where there was no interference from other trees. Maize yields (cob diameter and length) were measured along a line transect originating from tree base at intervals of 2 m, with sample points on the transect lines in order of 1 m, 3 m, 5 m, 7 m, etc.

To ensure same maize variety was planted in all farms, farmers were supplied with maize seed (Katumani variety) by the researcher. However, problems of mixed cropping arose where farmers mixed beans, millet, pigeon pea and maize to minimize risks of crop failure associated with inadequate rainfall, making evaluation of *Melia volkensii* root structure effect on maize an impossible task at some sites. Out of the 20 selected farms where appropriate isolated trees for this study were found and farmers were supplied with seeds, less than 10 farms had no mixed cropping. Consequently, few trees at each season were sampled, thus making estimation of the effect of tree size on maize yields difficult.

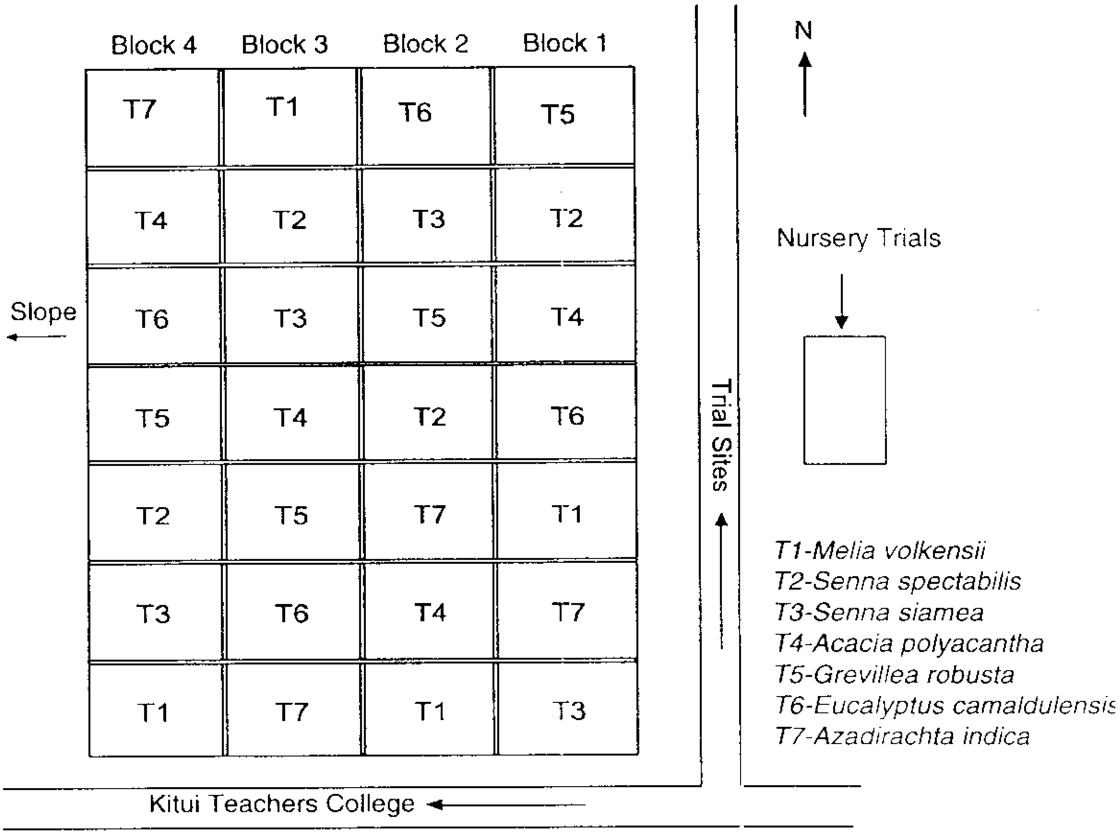


Figure 2.2.4 Field layout of trial 4 (species selection trial) planted in November 1995 at KEFRI Kitui site.

At Kibwezi site, ten *Melia volkensii* trees of varying size in the farmers' fields were selected and treated as trial 6 as described for Kitui trial 5. No crop yields were measured around the trees.

At Lower Embu (Mbeere) sites, a socio-economic survey on *Melia volkensii* propagation, establishment, interaction with food crops, marketing and constraints was conducted using questionnaires. Similar study was conducted at the Kitui sites.

2.3 Observations and measurements

The determined activities include; competition index determination, root architecture mapping, tree growth, crop growth analysis, soil moisture content, pot experiment on farm soils and on-farm grain yields estimation. Timetables of biological observations and measurements are presented in Table 2.3a and Table 2.3b.

Table 2.3a: On-station field activities, biological measurements and timetable of these observations, 1998-1999

Activity	Trial 1	Trial 2	Trial 3	Trial 4
Tree planting	Apr-96	Nov-95	Nov-97	Nov-95
Land preparation	Tractor ploughed every season	Tractor ploughed every season	Tractor ploughed before establishment	Tractor ploughed yearly
Maize sowing	Long rains of 1998 24/3/98 Short rains of 1998 9/11/98 Long rains of 1999 16/3/99	Long rains of 1998 24/3/98 Short rains of 1998 9/11/98 Long rains of 1999 16/3/99	-	-
Weeding	Weeded twice every season	Weeded twice every season	Weeded twice every season	Weeded once every season
Crop growth analysis	Long rains of 1998, short rains of 1998 and long rains of 1999 every 20 days after sowing for 90 days	-	-	-
Maize grain yield harvest	Aug-98 and Aug-99	Aug-98 and Aug-99	-	-
Competition index	Feb-98 and Mar-99	Feb-98 and Mar-99	-	Jul-98
Root architecture	Apr-99	-	Feb-99	-
Tree growth measurements	Feb-98, May -98, Aug-98, Dec-98, April- 99	Feb-98, Mar-99	Measured every month: first measured at 1 year old	Jul-98
Soil moisture (neutron probe)	From April-98 to Aug-99 weekly	-	-	-
Neutron probe calibration	Aug-99	-	-	-
Phenology	Every 2 weeks From April-98 to Jul-99	-	-	-
Sap flow (heat pulse)	May to July 1998 May to July 1999	-	-	-

Table 2.3b: On-farm activities, biological measurements and timetable of their observations, 1998-1999

Activity	Kitui farms	Kibwezi farms
Tree age	Aged between 3-8 years	Aged between 3-7 years
Land preparation	Oxen ploughed every season, or hand prepared by hoes	Oxen ploughed every season, or hand prepared by hoes
Maize sowing	Long rains of 1998 20-28/3/98 Short rains of 1998 7-11/11/1998 Long rains of 1999 10-20/3/99	-
Weeding	Weeded twice every season	Weeded twice every season
Maize grain harvest	Cob measurements Jul-98, Feb-99, Jul-99	-
Competition index	Jul-99	Aug-99
Tree growth measurements	Jun-98, Jul-99	Aug-99

2.4 Root quantification methods

Interaction between trees and crops occur both above and below ground but this study focuses more on below ground interactions. As mentioned earlier, understanding root architecture enables predicting trees with greater potential to compete with food crops. Quantification of root distribution is therefore crucial. There are several methods used for root quantification studies but Van Noordwijk *et al.* (1994) reckon that most of them are expensive and time consuming. Some of these methods have limitations. For instance, root fractal method was found to grossly underestimate fine root length (Ong *et al.*, 1997) while minirhizotron data was found to have poor agreement with core data (Odhiambo, 1999). Trenching and profile mapping methods are too involving and too disruptive to determine root dynamics (Van Noordjwik *et al.*, 1995). It is against this background that the proposed competition index (Van Noodjwik *et al.*, 1994) and root architecture methods were selected for this study. These two methods are described in more detail in sections 2.4.1 and 2.4.2.

2.4.1 Competition indices (CI) determination

The method of calculating CI as proposed by van Noordwijk and Purnomosidhi (1995) was adopted.

$$CI = \frac{\sum D^2_{horizontal}}{D^2}$$

where CI is competition index, $D^2_{horizontal}$ is the proximal diameter squared of the roots descending into soil at angles less than 45° (horizontal roots) and D^2 is either the square of the stem root collar diameter or diameter at breast height (dbh). Both root collar and dbh diameters were separately used in the CI calculation and root collar diameter was found to give more consistent values than dbh especially in multi-branched stems. Consequently, most of the CI value results presented in the study were derived using the tree root collar diameter.

Tree roots originating from the stem base (first order roots) in horizontal orientation were exposed through digging and measured as depicted in Figure 2.3.1. Horizontal root diameters were measured at the points where rapid root tapering was not occurring. This is so because some tree roots are swollen as they leave the stem bole due to tree support but taper to normal diameter within short distances. To minimize root damage, digging was carried out using hand tools such as shovels, hoes, screwdrivers and daggers, as appropriate.

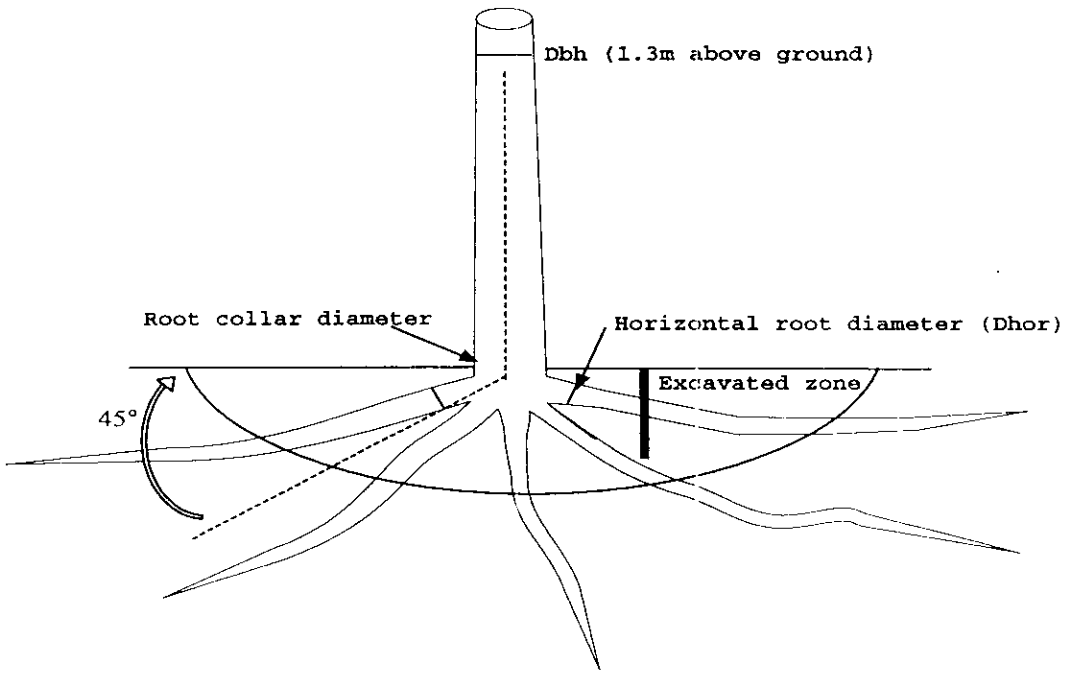


Figure 2.3.1 Diagrammatic representation of where to measure tree stem and horizontal roots diameters for competition index calculation.

2.4.2 Root architecture determination and mapping

Selected trees in trials 1 and 3 (see Chapter 5) were excavated carefully using hand tools as described in the Competition Index method. The whole root system was exposed down to a depth of 50 cm for seedling and cutting roots in trial 3 at the age of 1.5 months and to 60 cm soil depth for *Melia volkensii* provenance trial (trial 1) at age 3 years. This was so because shallow roots of young trees were easily exposed by excavating to a depth of 50 cm whereas 60 cm was necessary for older trees. During excavation, horizontal roots were followed from the stem base to the smallest root diameter of 3 mm within the said soil depths making sure that no roots were damaged. The soil depths of less than 40 cm was chosen because it is where most of crop roots are found (Odhiambo, 1999) and probably where serious competition for resources between tree roots and crops occurs.

While excavating to expose horizontal roots, trees were supported in their original positions by strings, wires and poles to prevent them falling over or sinking downwards in case of strong winds. Roots that penetrated the soil depth in vertical directions were dug up to 50- 60cm depths according to the tree size. Where roots were damaged during the digging process, they were rejoined using adhesive tape to facilitate their mapping.

Once the excavation was completed, the soil surface around the trees was levelled and a horizontal grid of 1 m x 1 m set using strings around the tree (Fig. 2.3,2). A predetermined origin (east = 0 cm, north = 0 cm, and depth = 0 cm) was set at one corner of the grid. Using this origin, the co-ordinates of all root branches and bends and diameters at these points were mapped (Plate 3).

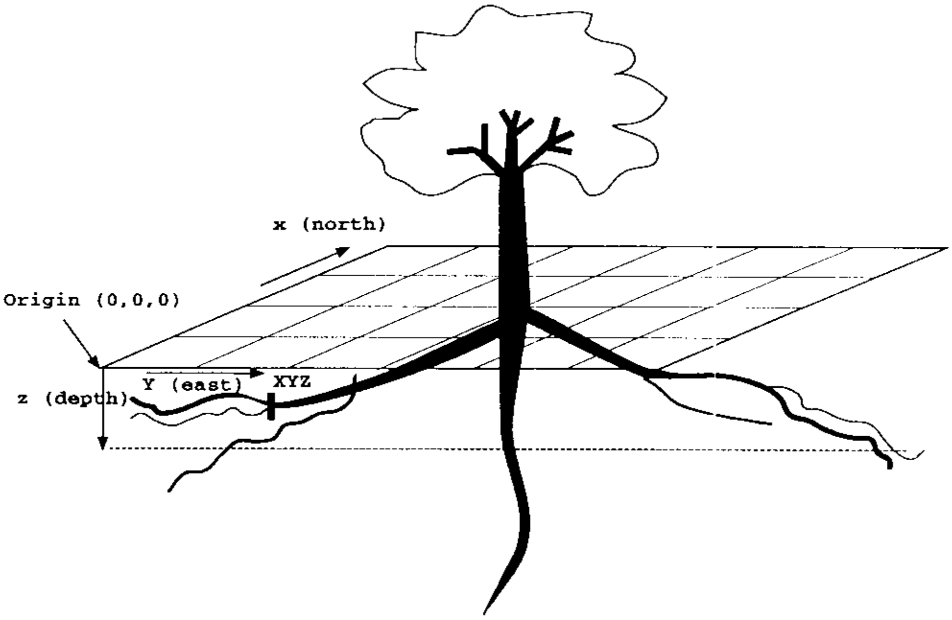


Figure 2.3.2 Diagrammatic representation of root architecture and how XYZ co-ordinates for roots' bending or branching are measured.

2.5 Production of *Melia volkensii* plant types used in the root architecture studies

The *M. volkensii* provenance trial was established using nursery raised seedlings. The seedlings were raised in pots which were not root pruned while at the nursery. They were planted in the field after three months.

Plants for the comparison of *Melia volkensii* seedlings, root cuttings and stem cuttings root architecture trial (trial 3) were also raised at the nursery. The seedlings were raised in pots as for trial 1 while the root and stem cuttings were raised from the same clone originating from the Kitui *Melia volkensii* provenance. The seedlings were also from the Kitui provenance.

To obtain root cuttings, the roots were dug out to expose parts of roots with 1-2 cm diameter sizes. These parts were cut into pieces of 5 cm length and then treated with fungicide (Captan) and IBA rooting hormone (Seradix 3) before inserting them into sterilised gravel within high humidity polythene propagators at Machakos field nursery. After 1-2 weeks, the rooted cuttings were transplanted from the polythene propagators into pots and left to grow for two months before establishing trial 3.

Stem cuttings were raised from young stem sprouting from coppiced *Melia volkensii* clones. The same rooting hormone was applied as was used for the root cuttings, and cuttings inserted in polythene propagators as before. Many of the stem cuttings formed root calli but failed to produce roots while others lost their leaves before rooting started, then rotted. With repeated propagation attempts only five stem cuttings could be planted into the field after being in the nursery for10 months (Fig. 2.2.3).

2.5.1 Tree growth assessment

The *Melia* plants established in trial 3 were assessed for root collar diameter, height and survival every month.
In trial 1, *M. volkensii* provenances had their diameter at breast height (dbh) and heights assessed every 3 months whereas in the trial 2 the same measurements as trial 1 were done once a year.

At KEFRI Kitui site, trial 4 had diameter at breast height and at root collar measured once in July 1998 during the CI determination.

On the farmers' fields, single trees had their diameters (dbh and root collar) and heights measured once a year when tree's effect on crop yields was being assessed.

2.6 Crop growth analysis

Maize (*Zea mays* L. cv. Katumani) growth analysis was monitored at trial 1 by a combination of destructive and non-destructive methods. It was carried out in the three maize seasons of long rains 1998, short rains of 1998 and in the long rains of 1999 (see Table 2.3a). Maize growth analysis was carried out in the tree plots and treeless control plots to enable comparing maize growth in the control plot with that of the plots containing trees. Furthermore, in each tree plot, the sampling was done at 1, 3 and 5 m from trees to enable evaluation of the effect of trees on crop yields with changing distance from trees. In addition, maize growth was assessed under controlled shade nets to enable evaluation of the effect of shading on maize plant growth in terms of maize leaf area (LA), diameter and height growth.

2.6.1 Leaf area assessment

Maize leaf area (LA) was measured destructively through leaf core samples taken at 20, 40, 60 and 90 days after sowing (DAS). Two maize plants from each of rows 1, 3 and 5 from each side of the tree line were removed per plot at each sampling occasion. In all, 12 maize plants were removed at each sampling visit per plot. To determine leaf area, leaf discs of known area were taken using a metal pipe of 5 mm diameter, sharpened at one end. As many leaf discs as possible were taken from the green part of 3 representative leaves per plant excluding the thickened mid-rib. After 60 DAS, a sample of 2 leaves was used to estimate LA for the whole plant because of the excess work of coring many and big leaves. The cored discs from the sample leaves per maize plant were counted and put in one envelope for oven drying at 70°C. The remaining leaf part of cored leaves and uncored for each plant were put into another envelope and also oven dried. Core disc weights before and after oven drying were determined by electronic balance. The weight of the rest of the plants before and after oven drying was also obtained. Plant leaf dry weight was obtained by addition of total core dry weight and the remainder of the plants dry weight. Leaf area (LA) was then calculated from the ratio of leaf dry weight to total dry weight of leaf core discs and total known area of all cores in a maize plant, expressed in the following equation:

$LA = (L_d/L_{ct})\ A_c.N$

where LA is the leaf area of the plant, L_d is plant's dry weight, L_{ct} is total dry weight of all cores, A_c is area of core discs and N is total number of discs.

2.6.2 Maize plant root collar diameter and height growth

Using the same rows and sampling dates as in 2.6.1, two maize plants per row were tagged with tape, excluding 6 guard row plants at the beginning of the rows. Their root collar diameters and heights of the leading shoot were measured at each sampling occasion. In order to maintain uniform spacing, destructive and non-destructive sampling was never conducted on adjacent plants.

To determine the shade effect on maize growth, 25% and 50% shade cloths (shade nets) plots were used to evaluate the effect of controlled shading on crop growth compared to that of the provenance plots.

2.6.3 Final maize grain yields harvest

Maize yield in each plot was assessed as grain dry weight at the end of every maize season. In order to assess maize yield at various distances from both sides of the tree rows, maize cobs were harvested from rows 1, 3 and 5 during maize 1 season, and rows 1, 3, 5, 7, 9, 11, 13 and 15 during maize 3 season in trial 1. For trial 2, maize grain yields were measured at rows 1, 3 and 5 during the maize 1 season and rows 1, 3, 5, 7 and 9 m from trees during maize 3 season. The maize rows were 1 m apart. No maize cobs were formed during the short rains of 1998 hence no harvesting was done. The number of sampled maize rows was increased to cater for an extended distance effect from trees as the trees aged. At every sampled row, maize cobs were picked from 10 alternate plants, starting from the 6th plant from the end (to avoid edge effects). The harvested cobs were separately put in labelled bags and oven (75°C) dried for one week before dry grain weights were taken after removing the grain from the cob.

For the on-farm trial 5, maize yield was measured along line transects (see 2.2). Five maize plants had their cob diameter and length measured at each sampling position on the transect. Using the relationship between maize cob volume and dry grain weight which was determined from maize cob samples taken at Machakos (Fig. 2.6.3), maize cob volume (cm^3) was converted into grain weight (g). At machakos, maize cobs of different sizes were tagged with tape when green and their cob diameter at the middle of cob and cob length measured. They were harvested, oven dried at 70°C and later shelled to determine their dry weights. The cob volume was calculated using cone volume formula as given below;

$$V = 1/3 (\pi r^2.L).$$

where V is cone volume, r is radius of cone and L is length of the cone.

The relationship between maize cob volume and dry grain weight (Fig. 2.6.3) is described as;

$$y = 0.39x - 0.63$$

where y is dry grain weight and x is cob cone volume.

The crop densities under the tree canopy and in the open were measured in order to correct for stocking density due to variability in tree physical and biological conditions beneath and outside the tree canopy. Sample plots of 2 m radius around the stem and 4 m x 5 m plots in the open were used respectively to estimate maize plant stocking under and outwith *Melia* canopies to enable the determination of maize plant density per hectare. Yields per hectare were obtained by multiplication of maize plant density per hectare by grain yield per plant.

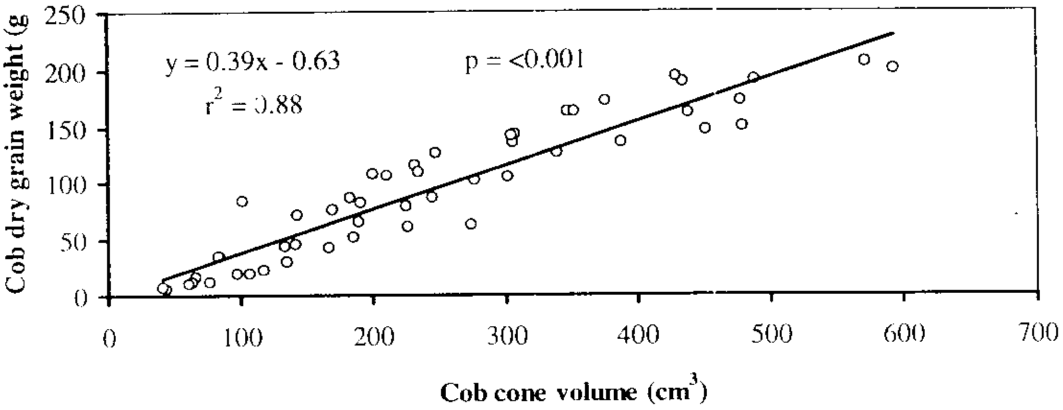


Figure 2.6.3 Relationship between maize cob cone volume and grain weight at Machakos field station.

2.7 Soil water and tree transpiration measurements methods

2.7.1 Soil moisture content

Soil moisture content was measured on a weekly basis in trial 1 (*Melia volkensii* provenance trial) using a neutron probe (Didcot Instrument Co. Ltd., Abingdon Oxon, England) at the centre of tree plots at 1.5, 2.5, 4.5, and 6 m from the tree rows and also in control plots lacking trees. At each sampling distance, soil moisture content was measured at 25, 45, 65, 85, 105, 125, 145, and 165 cm depths below ground level, guided by installed access tubes. The neutron probe was standardized by first taking probe count readings from a drum full of water before each field recording occasion.

The soil profile below 125 cm depth was found to be stony and neutron probe readings below this depth were consequently inaccurate and were therefore excluded from the VSWC analysis.

2.7.2 Neutron probe calibration

Soil moisture calibration of the neutron probe was done gravimetrically (Bell, 1987). Volumetric soil water content (VSWC) was calculated from equation derived by using 100% water counts (in a drum full of water), actual soil counts and known soil volume and weight of cored soil samples. Using the known volume of a ring core, soil cores were removed at the same depths as those of the probe count (from 25 to 165 cm at intervals of 20 cm) and then dried in the oven to determine % H_2O gravimetrically.

To enable neutron probe calibration, extra access tubes were installed close to where the soil moisture probe count in the plots was being recorded. Calibration of the neutron probe was done using eleven access tubes during the dry period (in September 1998). To achieve different soil water levels, the soil profile was wetted using three watering regimes of 0, 600 and 1300 litres. Three of the access tubes received no water representing driest period (2 in the east and 1 in the west of the experiment). Four other tubes received 600 litres (to saturation), 2 installed at the east and 2 in the west of experimental site. The remaining four tubes were installed in the same way as the 600 litres ones and each received 1300 litres (field capacity). The use of several watering regimes provides the opportunity to increase the accuracy of estimating soil moisture counts when using neutron probe counts between dry and completely wetted soils (Bell, 1987).

Circular iron cylinders (50 cm radius) were driven into the soil around the tubes to concentrate soil wetting around tubes. Wetting was done for 2 days and afterwards probe counts were made for all the calibration tubes. Before taking probe counts in the extra calibration tubes, the drum water count was recorded. The neutron probe counts were divided by 100% water count to provide H_2O count ratios at each soil depth.

From a trench of 2 m depth made on one side of the access tubes, soil cores for gravimetric water determination were taken down the profile at the same soil depth intervals as those of the neutron probe counts. That is, at 25, 45, 65, 85, 105, 125, 145 and 165 cm of soil depths. The soil depths presented here are the real soil depths after correcting for the depth (10 cm) from the top of the access tube.

Known soil volume was obtained by using metal cylinders measuring 5 cm diameter and 5 cm length. The cylinders were driven carefully into the soil profile walls to extract undisturbed soil core samples at approximately the same depths as those used in the recording of the probe counts. The extracted wet cored soil samples were tightly sealed by plastic paper and weighed. Their dry weights were obtained by oven drying at 105°C to constant weight. Volumetric soil water content was calculated directly as weight of water per unit volume of soil contained in sample cylinders. The percentage water content in sample rings was converted into volumetric soil water content by multiplying with soil bulk density (1.3g cm^{-3}). Regression of probe count ratios to volumetric soil water content provided the equation for converting probe count into volumetric soil water content (Fig. 2.7.2).

Two separate calibration regression equations for neutron probe for 0-45 cm and greater than 45 cm were used because (i) the neutron probe count sphere during dry periods may exceed the surface soil horizon into the atmosphere and (ii) in some plots hardpan and gravel occurred within less than 100 cm depths, thus having different soil texture between surface and deeper soils. For instance, Bell (1987) cautions that neutron probe sphere of influence in dry soils exceed 30 cm and therefore counts near the soil surface may give inaccurate readings due to loss of some neutrons into the atmosphere. Therefore using one calibration equation for both surface and at depth soil layers might exaggerate the real soil moisture situation at the surface.

Secondly, Bell (1987) recommended that where soils of different texture occur, different calibration equations for each soil texture should be carried out.

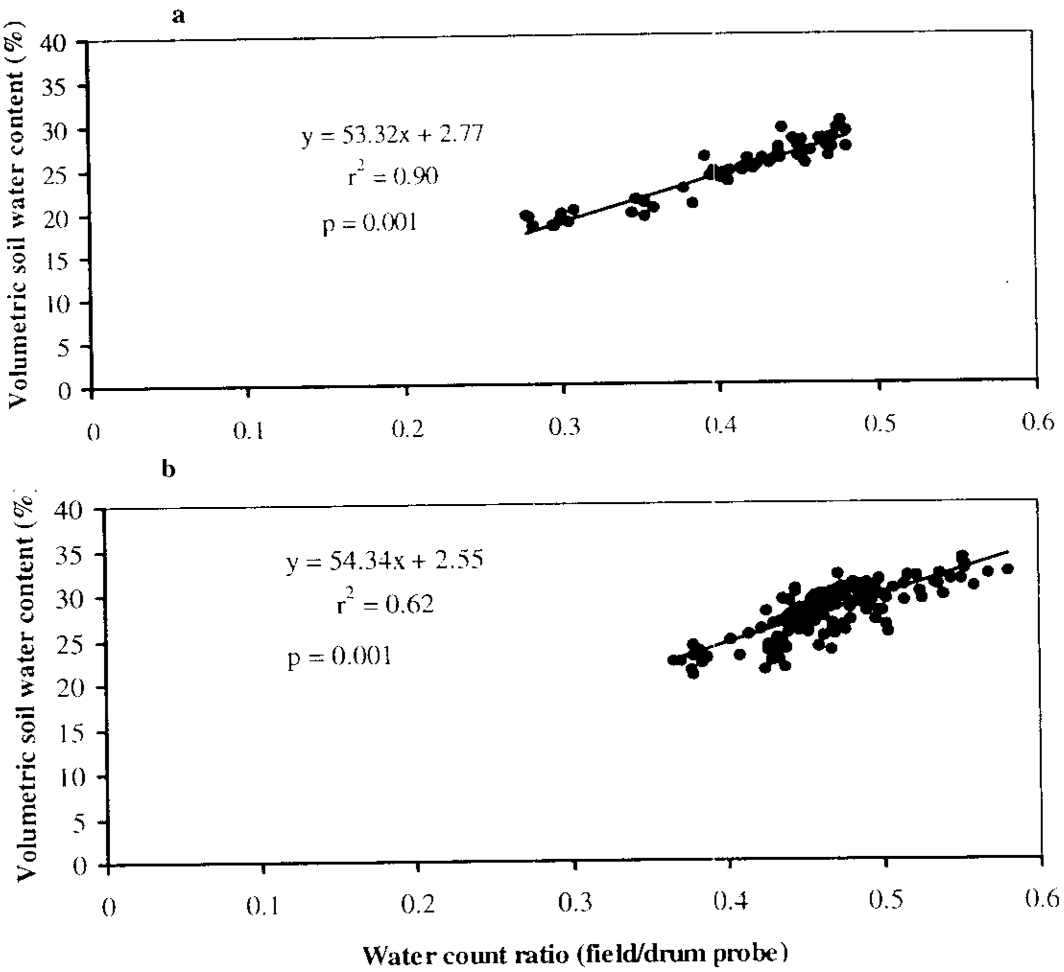


Figure 2.7.2 Regression equations of volumetric soil water content to probe count ratio **a)** 0- 45cm and **b)** 65-125cm soil depths.

2.7.3 Transpiration rate estimation methods

Sap flow is water and solute movement in plant's phloem. Sap movement in the plants is correlated with transpiration rates (Zang *et al.*, 1996; Cohen *et al.*, 1993). The heat balance and heat pulse methods have been described as the best for estimating transpiration in agroforestry systems (Khan and Ong, 1995; Hatton *et al.*, 1990). After evaluating the two methods, Cohen *et al.*, (1993) recommended the use of heat pulse to estimate transpiration of bigger trees in the field rather than the heat balance method because of systematic errors encountered with latter in estimating transpiration of bigger trees. For this reason the heat pulse method was used to estimate transpiration rates of *Melia volkensii* in this study (see Chapter 6). The method and measurements are more detailed in Chapter 6.

2.8 Pot experiment

A pot experiment was set at ICRAF nursery using soils collected from farmer's fields at Kitui, Embu and Machakos. The trial was conducted because maize grown under and outside the *Melia volkensii* tree canopies on farms had shown unexpected maize yield trends. Maize plants growing under the *Melia* trees had bigger growth and greater yields than those growing outside the canopy during maize 1 season when soil moisture was unlimited (El Nino rains). These results were rather unusual because under any competitive conditions (where trees and crops compete for moisture and nutrients) it is expected that better yields would be obtained away from the trees. Since soil moisture was unlimited, nutrients were thought to be the major cause of the growth and grain yield differences. For this reason, soil samples were collected under the trees and in the open to be tested for maize growth performance in the nursery pots experiment.

During soil collection in the farmers' fields, soil scoops each enough to fill a 20 litre pot were dug under and outwith the tree canopies. Six soil scoops, 3 in the open and 3 under the canopy were taken for each tree and put into 20 litre pots and arranged in a randomised block design at ICRAF headquarter nursery. Three maize seeds were sown in each pot and thinned within one week after germination to one plant. The plants were allowed to grow in the nursery for two months during which root collar diameters and heights were measured on a weekly basis. Finally, oven-dry (105°C) weights for maize plants were obtained.

2.9 Rainfall during the study period

Extreme variation in rainfall encountered in this area during the study period restricted some investigations to some seasons. For instance, soil water was not limiting during the maize season at the start of the study (see Chapter 6). The exceptionally high rains (El Nino rains) started late in 1997 and continued into short the rains of 1998 and its (El Nino) effects were carried through till the middle of the study period (second maize season). In addition, there were failed rains during the long rains of 1998 in which no maize cobs were formed. Because of these extreme conditions, some planned investigations were not done at these extreme rainfall seasons. The last season (third maize season) received just enough rainfall to enable comparison of trees and crop yields interactions.

2.10 Data analysis

Different data analysis methods were used depending on the design, experimental level and objective of the comparison. For instance, analysis of variance (ANOVA) was used to compare the effect of tree treatment on crop yields at each experimental level. An experimental unit is defined as a single unit in which a treatment is applied. These were classified as:

1. Main plot; where treatment means of e.g. dbh, CI, root length are compared. It is also applicable where overall treatment effect on crop yields or soil moisture is compared at the plot level.
2. Subplot: where effects of trees on soil moisture or crop yields are compared between treatments at fixed distances from tree rows. This is necessary when evaluating the interactions between trees and distance on soil moisture, crop yields or crop growth.
3. Sub subplot: where soil moisture at different soil depths is compared between treatments at each fixed distance from the trees. This is necessary also when evaluating interactions between tree treatments, distance and depth.

Microsoft Excel and Genstat 5 release 4.1 (Rothamsted Experimental Station) programme for Windows were used in data summaries and analysis.

Because of the need not only to compare treatment difference but also interaction between tree treatments, distance and depths, the structure of data analysis was treated as split plots in the main treatment plots (Mead *et al.*, 1993).

The structure of the ANOVA for split plot analysis was thus given as;

Source of variation	F.pr.
Block	-
Treatment	-
Distance	-
Distance x treatment	-
Depth x treatment	-
Depth x distance x treatment	-

where F.pr is probability value from ANOVA comparing treatments..

Where similar repeated measurements are involved (e.g. crop yields, soil moisture, light, etc.), residuals from the neighbouring sample units are likely to be more closely correlated at any measuring occasion than those measured at different times or those measured at the same time but further away. In such cases assumptions made for ANOVA (that sample units are random, error terms are normally distributed, homogeneity of variance and additivity effects occur in linear model) are violated and become invalid in estimating existing error. Other data analysis methods such as split-plot analysis, regression analysis and least significant difference of means (lsd) were adopted, as appropriate (Mead *et al.*, 1993).

In most cases repeated measurements were treated as split plots at each measuring occasion since they were repeated in intervals in space and time (Mead *et al.*, 1993). Although there are many ways of analysing repeated measurements such as multivariate analysis which is rather complex, split-plot analysis was recommended for similar studies (Mead *et al.*, 1993).

Furthermore, where effects of tree on crops or soil moisture were compared at specific times and space, summaries of data for each variable were made and tested by regression analysis (e.g. CI against crop yields).

Where individual tree planting (on-farm) or groups of trees e.g. stem and root cuttings, standard error or standard deviation of the means was used to test variations between individual values or means of tree-groups.

Prior to establishment of trial 1, a cover crop of beans was planted in 1993 on the same site in which yields were measured at varying positions across the slope to test whether crop yields difference occurred along the slope (Fig. 2.10.1). The results indicated that there was a systematic yield increase down the slope. Consequently, when laying out the experimental plots (see Fig. 2.2.1), randomization of blocks allowed for the gradient orientation.

Apart from cover crop yields, a further site variability test was carried out using soil moisture distribution along the slope after trial establishment. Soil moisture was measured using neutron probe in both the control plots and in the tree plots (at 6 m from trees) from the upper to lower side of the slope. The regression analysis between soil moisture content and distance (various positions) on the slope (Fig. 2.10.2) indicated that there was no significant moisture variation down the slope, implying that slope had no significant effect on soil moisture during rainy season.

To minimise crop yield difference due to tree shading, average yields of maize on both sides of tree rows was done. Furthermore, the trees in the experiment were planted in east west axis, so that shading on each side of the tree rows was symmetrical.

Specifically, to compare the effect of tree treatment on crop yields or soil moisture at plot level, ANOVA analysis was appropriate for these comparisons between treatments. To compare relationships between tree competition parameters (CI, root length and size) and crop yields or soil moisture, regression analysis was appropriate (Mead *et al.*, 1993) where independent variable (CI, root length) was correlated with dependent variable (crop yields or soil moisture).

At sub plot experimental level (e.g. at specific distance from the tree rows), effect of the interactions between trees and distance on crop yields or soil moisture was tested by ANOVA at each distance. However, regression analysis between yields or moisture summaries with distance was also done. To separate effects arising from the presence of trees as opposed to those resulting from differences between tree treatments, a factor, named "control", was included to distinguish plots containing trees from those lacking trees. Furthermore, since the control plots lacked corresponding distances from trees, treatment comparison with control to determine trees effects was carried out only when contrasting tree treatments with control at each sample distance using ANOVA.

At sub subplot level (soil depth at specific distance), soil moisture at each depth was regressed with depth. Regression analysis was also used to test the relationship between tree competition parameters (CI, root length) and soil moisture for all depths.

Rhinoceros NURBS Modelling Software (IDE, Product Design and Development, Kestrel, USA) for computer designs was used in drawing tree root architecture. Also, based on computer logical programming (e.g. root system length at less or equal or greater than certain depth), total root lengths or percentage proportions within a specified rooting depth were determined.

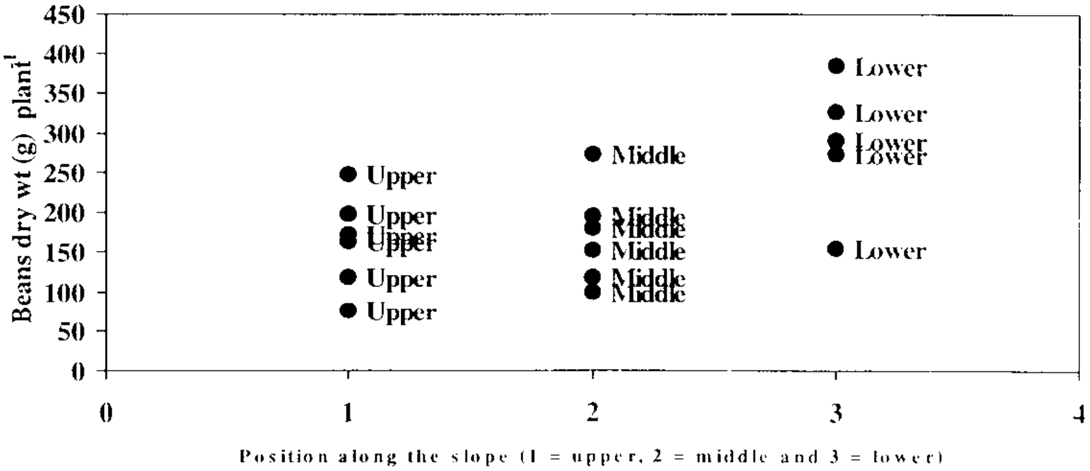


Figure 2.10.1 Bean yields (g plant^{-1}) of cover crop of long rains 1993; indicating that bean yields increased systematically along the gradient of the slope. n = 18.

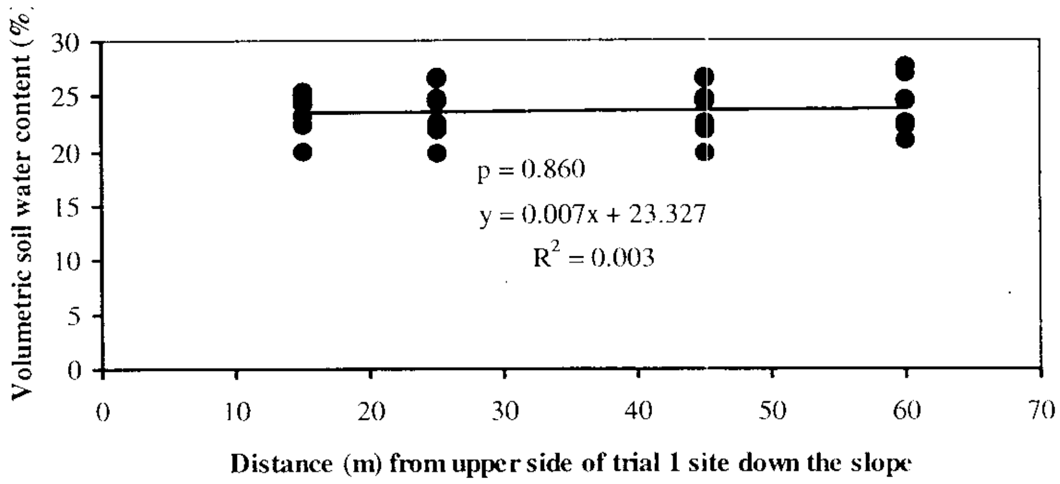


Figure 2.10.2 Volumetric soil water content (45 to 105 cm depth) at varying distance that began from the upper slope part of the *Melia* provenance trial site down the slope; measured both in the control plots and at tree plots (6 m distance from the trees) in which there was no significant ($p = 0.860$) moisture difference down the slope. $n = 16$.

CHAPTER THREE

3. *MELIA VOLKENSII* ESTABLISHMENT, ADOPTION AND EXTENSION CONSTRAINTS IN FARMERS' FIELDS AT KITUI AND MBEERE DISTRICTS OF SEMI-ARID KENYA

3.0 Introduction

Timber for construction and furniture is now in major demand by farmers in the semi-arid tropics. Forest products provide opportunities for earning cash and diversifying local farmers' income and are consequently used by them as part of their strategy to minimize risks associated with dryland crop farming (Ayuk *et al.*, 1999). The demand for timber products will increase as population growth in these areas increases (FAO, 1989). Consequently, natural timber stocks will be over exploited to meet the constantly increasing wood demand (Mattila, 1987). The rate of depletion of these useful tree species exceeds the rate of replenishment within natural forests and plantations (Kenya Forestry Master Plan, 1994). The problem is made even worse by the demand for more food cropping area at the expense of woodlands to meet the needs of the ever-increasing population. Alternatively, the solution is to plant trees and crops together (Kenya Forestry Master Plan, 1994).

3.1 *Melia volkensii* in agriculture

Melia volkensii is one of the important timber and fuelwood tree species in drylands of Kenya (Stewart and Blomley, 1994). It occurs naturally within lowland areas of eastern Kenya (Kidundo, 1997). Because of its usefulness as a source of durable timber and other products, it has been depleted in the communal lands and is now found only along the farm boundaries and scattered as single trees within fenced parklands and cultivated lands in many areas. The usefulness and value of *Melia volkensii* products, combined with its short rotation period, make it the most suitable cash tree crop for dryland agroforestry (Forest Department Report, 1999).

3.2 Problems faced in *Melia volkensii* planting

1. *Melia volkensii* is constrained by seedling propagation. Seed germination is reported to be very difficult (Milimo, 1989). The post germination survival in the nursery is also very low (Forestry Department Report, 1999). Furthermore, seed germination potential depends on the seed source (Kidundo, 1997). To overcome problems of seed germination, farmers have resorted to using other types of propagation such as natural regeneration, wildling transplanting and sometimes root or stem cuttings.

2. Farmers in some of the sites lack skill to manage trees to produce high quality timber. Instead they maintain shorter stem boles at their hands reach while standing on the ground thus leaving the bigger proportion of the stem unpruned (see Plate 1).

Plate 1: *Melia volkensii* on Mbeere farm. Note that trees have not been properly pruned.

3. The methods used by farmers in timber conversion are very crude resulting in huge timber wastage. They use axes and chisels to produce timber from logs for doors and window frames instead of using better tools (Mohammed pers. communication).

With the above background, a socio-economic survey was carried out in Kitui and Mbeere (formerly Lower Embu) districts in eastern Kenya in order to establish the extent of *Melia volkensii* planting on farms, its regeneration, management, utilization and constraints. Information gathering included management practices, planting techniques, type of planting material, tending regimes and crop interactions from the farmer's point of view.

3.3. Objectives

The overall aim was to evaluate the potential of *Melia volkensii* to provide extra income to farmers within cropland while documenting the factors that might hinder its establishment and adoption on farms.

The specific objectives:

- to find out the type of *Melia volkensii* planting materials used by farmers in farms;
- to identify the management practices applied to *Melia volkensii* within farms;
- to obtain information on farmers' perceptions of the use of *Melia volkensii* on farms and its interactions with crops;
- to identify the factors that hinder *Melia volkensii* establishment on farms;
- to gather information on pricing and marketing of *Melia volkensii*.

3. 4 Materials and Methods

3.4.1 Survey sites descriptions

The study sites were subjectively selected from the areas where *Melia volkensii* trees are extensively planted on farms. Furthermore, in order to validate results of field trials presented elsewhere in this overall study the selected sites also covered areas where *M. volkensii* seed sources for afforestation projects in Kenya are normally collected and areas where tree-crop interaction studies in farmer's fields were also conducted.

Using these criteria, the Kitui and Mbeere districts were found to be the best sites for the study objectives.

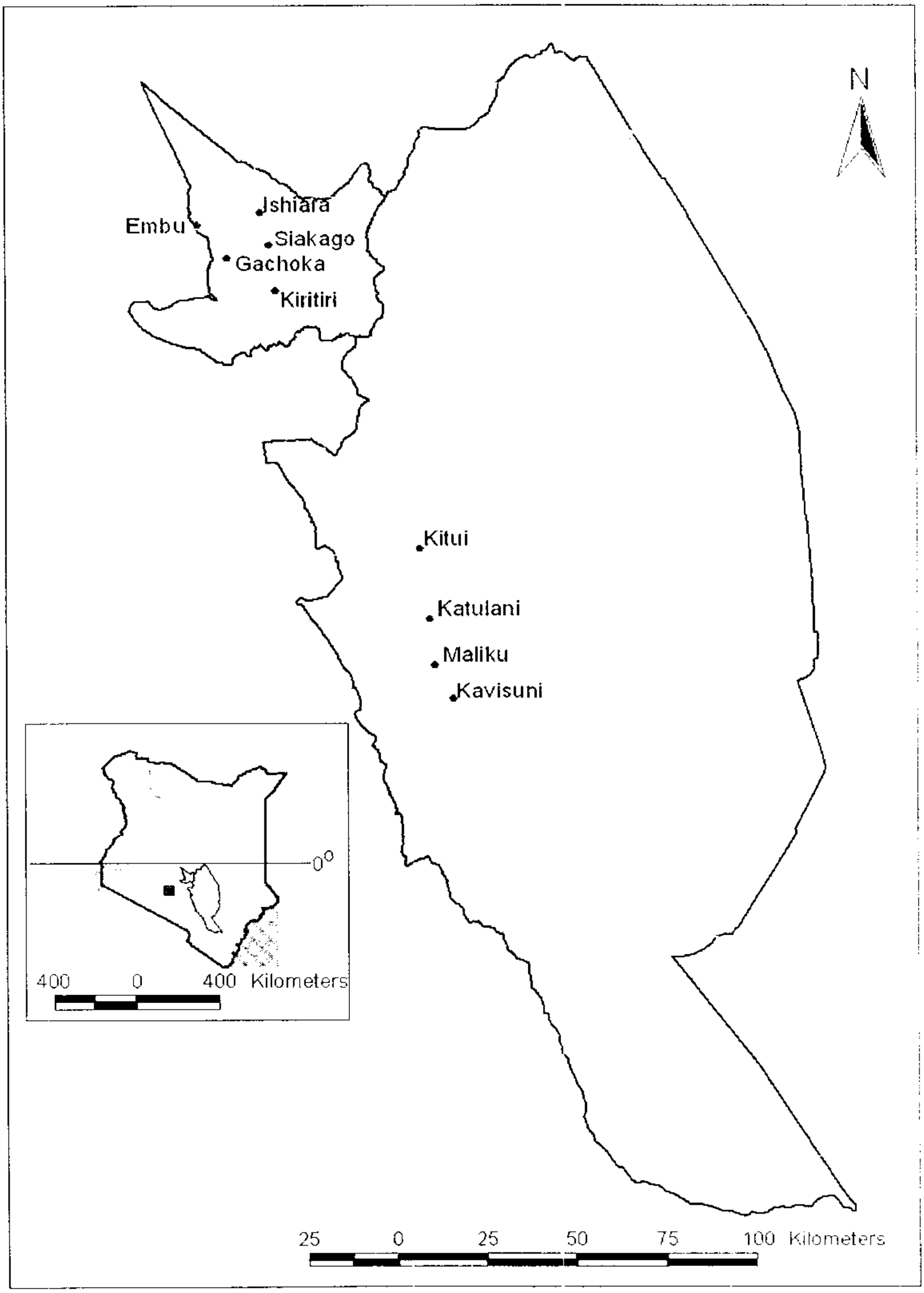


Figure 3.4.1 Sites of socio-economic survey of *Melia volkensii* establishment, adoption and challenges in semi-arid areas of Kitui and Mbeere/ Embu districts of eastern Kenya.

3.4.2 Kitui site

The survey was carried out in the Central division (Mulango) of Kitui district, covering Katulani, Maliku and Kavisuni locations. The roads to these areas are accessible all the year round. According to Jaetzold and Schmidt (1983) these areas lie at an elevation of 1000-1040 m above sea level and a latitude of 1°29' S and longitude 37°50'E. The mean annual temperature ranges between 26-30°C. Rainfall is bimodal and the yearly average is 700mm. The short-rains that occur during October to December are more reliable than the long-rains of March-May. The probability of a rainfall deficit within one season is 60% (Jaetzold and Schmidt, 1983). For more details on location of survey sites see Figure 3.4.1.

The topography of Lower Mulango (Katulani, Maliku and Kavisuni) comprises plains, riverines, hills and plateaux. According to the FAO/UNESCO (1977) soil classification, the soils are of gneiss origin and generally composed of luvisols and acrisols. In some areas black cotton soils are found. The soils are clay loam and sandy loam, friable to loose texture and fairly deep to shallow.

The major vegetation type is savanna bushland dominated by *Acacia*, *Combretum* and *Commiphora* thickets. Dense vegetation is found along the rivers and hills. Useful tree species growing in these areas include; *Melia volkensii*, *Terminalia brownii*, *Dalbergia melanoxylon*, *Tamarindus indica* and *Lennea buchananii*. Exotic species planted include *Senna siamea*, *Senna spectabilis*, *Azadirachta indica*. *Grevillea robusta* and *Eucalyptus camaldulensis*.

The indigenous people are Kamba. They speak Kikamba and Swahili. Those who received primary education also speak English. The population density exceeds 80 people per square kilometre (Kaudia, 1996) and the population growth rate approximates 3% annually. Kamba people used to be predominantly pastoral but with time changed to subsistence agriculturists. They keep cattle, goats, sheep and donkeys for economic benefits. People also keep bees for honey and sometimes go hunting. Since land demarcation and acquiring rights to land ownership, agricultural activities have dominated (GOK, 1989: 4-9). Because of unreliable rainfall, crop failures are common and usually livestock sale and external incomes provide for food needs. The main crops grown are maize, beans, cowpeas and pigeon peas for food and sale in case of surplus. Other drought resistant crops grown are cassava, millet, green grams and sorghum. Cotton is grown as a cash crop but its production has declined tremendously since the late 1980s because of poor prices. In densely populated areas, farmers till one piece of land for 6 years before allowing it to revert to fallow for 4-5 years.

3.4.3 Mbeere (Lower Embu) site

The survey was carried out at Gachoka and Siakago divisions. The farms in these divisions were selected according to accessibility and presence of many *Melia* trees.

The average annual rainfall within the study area varies between Kanyambora (1260 mm), Kiritiri (850 mm) and Machanga (830 mm) (Jaetzold and Schmidt, 1983). Temperature ranges between 20-23°C and rainfall is bimodal as at the Kitui site.

The topography consists of dissected plains and hills with low to medium soil fertility. Soils within Gachoka are generally of low fertility. They are developed from undifferentiated basement system rocks. The soils are well drained, shallow, dark red to yellow red, stony loamy sand to clay (Jaetzold and Schmidt, 1983). The soils of Kanyambora are well drained, deep to very deep, reddish to yellow brown, varying in consistency and texture (ferralic luvisols).

The natural vegetation consists of exploited indigenous trees of *Combretum, Newtonia, Croton, Melia* and *Ficus* species in the uplands and a Acacia-Commiphora zone interspersed with other trees in the low plains. *Melia volkensii* is found in both zones. Introduced trees like *Eucalyptus*, *Grevillea* and *Senna* dominate the landscape. Timber species consist of *Melia* (indigenous), *Grevillea robusta* and *Cupressus lusitanica* (exotic). Fodder tree species are usually few and sometimes lacking leaves during dry periods.

The local people are known as Mbeere. They speak Mbeere, Swahili and limited English. The population at Kanyambora area is approximately 120 people per km^2 and at Gachoka division, 100 people per km^2 with an average household size of 5 persons. Household labour needs are limited, but hired labour is available (Jaetzold and Schmidt, 1983).

Crop farming and livestock keeping are the major land use activities. Crops include maize, beans, cassava, sorghum, millet and cowpeas. Cotton is grown in drier areas (Machanga and Kiritiri) and tobacco in wetter parts (Kanyambora) as cash crops. Fertilizers are occasionally used, especially phosphates (Kidundo, 1997). Livestock serve as a complement to arable farming activity. Farmers keep cattle, sheep and goats and they sell them in case of emergency.

3.4.4 Sampling methods

Farm systems research (FSR) and rapid rural appraisal (RRA) approaches were combined in this study. These methods provide information about farming systems and challenges through interviews, seasonal calendars and transect walks (Scoones and Thompson, 1994).

The information gathering process was done on farmers' lands by the researcher and a research assistant. Information on *Melia volkensii* was gathered using structured questionnaires. The questionnaire form was structured by the researcher to give short answers like YES or NO and possibly a comment on their experiences and practices. Where farmers' personal welfare was required, open questions were structured to allow farmers to divulge answers to sensitive issues through dialoguing. The researchers' experience and knowledge on *Melia volkensii* within the same semi- arid conditions greatly helped in authenticating some of the farmer's local knowledge.

The questionnaire was divided into six sections namely household and farmers' general conditions, tree establishment, tree management, tree-crop interaction, harvesting and marketing and constraints. Because of spending more than one hour or even two hours on interviewing one person, the sample size was reduced to fewer representative households than originally planned. The sample size depended on whether varying information was adduced from the farmers. The more the variable the answers given to the same question the bigger the sample size used. Gender composition was considered while carrying out the survey.

In Kitui, 20 sample farms were selected along the Kitui to Kavisuni road on either side of the road. All the selected households had at least some *Melia* trees in the farms for crop yields interaction assessment. The sampling covered over 50 km between Wikililye to Kavisuni markets. Heads of households or their assistants were interviewed.

In Mbeere, 12 farms were covered, 7 along Embu- Kitui (Siakago division) and 5 along Embu- Ishiara (Gachoka division) roads. The Ishiara (Kanyambora) site was chosen because it represented the highest rainfall of all the *Melia* sites. The farmers interviewed were selected randomly on either side of the road, from among those who had trees on their farms.

An initial questionnaire was tested on four farmers at Kitui. It was then restructured to make it easier to use (Appendix1).

The researcher estimated the number of trees and land size for each household. Also, the researcher estimated household timber demand by observing signs of new houses under construction, recently constructed houses and asking farmers their future construction plans. In addition, amount of house furniture made from *Melia* timber provided an idea on the domestic *Melia* timber demand at household level.

Pricing was done on whole standing tree by (researcher) asking farmers their tree worth in comparison to other trees like mango trees and secondly by asking timber dealers how much they paid for trees on the farms. Prices given by both farmers and timber dealers varied because either both parties wanted to impress the researcher or would give lower prices to hide the huge profits they reap. The researcher averaged some of the given prices and using his judgement could tell farmers' honesty and in such circumstances recorded the said prices.

The value of sawn timber was estimated by dividing the stem cross sectional area at dbh by the area unit piece of a door frame to get the number of pieces from a log. The door frame unit cross section area of 10 x 5 cm and 2 m length. The log area was reduced by 40% to allow for wood wastage during timber sawing. The total sawn timber value (Tp) was calculated using the below equation;

$$Tp = 2.3/5(Aw/Df).Pdf$$

where Aw is cross sectional area of wood (dbh), Df is cross sectional area of a door frame piece and Pdf is price of a unit piece of a door frame. While 2 and 3/5 are number of the door frame pieces obtained from an average log length of 5 m and 60% timber recovery rate constants respectively.

Where farmers could not clearly estimate the dates of tree planting or crop or wood production or gave extremely varied values from those of neighbours, seasonal calendars and settlement periods were invoked to prompt the farmer to rethink his answers. Occasionally, with tree age estimations, farmers answers were modified using researchers' experience and information gained from other farmers.

Other independent additional information from people with knowledge about the area and *M. volkensii* growth and utilization are acknowledged as personal communications. Such information was used to counteract bias in survey and data reporting discrepancies.

3.5 Analysis

Variables from the data were quantified and information from the questionnaire was coded and analysed by SPSS computer programme (Erlbaum (UK) Tylar and Francis). Descriptive statistics, frequency percentages and T-test comparison of means, cross tabulation and data correlation were computed using the same programme.

3.6 Results

3.6.1 Household characteristics

About 90% and 83% of interviewed households in Kitui and Mbeere districts respectively were headed by men (Table 3.6.1). Nearly all farmers owned their land. The Kitui households on average owned more than 8 hectares of land while Mbeere households owned smaller pieces of land (4 ha). Results further indicate that the Kitui farmers who have more land than the Mbeere farmers, have a greater proportion of their land under fallow.

Over 50% of households in both districts depended on farming as the only source of income and less than 30% had formal employment or small business to supplement farm income and livestock sale (Table 3.6.1). Farmers practiced fallow farming in some parts of their farms. In every household, *Melia volkensii* trees were planted within cropland and some in parklands. While the average number of *Melia* trees on Kitui farms was 15, and 13 on Mbeere farms, extreme cases occurred of farmers having 2 trees while others had more than 60 trees. On average, trees took less than 10 years to harvest for timber in both districts (Table 3.6.1). Over 60 % of households spend some of their income in purchasing timber and poles for construction. Apart from timber, farmers also bought food during drought.

There was great price disparity per standing tree between the Kitui farms and Mbeere farms. Trees at Mbeere were worth three times more than at Kitui. However, pricing of individual standing *Melia volkensii* trees depended on tree size and quality and the demand and willingness of farmers to sell their trees. Better management resulted in higher *Melia* prices per tree at Mbeere than Kitui farms. Not unexpectedly, even, straight and longer boles fetched more money than shorter and uneven tree boles of similar age. Because of the poor tree management practice of not pruning trees properly (see plate 1), farmers receive less than 60% of the tree worth had they applied better management (Mohammed pers. communication).

The value of a tree to both farmers and timber merchants increased with tree age (Fig. 3.6.1). The value of sawn timber was greater than that of standing trees.

Table 3.6.1: Characteristics of households in Kitui and Mbeere districts, semi-arid Kenya.

Variables	Kitui	Mbeere
Total number of households	20	12
% Male headed households	90	83.3
% Female headed households	10	16.7
Average land holding (hectares)	13 (8.5)	4.7 (1.8)
Average cultivated land (hectares)	8.2 (6.1)	3.4 (0.97)
Average land under fallow (hectares)	4.8 (3.02)	1.3 (0.61)
% household owning land	95	100
% household not owning land	5	0
Average number of *Melia* trees on farm	14.9 (15.7)	13.3 (7.8)
Average standing *Melia* tree price (ksh.)	840.5 (346.1)	2700.6 (826.6)
Average rotation age of *Melia* tree	8.8 (2.4)	9.1 (2.2)
% households depending on farming only income	55	50
% households depending on farming and business income	35	25
% households depending on both farming and salary	10	25
% households spending income on timber and poles	60	75
% households spending income on timber + poles and food	40	16.7

Values in brackets are Standard deviation of means

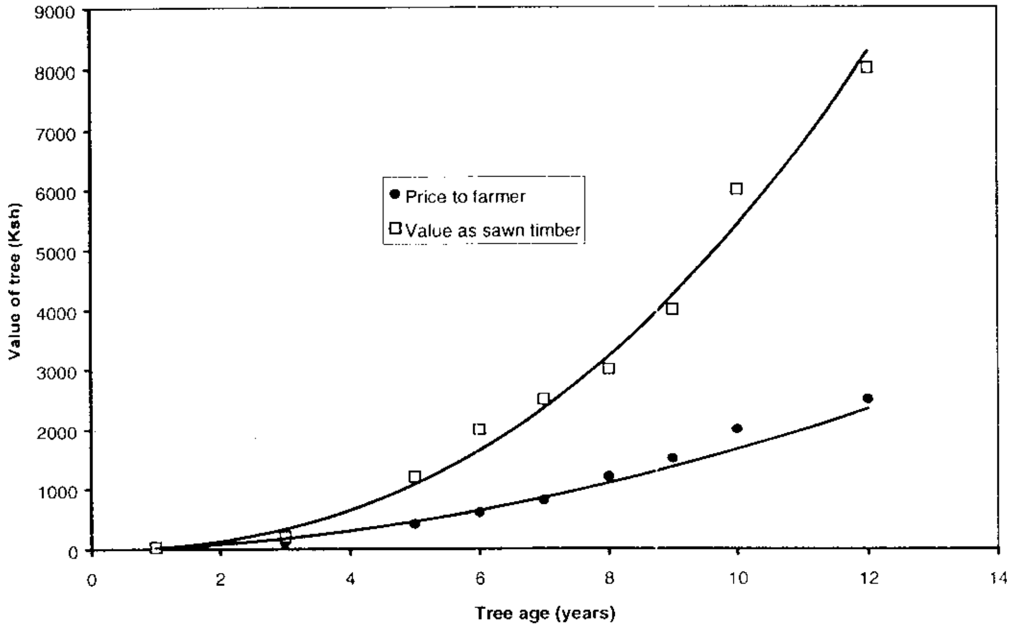


Figure 3.6.1 Relationship between tree age and value of a standing tree as sold by farmers, as well as value of sawn timber per tree as sold by merchants (shops) at Kitui and Mbeere districts of Kenya.

3.6.2 *Melia volkensii* establishment, tending and management effects

The majority of *M. volkensii* trees in the farmer's fields were established through natural regeneration and sapling transplants. *Melia* saplings under trees from either other farms or parklands were uprooted and transplanted in the farmers' fields. This mode of establishment was practiced more in Mbeere than in Kitui district (Table 3.6.2) where farmers relied more on natural regeneration. Combined natural regeneration and sapling transplant contributed to more than 90% of the plant types on farms. Few of the households used nursery seedlings (5%) or root cuttings (8.3%).

3.6.2.1 Management practices

Over 95% of households pruned their trees in both districts (Table 3.6.2). Thinning of clustered trees and on coppiced stems was done. Where trees naturally regenerated closely, weaker or crooked ones were removed. Both thinning and coppicing methods of *Melia* management were practiced by about 70% of the Kitui households and all households at Mbeere district (Table 3.6.2). Tree pollarding, where tree shoots are completely chopped off from the top in hope that the diameter would enlarge was practised by few farmers. About 15% and 25% of households applied all the management practises to their trees at Kitui and Mbeere districts respectively. Only one household at Kitui never managed its trees. There were more management practices on smaller farms than on bigger ones (Table 3.6.2).

3.6.2.2 Tree planting patterns on farms

The majority of farmers, 80% of households at Kitui and 58% at Mbeere districts, grew isolated trees on farms (Table 3.6.2). Farm boundaries or contour line tree planting were found in few households. Less than 10% of households had combined tree planting patterns in their farms.

3.6.2.3 Gender involvement in tree planting

Table 3.6.2 shows by percentage the gender involvement in tree planting and management activities. More than 85% of tree planting was done by both sexes. However, most of the mature tree pruning and felling work was done by men while women pruned or thinned young trees, particularly where tree climbing was not involved.

Table 3.6.2: Methods and plant types used in establishment of *Melia volkensii* trees on farms at Kitui and Mbeere districts. Frequency of variables at sampled farms.

	Site	
Variable	**Kitui**	**Mbeere**
Plant type		
% households using nursery raised seedlings*	5	0
% households using root cuttings	0	8.3
% households using natural regeneration	70	50
% households using sapling transplanting	25	41.7
Management practices		
% households pruning trees	95	100
% households thinning trees	70	100
% households coppicing trees	70	100
% households pollarding trees	5	16.7
% households doing all management practices to their trees	15	25
% households doing none of the practices to their trees	5	0
Planting pattern		
% households planting as woodlots with close spacing	10	8.3
% households planting in boundaries	5	16.7
% households planting in contours or lines	5	8.3
% households planting as isolated trees in farms	70	58.3
% households planting in any combination of above patterns	10	8.3
Gender involvement		
% households male planting trees only	10	0
% households female planting trees only	10	0
% households both male and female planting trees	70	91.7
% households with trees planted by none**	10	8.3
% households with male alone pruning and felling trees	85	82.4
% households with female alone pruning and felling trees	5	8.3
% households with both sexes pruning, felling and thinning of trees	10	8.3

* Seedlings were not available.

** They found trees growing on the farm.

3.6.3 Economic benefits of *Melia volkensii*

Because the households were selected on the basis of timber production, it was not surprising that all households in both districts used *Melia volkensii* as timber and pole species (Table 3.6.3). 75% also of the households used *Melia* as firewood, and *Melia volkensii* provides fodder to 25% of households at Kitui and 33% of households at Mbeere districts during dry periods. Apart from timber, poles, firewood and fodder, other uses like beehives, honey and pesticides were mentioned.

About 25% and 33% of households at Kitui and Mbeere districts respectively, use *Melia* products for household consumption (Table 3.6.3) and 70% of households at Kitui and 50% households at Mbeere sell tree products to the local markets. External markets receive *Melia* timber from 5% of the households at Kitui and from17% of Mbeere households. Over 75% of households in both districts rated *Melia* as a better timber than the exotics. Also, a majority of households preferred *Melia* timber to exotics in the local markets (Table 3.6.3). Price of standing trees on farmer's fields varied between individual trees and between sites (Table 3.6.1). Trees were worth more at Mbeere than at Kitui district.

In general, farmers earned more money annually from the sale of crops (maize and beans) than from the sale of trees but during drought, trees provide bigger income. In addition, fruits such as mango, orange and banana are sold in the local and external markets.

A simple cost-benefit analysis of *Melia*-crop intercropping where annuity value was used to calculate net present value (NPV) was adopted (Scherr *et al.*, 1992). Annuity value was used because it gave annual income of each component without using discounting rate (Scherr *et al.*, 1992) for the information for carrying out discount rate was not collected. Apart from establishment and pruning, trees enjoyed weeding and ploughing offered to crops. *Melia* timber rotation of 8 years and clear bole height of 6 m above ground with standing tree value of ksh.1500 in the final year, firewood value of ksh.100 per year and maize yield loss per year (4 %) due to *Melia* impact in 1 hectare and maize price of ksh.18 per kilogramme were used. Crop success over the rotation period was 60% (adapted from Kaudia, 1996), tree competition and pruning cost of ksh.20 per tree per season started after year 3. Results indicated 4 trees per hectare offset crop yield loss and were profitable when maintained on farmers' fields. Other tree benefits like fodder, pesticide, improved soil fertility, seed sales and bee hives were not included in the calculations.

Table 3.6.3: Economic importance of *Melia volkensii* in semi-arid Kenya.

Variable	**Site**	
	Kitui	**Mbeere**
Uses		
% households using *Melia* timber and poles	100	100
% households using *Melia* for firewood	75	75
% households using *Melia* as fodder	25	33.4
% households using *Melia* for other needs*	15	8.3
Marketing products		
% households using *Melia* products for self consumption	25	33.4
% households selling *Melia* in local markets	70	50
% households selling *Melia* outside their markets	5	16.7
% households rating *Melia* as best timber locally	75	81.9
% households earning more from sale of tree products than from sale of crops	30	42
% households preferring *Melia* timber to exotics	85	66.7
Other farm income		
% households selling maize alone	5	0
% households selling beans alone	15	16.7
% households selling maize and beans	20	25
% households selling mixed crops and fruits	60	58.3

* Other needs include; beehives, pesticides, pods

3.6.4 Tree-crop interaction effects

3.6.4.1 Tree-crop competition

Table 3.6.4 shows the responses of households to questions about competitivity of planted *Melia* trees in crop fields. 25% and 33% of households in Kitui and Mbeere districts respectively reported that *Melia volkensii* competed with crops. Conversely, 40% and 33% of households at Kitui and Mbeere respectively did not experience competition between trees and crops. However, about 30% of the households said that tree shading caused competition but once pruned no such competition occurred. At Kitui, 5% of households said that trees improved crop yields.

Plate 2: *Melia volkensii* growing on farmer's field indicating suppression of maize yields close to the tree.

3.6.4.2 Constraints

The major problem experienced in *Melia* growing is browsing of young trees. Also, domestic animals were reported to debark stems of mature trees. 80% and 58% of households at Kitui and Mbeere districts respectively reported browsing as the main problem in *Melia* tree farming. About 40% of Mbeere households said *Melia* growing had no constraints. Few farmers reported regenerated *Melia* saplings becoming a weed on farms where many mature trees have been kept.

Table 3.6.4: Effects of *Melia volkensii* trees on crop yields in farmers' fields and constraints faced at Kitui and Mbeere, semi-arid districts of Kenya.

Variable	Kitui	Mbeere
Effect on crops		
% households saying *Melia* competes with crops	25	33.3
% households saying *Melia* doesn't compete with crops	40	33.3
% households saying if *Melia* is pruned, no competition	30	33.3
% households saying *Melia* improves crop yields	5	0
Constraints		
% households saying *Melia* needs protection from browse	80	58.3
% households saying *Melia* has no problems	10	41.7
% households saying *Melia* can become a weed	5	0
% households saying *Melia* needs watering	5	0

3.6.5 Comparison of prices between products made from *Melia volkensii* and other species in local markets

Melia volkensii timber products had higher prices than those of the exotic species in the local markets (Table 3.6.5) and were often at least twice as expensive as the exotics. Exotic timber species sold in the markets include *Pinus patula* and *Cupressus lusitanica*.

Table 3.6.5: Merchants quoted timber prices in the markets at Kitui in 1998.
Exchange rate 1US dollar = Ksh 74

Item (One unit)	**Species**	**Prices (Ksh)** **At markets**	**Prices (Ksh)** **Town**
Door Frames	*Melia volkensii*	350	850
	Cupressus lusitanica	140	500
	Pinus patula	120	350
Beds	*Melia volkensii*	2400	5000
	Cupressus lusitanica	1800	3500
	Pinus patula	1600	2500
Coffee table	*Melia volkensii*	950	2000
	Cupressus lusitanica	650	1200
	Pinus patula	550	1000
Timber (4"x2")	*Melia volkensii*	25	
per foot	*Cupressus lusitanica*	14	
	Pinus patula	12	

3.6.6 Crosschecking on whether different plant types affect crop yields differently

The survey results did not establish clearly the effect of different plant types on crop yields (Table 3.6.6). However, transplanted saplings appeared relatively more competitive than natural regeneration. At Kitui, 70% households had naturally regenerated trees, but only 40% of them experienced competition between *Melia* trees and crops (Table 3.6.6) whereas the 25% of Kitui households who used transplanted saplings, 75% of them reported competition between *Melia* trees and crops. The only household that had planted root cuttings experienced competition between trees and crops. One household that had used seedlings experienced no competition between trees and crops. He attributed lack of competition to the pruning he did to his trees.

Table 3.6.6: Cross tabulation of plant types and competition status.

Site	Plant type	% of households (a) using the plant type	% of these households (a) saying *Melia* is competitive
Kitui	Natural regeneration	70	40
	Transplanted saplings	25	75
	Root cuttings		
	Seedlings	5	*
Mbeere	Natural regeneration	50	50
	Transplanted saplings	41.7	75
	Root cuttings	8.3	100
	Seedlings		

* no competition if pruned

3.6.7 Farmers opinion on tree effect on crop yields

Crop yields assessment was not carried out in the farmer's fields during the survey, but was done at other times and the results of tree effects are presented in Chapter 7 on the section dealing with tree effect on crop yields in farmer's fields. In this study, only the farmer's opinion on tree effect on crop yields was sought and results are presented in 3.6.4.1.

3.7 Discussion

From an extension point of view, the expansion of *Melia volkensii* on farmer's fields is feasible and the results from various facets of the study support this. For instance, factors associated with lack of tree planting in farmers fields such as security of land tenure and tree ownership have been overcome for the majority of households interviewed. More than 95 % of farmers interviewed owned their land and consequently, farmers had rights to their trees. Previous studies indicated that farmers at Bura irrigation scheme failed to plant trees because of lack of security of land tenure (Mattila, 1987). In contrast, Kaudia (1996) reported that farmers do not plant trees just because of land tenure issues and lack of seedlings per se, but other issues such as direct tree benefits are also involved.

In this study, the majority of farmers had sufficient land to allow tree planting. Some other farmers could afford to leave part of their land as fallow for 5 years and therefore such fallow lands could be utilised to raise more trees.

Factors that encourage farmers to plant trees include good returns in a relatively short time, strong demand for the product, high value timber and the ability to produce a range of products continuously. Survey results indicated durable high value timber could be produced within 10 years (at Kitui) and products like fuelwood (75% of farmers), fodder (30% of farmers) and poles (90% of farmers) can be produced at each pruning or lopping or thinning occasion. Previous studies have indicated that *Melia* can produce poles in less than 3 years, timber logs in less than 5 years on coppiced stems, and once planted in farms, grows faster than in the wild (Tedd, 1997; Stewart and Blomley, 1994).

Since shading of crops by *Melia* trees is greater when trees have full canopy, farmers believe that management practices like shoot pruning, lopping and thinning should reduce not only the leaf area, but also competition for other resources between trees and crops. Dense shading has been reported to reduce crop yields (Rao *et al.*, 1998) and reducing tree canopy size by pruning have shown increased crop yields. Rao *et al.*, (1998) reported that heavy tree shading reduced millet yields by 85% at parkland farming in Burkina Faso.

Trees are usually heavily pruned and even pollarded to reduce shading as well as to improve timber quality and a third of households believed that competition between trees and crops was caused solely by shading. Thus, 33% of households believe that *Melia* trees do not compete with crops after the trees have been pruned. However, a similar percentage of households who had pruned their trees, reported competition between trees and crops thus highlighting the fact that below ground competition also contributes to crop yield reduction. In general, farmers were ignorant about below ground competition, only 5% of households were aware of its significance. The competition for resources below ground between trees and crops is covered in Chapters 4 and 5 of this study.

The value of *Melia* products has probably encouraged farmers to ignore its competitive effect on crops. Consequently, some farmers have increased tree planting density in their cropland and seem willing to sacrifice some of their crop yields in exchange for anticipated benefits from the trees. That some farmers appreciate that some crop yield is sacrificed when trees occupy crop land, was further demonstrated by unwillingness of some farmers to sell their trees until they are satisfied that the value of trees would compensate for the crop yields forgone. Farmers were aware that crop failures are common and that during dry periods, *Melia* trees can provide useful products for either home consumption or sale such as fodder or fuelwood. Thus, keeping trees on farms spreads farmers' income failure risks. Instead of selling food crops to earn income for other purposes such as school fees, marriages etc, farmers could be encouraged to plant more trees on their fallow land for this purpose. Some farmers have already done this and one farmer has planted more than 60 trees on his fallow and cropland to provide for home timber/fuelwood needs as well as surplus material for sale. While appreciating tree planting in the fallow land will require more labour than already shared in the cropland, more commitment with extra help of hired labour can make this high rewarding *Melia* planting in the fallow lands a success as already demonstrated by the farmer who planted over 60 trees.

There are environmental benefits deriving from the presence of trees on-farm *e.g.* shade, organic matter enrichment and attraction of insects (particularly honey making bees) and birds that increase biodiversity. The ability of *Melia* trees to enhance soil fertility on farms is discussed in Chapter 7.

Unless stricken by drought or other financially damaging event, farmers can delay selling timber from young trees because the value of each semi-mature tree increases with time. However such options are only possible when household maintenance is sustained via other sources of income. Thus, it was easier to delay tree sales on farms at Mbeere (Ishiara) than at Kitui because of the better external income opportunities available at the former. However, delay in marketing may also be attributed to production of alternative crops for sale such as tobacco, fruits and vegetables as well as the proximity to bigger markets at Mbeere. At Mbeere, some households maintained mature trees for more than 10 years and as result earned twice as much from their trees as farmers at Kitui. At the latter site, trees tend to be sold at a younger age (7 years) due to frequent crop failures.

The survey results indicate diversity of opinion regarding competitivity of *Melia* trees when grown with crops. Approximately equal numbers of households felt that *Melia* trees did, and did not compete with crops. This result contrasts with previous studies (Tedd, 1997) who asserted that farmers believed that *Melia* trees did not compete with crops. It was interesting that 33% of farmers knew that *Melia* was competitive with crops, but most felt that its negative impact could be suppressed by heavy crown pruning to reduce shading at the beginning of each cropping season. It seems probable that at least some of the reported competition might have been due to the type of plant material used for tree establishment. For example, 75% of households who used transplanted wildlings reported crop yield losses. Such losses were probably caused by shallow root system structure. Root proliferation that normally follows root system damage, an unavoidable consequence of uprooting of saplings, could well be exacerbated if the vertically descending roots that exploit resources beyond crop rooting zone, are also severed during uprooting.

There seem few limitations hindering the expansion of *Melia* tree farming. Two constraints that were mentioned were poor availability of planting materials and browsing of newly established plants. For instance, seedling production in farmer's fields was very poor. Only 5% of the households at Kitui managed to use seedlings, the remainder established their trees using other plant types obtained from natural regeneration (Table 3.6.2). Clearly, this mode of establishment is only applicable to those who have mature trees on their farms. And despite success in improving germination of *Melia* seed (Milimo, 1989; Nyambati and Konishi, 1992), most extension nurseries failed to raise enough seedlings to meet the demand of farm afforestation projects (Mohammed, Jaenicke, pers. comm.). Shortage of planting stock has led to a new interest in other methods of propagating *Melia volkensii*. Previous reports (Tedd, 1997; Kidundo, 1997) indicated that more than 90% of *Melia* trees in the farmer's fields at Kibwezi and Mbeere originated from natural regeneration. In Kibwezi, where tree rotations are much shorter (2 to 3 years) and hence the need for planting stock is greater, farmers are establishing communal nurseries for raising transplanted saplings or wildlings. The produce is sold to rural afforestation projects and also to other farmers who lack planting stock (Mohammed pers. communication). A few farmers use root cuttings or sprouts on intentionally damaged *Melia* roots as planting materials on their farms.

3.8 Conclusion and recommendations

Melia volkensii is highly treasured by farmers for its valuable, durable, termite resistant timber. Other attractions to *Melia* are that it also provides essentials such as firewood, dry season fodder, pesticides and beehives for which there is either household need or strong local markets. There is great potential to extend *Melia* farming to all dryland areas of Kenya. Efforts to propagate *Melia* seedlings or other planting materials in large numbers should be doubled in order to satisfy the increasing demand.

Propagation of *M. volkensii* as seedlings remains problematical. Currently, farmers overcome the shortage of seedlings by obtaining their planting material from various forms of natural regeneration. Clearly, low cost propagation methods, which provide quality plants with root system structure rendering them of low competition potential are required. From this survey, it was not clear whether plants raised through seedlings were less competitive compared to those raised from cuttings or transplants of wildlings. However, the next Chapters 4 and 5 of the study evaluate the differences in root architecture and competition potential between *Melia* provenances and also between different *Melia* plant types. Furthermore, based on root architecture studies, water use and crop yield relationships are developed to clearly understand whether the differences in yields on farmers' fields result from root architecture differences.

Farmers have some ideas of how to manage their trees but management is more or less restricted to pruning and has developed from either fodder or fuelwood harvesting. Although pruning or pollarding are applied at the beginning of the rainy season to reduce crown size and crop shading, farmers need to be made aware that once applied correctly allowing longer bole length could greatly increase the value of planted trees when selling clear knot-free stems. In this study many farmers, particularly at Kitui pruned their tree boles to half the tree height thus leaving the rest of stem with protruding branches (cut and uncut) to provide a convenient ladder for gaining access to higher crown to harvest products such as fuelwood and fodder. These protruding branch stumps continue to grow and eventually ruin the quality of the stem boles.

Farmers need to be made aware of the competitive effects that *Melia* trees exert on their crops. From this survey, most farmers who observed competition between trees and crops think that it was due to tree shading. To investigate this aspect, tree shading effect on crops studies were planned and carried out, and are described in Chapter 7. That many farmers do not "see" competition often derives from the fact that they have too many trees in their fields (not only *Melia*). In such cases, the trend of increasing yield as distance from trees increases is not apparent because all parts of the fields are influenced by trees and all areas produce diminished crop yields. From this observation on-farm trials to evaluate tree-crop interaction at different distances from trees towards the directions where there was no other tree influence were planned and results are reported also in Chapter 7.

Melia volkensii produces timber in shorter rotations than any other timber species. It takes less than ten years to produce large sized timber and even shorter rotations are required, as little as 5 years, if the timber is derived from coppiced stumps. However, profits from timber tend to be greater for dealers and processors than for farmers. Where possible, farmers should be encouraged to at least semi-process their timber on-farm in order to maximise profitability. Additionally, improved marketing systems and collaborative ventures among farmers could increase income generation from tree products. Consequently, co-operative societies or farmers' groups should be formed to produce, process and market *M. volkensii* products in each area where it is grown.

CHAPTER FOUR

4.0 EVALUATION OF THE COMPETITION INDEX METHOD FOR PREDICTING TREE COMPETITION WITH CROPS IN SIMULTANEOUS AGROFORESTRY SYSTEMS.

4.1 Introduction

In addressing the subject of competition between trees and crops for below ground resources, Van Noordwijk *et al.* (1994) proposed that the competitive potential of trees grown with crop plants could be predicted by the shallowness of their root systems. They proposed the use of competition index (CI) (see Chapter 2); suggested as a time-saving substitute for the standard methods (trenching, coring and minirhizotron) to predict tree competitiveness with food crops in simultaneous agroforestry systems (Chapter 1).

The present study was planned to evaluate the competition index method and determine whether it could be used to predict the ability of trees to compete with food crops.

4.2 Experiments and measurements

The study examined the CI values of *Melia volkensii* provenances and different tree species: *Grevillea robusta, Senna spectabilis, Gliricidia sepium, Eucalyptus camaldulensis, Azadirachta indica* and *Acacia polyacantha*. Six trials of different age and locations were covered (see Table 2.2.1). The locations and species used in these trials are detailed in Chapter 2. They were chosen to represent the planting methods used by various interest groups. For instance, researchers and small scale farmers use line planting to suit small farm sizes; forest departments and farmers with big fields prefer planting trees as blocks or woodlots and medium scale farmers prefer isolated trees. In order to cover these planting patterns, many sites were included.

The tree species chosen for root excavation studies were ones preferred in dryland agroforestry. The excavated area ranged from 0.4 to 1 m radius depending on the tree size under consideration. Two to four year old trees were excavated to a radius of 0.4 m while those over 5 years (on farms) at 1 m radius due to bigger more tapering roots than those of young trees.

Competition index (CI) is determined as described in Chapter 2. However, when determining the tree competition potential in which tree size is incorporated (adapted from Ong *et al.*, 1999), the competition potential is determined by multiplying sum of the squares of horizontal root diameter by stem diameter i.e.

$$CIp = \Sigma D_{hor}^2 . D$$

where CIp is tree competition potential, ΣD_{hor}^2 is sum of squares of horizontal root diameter and D is stem diameter (root collar diameter or dbh)

The CI values in trials 1 and 2 were determined twice, at age 2 and 3 years and 3 and 4 years respectively. Each time the excavation was done, two new trees whose diameters' at breast height were closest to the plot mean were selected. Trees of uniform size were desirable to avoid differences in crop yield and soil moisture content which might be caused by tree size (Ong *et al.*, 1999). In other trials at Kitui and Kibwezi, CI was determined once. The CI for the Kitui on-station trial was determined when trees were 3 years old while the on-farm trees at Kitui and Kibwezi were of different ages, ranging between 3 and 8 years (see Table 2.2.1).

Crop yields at both on-station and on-farm trials were measured as described in Chapter 2. Soil moisture content in trial 1 was measured at varying distances from trees at a depth of 0-65 cm and then averaged for all distances during dry period 1 and dry period 3 (before long rains of 1998 and 1999 respectively). It was also measured at maize seasons 1 and 3 (long rains of 1998 and long rains of 1999 respectively) when maize growth was at the grain formation stage. The soil moisture studies at varying distance from trees and at varying soil depths are covered in chapter six. Soil moisture was not measured in trial 2 because of logistic problems.

ANOVA was used to compare the differences in CI among a) provenances and b) species. Regression analysis was used to estimate the relationships between CI and a) tree size, b) soil moisture and c) crop yields.

4.3 Results

4.3.1 Competition indices of the *Melia* provenances (trial 1)

When comparing average competition index between *Melia volkensii* provenances at 2 and 3 years (Table 4.3.1), the Kibwezi provenance had a significantly ($p < 0.05$) larger CI value than those of other provenances at age 2. However, at age 3 there was no significant difference in CI between provenances. Furthermore, competition indices varied greatly between individual trees within each provenance (Table 4.3.1.1); the Siakago provenance showed more variation in CI between individual trees at age 3 whereas the Kibwezi provenance had the least at age 3 compared to the Kitui and Ishiara provenances.

Table 4.3.1: Competition indices of 2 and 3 years old *Melia volkensii* provenances in trial 1 at Machakos, semi-arid Kenya.

***Melia* provenance**	**CI at 2 years**	**CI at 3 years**
Kitui	0.42^{b}	0.44^{a}
Ishiara	0.42^{b}	0.33^{a}
Siakago	0.53^{b}	0.59^{a}
Kibwezi	0.92^{a}	0.48^{a}
Least significant difference ($p<0.05$)	0.31	0.26

CI values appended with different letters in each CI column are significantly different

Table 4.3.1.1: Competition indices of individual 2 and 3 year old *Melia volkensii* trees per provenance in trial 1, sampled at Machakos in 1998 and 1999 respectively.

	Kitui		Ishiara		Siakago		Kibwezi	
Sample tree	2 years	3 years	2 years	3 years	2 years	3 years	2 years	3 years
1	0.21	0	0.16	0.43	0.50	0.28	0.59	0.33
2	0.43	0.98	0.02	0.34	0.00	0.40	1.02	0.52
3	0.75	0.12	0.63	0.03	0.68	0.04	0.85	0.34
4	0.02	0.23	0.63	0.02	0.19	1.06	1.02	0.48
5	0.29	0.61	0.94	0.93	0.91	1.02	0.60	0.33
6	0.35	0.18	0.33	0.34	0.31	1.40	1.70	0.75
7	0.57	0.46	0.00	0.23	0.64	0.10	0.76	0.32
8	0.71	0.71	0.66	0.28	1.04	0.43	0.83	0.77
Mean	0.42	0.41	0.42	0.32	0.53	0.59	0.92	0.48
Std. deviation	0.25	0.33	0.34	0.28	0.35	0.5	0.35	0.19

4.3.2 Relationship between competition index and diameter

When examining the relationship between competition indices and tree sizes for each separate *Melia* provenance with ages ranging from 2 to 3 years (Fig. 4.3.2.1), there was no significant relationship or trend between CI values and diameters. Furthermore, regression analysis between CI values and diameters (Table 4.3.2.1) indicated that there was no significant relationship between competition index and tree size.

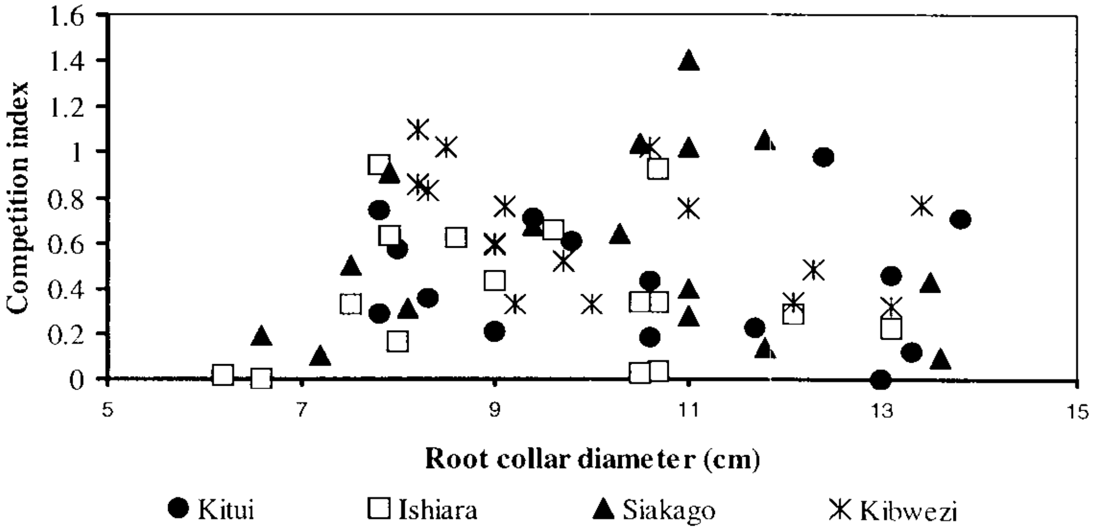


Figure 4.3.2.1 Relationship between the CI values and root collar diameter of individual *Melia volkensii* provenances trees with age ranging from 2 to 3 years in trial 1 at Machakos.

Table 4.3.2.1: Probability values from regression analysis between diameters and competition indices within each *Melia volkensii* provenances in trial 1 at Machakos

Source of variation	F.pr
Kitui *Melia* provenance	0.712
Ishiara *Melia* provenance	0.961
Siakago *Melia* provenance	0.662
Kibwezi *Melia* provenance	0.084

4.3.3 Relationship between competition index and soil moisture content at shallow depth (0-65 cm) in plots occupied by provenances.

Before regression analysis between competition indices and soil moisture content in the overall provenance plots was carried out, soil moisture content at all distances at 0-65 cm depth for each provenance plots (Table 4.3.3.1) and competition indices for the provenances at same plots at each determining season (Table 4.3.1) were averaged. When regression analysis between CI values and soil moisture content was carried out (Table 4.3.3.2), there was no significant relationship between CI values and soil moisture. However, when regression analysis between CI values and soil moisture at each sampled distance from the trees were carried out (Table 4.3.3.3), there was a significant relationship between CI and VSWC at 6 m from the trees during maize 3 season of long rains of 1999.

Table 4.3.3.1: Soil moisture content in the plots with *Melia volkensii* provenances at age 2 and 3 years at trial 1 during dry period and at crop grain formation stage in the rain season.

Melia provenance	Soil moisture content (%)			
	Dry season		Rainy season	
	2yrs	3yrs	2yrs	3yrs
Kitui	22.5^a	15.0^a	24.6^a	17.8^a
Ishiara	22.9^a	15.2^a	25.4^a	18.3^a
Siakago	22.7^a	15.1^a	25.0^a	17.9^a
Kibwezi	22.9^a	15.2^a	25.1^a	18.4^a
Least significant difference ($p = 0.05$)	0.7	1.3	0.9	1.5

Values of soil moisture content at each column appended with same letter are not significantly different.

Table 4.3.3.2: Probability values from regression analysis between competition index and soil moisture content at 0-65 cm averaged over all distances from the trees in the *Melia* provenances plots during dry and rainy seasons of long rains of 1998 and long rain of 1999 respectively at Machakos.

Source of variation	F.pr
Dry season 1 (LR98)	0.490
Dry season 3 (LR99)	0.708
Maize 1 season (LR98)	0.852
Maize 3 season (LR99)	0.578

Table 4.3.3.3: Probability values from regression analysis between competition index and soil moisture content at 0-65 cm at varying distance from the *Melia* provenance trees during dry and rainy seasons of long rains of 1998 and long rain of 1999 respectively at Machakos.

Source of variation	Distance from trees			
	1.5 m	2.5 m	4.5 m	6.0 m
Dry season 1	0.752	0.965	0.244	0.631
Dry season 3	0.110	0.222	0.221	0.363
Maize 1 season	0.735	0.913	0.837	0.868
Maize 3 season	0.261	0.327	0.110	0.038*

* means significant at $p < 0.05$

4.3.4 Relationship between competition indices and crop yield

When comparing maize yields at varying distances from trees in chapter seven (Fig. 7.3.3.2) there was a greater grain yield reduction at 1-3 m than at 5 m from the trees. For this reason, relationships between crop yields and the tree competition potential are based on average maize yields at 1-3 m from the trees. Relationship between CI values and crop yield was carried out in maize 3 season, when soil water was limiting and maize formed cobs and when trees were 3 years old.

When analysing regression between average crop yields at 1- 3 m from the trees and average competition index of the provenance in that plot (Fig. 4.3.4.1), there was no significant (p = 0.158) relationship between crop yields and competition indices during maize 3 season. Furthermore, when regression analysis between crop yields and standardised CI for tree size was done (Fig. 4.3.4.2), there was also no significant (p = 0.056) relationship between crop yield and the standardised CI values.

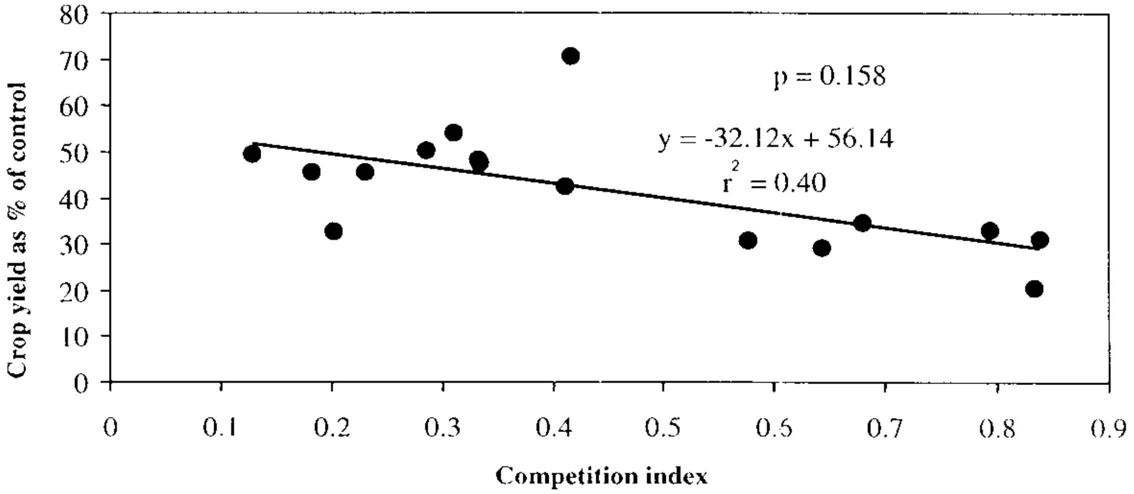


Figure 4.3.4.1 Relationship between average crop yield at 1- 3 m from a single row of trees and competition indices of *Melia volkensii* provenances in trial 1 during maize 3 season (LR99) at Machakos. Probability value from their regression analysis is indicated.

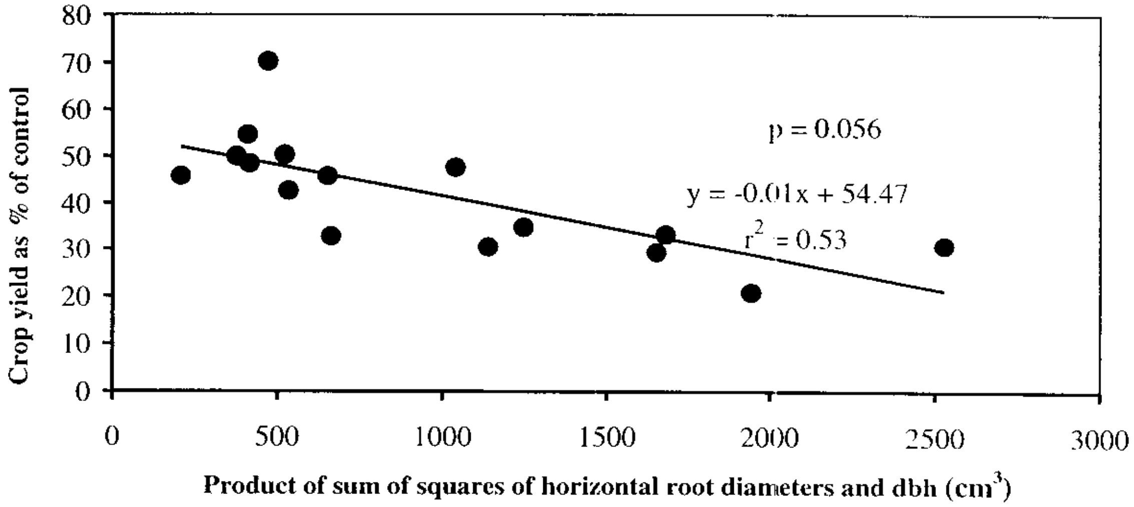


Figure 4.3.4.2 Relationship between crop yield and standardised CI to account for tree size, and the probability value from their regression analysis in trial 1 at Machakos during maize 3 season is indicated as in **Figure 4.3.4.1**.

Similarly, the CI values of the other tree species in trials 2, 4 and 6 were evaluated as was done for *Melia volkensii* in the provenance trial (trial 1). The results from these assessments are summarized in Table 4.3.4.3. CI was extremely variable between individuals of a species and apart from trial 4, where *Melia volkensii* had a significantly greater CI than other species, there were no differences in CI between species. Furthermore, there was no significant relationships between CI and tree diameter, or between CI and plot crop yield.

Table 4.3.4.3: Summaries of CI evaluation results from trials 2, 4 and 6.

Trial	Variation	Comments
2	*Comparison*	
	CI between species	ns
	CI between individuals within species	hv
	Relationship	
	CI and Diameter within species	All ns
	CI and crop yield (all species combined)	ns
4	*Comparison*	
	CI between species	*Melia* s. greater
	CI between individual trees within species	hv
	Relationship	
	CI and Diameter within species	ns
6	CI of isolated *Melia volkensii* trees	hv

ns = not significant
hv = highly variable
s = significant

4.3.5 Competition index of isolated *Melia volkensii* trees on the farmers' fields at Kitui (trial 5)

In this trial, CI values of isolated *Melia* trees on farmers' fields were determined to represent the single tree planting pattern in addition to those of the line tree planting examined in the on-station research trials (trial 1 and 2) and tree planting in blocks as in species selection trial at Kitui (trial 4). The on-farm studies in this trial also provided the opportunity to select isolated trees of variable age unlike in the previous trials. Maize grain yields were measured as described in Chapter 2.

Regression analysis was used to test whether significant relationship existed between CI values and a) tree size and b) crop yields.

Diameter at breast height and competition indices for single *Melia* trees within Kitui farms were measured (Table 4.3.5.1); CI values ranged between 0.41 to 0.95. Some of smaller trees had larger CI values than bigger ones.

Table 4.3.5.1: Diameters and competition indices for 10 isolated *Melia volkensii* trees of different age ranging from 3 to 8 years in trial 5, measured in 1999 at the Kitui farmers' fields.

Sampled trees	Diameter (dbh) (cm)	Competition index
1	23.5	0.66
2	20.0	0.41
3	34.7	0.95
4	32.8	0.72
5	26.5	0.50
6	28.8	0.47
7	21.4	0.44
8	30.0	0.87
9	22.9	0.81
10	12.6	0.62
Mean	25.3	0.65
Std. deviation	6.6	0.19

4.3.5.1 Relationship between competition indices and diameters (dbh)

There was no significant (p = 0.157) relationship between competition indices and diameters (Fig. 4.3.5.1). However, the diameter component contributed to 23% of the changes in the CI values.

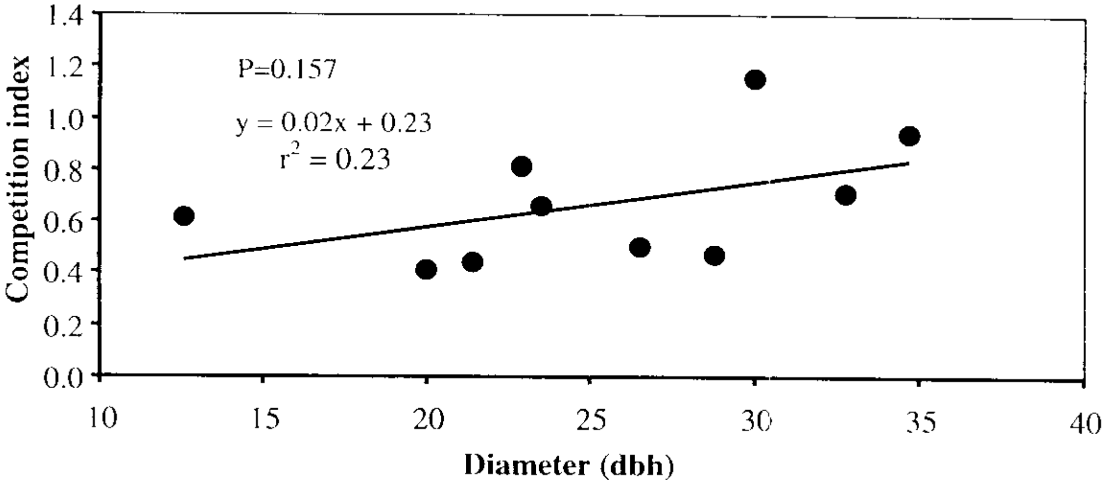


Figure 4.3.5.1 Relationship between competition indices and diameters of isolated *Melia volkensii* trees of different age (3 to 8 years) and probability value from their regression analysis in trial 5 at the farmers' fields at Kitui.

4.3.5.2 Relationship between competition indices and crop yields

Only six trees were used for the maize yield and CI relationship studies during the maize 3 season of the long rains of 1999 because of unavoidable conditions on the farmers' fields (Chapter 2).

There was a significant (p = 0.014) relationship between maize yields at 10 m annulus from individual trees and CI values (Fig. 4.3.5.2). When similar comparison was also done between standardised CI for tree size and maize grain yields (Fig. 4.3.5.3), there was an even more significant (p = 0.012) relationship.

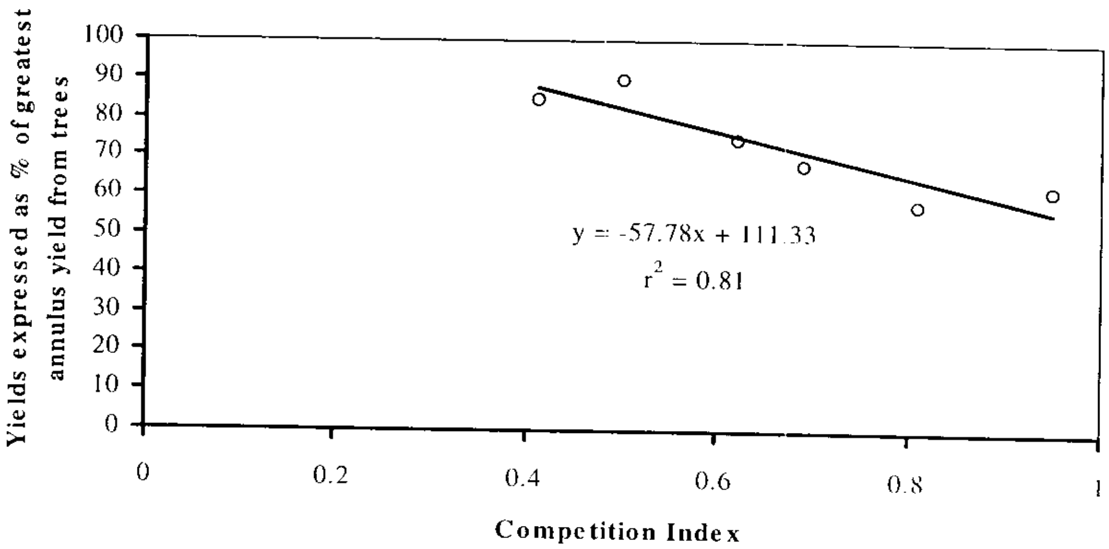


Figure 4.3.5.2 Relationship between maize grain yield expressed as percentage of the greatest of the 2 m annulus intervals from the trees and competition indices in trial 5, at Kitui farmers' fields during the long rains of 1999.

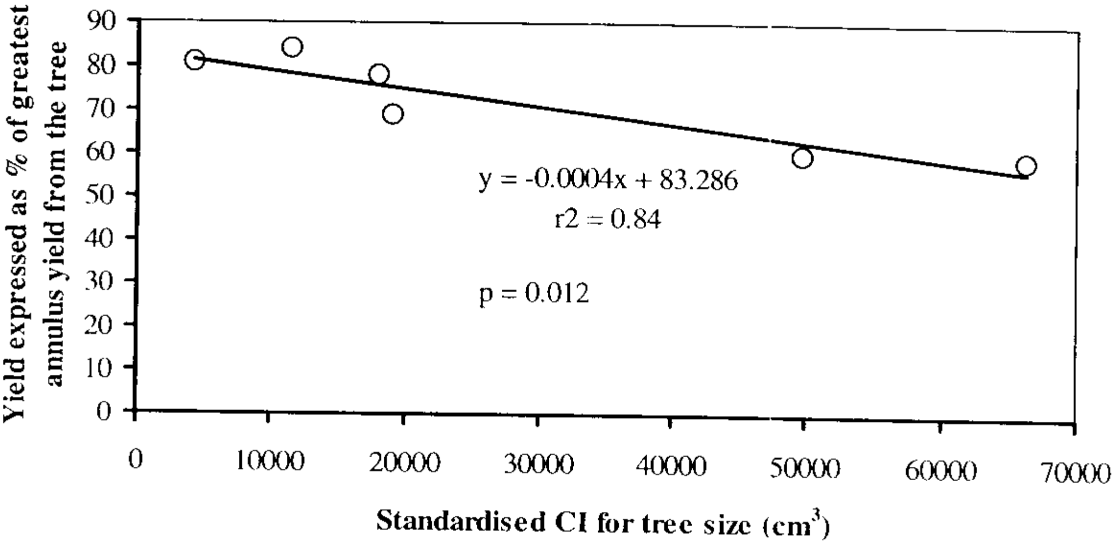


Figure 4.3.5.3 Relationship between maize grain yield expressed as percentage of the greatest 2 m annulus yield intervals from the trees as in Figure 4.3.5.2 and standardised CI for tree size in trial 5, at Kitui farmers' fields during the long rains of 1999.

4.4 Discussion

Surprisingly, CI method has not been a useful predictor of tree competition potential with crops as suggested by Van Noordwijk and his colleagues. There was no significant relationship between competition indices and maize grain yields when trees are closely spaced. After evaluating the CI method at different sites where different *Melia volkensii* provenances and different tree species were planted in different patterns, observations indicated that it is not specifically a characteristic of a provenance or tree species but rather reflects an individual tree root's behaviour under prevailing conditions. For instance, at each determination occasion, CI values for different *Melia volkensii* provenances and tree species were either increasing or decreasing or even constant with time (Table 4.3.1.1) i.e. there was no consistency. The other interesting observation was that there was high variability in CI value of individual trees within species. This assertion was supported by the results of individual tree CI values sampled in the *Melia* provenances and species trials. In these observations, the CI values of individual trees varied greatly per *Melia* provenance and per species.

The study could not establish a definite relationship between the competition indices and tree size although previous studies (Mutua, 1997) had indicated that CI value would increase with time before stabilising. Although the same trees could not be repeatedly re-assessed to avoid further tree damage to evaluate CI stability with time, it seems likely that root system variation between individual trees contributed to the variation in CI between the Kibwezi and other provenances at age 2 (Table 4.3.1).

Contrary to the previous study (Ong *et al.*, 1999) which showed that including tree size in the competition index method improved the chances of predicting tree competitiveness with crops, the results of this study indicated the standardised CI for tree size did not improve the relationship between the species competition potential and crop yields at closely spaced trees. The poor relationship observed between competition indices and crop yields might have been due to the small number of trees (2 trees) used to represent many trees in large plots. Furthermore, there was a greater CI variation between individual trees of a particular provenance or tree species than between provenances and species and therefore using two trees in a plot of many trees may totally have misrepresented the plot's overall CI true value.

The CI method however, turned out to be useful on farmers' fields where it reliably predicted competitiveness of isolated *Melia volkensii* trees with crops (Fig. 4.3.5.3). Unlike in the cases where trees are planted closely (e.g. line planting), when the CI method was standardized for tree size, it improved the chances of predicting tree competitiveness with crops (Fig. 4.3.5.4).

Generally, the study highlighted that the CI method (and possibly with modification to allow for tree size) was able to predict tree competitiveness with associated crops only in isolated *Melia* trees. However, for closely spaced tree planting patterns such as line tree planting, hedgerows or woodlots, the CI method has not been able to predict tree competitiveness with crops. There is need therefore to investigate other methods e.g. root architecture to quantify tree root systems and evaluate their impact on crops.

CHAPTER FIVE

5.0 GROWTH, SURVIVAL AND ROOT ARCHITECTURE OF DIFFERENT PLANTING STOCK USED IN *MELIA VOLKENSII* ESTABLISHMENT.

5.1 Introduction

Farmers believe that *Melia* trees do not compete with crops, even though shallow ploughing may expose expose lateral roots (Tedd, 1997). It is possible that root architecture varies with provenance and plant type (seedling and root or stem cuttings), so this was investigated and is reported in the present Chapter, so that *Melia* root growth could be evaluated in situations found on farms. Furthermore, root architecture study was done to ascertain whether shallow rootedness is maintained throughout the entire rooting for lateral roots originating from stem base, including those of secondary root interlinks or internodes and also to validate the results of the competition index method (Chapter 4). The root "internode"; this word strictly applies to leaf spacing on stems but for root growth, there is no word for it, so it is used to denote root segments between branches or bends (see Plate 3).

The original cloned trees (stem and root cuttings) and seedlings came from the Kitui provenance and raised at Machakos field station. The raised plants were planted in the fields at the same station.

The aim of the study is to determine the influence of propagation method and provenance on the rooting structure of *M. volkensii*.

5.2 Experiments and measurements

In this study; trials 1 and 3 (Table 2.1) were used. Trial 3 consisted of 3 separate groups of planted seedlings, root cuttings and stem cuttings as detailed in Chapter 2 (Fig. 2.2.3). In trial 3, 4 stem cuttings, 8 root cuttings and 8 nursery seedlings were excavated for root architecture studies when trees were sixteen months old. Trial 1 consisted of seedlings of four different *Melia volkensii* provenances which were planted in a randomised complete block design and replicated four times (see Chapter

2, Fig. 2.2.1). One tree of each provenance for each replicate was excavated for root architecture studies. Results are presented separately for each trial and discussed jointly.

The plant growth, angles of descent of roots and root length were obtained for each plant type. For measurement procedures see Chapter 2. In brief, where the roots starts, branches, forks, bends and ends the east, north and depth distances from a fixed point of horizontal grid were measured and recorded as XYZ co-ordinates.

In order to determine whether the growth of plants raised from different plant types was different, stem diameter (dbh) between seedlings and cuttings were compared.

During root architecture measurements, root diameters at each root event (branching, bends etc.) were measured so that when drawing root structure by a computer NURB software could give proper root size dimensions (thickness proportions). The XYZ co-ordinates were necessary in calculating the root length along the hypotenuse defined by east, north and depth distances. In addition, angles of descent of root branches were calculated from the trigonometry of XYZ co-ordinates. The sum of all root links length and weighted angle of descent of each root link from root origin to where it ends (3 mm) gave total length and general angle of descent of that particular lateral root respectively. The total root length and its general angle of descent were calculated by algebraic relationships keyed in the Excel computer programme.

Plate 3: Root architecture of 3 year-old *Melia volkensii* indicating grid (1 x 1 m) used in measuring XYZ co-ordinates of root branching, bending and end events from a set origin (see Fig. 2.3.2).

Data analysis is detailed in Chapter 2 (section 2.6). In summary, student's t-tests and least significant difference (l.s.d) where possible were used to compare the means of angles of descent, CI value, survival and diameter growth between plant type in trial 3. Regression analysis was used to compare relationship between initial angle of descent and average angle of descent for all root system internodes and the proportion of the whole tree root length existing at given soil depths as well as the relationship between total root length and crop yields.

5.3 Results

5.3.1 Growth of different plant types in trial 3

Generally, stem diameter for all plant types increased greatly within a year (Fig. 5.3.1). The mean diameter of cuttings was significantly ($p = 0.05$) greater than that of the seedlings (Table 5.3.1). The survival rates at the end of the study were; stem cuttings 90%, root cuttings 92% and nursery seedlings 64% which showed clearly that the cuttings (root and stem) were superior in survival over the nursery raised seedlings (Table 5.3.1).

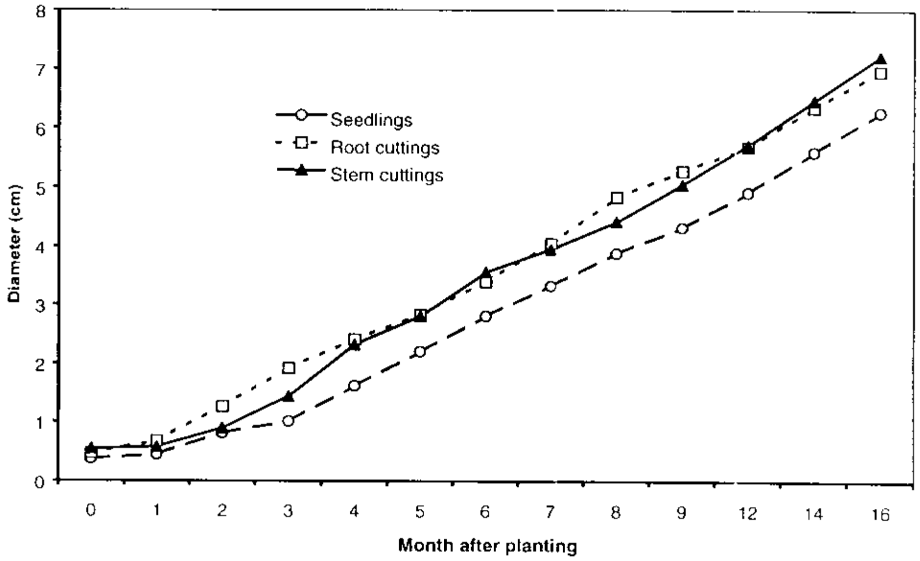


Figure 5.3.1 Diameter growth after planting *Melia volkensii* seedlings, root and stem cuttings in trial 3 at Machakos measured in the first 16 months of establishment.

Table 5.3.1: Field survival and diameters of 16 month old seedlings, root and stem cuttings in trial 3 measured in 1999 at Machakos, Kenya.

Plant type	Planted number	Surviving number	Survival (%)	Diameter (cm)
Seedlings	25	16	64^{b}	6.2^{b}
Root cuttings	25	23	92^{a}	7.1^{a}
Stem cuttings	5	4	90^{a}	7.3^{a}
Mean			82	6.8
S.e.d			15.6	0.54

S.e.d = standard deviation of mean (p = 0.05)

Values in same column appended with different letters are significantly different.

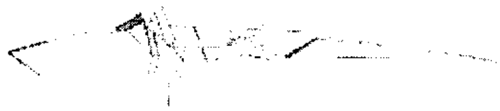
5.3.2 Root architecture of seedlings and cuttings

Figure 5.3.2 illustrates typical root system architecture for the three plant types. The first order lateral roots of seedlings appeared to descend into soils at steeper angles than first order lateral roots of cuttings. In consequence, these shallower lateral roots of cuttings tended to extend further horizontally from stems than those of seedlings. Extreme root architecture of the plant types was observed (Fig. 5.3.2). Out of these observed extreme cases, one of the seedlings produced first order roots that descended very steeply into the soil while a cutting produced contrasting first order lateral roots that grew relatively horizontally. Nevertheless, all root systems examined possessed at least some roots which grew vertically downwards.

a) Seedling (8)

b) Stem cutting (4)

c) Root cutting (8)



d) Seedling

e) Root cutting

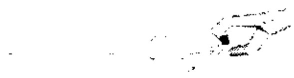


Figure 5.3.2. Typical root systems of 16 months-old *Melia volkensii* raised from **a)** seedling, **b)** stem cutting and **c)** root cutting. Extreme cases of root systems were encountered as indicated in **d)** seedling and **e)** root cutting Numbers in brackets indicate number of tree sampled.

5.3.3 Angle of descent

Initial angles of descent into soil of first order lateral roots of the plant type, CI values and average angle of descent for all root system internodes are presented in Table 5.3.2. Seedlings had significantly smaller CI values than cuttings but there were no significant differences of CI values between the two types of cuttings. The first order lateral roots of seedlings descend into soil at greater angles than those of the cuttings. From the point of view of the applicability of CI as an indicator of competition potential, the relationship between the initial angle of descent of first order lateral roots and the general angle of descent was significant. That is, the angle between the root's starting point on the root collar and the deepest position observed in the soil for that main root axis.

The relationship could be described by the following equation:-

$$y = 12.1 + 0.833x$$

where y is the general angle of descent and x is the initial angle of descent of the first order lateral roots.

Probability was $p = 0.05$ and r^2 accounted for 51% of the variation in the general angle of descent of the first order lateral roots.

Table 5.3.2: Root architecture variables for 16 month-old *Melia volkensii* seedlings, root and stem cuttings growing at Machakos in semi-arid Kenya.

Plant Type	CI	Mean angle of descent (degrees) from horizontal first order roots	Mean angle of descent (degrees) for all root internodes on tree originating from first order roots with angle of descent of [illegible]45^{0}	Fraction of root length existing at depths equal to or less than 30 cm
Seedling (n=8)	0.31^{b}	54.22^{a}	33.2^{a}	$.57^{b}$
Root cutting (n=8)	1.01^{a}	34.71^{b}	24.1^{a}	$.78^{a}$
Stem cutting (n=4)	0.99^{a}	31.89^{b}	24.1^{a}	$.71^{a}$
Probability (t-test)	0.007	0.002	0.081	0.026

Values in the same column appended with different letters are significantly different from each other at $p< 0.05$.

5.3.4 Comparisons of root length between seedling and cuttings at age 1.5 years

The data presented here did not cover the entire length of root cuttings at 30 cm depth beyond 2 m from the tree stems, therefore it underestimates the real length of cuttings. This also underestimated the differences in root length at shallow depths between seedling and cuttings which are otherwise greater.

The fractions of root systems located at shallow depth differed significantly ($p< 0.05$) between seedlings and cuttings (Table 5.3.2). The cuttings had significantly ($p< 0.05$) greater root length fractions in the upper 30 cm of soil compared to that of the seedlings. Furthermore, when all plant types were pooled, there was a significant ($p< 0.001$ and $r^2 = 0.64$) relationship between the tree size and root length (Fig. 5.3.4).

Results of figure 5.3.4, indicates that the differences in root lengths at 0-30 cm within 4 m^2 between seedlings and cuttings were not because of tree size.

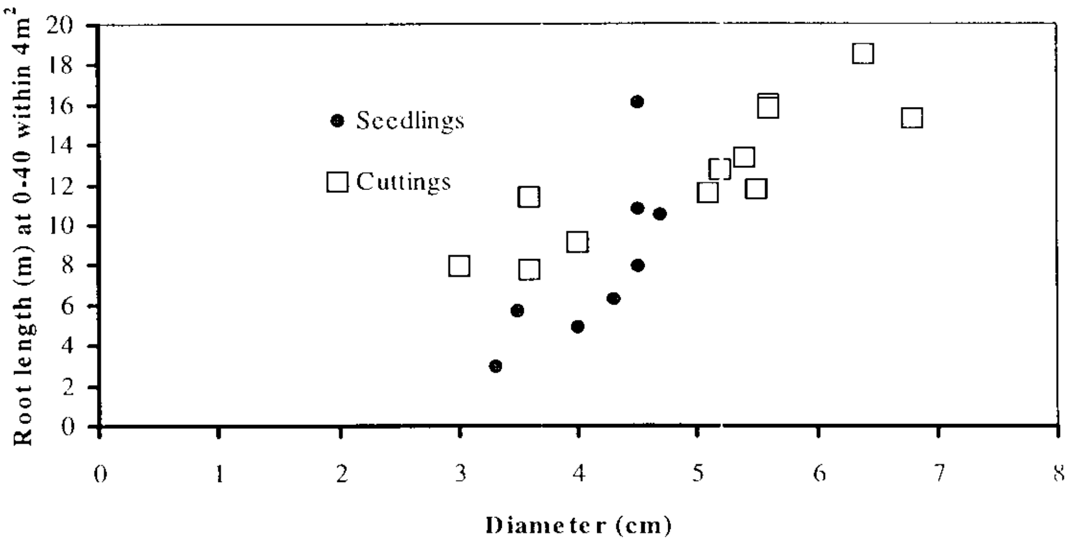


Figure 5.3.4 Relationship between root length between 0 to 30 cm of soil depth within 4 m^2 around the tree and pooled tree diameters of seedlings, root cuttings and stem cuttings of *Melia volkensii* of the trees.

5.4 Machakos: *Melia volkensii* provenances root architecture (trial 1)

Only one tree per provenance per block was used. Means of angles of descent for first order lateral roots, general angle of descent for all root system internodes and the proportion of root length existing at given depths were separately compared between provenances by ANOVA. Root length at soil depths 0 – 50 cm for each provenance were calculated using equations derived from the trigonometry or geometry of root framework (see Chapter 2, Fig 2.3.2). Roots length appearing within the specified depth was estimated using trigonometrical equations.

5.4.1 Root architecture of the *Melia* provenances

The Siakago and Kitui provenances had significantly higher indices of shallow rootedness (CI) than the Kibwezi and Ishiara provenances (Table 5.4.1), however, in all provenances except Siakago, there was considerable variability in CI: and these provenances had more shallow oriented roots than the Kibwezi and Ishiara provenances as shown in Figure 5.4.1a. One tree out of four in both Kibwezi and Ishiara provenances showed shallow rooting while the rest tended to be deep rooted. Conversely, one out of the four Kitui provenance trees excavated in the Kitui provenance tended to grow vertically while the others tended to grow horizontally (Fig.5.4.1b).

Table 5.4.1: Root architecture variables in trial 1 for 3 year-old *Melia volkensii* provenances at Machakos.

Provenance	Dbh	Root length (m) at 0-60cm of soil depth	Angle of descent for horizontal roots of first order (degrees)	General angle of descent for all root internodes (degrees)	CI	Yield as % of control
Ishiara	9.9^{a}	22.3^{ab}	43.9^{a}	47.1^{a}	0.09^{b}	71.1^{a}
Kibwezi	9.8^{a}	17.0^{b}	41.1^{a}	48.8^{a}	0.32^{c}	66.4^{a}
Kitui	10.4^{a}	25.2^{ab}	35.3^{a}	46.6^{a}	0.86^{a}	63.1^{a}
Siakago	10.0^{a}	35.7^{a}	41.0^{a}	41.8^{a}	0.88^{a}	67.4^{a}
L.s.d	1.4	16.9	9.3	13.0	1.4	18.5

Values in the same column appended with different letters are significantly different (p 0.05)

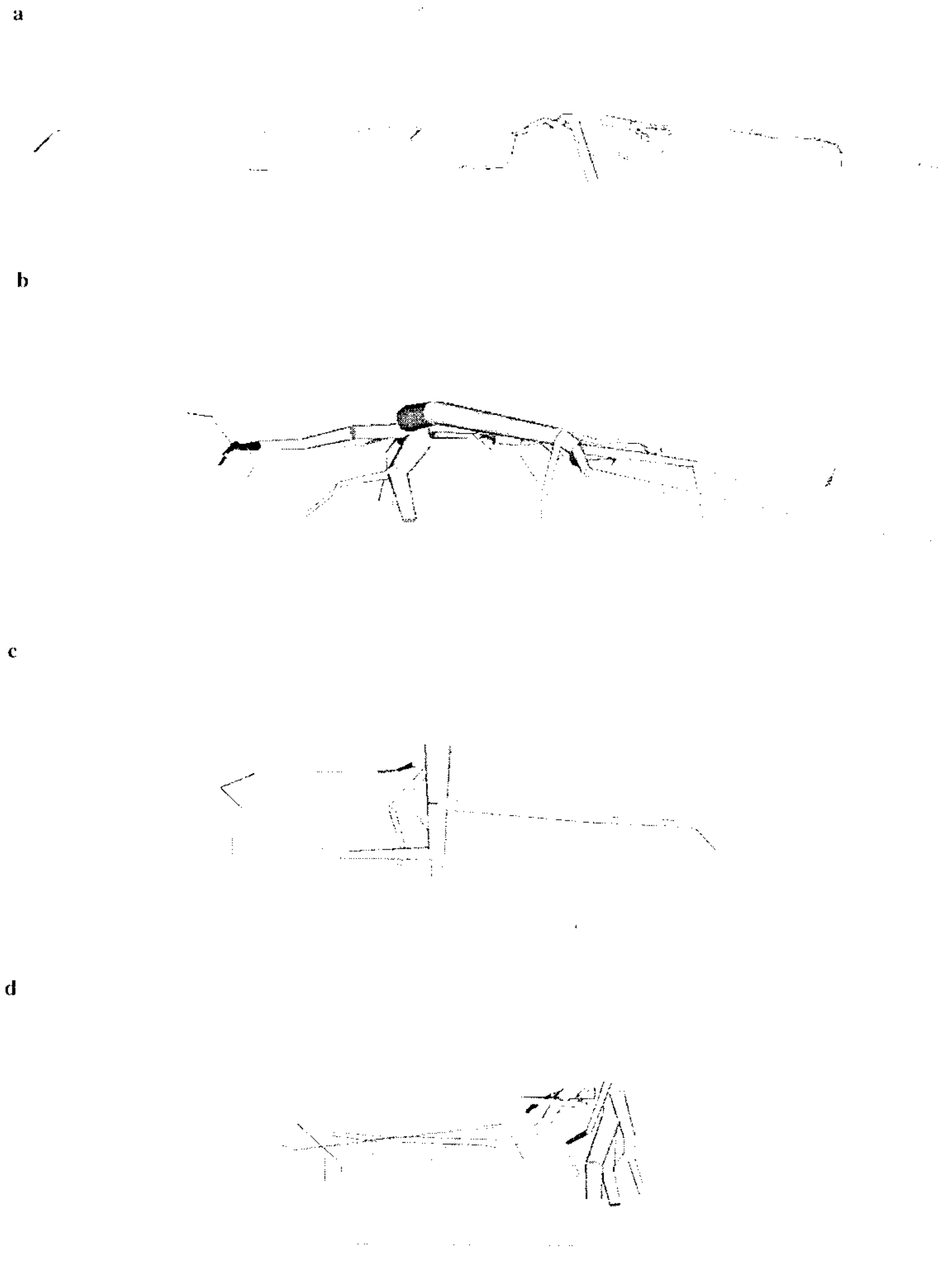


Figure 5.4.1a Typical root architecture found in four sample trees of 3 year-old *Melia volkensii* provenances at trial 1 at Machakos, **a)** Kitui, **b)** Siakago, **c)** Kibwezi and **d)**

Ishiara. A scale of 1 m line is inserted. Note; **a,** is drawn to smaller scale because of root size.

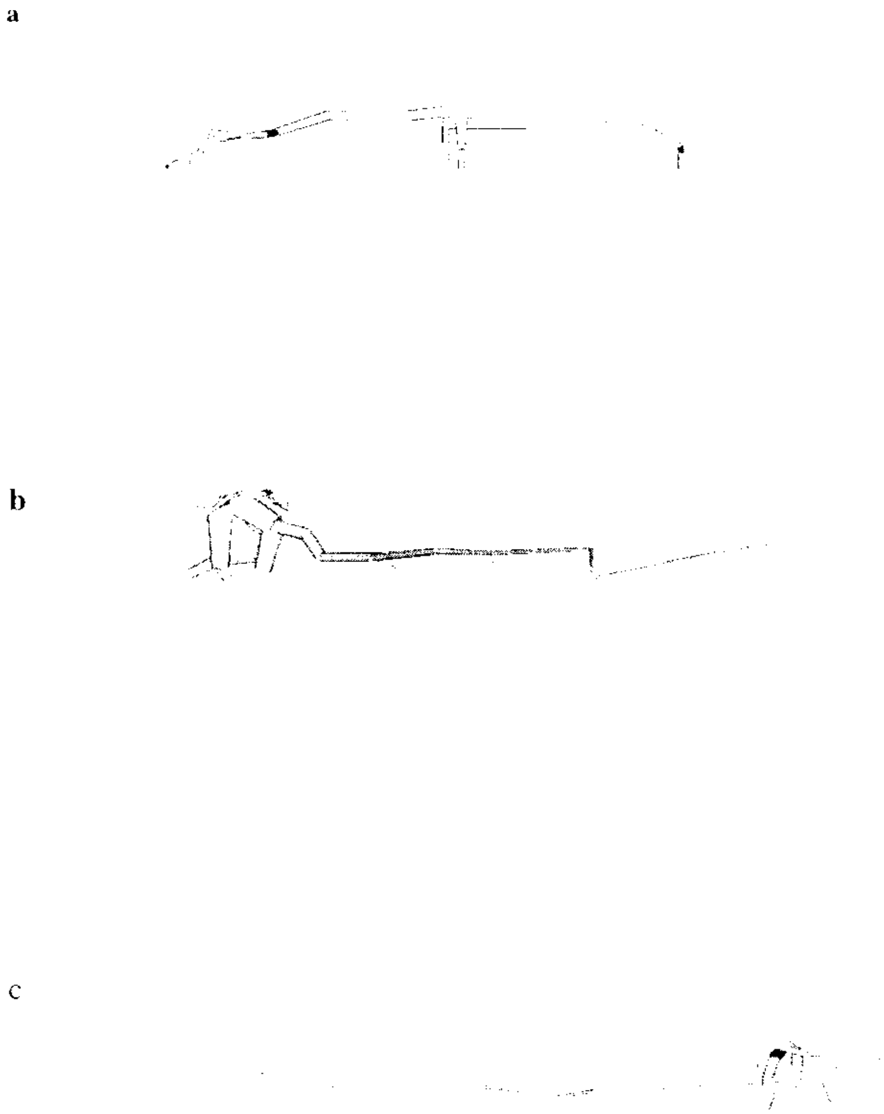


Figure 5.4.1b Exceptions to common root architecture of *Melia* provenances shown in Figure 5.4.1a. **a**) Kitui as deep rooted, **b**) Ishiara and **c**) Kibwezi as shallow rooted. 1 m line scale is inserted.

5.4.3 Angle of descent

Table 5.4.1 shows that average angles of descent into the soil from first order horizontal roots compared between provenances were not significantly different. However, the average angles of descent of the Kitui provenance were 8.6° shallower than that of the Ishiara provenance.

The competition indices of trees with horizontal roots descending into soil profile at angles equal or less than 45° generated by computer (and using same equation of CI as Chapter 4) indicated that the Kitui and Siakago provenances had significantly greater CI values than the Kibwezi provenance, and that all these provenances had greater CI than the Ishiara provenance (Table 5.4.1). The relationship between initial angle of descent of the first order lateral roots and the general angle of descent of all root internodes unlike that of plant types in trial 3 showed a regression line whose correlation value accounted for only 25% of the variation (Fig 5.4.3). The relationship was not significant ($p = 0.056$).

The relationship between the angle of descent of lateral root's starting point on the root collar and the deepest position observed in the soil for that main root axis is thus described by the following equation;

$$y = 0.67x + 18.6$$

where y is the general angle of descent and x is the initial angle of descent of the first order lateral roots.

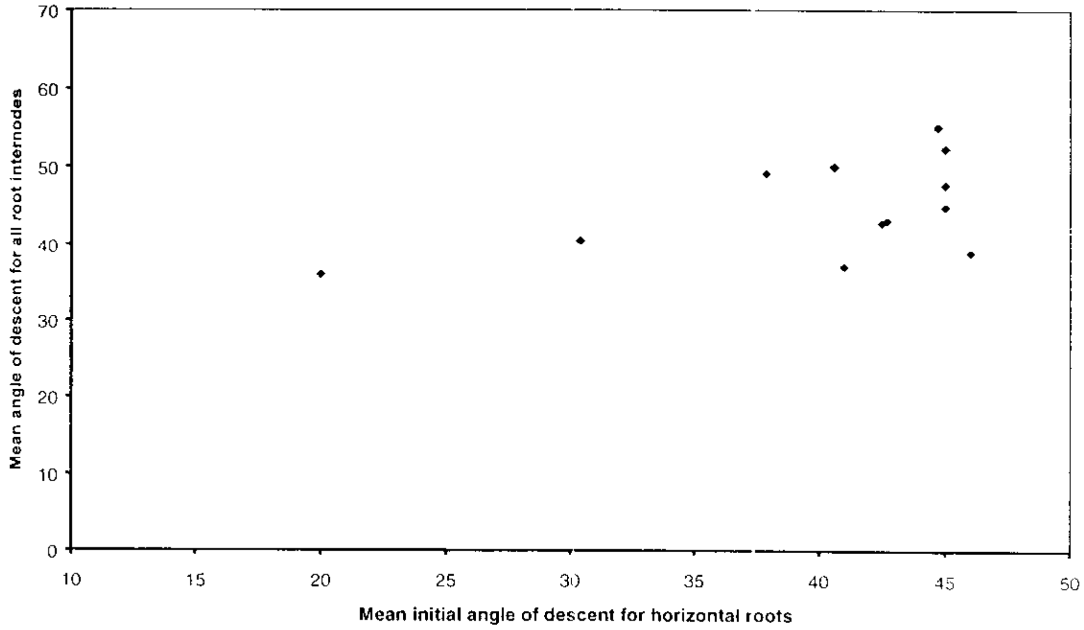


Figure 5.4.3 Relationship between initial angle of descent of horizontal first order roots and general angle of descent of all the roots internodes per tree in the shallow excavated soil depth: indicating no relationship at all.

5.4.4 Root proportions at shallow soil depths

The Siakago provenance had significantly ($p < 0.05$) greater root length at shallow depth than the Kibwezi and Ishiara provenances (Table 5.4.1). Generally, the root length of the Kitui provenance was longer than the Kibwezi and Ishiara provenances although not statistically different.

5.4.5 Relationship between root length and crop yields

Root length at 0-50 cm of soil depth contributed 53% of variation in maize yields in the plots containing trees (Fig. 5.4.5). That is, the coefficient of determination (r^2) for regression between maize yields and root length data had $r^2 = 0.53$ and $p = 0.006$. Although root length of the Siakago provenance was significantly longer than that of the Kibwezi provenance, the maize yields in the plots containing the former and the latter provenances were not significantly different at 1-3 m from the trees (Table 5.4.1).

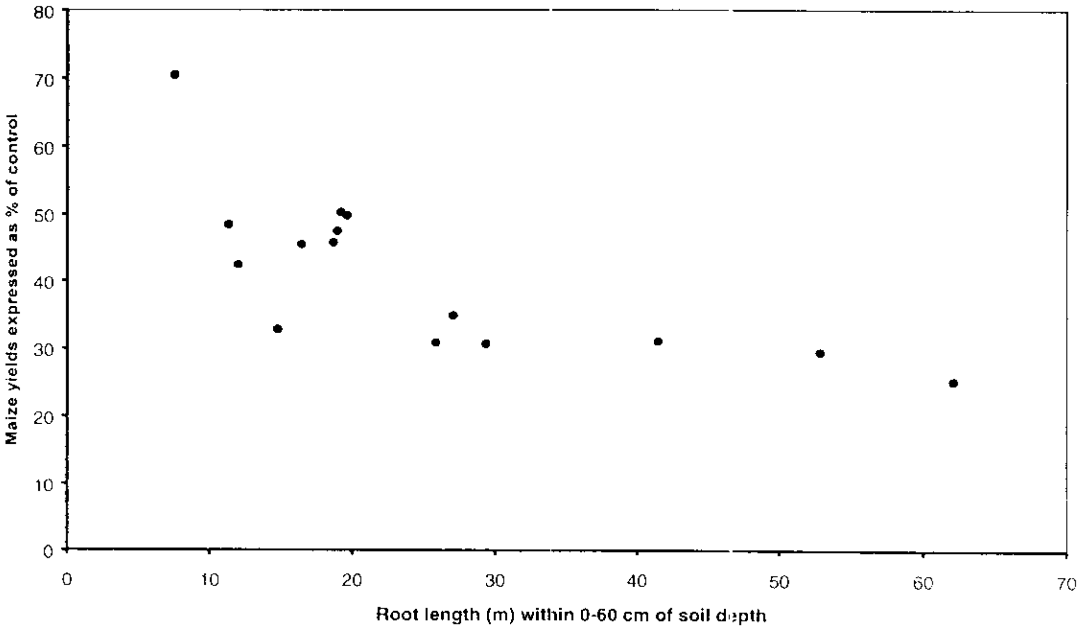


Figure 5.4.5 Relationship between root length within 0-50 cm of soil depths and maize yields expressed as percentage of control of the 3 years old *Melia volkensii* provenance (trial 1) at Machakos, semi-arid Kenya in 1999.

5.5 Discussion

Growth of *Melia* raised by different propagation methods highlighted that the stem and root cuttings were superior in growth to seedlings. However, the growth trend of these plant types indicated that the observed differences might diminish with time, suggesting that there was no comparative advantage in growth for using either plant type. In addition, cuttings had higher survival than the seedlings, implying that cuttings had least wastage of propagated plants. Similar findings of higher survival and shoot growth rates of stem cuttings compared to the nursery seedlings were reported in *Hopea odorata* (Aminah, 1996). However, *Melia volkensii* has proved difficult to raise from stem cuttings as reported in previous studies (Milimo, 1989b, Kidundo, 1997, Jaenicke, pers. communication), although root cuttings are successful. Root cuttings were easier to raise in the nursery than stem cuttings, had higher survival and better diameter growth than seedlings. But too, earlier unpublished studies reported that root cutting propagation method had more potential for mass propagation of *Melia* plants than the seedling propagation method (Jaenicke pers.

communication) and therefore future *Melia* afforestation projects may rely on root cuttings.

Root architecture was not exhaustively studied. CI studies in Chapter 4 indicated that relying on few trees in large plots to evaluate tree:crop competition might be misleading. Ong *et al.* (1999) expressed concern over the use of smaller number of trees sample to estimate the true effects of more trees on crop yields within large plots. However, some of the results highlight useful information. For example, despite the limitation of the number of trees excavated per plant type, the study indicated that plants raised from the cuttings had proportionately more first order roots at shallow depth than those raised from nursery seedlings. Extreme root structure within each plant type (Fig.5.3.3) where the tendency of seedling to root deeply and root cuttings to develop most of its first order roots horizontally was observed. Nevertheless, all root systems examined possessed at least some roots which grew vertically downwards and which might be used to draw resources from deeper soil horizons.

Roots of plants raised from seedlings penetrated the soil at steeper angles than those of the cuttings implying that roots of the cuttings were shallower than those of the seedlings. Previous studies render support to these findings. For instance, Riedacker and Belgrand (1983) showed that stem cuttings of *Quercus robur* had significantly shallower roots than the seedlings and Khurana *et al.* (1997) observed that first order roots of poplar stem cuttings grew horizontally and vertical roots only branched from the lateral ones.

The results further highlight that root architecture of cuttings and seedling could be predicted by orientation of first order roots. For instance, roots of plants raised from seedlings had lower CI values, deeper angles of descent and less root fractions at shallow soil depths (0-40 cm) which are the qualities of deep rooting while those of plants raised from cuttings had smaller angles of descent, higher CI values and high proportions of roots at shallow soil depths implying some tendency of shallow rootedness. Consequently, plants raised from cuttings could be more competitive with associated crops than seedling plants. In contrast, *Melia volkensii* provenances showed no specific rooting system that was clearly associated with a particular provenance. For instance, the CI values, initial angles of descent for lateral roots and general angle of descent for main root axis between provenances were not significantly different (Table 5.4.1). Even though Figure 5.4.1a depicted the Kitui and Siakago provenance as having more laterally oriented roots than the Kibwezi and Ishiara provenances, Figure 5.4.1b indicated that some trees among these provenances showed the opposite of the common rooting behaviour, thus rendering this classification inappropriate.

Although significant ($p = 0.05$) differences in root lengths existed between some of the provenances, crop yield in the plots occupied by these provenances were not significantly different. The discrepancies could be attributed to either poor estimation of shallow root length or unrepresentative samples used in determining the provenances root structure at overall plot level. As reported earlier (Chapter 4), root architecture based on one tree in a plot of 21 trees to predict tree:crop competition might be inappropriate and hence could not have truly shown the inherent provenances root architecture effects on crop yields. For instance, Reidacker and Belgrand (1996) reported that apart from genetic composition, root formation might respond to localised soil conditions of moisture and nutrient pockets and therefore relying on one tree's root architecture might completely misrepresent the true genetically controlled root morphology. Alternatively, root architecture (root length) alone, just as was found with the CI method (see Chapter 4), could not have predicted tree:crop competition appropriately unless other factors such as tree size were taken into account. For instance, although the Siakago *Melia* provenance, which had significantly larger root length at shallow depth than the Ishiara and Kibwezi provenances, did not significantly suppress crop yields over the latter provenances (Table 5.4.1), suggesting that other factors are also involved.

Although seedling plants and cuttings assumed distinct rooting systems (seedlings as deep rooted and cuttings as shallow rooted), unfortunately these plant types were not intercropped so as to evaluate whether these morphological differences had a significant effect on crop yields. Further studies are therefore suggested to evaluate the relationship between root architecture and crop yield. In addition, studies where isolated trees on farms are established from seedlings, stem cuttings, root cuttings and sapling transplants are needed also to evaluate the relationship between CI and crop yield. Root architecture of *Melia* provenances should be determined for all trees in a plot and for isolated trees at the sites of origin in order to come up with a representative root architecture for each provenance and consequently evaluate relationship between root architecture of provenances and the associated crops. These are the issues this study could not cover.

The results of the study also highlight that some second order roots originating from the deeply orientated first order initial roots grew towards the surface thus making roots descending steeply into soil profile grow partly shallow as illustrated by Figure 5.3.2 and 5.4.1. This would render plants with low CI values highly competitive. In other studies done in similar dryland sites, Groot and Soumaré (1995) found that lateral roots and some of the vertical roots of *Acacia senegal* resurfaced and extended to more than 28m from the tree base. For this reason, rooting architecture studies should equally cover first order as well as second order roots and probably it was because of not considering second order root orientation that the CI method was ineffective in predicting tree:crop competition (Chapter 4).

The relationship between root length and crop yields indicated that *Melia* provenance roots at 0-65 cm accounted for 53% of the yields variation (Fig. 5.4.5); meaning shallow rooting affects crop yield.

Generally, if *Melia* provenance is shallow rooting, it will affect crop yields greater than deep rooted ones. Although there was no difference in root architecture between provenances, the quantity of root length at shallow depth affected crop yield significantly (Fig. 5.4.5). Since there was a difference in root fractions at 0-45 cm between seedlings and cuttings, it is worthwhile to examine how the root architecture helps in capturing the resources below ground such as soil water.

CHAPTER SIX

6.0 SOIL MOISTURE AND SAP FLOW

6.1 Introduction

The way trees use soil water is reviewed in chapter 1. The main points of the review were that (i) soil moisture is inversely related to the root length of both trees and crops (Odhiambo, 1999), (ii) that if tree root systems occupy the same soil horizons as crop roots, competition for soil water occurs and (iii) that trees could be exploiting soil water below crop rooting zone (Odhiambo *et al.*, 1999; Org *et al.*, 1999).

In control plots lacking trees, below ground moisture is exploited by crops during cropping seasons and is expected to be greater than that in plots occupied by both trees and crops because the demand for water is less in the control plots (Schroth, 1996). Therefore, tree's ability to transpire soil water can be measured by how much soil water is depleted in its vicinity compared to control plots.

Most food crops grown in semi-arid areas rely on seasonal rainfall because they are shallow-rooted. Soil moisture is usually recharged when i. rains and declines in the later stages of crop development when rainfall ceases. At these stages, serious competition for water between tree and crop roots may result in reduced yield near trees (Schroth, 1996). Surface soil horizons dry faster than deeper layers due to evaporation and drainage and cannot support shallow-rooted crop growth during drought. In contrast, trees in intercropping systems may continue to use deep soil water in the profile even during dry seasons if there is transpirational demand.

Transpiration rate will depend partly on soil water content and the distribution of roots within the soil horizons where water is located (Lott, 1998; Namirembe, 1999). It is also influenced by environmental conditions such as solar radiation, relative humidity and temperature (Hatton *et al.*, 1992).

In this study, four *Melia volkensii* provenances in trial 1 (Table 2.2.1) whose root architecture and their potential to compete with crops (CI) were also determined

(Chapter 4 and 5), were evaluated to determine whether they exploited soil water differently. Investigations focused on the effects of provenance of *Melia* trees on soil water during dry seasons and the maize grain formation stages when soil water demand is critical for grain formation. Soil moisture was measured at different distances and depths from trees and also in the control plots lacking trees. Because water use depends on tree and canopy size (Ong *et al.*, 1999; Hatton *et al.*, 1992), the relatively fast growing Kitui provenance and the slowest growing Kibwezi provenance were used in determining the overall transpiration rates of *Melia volkensii* provenances.

There are two sections of the study. The first deals with soil water. The second section deals with the sap flow method to estimate transpiration rate of the *Melia* species. The two sections are separately presented and discussed.

6.2 Experimental design and measurements

Soil moisture in trial 1 was measured as described in section 2.4. for both control and tree plots.

Because a previous study at the same site (Odhiambo, 1999) reported significant soil water tree-crop interactions in the late stages of crop development, a four week period between the maize development stages of "silking" and "grain formation" was selected for presentation here. These maize development stages were chosen because adequate soil moisture is critical at this stage for grain development (Mooney, 1980). The soil moisture differences between provenances were also assessed during a four week dry period before the onset of rains to evaluate soil moisture use between provenances and control plots lacking trees and crops.

The study covered the long rains of 1998 (LR98) during the latter part of El Nino rains which had commenced in the short rains of 1997, the short rains of 1998 (SR98) which failed, and the long rains of 1999 (LR99) which were below the seasonal average (6.3.1).

ANOVA was used to compare interactions between provenances, distance and depth effect on soil moisture content. Contrasting of individual provenances with control plots was also carried out at each distance to determine the effect of trees on soil moisture at different distance from the trees. The repeated measurements of soil moisture were analysed separately for each measuring occasion as split plots and compared using least significant differences of means (lsd) between provenances. When examining soil moisture with depth, VSWC at different depth ranges between provenances and control plots were analysed by ANOVA separately at 1.5 and 6 m from the trees and tested by least significant difference of means (lsd) when Fisher's F test indicated that differences were significant.

Because control plots had no trees, the results presented here comparing provenance and control plots at different distances from trees, are made when each particular distance from trees is treated separately as an entity and then compared with soil moisture in the control plots.

6.3 Results

6.3.1 Rainfall

Figure 6.3.1.1 illustrates the rainfall amounts and patterns during the study period. There was more than annual average rainfall in the long rains of 1998 (550 mm) but in the following seasons, rainfall was below average (120 and 220 mm in SR98 and LR99 respectively). The long term seasonal average is 350 mm (Odhiambo, 1999).

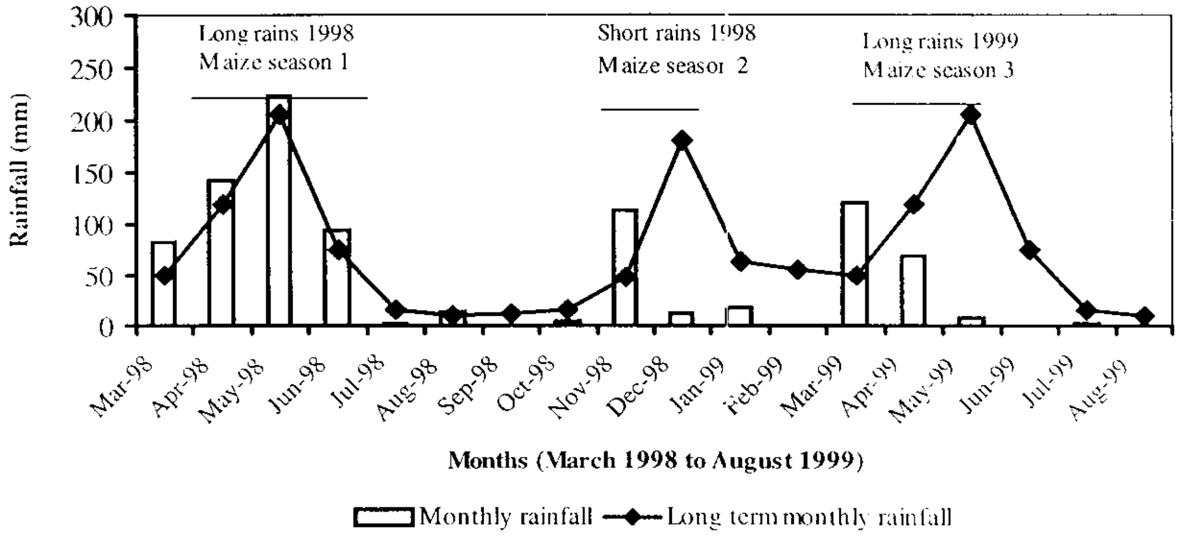


Figure 6.3.1.1 Actual monthly rainfall (mm) and maize growing seasons during the study period as from March 1998 to August 1999 at Machakos and the long term (50 years) monthly average rainfall (mm), from nearby Katumani weather station.

6.3.2 Soil moisture content during the experimental period (April 1998 to August 1999)

When soil moisture in the provenance plots and rainfall amounts were plotted over the study period (Fig. 6.3.2.1), there was overall a gradual decline in soil moisture as plots dried out gradually after the El Nino rains, although some replenishment was evident in each rainy season. The VSWC was generally greater in the maize 1 season (long rains of 1998) than in the subsequent maize seasons (maize season 2 and 3 of short rains season of 1998 and long rains of 1999 respectively). Furthermore, the VSWC trends in the provenances and sole maize plots indicated that the provenance plots were drier than the control plots.

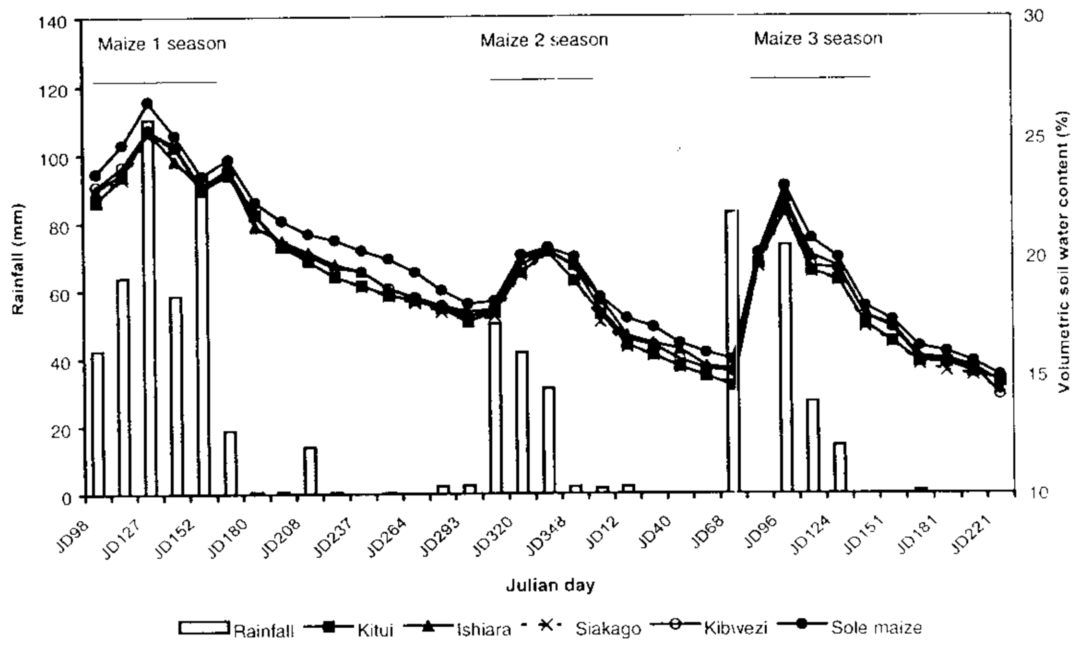


Figure 6.3.2.1 Effect of rainfall on mean volumetric soil water content of all sampled distances and depths from trees in the *Melia volkensii* provenances and control plots lacking trees in trial 1, during the study period "8th April 1998 (JD98) to 8th August 1999 (JD221)" at Machakos, in semi-arid Kenya.

6.3.3 VSWC in the provenance plots during the study period (8th April 1998 to 8th August 1999)

When comparing provenances, distance and depth interactions were analysed (Table 6.3.3.1), there were no significant provenance x distance interactions at any season (dry and rainy seasons). However, there was a significant main effect of depth.

During the first season (long rains of 1998) soil water was freely available, exceeding crop growth requirement and the trees were too young to cause soil moisture differences between provenances (Table 6.3.3.1). Consequently, the maize 1 season was excluded from further detailed soil moisture presentation here. Furthermore, the second season (maize 2 season of short rains of 1998) received insufficient rainfall resulting in less soil moisture recharge (Table 6.3.3.1) and was similarly excluded from detailed presentation here. The last season (maize 3 season of long rains of 1999) received below average seasonal rainfall and trees at this time were more mature enabling comparisons of water use differences between the provenances and evaluation of interactions between provenances, distance and depths. For this reason, soil moisture differences between provenances are presented here in detail for the maize 3 season. The soil moisture results of maize seasons 1 and 2 when trees were younger are excluded.

Table 6.3.3.1: Probability values from ANOVA examining interactions between *Melia volkensii*, all sampled distances and depths from tree rows of VSWC for four weeks of dry seasons preceding rain seasons and of four weeks at maize silking to grain filling rainy seasons during the long rains of 1998, short rains of 1998 and long rains of 1999 in trial 1 at Machakos.

Source of variation	**Maize 1 season**		**Maize 2 season**		**Maize 3 season**	
	Dry season	Rainy season	Dry season	Rainy season	Dry season	Rainy season
	F pr	F pr	F pr	F pr	F pr	F pr
Distance	0.794	0.97	0.249	0.147	0.904	0.598
Provenance x distance	0.972	0.672	0.996	0.558	0.986	0.534
Depth	0.001**	0.569	0.001**	0.001**	0.001**	0.001**
Provenance x depth	0.056	0.128	0.193	0.524	0.444	0.196
Distance x depth	0.292	0.995	0.794	0.985	0.956	0.233
Provenance x distance x depth	0.956	0.823	0.835	0.925	0.922	0.971
Provenance	0.837	0.713	0.971	0.849	0.942	0.520
Provenances x control	0.052	0.043*	0.277	0.051	0.157	0.294

*, ** = significant at p = 0.05 and p = 0.001 respectively.
F pr = Probability value from ANOVA output and Fisher's F test

6.3.3.1 Soil moisture in the dry period preceding the rainy season of long rains 1999 (9th February to 2nd March 1999)

As indicated in Table 6.3.3.1, there were neither provenance x distance nor provenance x depth interactions when provenances, distance and depth effect were analysed. Furthermore, when comparing soil moisture for all distances and depths between provenances, there was also no significant difference in VSWC between provenances during the dry period preceding the maize 3 season.

However, when comparisons were made between provenances and control plots at plot level (Table 6.3.3.2), there was a significantly lower VSWC in the provenance plots than that of control plots during the dry period preceding the maize 3 season. Similar comparison in the previous maize seasons 1 and 2 (Table 6.3.3.2) indicated that significant difference in VSWC between provenances and control plots occurred only between control plots lacking trees and the Kitui and Siakago provenances.

Table 6.3.3.2: VSWC for all distances and depths in the plots containing provenance trees and mean of the control plots during dry seasons 1, 2 and 3 preceding maize seasons 1, 2 and 3 of the long rains of 1998, the short rains of 1998 and the long rains of 1999 respectively in trial 1 at Machakos.

Provenance	Long rains 1998 Dry season 1	Short rains 1998 Dry season 2	Long rains 1999 Dry season 3
Control	23.6^{a}	18.1^{a}	16.3^{a}
Ishiara	23.0^{ab}	17.1^{ab}	15.4^{b}
Kibwezi	22.9^{ab}	17.0^{ab}	15.3^{b}
Kitui	22.5^{b}	16.8^{b}	15.2^{b}
Siakago	22.7^{b}	16.7^{b}	15.1^{b}
Mean	23	17.2	15.5
Lsd	0.7	1.3	0.9

Lsd = least significant difference of treatment means.
Mean values in each columns followed by different letters are significantly different.

6.3.3.1.1 Soil moisture at different distances from the tree rows

When comparing all depth VSWC between provenances separately at 1.5 m, 2.5 m, 4.5 m and 6 m from tree rows during dry season 3 (Table 6.3.3.1.1), results indicated that there was no significant difference in VSWC between provenances at any distance. However, when comparing individual provenance and control at each sampled distance, results indicated that the Kitui and Siakago provenance plots had significantly lower VSWC than the control plots at 1.5, 2.5 and 4.5 m from trees.

The probability values from the ANOVA output of contrasts between provenances and control plots at each distance from trees for all seasons are presented in Appendix 2, in which there was a significantly lower VSWC in the provenance plots compared to control at 1.5 m from the trees during the maize 3 season.

Table 6.3.3.1.1: VSWC in the plots containing *M. volkensii* provenances at varying horizontal distances from tree rows and that of control plots lacking trees during four weeks dry season preceding maize 3 season of long rains of 1999 in trial 1 at Machakos.

	Distance from trees				
Provenance	1.5 m	2.5 m	4.5 m	6.0 m	Mean
Ishiara	15.4^{ab}	15.3^{ab}	15.4^{b}	15.4^{ab}	15.4^{ab}
Kibwezi	15.2^{ab}	15.2^{ab}	15.3^{b}	15.5^{ab}	15.3^{b}
Kitui	15.0^{b}	15.1^{b}	15.2^{b}	15.3^{ab}	15.2^{b}
Siakago	14.8^{b}	15.1^{b}	15.2^{b}	15.2^{ab}	15.1^{b}
Control	16.3^{a}	16.3^{a}	16.3^{a}	16.3^{a}	16.3^{a}
Lsd	1.2	1.3	0.8	1.2	0.9

Lsd = least significant difference ($p = 0.05$)

Mean values in same column followed by different letters are significantly different

6.3.3.1.2 Soil moisture at different depths in the soil profile

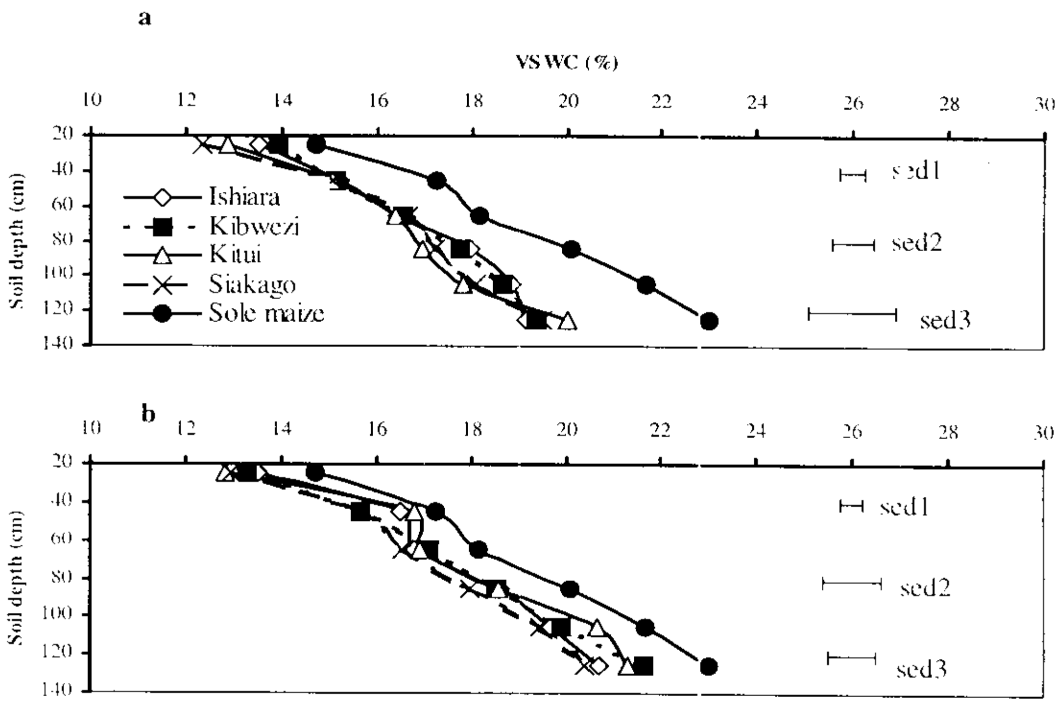
When comparing soil moisture between provenances at each of 0-40, 45-80 and 85-125 cm depth ranges using lsd at both 1.5 m (near trees) and at 6 m (away from the trees) (Table 6.3.3.1.2), results indicated that there was no difference in VSWC between provenances. However, when comparing individual provenance with control there was a significantly lower VSWC in the dry season with Kitui and Siakago provenances at 0-40 cm than that of control plots at same depth at 1.5 m from the trees. At the same distance, during the rainy season, the plots with trees were significantly drier than the control plots at all depths (Fig. 6.3.3.1.2). At 6.0 m from the trees, the top 0-40 cm layer of soil was significantly drier with trees than in the control plot during the dry season, and during the rainy season it was also drier with the Kitui and Siakago provenances. Furthermore, the plots with trees were drier at greater depths during dry season 3 (85-125 cm) than the control plots (Fig. 6.3.3.1.2).

Table 6.3.3.1.2: Comparison of VSWC between provenances and control using lsd at soil depth ranges of 0-40, 45-80 and 85- 125cm measured at 1.5 and 6 m from tree rows in trial 1 at Machakos during dry season 3 and maize 3 season of the long rains of 1999.

Provenance and control	1.5 m from the trees					
	Dry season			**Rainy season**		
	0-40 cm	45-80 cm	85-125 cm	0-40 cm	45-80 cm	85-125 cm
Ishiara	14.4^{ab}	17.4^{ab}	18.9^{a}	17.4^{b}	18.8^{b}	19.0^{b}
Kibwezi	14.3^{ab}	17.2^{ab}	19.1^{a}	17.3^{b}	18.7^{b}	19.3^{b}
Kitui	14.0^{b}	16.8^{b}	19.2^{a}	17.1^{b}	18.2^{b}	19.1^{b}
Siakago	14.2^{b}	17.0^{ab}	19.1^{a}	17.2^{b}	18.5^{b}	18.8^{b}
Control	15.5^{a}	18.8^{a}	20.3^{a}	18.5^{a}	21.7^{a}	22.1^{a}
Sed	0.5	0.9	0.9	0.6	1.3	1.1
Lsd	1.2	1.9	1.9	1.0	2.7	2.2
	6.0 m from the trees					
Ishiara	14.6^{b}	17.8^{a}	19.1^{a}	17.9^{ab}	20.3^{a}	19.3^{b}
Kibwezi	14.6^{b}	17.4^{a}	19.4^{a}	17.7^{ab}	20.2^{a}	19.9^{ab}
Kitui	14.4^{b}	17.2^{a}	19.3^{a}	17.3^{b}	20.0^{a}	20.2^{ab}
Siakago	14.3^{b}	17.0^{a}	19.8^{a}	17.2^{b}	19.9^{a}	19.3^{b}
Control	15.5^{a}	18.8^{a}	20.3^{a}	18.5^{a}	21.7^{a}	22.1^{a}
Sed	0.4	1.5	1.0	0.6	0.8	0.9
Lsd	0.9	2.9	2.2	1.2	1.9	2.1

Lsd = least significant difference (p = 0.05), sed = standard error of differences of means.

Mean values in same column followed by different letters are significantly different



Horizontal bars denoted by sed 1, sed 2 and sed 3 are standard errors of difference between means when comparing treatment at 40, 80 and 125 cm of soil depths respectively.

Figure 6.3.3.1.2 VSWC in the plots containing *Melia* provenances and in control plots vertically into the soil profile **a)** 1.5 m and **b)** 6.0 m from tree rows in trial 1 at Machakos during four weeks of dry season preceding the maize 3 season.

6.3.3.2 Effect of provenances on soil moisture content between silking and maize grain filling stages (18th May to 15th June 1999)

When analysis of interaction between provenances, distance and depth was carried out during the maize grain formation stage of maize 3 season as that in dry season 3 (Table 6.3.3.1), there was no significant interaction between provenances, distance and depth. However, when comparing individual provenances with control plots (Table 6.3.3.2.1) there was a significantly (p = 0.05) lower VSWC in the Kitui and Siakago provenance plots than that of control plots.

6.3.3.2.1 Soil moisture at different distances from the tree rows

When comparing provenances at each sampled distance from trees with control plots (Table 6.3.3.2.1), there was a significantly lower VSWC in the Siakago and Kitui provenances than control plots at 0- 4.5 m and 0- 2.5 m from the trees respectively.

Table 6.3.3.2.1: VSWC in the plots containing *M. volkensii* provenances at different distances from tree rows and that of control plots lacking trees between maize "silking" and "grain filling" stage during the maize 3 season of the long rains of 1999 in trial 1 at Machakos.

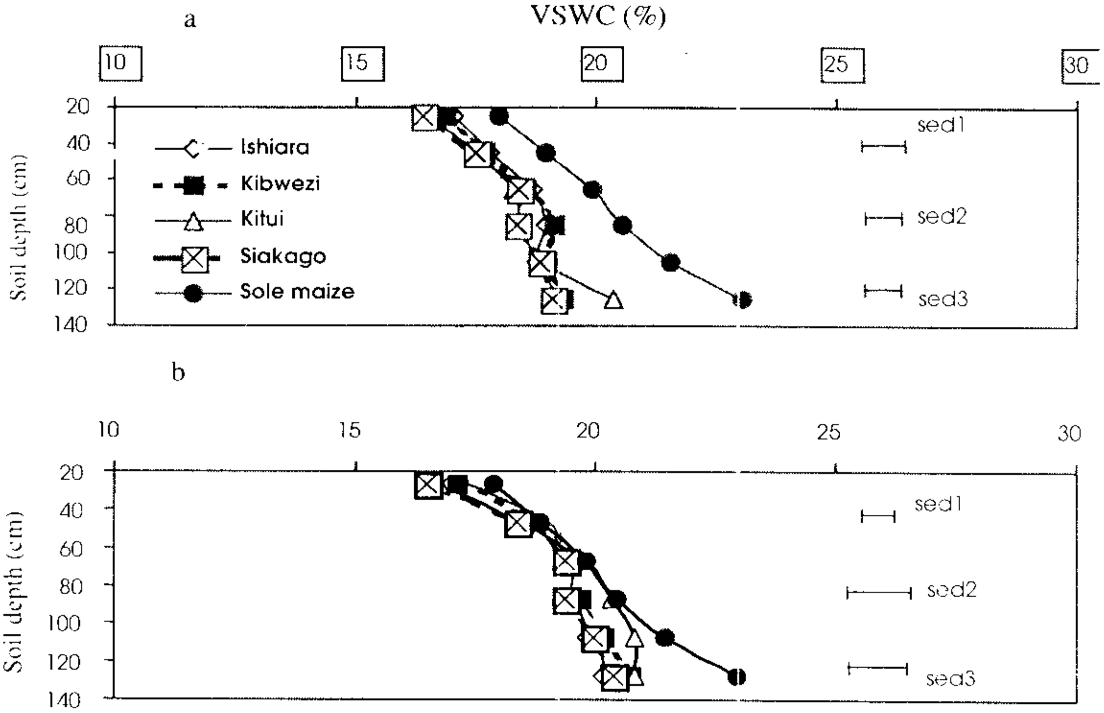
	Distance from tree rows				
Provenance	1.5 m	2.5 m	4.5 m	6.0 m	Mean
Ishiara	18.3^{ab}	18.4^{ab}	18.4^{a}	18.5^{a}	18.4^{ab}
Kibwezi	18.2^{ab}	18.3^{ab}	18.3^{a}	18.4^{a}	18.3^{ab}
Kitui	17.8^{b}	17.9^{b}	18.2^{a}	18.4^{a}	18.2^{ab}
Siakago	17.7^{b}	17.9^{b}	18.1^{b}	18.2^{a}	18.0^{b}
Control	19.3^{a}	19.3^{a}	19.3^{a}	19.3^{a}	19.3^{a}
Lsd	1.5	1.4	1.3	1.5	1.2

Lsd = least significant difference ($p = 0.05$)

Mean values in same column followed by different letters are significantly different

6.3.3.2.2 Soil moisture at different depths in the soil profile

Vertical depletion of soil moisture in the profile was determined separately at 1.5 and 6.0 m from trees as done previously for dry season 3 (section 6.3.3.1.2). When comparing provenances at each depth range at 1.5 m and 6 m from trees (Table 6.3.3.1.2), results indicated that there was significantly lower soil water in the provenance plots at 0-40 cm depth at both 1.5 m and 6 m from trees when compared with that of control plots at same depth. Furthermore, when comparing provenances using SED at each depth range (Fig. 6.3.3.2.2), there was no significant difference in soil moisture between the provenances at all depths. However, when comparing provenances and control plots, there was a significantly lower VSWC in the provenance plots at all depths when compared with control at 1.5 m from the trees and only at 0-40 cm depth at 6 m from trees. In addition, trees exploited soil moisture beyond 85-125 cm depth when compared with that of control plot at the same depths.



Horizontal bars denoted by sed 1, sed 2 and sed 3 are standard errors of difference between means when comparing treatment at 40, 80 and 125 cm of soil depths respectively.

Figure 6.3.3.2.2 VSWC in the plots containing *Melia* provenaces and in control plots vertically into the soil profile **a)** 1.5 m and **b)** 6.0 m from tree rows in trial 1 at Machakos for four weeks period during maize 3 season at silking to maize grain filling stages.

6.4 Discussion: impacts of trees on soil moisture

The study covered 3 seasons, representing three different rainfall conditions.
The first maize season of long rains of 1998 received exceptionally high rainfall when El Nino rains which started in 1997 were subsiding. The second season of short rains of 1998 received very low rainfall leading to failure of maize cob formation and the third season of long rains of 1999 received moderate rainfall which was below the seasonal average (Fig. 6.3.1.1). Soil moisture recharge at each season depended on the rainfall amounts. The highest soil recharge occurred in maize 1 season when more than average seasonal rainfall was received and least recharge occurred in maize 2

season when little rainfall was received. At the long rains of 1999 (maize 3 season) when trees were 3 years old, moderate rainfall was received enabling evaluation of tree effects on soil water in horizontal and vertical distance from trees.

Generally, the results indicated that whenever it rained, soil moisture was recharged and gradually decreased as rainfall ceased and reached the lowest point during the dry seasons. At each sampling date, the provenance plots were drier than the control plots lacking trees (Fig. 6.3.2.1). However, there was no soil moisture difference between provenances at the plot level. The fact that there was more soil drying in the provenance plots than in control plots at each season, implies that soil water was being lost either through evaporation, deep drainage or transpiration and since control plots lacking trees were replicated in the same manner and experienced similar environmental conditions to those of replicated provenance plots; and that control plots were wetter than those of provenances, it implies that the difference in these was mainly as a result of trees' transpiration. Additionally, interception of rainfall by the tree canopy might have contributed to less recharge close to trees than in the control plot. Broadhead (2000) reported that *Melia* canopy intercepted about 5% of incident rainfall when trees were 5 years old.

In the provenance plots where all distance and depths under observation were examined, the results highlighted that the Kitui and Siakago provenances were drier than the sole maize control plots close to the trees e.g. Table 6.3.3.1.2. However, when provenances, distance and depth interactions were examined (Table 6.3.3.1), the results further highlighted that there was no significant interactions between provenance x distance, provenance x depth and distance x depth. Lack of clear interactions between provenance, distance and depth could be probably due to tree age, because trees at 2 to 3 years may be too young to cause a significant distance effect on soil water. For example, Mutua (1997) reported that 2 year old *Grevillea robusta* affected crop yield very close to the tree but at age 4, its impact on crop yield extended beyond 5 m from trees. During Mutua's study, soil moisture content was 15-16% (which was closer to 11% wilting point (Kiepe, 1995)) and tree dbh was 3.4 cm and 6.1 cm at age 2 and age 4 respectively compared with 9 cm diameter of *Melia* trees at age 3 and soil moisture content of 20% in this study. Alternatively soil water availability at VSWC of 20% at varying distance from trees was equally high thus making interaction between provenance and distance insignificant in this study. In this study, soil water increased by 3 % from 1.5 to 6 m from trees at age 3, when soil moisture content was 9% (VSWC) above the plant wilting point. Previous studies (Odhiambo, 1999) at the same site indicated that the difference in VSWC at 2 m and 6.5 m from *Grevillea robusta* trees was 10% when trees were 5 years old implying that, with time, trees influence on VSWC increases in magnitude both vertically and horizontally. Compared to the Odhiambo study, the current study had 30% higher soil moisture than Odhiambo's because of the carried over El Nino rains effect and therefore tree's impact on soil moisture might have been negligible. For instance, during Odhiambo's study the VSWC in the control plots was 16.0 % while in this study VSWC was 20.4 %: a 30% more of the available soil water. Kiepe (1995) reported that intercropped maize were water stressed at around 14% VSWC before wilting point. In this study crops had far greater available soil water, thus explaining the lack of significant differences in VSWC between provenances x distance interactions.

When examining the provenance effects on soil profile moisture by comparing VSWC in the provenances plots at specified depths (Table 6.3.3.1.2), results highlighted that the provenances had 9% lower soil moisture at the surface (0-40 cm depth) closer to the trees compared to control plots. Furthermore, the provenances were found to exploit soil water also at deeper layers when compared to control plots at same depths e.g. Table 6.3.3.1.2.

Generally, the results did not indicate any significant interactions between provenances, distance and depths but there was some indication that interactions will probably be manifested with time as trees mature. This was so because at age 3 years, provenances had significant impact on surface soil moisture extending to 4.5 m from tree rows. There are however other underlying factors that may have caused provenance differences not to show. These include, (i) the trees were too young i.e. < 3 years during the study period to exert any significant impact on total VSWC in the large plots and (ii) the *Melia* provenances might not differ in the way they exploited soil water.

Because of the absence of differences in soil water between provenances and lack of interaction between provenances, distance and depths, further evaluations are required to investigate whether provenance differences will show with time, as differences in soil water between provenances have been reported to be influenced by other factors such as tree size and transpiration demands. For instance, Ong *et al.* (1999) reported that trees size differences may impose different water demands thus affecting soil water requirements between plots occupied by different tree sizes. The provenances were planted at the same time and diameter difference between provenances was less than 5% with largest diameter (dbh) of 10 cm which still indicated that they were too small to differently affect soil water.

6.5 SAP FLOW

6.5.1 Introduction

The processes governing transpiration, namely soil, tree and environmental conditions are reviewed in Chapter 1. Environmental factors affecting transpiration rates include radiation, temperature and relative humidity (McIntyre *et al.*, 1996). Whenever soil water is unlimited and evaporative mechanism e.g. relative humidity and radiation are adequate, transpiration rates are highest when leaf area and stomatal conductance are greatest (Jarvis, 1975).

Sap flow measurements have been used in estimating transpiration rates in conditions where soil moisture is limited (McIntyre *et al.*, 1996) especially where atmospheric demand exceeds transpiration rates. The heat pulse method was recommended as the most appropriate for estimating transpiration rates of trees (Hatton *et al.*, 1995) and for this reason, was used in this section of the study. Shulze *et al.*, (1995) observed that sap flow movement was closely related to transpiration rates and could therefore be used to measure transpiration rates.

For this study, the two *Melia* provanances which showed greatest difference in growth rates and soil water contents within their plots were selected. These were the Kitui and Kibwezi provenances, (Kitui has greater dbh than Kibwezi) (see Chapter 5) and had more effect on soil water. The selection of trees depending on size was done because earlier studies had reported that the tree size is positively related to transpiration rates (Hatton *et al.*, 1995). The study tested; (i) transpiration in relation to tree size, (ii) transpiration rate in relation to leaf cover, (iii) transpiration rate in relation to soil moisture and environmental factors and (iv) potential transpiration rates of the *Melia* provenances.

6.5.2 Methodology

6.5.2.1 Sap flow

The Kitui and Kibwezi *Melia volkensii* provenances were used in the sap flow estimation study for the reasons stated earlier. The sap flow was measured using the heat pulse gauges developed at ICRAF (Khan and Ong, 1996). The design was adopted from QM-54 heat pulse theory (Greenspan Technology Queensland, Australia, 1995). The heat pulse gauges consist of two sensor probes embedded in the downstream and upstream of xylem sapwood and separated by a heater probe. The heater probe normally sends a pulse of heat which is eventually detected by probe sensors down and up stream. Each sensor probe is made of thermocouples placed at 0.5 cm, 1.5 cm and 2.5 cm from the tip. The sensor probe pair is placed in vertical plane to measure sap flow velocities upstream and downstream at 0.6 cm below and 1.2 cm above the heater probe respectively (Fig. 6.5.2). A heat pulse which is sent from the heater probe travels downstream through sap by conduction and convection and upstream through diffusion. The difference in time taken for the heat pulse sent by the heater probe to reach maximum temperature at the down and upstream sensor probes is called the heat pulse time. When sap flow is high, the heat pulse is rapidly detected and when it is low, it takes a longer time to detect.

Three sets of gauges were used to measure heat pulse velocities at different loci on the stem to allow for variability in sap flow density due to uneven development of xylem conducting sapwood between cambium and heartwood.

Heat pulse velocity i.e. the rate of ascent heat pulse within conducting wood (Vh) was calculated using the following equation.

$Vh = (X_d - X_u)/2t_o$ (mm/ min) Equation (1)

where X_d and X_u are distances downstream and upstream respectively from the heater and t_o is the heat pulse time.

Heat pulse velocity (Vh) was converted to sap flow rate using the equation described in section 1.4.1.1.2.

Datalogger (CR21X, Campbell Scientific, Leics, UK) was used to record heat pulse velocity from the heat pulse gauges every 30 minutes. Because of the limitations of the datalogger, the two provenances could not be measured simultaneously. For this reason, transpiration rates between the provenances could not be compared directly because they were measured at different occasions. However, regression relationships between transpiration rates and soil moisture and leaf cover were used to evaluate transpiration rates for each provenance.

Heat gauges were installed on each *Melia* provenance for 14-16 days and then shifted to the other for the same period of time. Three trees per treatment were wired at the same time, each with 3 sets of probe gauges thus allowing nine probes at each recording. Because of the probes' limited wire length, only three closely planted trees could be used. For the next visit on the same provenance, another different set of three closely planted trees were wired for a new set of sap flow measurements. Use of this number of trees and sensors should allow for problems associated with the varying structure of conducting tissues, tree sizes under study and fluctuating rates of flow between different sections of the xylem. Sap flow measurements were taken during maize seasons (May 1998 to July 1998 and May 1999 to July 1999).

The heat probes were inserted into the trees through pre-drilled holes. The holes were drilled with the help of a guide jig block that contained holes spaced at the appropriate distances for probe spacing. The probe needles were embedded into trees at height of 1.2 m and the diameter of the stem at this height was measured. The drilling was carefully done to avoid (a) disturbing the tissues, (b) tilting from horizontal drill line and (c) drilling through a deformed part of the stem. After inserting the heat gauges, aluminium foil was used to cover the needles to reduce effect of ambient temperatures from interfering with that measured at the probes.

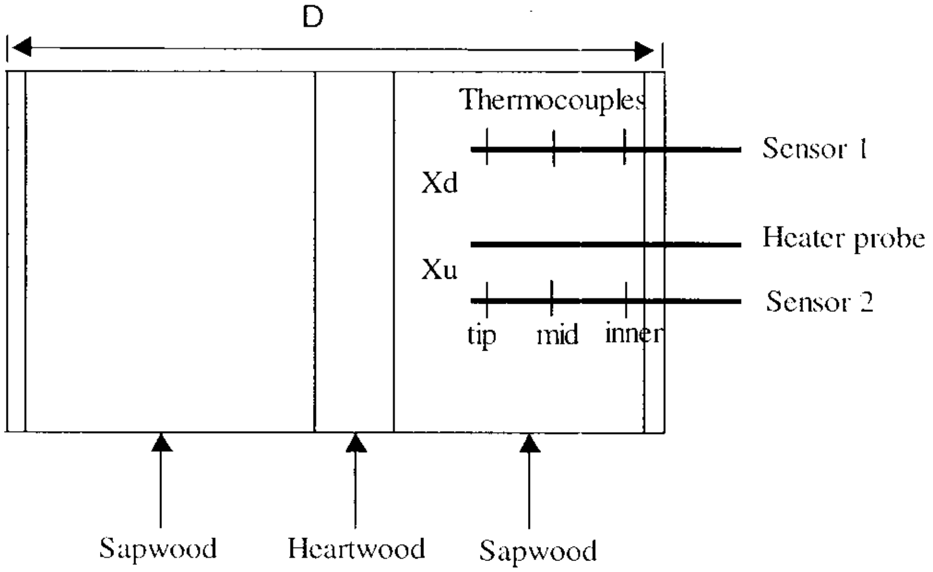


Figure 6.5.2 Illustration of a set of heat pulse gauges inserted into a stem of diameter D and indicating sapwood and heartwood proportion. Xd and Xu are predetermined distances downstream between sensor 1 and the heater probe and upstream between sensor 2 and heater probe for calculating sap velocity respectively. The tip, middle and outer thermocouple positions on the probe sensor are indicated.

6.5.2.2 Sap flow calculations

Sap flow (Q) was calculated from sap flow velocity (Vs) using the following equation (see Appendix 2 for more detailed calculations);

$Q = Vs.A$

where, Q = sap flux, Vs = sap flow velocity and A = wood conducting area.

Wood conducting area (A) was determined by removing a cross section of wood where the heat sensors were implanted. Two stem cross sections were obtained from each provenance at the height where probes were inserted to give an indication of sapwood and heart wood fractions (Fig. 6.5.2.2). The red colour of the heartwood indicates closed lumen vessels and therefore is used to indicate the non-conducting part of the stem (Namirembe, 1999). The radius of sapwood and heartwood and finally the annulus area of conducting wood (Aw) were calculated.

To demonstrate how the conducting wood area was determined, the Kitui provenance whose stem diameter at the height where probes were inserted was 6.8 cm is used here as an example. The sap flow (by probes) was estimated in an annulus of 2.5 cm as follows;

(i) Area covered by probes and conducting (A1) as depicted in Figure 6.5.2.2., is calculated as;

$A1 = \pi\, 3.4^2 - \pi(3.4-2.5)^2 = 33.76$ cm^2

(ii) Area potentially conducting and not covered by probes (A2) is calculated as

$A2 = \pi\, 3.4^2 - [\pi\, 3.4^2 - \pi(3.4-2.5)^2] - \pi\, 0.5^2 = 1.77$ cm^2

The wood conducting area (Aw) is therefore given as;

$Aw = A1+A2$

$= 35.53$ cm^2

The stem cross sectional area is $\pi\, 3.4^2 = 36.54$ cm^2.

The conducting area was 97% of total annulus area of the stem.

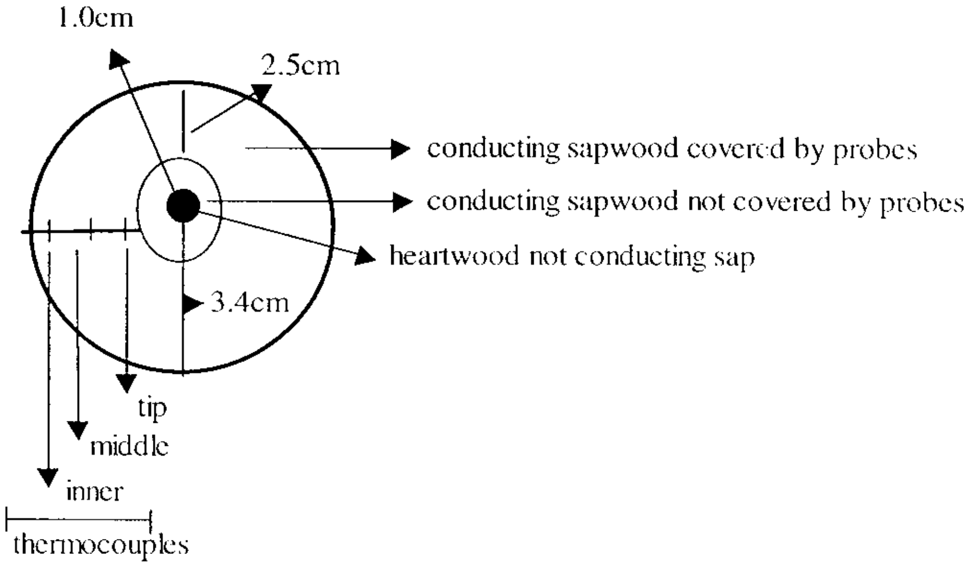


Figure 6.5.2.2 Cross section of a stem illustrating annulus of conducting and non-conducting areas of wood and inserted probe indicating the three positions of the thermocouples.

The sap velocity data was averaged in half hourly intervals for each probe thermocouples and stored in the datalogger. From these recorded data, average sap velocity of 12 hours a day during sun light hours for each thermocouple was obtained. The 12 hour sap velocity (mm hr^{-1}) was further adjusted by a constant value of 4.2, indicated in the night flow. This night flow value was subtracted from daytime sap flow and then multiplied with wood conducting area to give sap flow rate (cm^3 hr^{-1}) by using the derived sap flow equation. Conversions of sap flow from cm^3 hr^{-1} to litres day^{-1} were also done.

6.5.2.3 Phenology

The status of tree canopy was scored subjectively according to leaf abundance. In each plot, two weekly canopy assessments were carried out on ten trees (from trees 3 to 12). Abundance of leaf cover was estimated at five randomly selected branch tips visually by scores of 1 to 5 which were expressed as percentage of the highest score (5). Leaf gaps or yellowing at the branch tips were used to indicate abundance of leaf production and loss. Maximum canopy cover was scored as 5 and canopy without green leaves was scored as 1. Flowering and fruiting were not considered because the trees were not yet mature.

6.5.3 Results

6.5.3.1 Factors affecting transpiration rates

Because sap flow was not measured simultaneously on both provenances but at different times, environmental factors e.g. radiation, temperature, relative humidity and soil moisture might have differed at each measuring occasion between provenances. For this reason, multiple regression was used to analyse which environmental factors influenced sap flow at each measuring occasion.

When multiple regression analysis of environmental factors affecting transpiration was carried out (Table 6.5.3.1) there was a significant ($p = <0.001$) influence of radiation and temperature on transpiration rate. For example, when relationship between sap flux and solar radiation of the combined provenances with time was obtained (Fig. 6.5.3.1), results indicated that radiation positively influenced sap flow. Similarly, when relationship between sap flux and soil moisture for each provenance was obtained (Fig. 6.5.3.2) there was a positive increase of transpiration rate with soil moisture. Furthermore, there was no significant difference ($p = 0.737$) in sap flow between provenances.

Transpiration rates of 2-3 year-old *Melia* trees ranged between 2 to 5 liters day^{-1} during dry and wet seasons respectively (Fig. 6.5.3.1).

Table 6.5.3.1: Probability values from multiple regression analysis examining the environmental factors affecting transpiration rates of *Melia volkensii* provenances at Machakos.

Source of variation	F pr.
Radiation	0.001**
Temperature	0.001**
VSWC	0.077
Relative humidity	0.437
Provenance	0.737

** means significant at $p = 0.001$

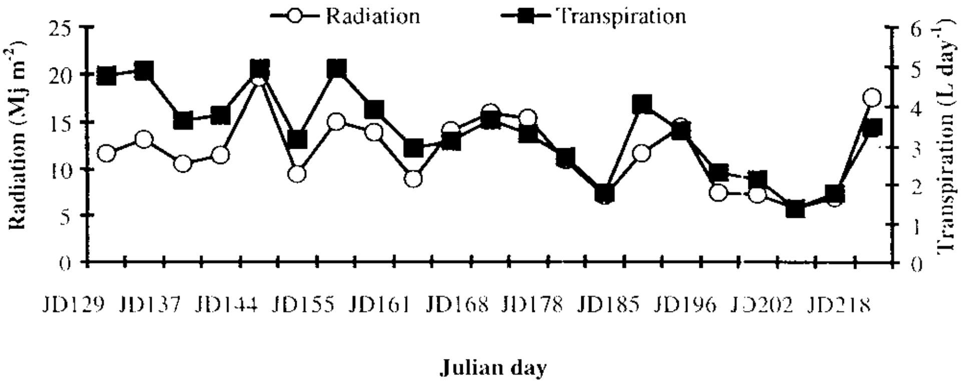


Figure 6.5.3.1 Trends of transpiration rates and solar radiation with time indicating that transpiration rates are influenced by radiation in trial 1 at Machakos.

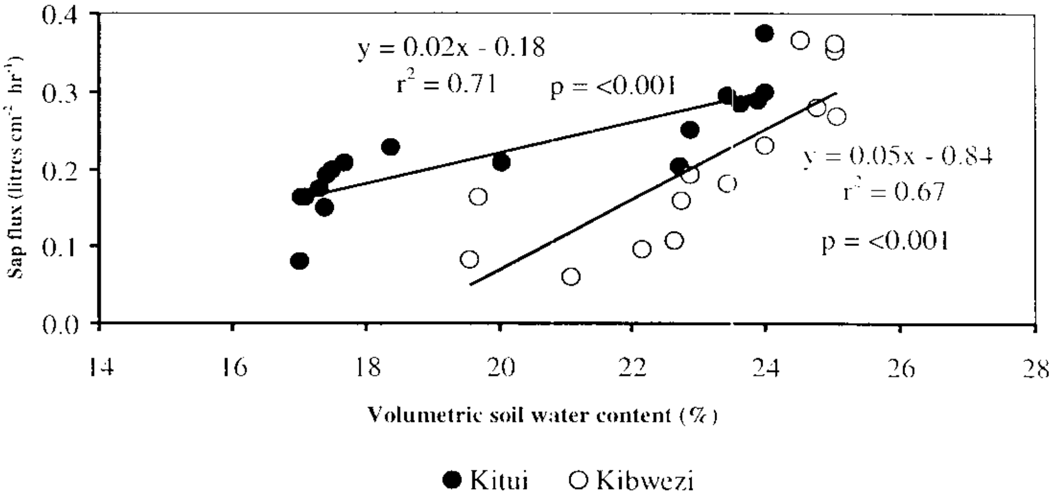


Figure 6.5.3.2 Relationship between transpiration rates and all distance and depth volumetric soil water content for both the Kitui and Kibwezi *Melia volkensii* provenances during sap flow determination in trial 1 at Machakos at age 2-3 years.

When examining the relationship between tree size and sap flow rate (Fig. 6.5.3.4) there was a significant relationship ($r^2 = 0.78$, $p = 0.019$).

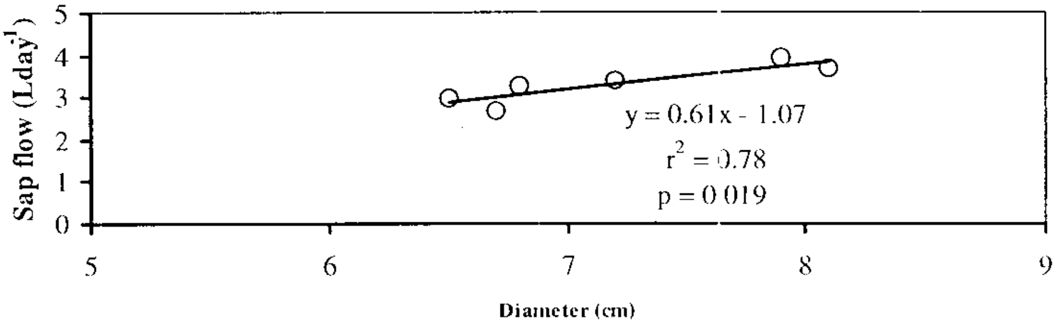


Figure 6.5.3.3 Relationship between tree size and daily sap flow per tree in trial 1 at Machakos.

6.5.3.1.1 Effect of leaf cover on transpiration rates

When the relationship between leaf cover and transpiration was obtained (Fig. 6.5.3.1.1) results indicated that the transpiration rate does not always change directly with increased leaf cover. Furthermore, when regression analysis between transpiration and leaf cover for each provenance was carried out, results indicated that there was no significant relationship between sap flux and leaf cover (Kitui, $r^2 = 0.23$, $p = 0.123$ and Kibwezi, $r^2 = 0.54$, $p = 0.081$).

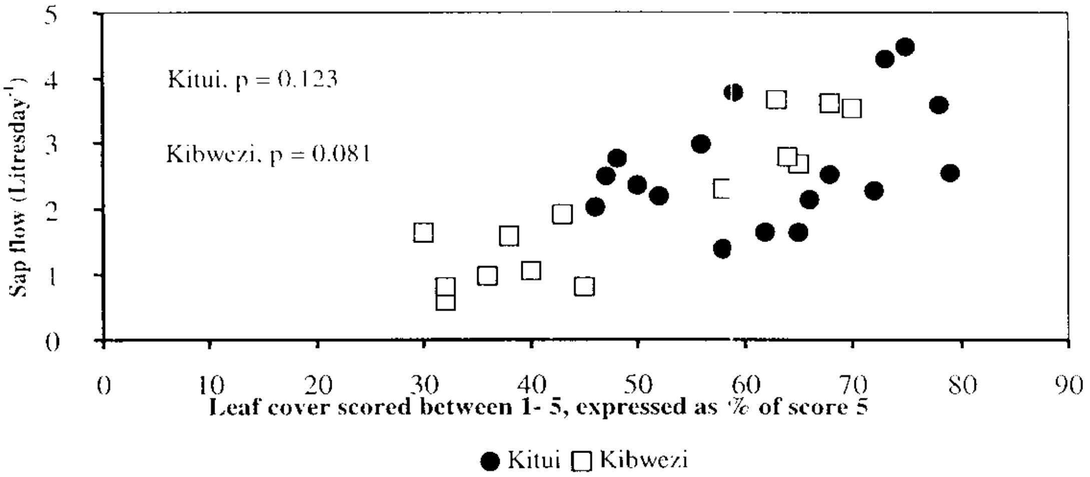


Figure 6.5.3.1.1 Trends of leaf cover and transpiration rates over same period for the Kitui and Kibwezi provenances in trial 1 at Machakos.

While examining phenology of the *Melia* provenances with time (Fig. 6.5.3.1.2), results indicated that the leaf cover percentage reach a peak twice a year at the beginning of each rain season. The canopy cover was lowest in the mid of dry seasons (Fig. 6.5.3.1.2), but at least 30% of the leaves were retained.

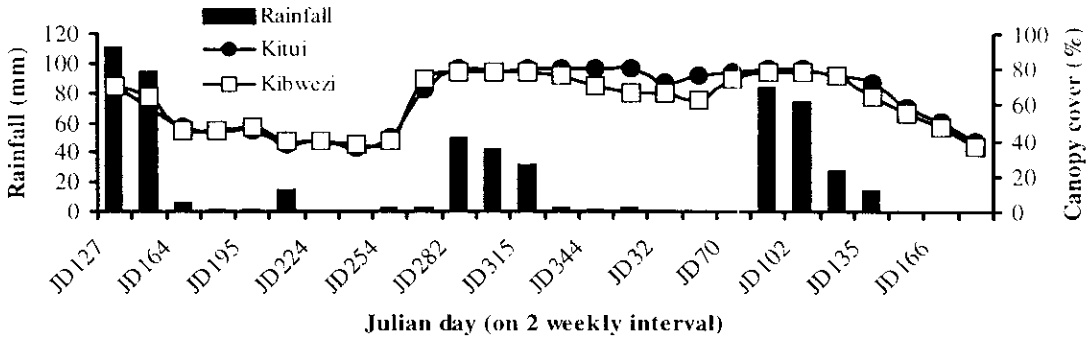


Figure 6.5.3.1.2 Canopy cover expressed as percentage of full leaf cover for the Kitui and Kibwezi *Melia volkensii* provenances in trial 1 at Machakos.

6.5.3.3 Sap flow density between sapwood and heartwood

The diameters at breast height (dbh) where the probe needles were inserted for the Kitui and Kibwezi provenance were 6.8 and 6.6 cm respectively. The probe needles penetrated 2.5 cm into the stem. After cutting across the wood section where probe needles were inserted (Table 6.5.3.3.1) results indicated that the probes did not reach the heartwood, thus there was some potentially conducting wood unmeasured. The heartwood covered less than 1 cm annulus in both the provenances. By ranking the Kibwezi had greater heartwood area than the Kitui provenance when trees were 3 years old (Table 6.5.3.3.1).

When comparing sap flow rate between thermocouples on a probe, the inner (thermocouple near the outer part of the stem) had greater sap flow rates than those of the middle and tip thermocouples (Fig. 6.5.3.3.1). Because of the differences between thermocouples, transpiration rates in this study were calculated from the average of the three thermocouples.

Table 6.5.3.3.1: The cross section of stem of the Kitui and Kibwezi *Melia* provenances indicating the diameter of heartwood and sap wood where heat pulse probes were inserted

Provenance	Tree no.	Diameter (dbh) cm	Heartwood (cm)	Sapwood (cm)
Kitui	1	7.2	1.0	6.2
Kitui	2	6.4	0.9	5.5
Kibwezi	1	6.9	1.1	5.8
Kibwezi	2	6.4	1.0	5.4

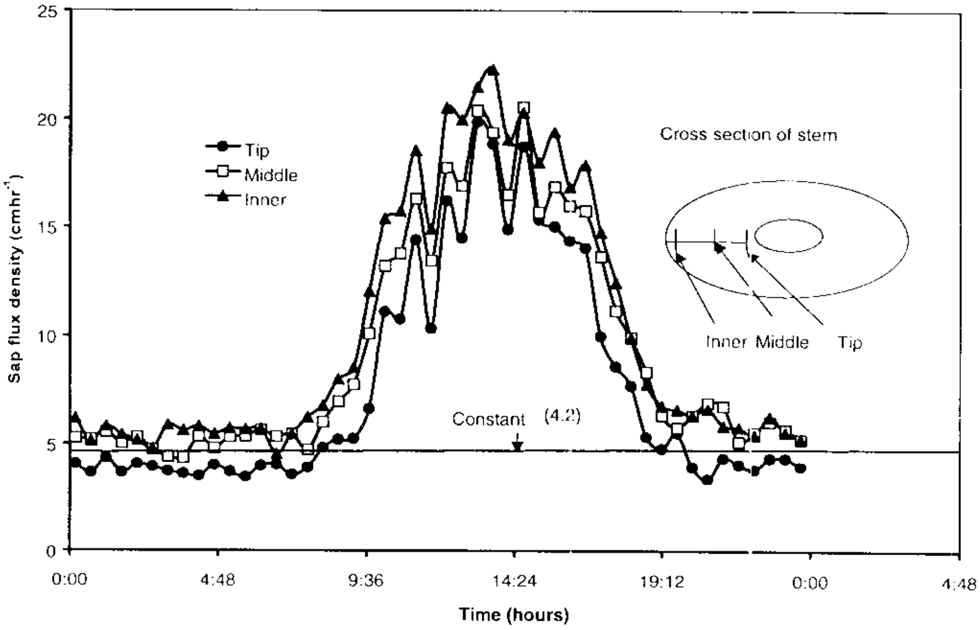


Figure 6.5.3.3.1 Diurnal sap flow rate in *Melia volkensii* stem at inner (0.5 cm), middle (1.5 cm) and tip (2.5 cm) of probe thermocouples for the Kitui provenance during maize 1 season. A constant value of 4.2 recorded when the stems are not transpiring (night) which is normally subtracted from sap flux densities is superimposed.

6.5.4 Discussion: sap flow rate of *Melia* provenances

Using the heat pulse method, results highlighted that the *Melia volkensii* provenances transpired as much as 5 litres per day per tree at near maximum canopy cover (Fig. 6.5.3.1). Transpiration continued throughout the dry season but at a reduced rate of approximately 2 litres per day, at reduced canopy cover of about 35%. Although leaf cover closely matched the soil moisture patterns, exceptions occurred when *Melia* trees started leaf flushing during the dry periods and leaf shedding in the middle of rain season. Such incidences where leaf shedding occurred during rain seasons have been attributed to either flowering, fruiting or simply leaf senescence and leaf flushing during drought have been attributed to hormonal activities induced by environmental changes (Kramer, 1980).

The results further indicated that transpiration rate is positively influenced by solar radiation, temperature, soil moisture and tree size. For instance, when effects of environmental conditions on transpiration were analysed (Table. 6.5.3.1), there was a significant effect of radiation and temperature on transpiration rate. When evaluating the relationship between transpiration rate and soil moisture for individual provenances there was also a significant relationship between soil moisture and transpiration. Thus, the difference in sap flow rates between provenances indicated in Figure 6.5.3.2 was more related to environmental conditions than to provenance differences. Furthermore, tree size influenced the amount of the transpiration rates per day ($r^2 = 0.78$, $p = 0.019$) (Fig. 6.5.3.3). This is expected, for bigger trees have extensive root networks which capture soil water from deeper soil profiles. However, the relationship between transpiration rate and leaf cover highlighted that transpiration rates of the *Melia* provenances were not directly influenced by leaf area. This is probably because transpiration rates are reported not only to depend on the percentage of canopy cover but also on other factors such as environmental and soil conditions (Grime, 1992). For instance, Kramer (1980) reported that trees manage environmental stress by adjusting to atmospheric conditions and when moisture becomes limiting by either closing some leaf stomata or eventually by leaf loss. Similar results were reported by Hatton *et al.* (1995) in which transpiration rates of *Eucalyptus* spp. were largely influenced by tree size as well as environmental conditions. In contrast, Namirembe (1999) reported transpiration rates responded positively to leaf cover when reduced by physically removing some of the leaves, in which transpiration rate of *Senna spectabilis* reduced drastically as leaves were removed.

The sap conducting wood of *Melia* provenances between 2 and 3 years of age covered 97 percent of wood cross sectional area and more heartwood was deposited as trees matured, thus leading to decrease of the sap flow density towards the heartwood. When cross sections of 12 a year old tree stem was obtained (results were not presented in this study), heartwood had covered 90% of the wood cross section indicating less wood conducting area as trees mature. Previous studies indicated that the conducting vessel size of *Senna* trees is greatly reduced towards heartwood as was sap flux density (Namirembe, 1999).

There were however some limitations in the study e.g. it was not possible to make comparison of transpiration rate between *Melia* provenances. That is, the heat pulse method could not be installed simultaneously on different provenances for comparisons. Also, the trees used in the study did not have sufficiently different diameters to enable studies of tree size effect on soil moisture.

In general, the overall results of this chapter indicated that the *Melia* provenances were not different in the way they exploit soil moisture. This assertion was supported by the fact that there was no significant difference in VSWC between provenances and furthermore no significant interactions between provenances, distance and depths occurred. In addition, transpiration rate for 2-3 years old *Melia* provenances ranged between 2 to 5 litres per day per tree during dry and wet season respectively. This rate of transpiration was greater than that of *Senna spectabilis* of 4 litres per day per tree reported in previous studies carried out in the same site (Namirembe, 1999). Transpiration rates and water use were largely dependent on tree size, soil moisture and solar radiation. Additionally, the *Melia* provenance had significant impact on soil moisture at shallow depths close to the trees compared with treeless plots at age 3 years but greater negative impact might occur as trees mature. The results further highlighted that the *Melia* provenances were able to exploit soil moisture below the crop rooting zone. Without differences in soil moisture between provenances, were there differences in crop yield between provenances? Results of this study are presented in Chapter 7.

CHAPTER SEVEN

7.0 CROP GROWTH AND YIELDS

7.1 Introduction

This study was conducted because in simultaneous agroforestry systems where tree and crop roots share the same soil horizons, competition for below ground resources between trees and crops is exhibited through the crop growth and grain yields. Previous studies have reported that competition for soil moisture produced crops with smaller diameter and height than those grown without trees (Howard *et al.*, 1995; Namirembe, 1999; Odhiambo, 1999). Consequently, the affected crops produce smaller cobs and lower grain yield compared to crops free from competition (Jonsson *et al.*, 1988).

Whereas others (Odhiambo, 1999; Schroth, 1996; Jonsson *et al.*, 1988) have evaluated interspecific differences in competition between trees and crops, the current study (trial 1) looks at provenance variations of *Melia volkensii* and how they affect the associated crop growth. For comparison, other species were also used (trial 2).

Although crop yield effects are a summation of below and above ground competition, this study focused more on below ground competition. Howard, (1997) reported that shading of crops by overstorey trees affect crop photosynthesis which results in reduced crop leaf area and less dry matter production than the unshaded crops. For this reason, light interception by *Melia* trees was also evaluated to indicate whether crop shading by trees had an effect on crop growth and yield (trial 1, 2 and 5). Trial 5 consists of isolated *Melia* trees on farmers' fields.

In addition, the effect of *Melia* litter fall on soil fertility was evaluated using growth of maize plants grown in potted soil collected under and outside tree canopies. This experiment (trial 7) was carried out after observations made during freely available soil water conditions (El Nino rains) indicated that maize plants under the *Melia* canopy produced greater yield than those in the open, implying that soil under the canopy was more fertile.

Crop measurements such as root collar diameter, shoot height, leaf area and grain yield (Wilson *et al.*, 1998) were used to indicate tree effects on crops by comparing sole crop with those grown in tree plots.

7.2 Methodology

7.2.1 Maize growth measurement

Growth was monitored in trial 1 by conducting non-destructive and destructive measurements of crop growth as in previous studies (Namirembe, 1999; Lott, 1998; Howard, 1997), in plots with and without trees between 20 and 90 days after sowing (DAS). The measurements were done during the three maize seasons 1, 2 and 3 (long rains of 1998 (LR98), short rains of 1998 (SR98 and long rains of 1999 (LR99) respectively). In trial 1, measurements were restricted to the plots containing Kitui and Kibwezi provenances which differed significantly in their growth. As mentioned earlier (Chapter 4), the Kitui provenance had greater diameter than that of the Kibwezi provenance. In trials 2 and 5, only the grain yield measurements were obtained. In trial 7 (pot experiment), maize dry weight was measured destructively.

For non-destructive measurements, a total of 12 maize plants per plot were labelled with tape and used for repeated measurements of maize root collar diameter and heights for 90 DAS as described in 2.3.5.1. The labelled plants were located 6 plants away from the edge of the plot to avoid edge effects.

For destructive sampling to estimate leaf area (LA), the same number of maize plants from the same maize rows as in the non-destructive method were cut at ground level and leaves for each plant were put in labelled bags. After removing the leaves the remainder of the maize plant which at some stage included stem and cobs was put in another bag. Leaf area was determined using 0.5 cm diameter core samples as described in Chapter 2 section 2.3.5.1.

7.2.2 Maize grain harvesting

The maize yields in trials 1 and 2 were obtained from harvesting the mature maize cobs in the plots at specified maize rows on both sides of the tree during the long rains of 1998 and the long rains of 1999 as described in Chapter 2 section 2.6.3. Yields per hectare were determined by multiplying average yield per plant with number of plants in a hectare. In trial 1, the plots measured 20 x 30 m as described in Chapter 2 and since planting density was pre-determined (1 x 0.3 m), with row length along the 20 m side thus obtaining 66 maize plants per row and stocking density of 33,333 maize plants ha^{-1}.

On the farmers' fields (trial 5), maize grain yield per hectare were estimated non-destructively from measurements of maize cob diameter and length since the destructive maize harvesting method used in the research trials (trial 1and 2) above was unacceptable to farmers because it took away some of their harvest. Instead, the relationship between maize cob volume and dry grain weight determined from maize cob samples taken at Machakos as described in section 2.3.6 (Fig. 2.3.6.1) was used to convert cob volume to grain yields which was later multiplied by stocking density to give yield per hectare.

The dry biomass of the maize pot experiment (trial 7) which was established at ICRAF headquarters nursery to evaluate soil fertility between soil collected under and outwith the *Melia* canopy was destructively sampled by cutting plants at root collar diameter and after drying them in the oven at 70°C for 4 days.

7.2.3 Light interception by *Melia* tree canopy

Photosynthetic active radiation (PAR) was measured using a Sunfleck Ceptometer (Decagon Devices Inc., Oregon, U.S.A) between the 12:00 hrs and 14:00 hrs under and outwith tree canopy ensuring that light conditions did not vary greatly when measuring PAR under and above or under and outwith canopy. Since PAR readings were found to vary within short distances under the canopy (McIntyre *et al.*, 1996), the average of several measurements were used.

At Machakos research trial 1, PAR was recorded on north and south side of the tree rows at maize rows 1, 3 and 5 to determine the extent of tree shade. The trees were planted along east to west direction for reasons explained in Chapter 2. Measurements were done during the maize seasons (April to May in the LR98 and LR99) at maize cob formation stages when the trees had most of their leaves. The intercepted light fraction was estimated using the equation adopted from McIntyre *et al.*, (1996):

$$L_{par} = 1-(Pu / Po)$$

where L_{par} is the fraction of intercepted light, Pu is the PAR reading under the canopy and Po is the PAR reading in the open.

In farmer's fields at Kitui, PAR was recorded during the maize growing season of the long rains of 1999 during the month of April when maize growth was at the cob formation stage. For each single tree average light interception was determined as in the Machakos trial above.

7.2.4 Analysis

Crop growth and yield measurements for each sampling occasion for whole plots were compared between treatments by ANOVA.

Since repeated measurements were carried out for crop growth, split-plot analysis of variance was used to establish differences between provenances at each measuring occasion. The interaction between provenance and distance was also examined, with each distance from tree rows treated as a sub plot. In addition, provenances and control at each specified distance from trees were compared. Least significant differences (lsd) were determined when Fisher's F-test was significant.

The relationship between maize grain yield and distance from trees at the farmer's fields was tested by regression.

When comparing potted maize biomass grown in soil from under and outwith the tree canopy, difference in maize growth was tested by ANOVA using canopy position and site as factors.

7.3 Results

7.3.1 Effect of provenances on maize leaf area in trial 1

When examining the interaction between provenances and distance (Table 7.3.1.1), results indicated that there was no significant interaction between provenances and distance at any of the dates, at any maize seasons. Furthermore, when comparing the effect of provenance (Table 7.3.1.1), results indicated that there was a significant leaf area difference between provenances only at 20 DAS during maize 1 season (long rains of 1998). There was also a significant LA difference between individual provenance and control plots at 20 DAS during the maize seasons 1 and 2.

Table 7.3.1.1: Probability values of ANOVA examining interactions of maize leaf area (LA) between *Melia* provenances and distances from trees at different dates after sowing in trial 1 during maize seasons 1, 2 and 3 at Machakos.

Source of variation	Days after sowing (DAS)			
	20	40	60	90
		Maize 1 season		
Provenances (P)	0.049*	0.476	0.961	0.558
Distance (D)	0.026*	0.097	0.964	0.363
P x D	0.324	0.942	0.977	0.871
Kitui x control	0.028*	0.101	0.961	0.284
Kibwezi x control	0.039*	0.174	0.943	0.348
		Maize 2 season		
Provenances (P)	0.158	0.471	0.533	0.688
Distance (D)	0.077	0.002*	0.019*	0.147
P x D	0.921	0.855	0.669	0.777
Kitui x control	0.011*	0.119	0.162	0.299
Kibwezi x control	0.048*	0.233	0.321	0.337
		Maize 3 season		
Provenances (P)	0.318	0.961	0.533	0.329
Distance (D)	0.008*	0.964	0.314	0.361
P x D	0.461	0.977	0.757	0.886
Kitui x control	0.123	0.955	0.399	0.158
Kibwezi x control	0.257	0.944	0.349	0.213

* means significant at $p = 0.05$

There were significant distance effects in maize seasons 1 and 3 at 20 DAS (Table 7.3.1.1), because there was greater LA close to trees than in the open during the maize 1 season and the reverse occurred at the maize 3 season (see also Table 7.3.1.1).

Table 7.3.1.2: Comparison of LA (m^2) per plant between provenances at different distances from trees at 20 DAS, during maize seasons 1 and 3 at Machakos.

Distance from tree rows	Maize 1 season		Maize 3 season	
	Provenances			
	Kitui	Kibwezi	Kitui	Kibwezi
1 m	0.14^a	0.15^a	0.27^b	0.31^b
3 m	0.10^b	0.11^b	0.35^a	0.38^a
5 m	0.10^b	0.11^b	0.36^a	0.39^a
lsd	0.04	0.04	0.08	0.08

Values with similar letter across the row or down the column are significantly different.

7.3.2 Effect of provenances on maize root collar diameter and height in trial 1

When comparing *Melia* provenances (Table 7.3.2.1), there was no significant difference in diameter between provenances at any of the dates, at any maize season. However, when comparing provenances and control plots, there was a significantly greater average diameter in the control plots than in the provenance plots at all the dates during maize seasons 2 and 3 and at 40-90 DAS during the maize 1 season.

Furthermore, when evaluating the effect of shading on maize diameter by comparing provenances with shade cloths and control plots (Table 7.3.2.1), there was only a significant difference between provenances and shade cloths at 20 DAS during the maize 1 season.

Table 7.3.2.1: Comparison of maize root collar diameter (mm) between *Melia* provenances, shade cloths and control plots at different dates after sowing in trial 1 during maize seasons 1, 2 and 3 (LR98, SR98 and LR99 respectively) at Machakos.

Treatments	Days after sowing			
	20	40	60	90
		Maize 1 season		
Control	9.9^{b}	18.9^{a}	19.2^{a}	18.8^{a}
25% shade	13.2^{a}	15.3^{b}	15.0^{b}	14.9^{b}
50% shade	13.6^{a}	15.7^{b}	14.9^{b}	13.8^{b}
Kibwezi	9.3^{b}	16.3^{b}	16.3^{b}	16.1^{b}
Kitui	8.7^{b}	15.9^{b}	16.5^{b}	15.9^{b}
lsd	2.3	2.5	2.4	2.6
		Maize 2 season		
Control	13.5^{a}	15.1^{a}	15.3^{a}	15.2^{a}
25% shade	9.9^{b}	12.1^{b}	12.4^{b}	12.5^{b}
50% shade	10.3^{b}	12.3^{b}	13.1^{b}	12.9^{b}
Kibwezi	11.2^{b}	12.2^{b}	11.9^{b}	10.8^{b}
Kitui	10.7^{b}	10.9^{b}	10.8^{b}	10.5^{b}
lsd	2.1	2.1	2.2	2.1
		Maize 3 season		
Control	17.2^{a}	19.8^{a}	20.3^{a}	18.8^{a}
25% shade	13.2^{b}	16.4^{b}	16.2^{b}	16.6^{ab}
50% shade	12.4^{b}	14.7^{b}	15.1^{b}	14.9^{b}
Kibwezi	13.2^{b}	15.3^{b}	15.9^{b}	15.1^{b}
Kitui	13.2^{b}	15.8^{b}	16.6^{b}	15.7^{b}
lsd	2.9	2.5	2.3	2.5

Diameter values in the same column in each maize season followed with different letters are significantly different at p = 0.05.

Similarly, when comparing average maize height between treatments as carried out for diameter above (Table 7.3.2.2), there was no significant difference between *Melia* provenances at any date in all the maize seasons. However. there was a significant difference in height between provenances and control at 40- 90 DAS during the maize seasons 2 and 3. Furthermore, when examining the shade effect on height growth (Table 7.3.2.2), there was a significant difference in height between shade cloths and provenances at 60-90 DAS during maize 3 season, with plants performing better with shade than with trees.

Table 7.3.2.2: Comparison of maize heights (cm) between *Melia* provenances, shade cloths and control plots at different dates after sowing in trial 1 during maize seasons 1, 2 and 3 (LR98, SR98 and LR99 respectively) at Machakos.

Treatments	Days after sowing			
	20	40	60	90
Maize 1 season				
Control	58.8^{b}	135.4^{a}	186.9^{a}	179.3^{a}
25% shade	94.1^{a}	108.5^{b}	160.7^{b}	166.9^{a}
50% shade	99.6^{a}	116.7^{b}	165.4^{b}	146.8^{a}
Kibwezi	58.2^{b}	120.6^{ab}	174.1^{ab}	171.5^{a}
Kitui	57.7^{b}	118.3^{ab}	169.9^{ab}	168.9^{a}
lsd	12.8	18.3	19.8	22.9
Maize 2 season				
Control	67.6^{a}	90.7^{a}	92.8^{a}	90.1^{a}
25% shade	60.8^{a}	83.8^{ab}	85.6^{a}	85.3^{ab}
50% shade	61.1^{a}	76.4^{ab}	79.3^{a}	78.9^{ab}
Kibwezi	63.5^{a}	71.5^{b}	72.9^{b}	70.5^{b}
Kitui	60.9^{a}	67.6^{b}	69.3^{b}	66.9^{b}
lsd	10.4	19.3	18.8	19.6
Maize 3 season				
Control	92.0^{a}	136.0^{a}	182.5^{a}	176.4^{a}
25% shade	80.5^{a}	124.2^{ab}	173.7^{a}	172.9^{a}
50% shade	85.7^{a}	124.5^{ab}	171.9^{a}	171.1^{a}
Kibwezi	77.4^{a}	112.1^{b}	138.2^{b}	139.5^{b}
Kitui	78.8^{a}	113.7^{b}	138.5^{b}	140.0^{b}
lsd	18.2	23.2	29.5	25.8

Height values in the same column followed with different letters in each maize season are significantly different.

7.3.3 Interactions between provenance and distance

When interaction between provenances and distance was analysed (Table 7.3.3.1), there was a significant interaction between provenances and distance from trees at 20 DAS during maize 1 season and at all dates during maize 2 season when examining the maize diameter growth.

Furthermore, when interaction between provenances and distance was examined for maize height (Table 7.3.3.1), there was no significant interaction between provenances and distance at any date, at any season.

Table 7.3.3.1: Probability values from ANOVA examining the interaction between provenances and distance of maize root collar diameter and height at different dates after sowing in trial 1 during the maize seasons 1, 2 and 3 (LR98, SR98 and LR99 respectively) at Machakos.

Source of variation	**Diameter**				**Height**			
	Days after sowing (DAS)							
	20	40	60	90	20	40	60	90
Maize 1 season								
Provenances (P)	0.447	0.758	0.930	0.844	0.761	0.795	0.631	0.491
Distance (D)	0.001**	0.001**	0.001**	0.001**	0.022*	0.001**	0.002*	0.001**
P x D	0.005*	0.329	0.541	0.404	0.081	0.940	0.492	0.329
Maize 2 season								
Provenances (P)	0.361	0.229	0.234	0.333	0.609	0.573	0.568	0.611
Distance (D)	0.039*	0.008*	0.005*	0.014*	0.251	0.022*	0.023*	0.003*
P x D	0.027*	0.036*	0.039*	0.045*	0.069	0.051	0.063	0.051
Maize 3 season								
Provenances (P)	0.994	0.667	0.234	0.736	0.753	0.898	0.984	0.999
Distance (D)	0.013*	0.170	0.055	0.215	0.038*	0.087	0.036*	0.056
P x D	0.229	0.609	0.070	0.556	0.143	0.818	0.963	0.914

*, ** means significant at p = 0.05 and 0.001 respectively.

Because significant interactions between provenance and distance only occurred at 20DAS during maize seasons 1 and 2, distance effects were therefore examined at different distances from trees at these dates (Table 7.3.3.2). Results indicated that diameters were smaller close to the trees than away from trees.

Table 7.3.3.2: Comparison of maize root collar diameter between provenances at different distance from trees at 20 DAS during maize seasons 1 and 2 at Machakos.

Distance from tree rows	Maize 1 season	Maize 2 season
1 m	7.3^b	9.2^b
3 m	9.4^a	11.7^a
5 m	9.6^a	11.4^a
lsd	2.2	2.1

Values with similar letter in each column are significantly different.

7.3.4 Effect of different *Melia* provenances on maize yield in trial 1

When comparing provenances (Table 7.3.4.1), there was no significant difference in grain yield between provenances at any maize season. However, when comparing provenances and shade cloths, there was a significantly greater maize grain yield in the Ishiara and Kibwezi provenances than in the 50% shade cloth plots during the maize1 season.

Similarly, when comparing provenances during the maize 3 season as in the maize 1 season, there was also no significant difference in yields between provenances. However, when comparing provenances, shade cloths and control plots, there was significantly greater grain yield in the controls and 25% shade cloths than in the provenance plots during maize 3 season. Furthermore; the Kitui, Siakago and Kibwezi provenances had lower grain yield than that under the 50% shade net.

Table 7.3.4.1: Comparison of maize grain yields (tonnes ha^{-1}) between *Melia* provenances and control plots at trial 1 during maize seasons 1 and 3 (long rains of 1998 and long rains of 1999 respectively) at Machakos.

Source of variation	Maize 1 season	Maize 3 season
Control	3.0^{ab}	1.9^{a}
25% shade	2.9^{ab}	1.7^{a}
50% shade	2.7^{b}	1.6^{ac}
Ishiara	3.2^{a}	1.3^{bc}
Kibwezi	3.2^{a}	1.2^{b}
Kitui	3.1^{ab}	1.1^{b}
Siakago	3.1^{ab}	1.1^{b}
lsd	0.4	0.4

Lsd = least significant difference of means (p = 0.05)

Values in the same column followed by different letters are significantly different

7.3.5 Effect of tree species on maize grain yields in trial 2

When comparing species (Table 7.3.5.1), there was no significant difference in maize grain yield between *Melia* and other species during the maize 1 season. However, when similar comparison was carried out during maize 3 season (Table 7.3.5.1), there was a significantly greater maize yield in the *Melia volkensii* than in *Senna spectabilis* plots. Furthermore, there was a significantly reduced grain yield close to the tree species compared to that of control plots, during maize 3 season.

Table 7.3.5.1: Comparison of maize grain yields (tonnes ha^{-1}) between species and control plots at trial 2 during maize seasons 1 and 3 (long rains of 1998 and long rains of 1999 respectively) at Machakos.

Source of variation	Maize 1 season	Maize 3 season
Control	3.7a	2.2^{a}
Gliricidia sepium	3.6a	0.7^{bc}
Grevillea robusta	3.7a	0.8^{bc}
Melia volkensii	3.4a	0.9^{b}
Senna spectabilis	3.3a	0.5^{c}
lsd	0.5	0.4

Lsd = least significant difference of means (p = 0.05)

Values in the same column followed by different letters are significantly different.

7.3.6 Effect of distance from trees on maize grain yield in trial 1 and trial 2

When provenances and distance effects were analysed (Table 7.3.6.1), there was no significant provenance x distance interaction in trial 1 at any season. There was also no significant interaction between species and distance in trial 2 at any season.

Table 7.3.6.1: Probability values from ANOVA examining interactions between provenances and distance from the trees in trial 1 and 2 during maize seasons 1 and 3 (LR98 and LR99 respectively) at Machakos.

Source of variation	Maize 1 season	Maize 3 season
	Melia provenances (trial 1)	
Provenance (P)	0.725	0.773
Distance (D)	0.251	0.001**
P x D	0.415	0.517
	Species trial (trial 2)	
Species (S)	0.511	0.102
Distance (D)	0.001**	0.001**
S x D	0.751	0.118

** means significant at p = 0.001.

Interestingly, in both trials, maize grain yields were greater close to the trees during the maize 1 season, and the reverse in the maize 3 season (Table 7.3.6.2).

Table 7.3.6.2: Comparison of maize grain yields (tonnes ha^{-1}) between tree treatments and control plots in both trials 1 and 2 during the maize seasons 1 and 3 (long rains of 1998 and long rains of 1999 respectively) at Machakos.

Source of variation	**Distance from the trees**					
	1 m	3 m	5 m	1 m	3 m	5 m
	Maize 1 season			**Maize 3 season**		
	Melia provenance trial (trial 1)					
Control	3.0^{a}	3.0^{a}	3.0^{a}	1.9^{a}	1.9^{a}	1.9^{a}
Ishiara	3.3^{a}	3.1^{a}	3.1^{a}	0.9^{b}	0.9^{b}	1.2^{b}
Kibwezi	3.2^{a}	3.1^{a}	3.0^{a}	1.0^{b}	0.9^{b}	1.1^{b}
Kitui	3.2^{a}	3.0^{a}	2.9^{a}	0.7^{b}	0.7^{b}	0.8^{b}
Siakago	3.3^{a}	3.1^{a}	2.8^{a}	0.7^{b}	0.8^{b}	0.9^{b}
lsd	0.6	0.6	0.5	0.6	0.6	0.7
	Species trial (trial 2)					
Control	3.5^{a}	3.5^{a}	3.5^{a}	2.1^{a}	2.1^{a}	2.1^{a}
Gliricidia sepium	3.9^{a}	3.6^{a}	3.3^{a}	0.1^{c}	0.5^{b}	0.9^{bc}
Grevillea robusta	3.9^{a}	3.7^{a}	3.4^{a}	0.6^{b}	0.6^{b}	1.2^{b}
Melia volkensii	3.5^{a}	3.6^{a}	3.3^{a}	0.7^{b}	0.7^{b}	1.3^{b}
Senna spectabilis	3.6^{a}	3.4^{a}	3.1^{a}	0.2^{c}	0.5^{b}	0.6^{c}
lsd	0.6	0.5	0.6	0.4	0.6	0.5

Lsd = least significant difference of means ($p = 0.05$)

Values in the same column followed by different letters in each trial are significantly different.

When relationship between provenances and distance from the trees was obtained (Fig. 7.3.6.1), results indicated that there was a suppressed maize grain yield close to the trees in trial 1 during the maize 3 season. Furthermore, the provenance trees had negatively affected maize yield up to 9 m from trees compared with control plots lacking trees. Similarly, when relationships between species and distance from the trees were obtained (Fig.7.3.6.2), there was maize yield reduction close to the trees compared with control plots. Furthermore, maize yield was significantly reduced in the *Senna spectabilis* and *Gliricidia sepium* plots compared with the *Melia volkensii* close to the trees during the maize 3 season.

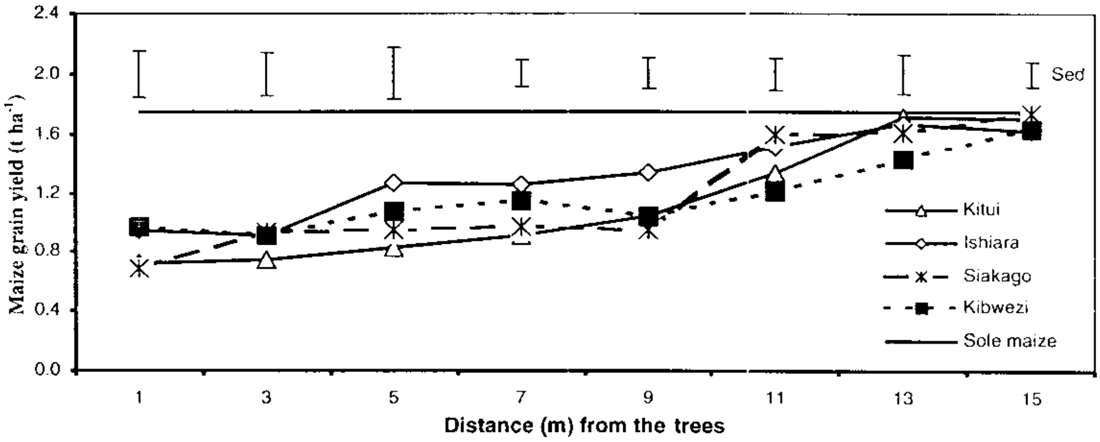


Figure 7.3.6.1 Relationship between maize yield and distance from the trees in trial 1 during maize 3 seasons (long rains of 1999) at Machakos.

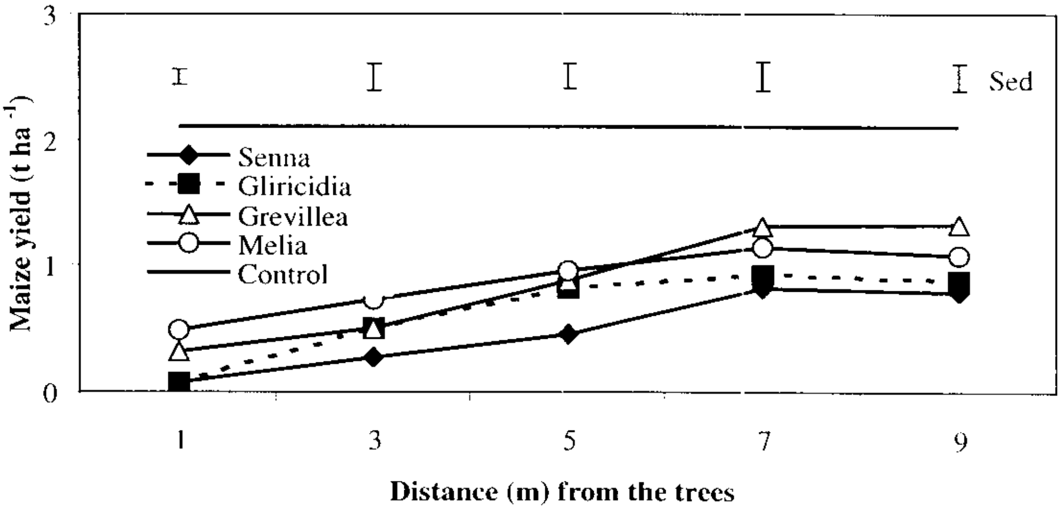


Figure 7.3.6.2 Relationship between maize yield and distance from the trees in trial 2 during maize 3 seasons (long rains of 1999) at Machakos.

7.4 Effect of isolated *Melia volkensii* trees on maize yield in trial 5 (on farmers' fields)

When the relationship between maize yields and distance from trees was obtained (Fig. 7.4.1a), there was a greater yield under the tree canopies than in the open during maize 1 season, similar to the results from trial 1 in the same season. Maize yield under the canopy was 18% greater than outwith the canopy during the maize 1 season

(El Nino rains). However, the yields during maize 3 season were the reverse of maize 1 season (Fig.7.4.1b) in which greater maize yield was obtained away from the trees.

Furthermore, when tree size effect on maize yield was evaluated for maize 3 season (Fig. 7.4.2), there was a negative relationship between tree size (dbh) and maize yield within10 m annulus from the trees.

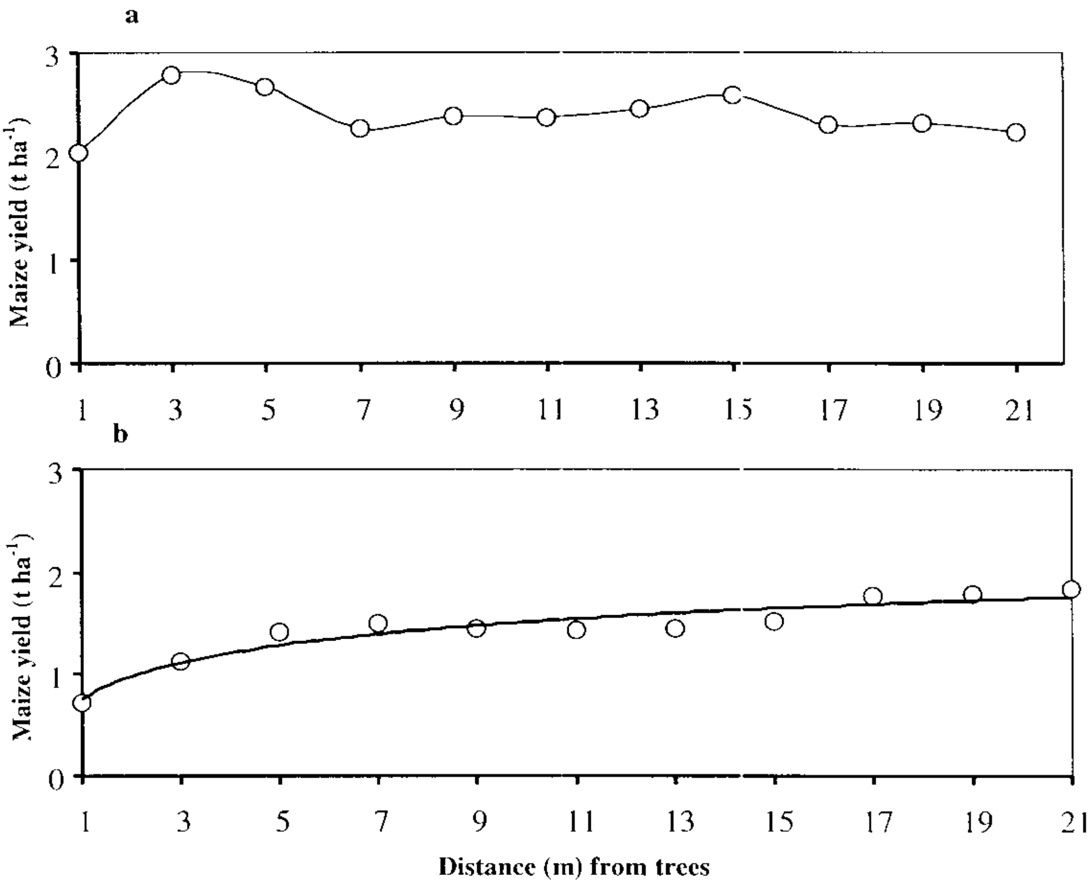


Figure 7.4.1 Relationship between maize grain yield and distance from the isolated trees during **a)** the long rains of 1998 (El Nino rains season) and **b)** the long rains of 1999 at Kitui farmers fields.

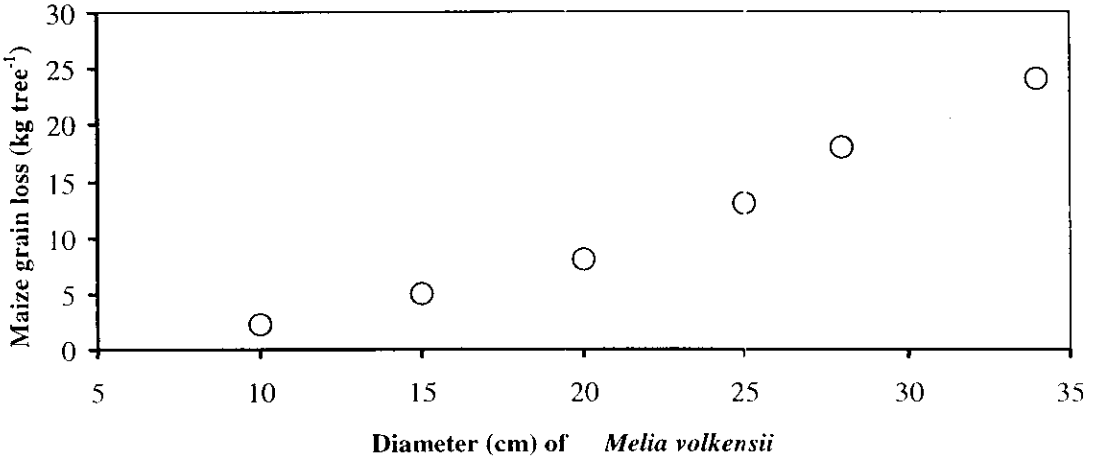


Figure 7.4.2 Relationship between the *Melia volkensii* tree size with maize grain yield loss on the farmers' fields at Kitui during the maize 3 season.

7.5 Effect of *Melia volkensii* trees on soil fertility under the canopy

In follow up to the results of maize grain yield during maize 1 season (Fig. 7.4.1a) when greater yields were obtained under than outwith the tree canopy, trial 7 examined whether these unexpected results were due to enhanced soil fertility under the canopy. A comparison of maize dry biomass grown in soils collected under and outwith the *Melia* tree canopies from sites at Kitui, Machakos and Embu was made (Fig. 7.5.1). Results indicated that maize plants grown in the under canopy soils had a significantly ($p = 0.015$) greater biomass compared with those grown in the outwith canopy soils (see Plate 4). Furthermore, when soil positions and site interaction were analysed (Table 7.5.1) there was no significant interaction between site and sampling positions.

Table 7.5.1: Probability values from ANOVA examining dry matter of 8 week old maize seedling grown in soil collected under or outwith isolated *Melia volkensii* tree canopies, in farmers fields.

Source of variation	F.pr
Block	0.991
Site	0.859
Position	0.015*
Site x position	0.64

* means significant at $p< 0.05$

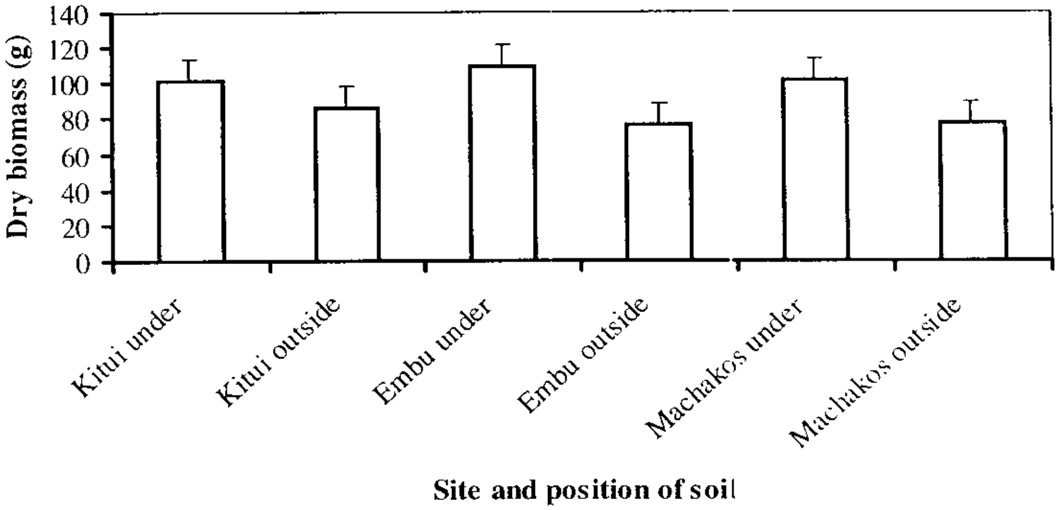


Figure 7.5.1 Dry biomass of 8 weeks old maize plants grown in soils collected from under or outwith *Melia volkensii* tree canopies at Kitui, Embu and Machakos farmers fields.

Plate 4: Pot soil fertility experiment showing maize plants grown in soils collected from outwith (left) and under the tree canopies (right).

7.6 Effect of tree shade on maize yield

Studies on light interception were carried out to determine whether the amount of shade cast by different trees at different trials (trials 1, 2 and 5) was related to differences in crop yield.

When intercepted photosynthetically active radiation (PAR) in trial 1 was compared between tree plots and control plots at different distance from trees (Table 7.6.1), results indicated that the tree canopy intercepted 37 and 50% of incident radiation at 1 m from trees during maize seasons 1 and 3 respectively, at maize cob formation stages. However, at 5 m from trees, the intercepted PAR in the tree plots was close to that in the control plots lacking trees.

When similar comparison of intercepted PAR was carried out in trial 2 as trial 1 above, the intercepted PAR in the tree plots at 1 m from the trees was significantly greater than that in the control plots lacking trees (Table 7.6.1). Furthermore, the light intercepted by *Gliricidia sepium* and *Senna spectabilis* plots (70 and 60%

respectively) greatly exceeded that intercepted by *Melia volkensii* (42%) and *Grevillea robusta* (43%) at 1 m from the trees during maize 3 season.

In trial 5, When comparing PAR between under and outwith isolated *Melia* trees canopies in the farmers fields (Table 7.6.2), the amount of intercepted light was 80% of the incident radiation during the maize cob formation stage, which greatly exceeded that of shade cloths. However, on average, the incident PAR passing through tree canopies exceeded 350MJ.m^{-2}.

Table 7.6.1: Comparison of intercepted light PAR expressed as % of PAR in the open between tree plots and control plots at different distances from trees in trials 1 and 2 at Machakos.

Treatment	Distance from trees					
	1 m	3 m	5 m	1 m	3 m	5 m
	Trial 1 (*Melia volkensii* provenance trial)					
	Maize 1 season			Maize 3 season		
Control	0^{b}	0^{b}	0^{a}	0^{b}	0^{b}	0^{a}
Kibwezi	38^{a}	12^{a}	2^{a}	48^{a}	25^{a}	5^{a}
Kitui	37^{a}	15^{a}	2^{a}	46^{a}	28^{a}	6^{a}
lsd	7	8	4	8	6	8
	Trial 2 (Species comparison trial)					
Control	0^{c}	0^{b}	0^{a}	0^{d}	0^{b}	0a
Gliricidia sepium	70^{a}	14^{a}	3^{a}	68^{a}	15^{a}	0^{a}
Grevillea robusta	38^{b}	13^{a}	2^{a}	43^{c}	13^{a}	3^{a}
Melia volkensii	36^{b}	17^{a}	2^{a}	42^{c}	16^{a}	4^{a}
Senna spectabilis	61^{a}	14^{a}	1^{a}	58^{b}	14^{a}	3^{a}
lsd	10	11	8	10	9	9

Values in the same column followed with different letters in each trial are significantly different

Table 7.6.2: Light interception by isolated *Melia volkensii* trees on the farmers' fields during maize cob formation stages of long rains of 1999 at Kitui.

Tree number	Open PAR(Mj.m^{-2})	Under PAR(Mj.m^{-2})	Intercepted light (%)
1	1907	350	82
2	1893	333	82
3	1926	568	71
4	1816	334	82
5	1972	402	80
6	1940	406	79
7	1210	276	77
8	1469	278	81
9	1637	327	80
Mean	1752	364	79
Se	87	30	2

Se = Standard error of means

7.7 Discussion

In each season, crop yield will be determined by water, nutrient and light availability. In the maize 1 season, rainfall was in excess of the seasonal average and the only limiting resources at this season were either soil nutrients or light. During the maize 2 season, soil water was limiting because inadequate rainfall was received. At this season, only growth analysis results were obtained because maize plants failed to form cobs.

Furthermore, trees during the maize 1 season were too young and were therefore not expected to affect maize yield greatly. Given that the amounts of rainfall in maize seasons 1 and 2 were extreme rainfall cases for the study site (see Chapter 6), tree effect on crop yield was evaluated in detail during the maize 3 season when close to average rainfall (see Chapter 6) was received and when trees were more mature and likely to have more impact on crops.

When comparing provenances, there were no significant differences in LA between provenances on any of the sampling occasions, at maize seasons 2 and 3 (Table 7.3.1.1), although LA generally increased with time after sowing reaching a peak at

60 days after sowing (Table 7.3.2.1). There was no difference in crop growth between provenances. For example, no differences in maize LA, diameter and height occurred between provenances at any dates, at any season. However, there were differences in leaf area when maize plants at 1 m from the trees were compared with treeless control plots at 20 days after sowing during the maize 1 season when water was freely available. At this period soil moisture was freely available and differences could have been due to tree shading. Similarly, there was also a significant difference in diameter when maize plants in the tree plots at 1 m from the trees were compared with control plots at any dates during the maize seasons 2 and 3 and at 40-90 DAS during maize 1 season. This implies that maize diameter was more sensitive to imposed tree effects (i.e. shade, competitive use of below ground resources) than with LA and height.

At final harvesting, when comparing provenances (Table 7.3.4.1), there was no significant difference in maize grain yields between provenances. Furthermore, when comparing *Melia volkensii* and other species (Table 7.3.5.1), results showed higher yields in the *Melia* plots close to trees than in the *Senna* plots during the maize 3 season. Generally, maize yield observations in the provenance and species trials, indicated that there was greater yield close to the trees during the maize 1 season and the reverse in the maize 3 season (Fig. 7.5.1). Similarly, when the relationship between maize yield and distance from isolated trees was obtained (Fig. 7.6.1), there was also greater yield close to trees (under the canopy) during maize 1 season and the reverse during the maize 3 season, similar results as trial 1 for same seasons. During the maize 3 season when seasonal rainfall was close to that of the site, the closer to the trees the lesser the yields. In fact, reduced maize yield extended up to 9 m from trees in both trials during the maize 3 season when trees were 3-4 years old.

When evaluating the effect of shading on crop growth and yield, there was a significant difference in maize diameter between control plots and shade cloths during maize 3 season whereas no such differences occurred with maize height. Furthermore, when comparing control with shade cloths (Fig. 7.3.4.1), there was no difference in maize grain yield between shade cloths and control. These results imply that although the shading affected maize diameters the final grain harvest was not greatly affected compared to control plot. However, when comparing shade cloths and provenances during the same season, there was a significant difference in maize yield between provenances and shade cloths, although the shade intensity between them were not different. Thus, the shading effects with shade cloths or trees did not affect maize yield greatly but other factors e.g. below ground competition was involved too. Results highlighted that tree canopies of *Melia* provenances intercepted about 37-50% of incident radiation at 1 m from the trees. *Gliricidia* and *Senna* intercepted about 60 and 70% incident radiation respectively at 1 m from the trees. Similar findings were reported by McIntyre *et al.* (1996) in which *Senna spectabilis* intercepted 44 to 75% of incident PAR in the 1st maize row depending on plant density and none at 6th maize row from the trees at Machakos. In this study, *Melia* provenances intercepted greater light (PAR) than the 25% shade cloth but less than 50% shade cloths, and *Gliricidia sepium* and *Senna spectabilis* intercepted greater light than 50% shade cloths. However, mature isolated *Melia* trees on farmers' fields intercepted about 80 % of the incident radiation which greatly exceeded those of 3 year old *Melia* and 50% shade nets. Given the shading effects of trees, shade cloths and control plots, the only significant difference in maize yields that can be associated with shading occurred in *Senna* and *Gliricidia* tree plots where 60-70% shading reduced yield greatly compared to those of *Melia* and *Grevillea* at 1 m from trees. The radiation use efficiency for maize was estimated as 1.4-1.7 g MJ^{-1} (Lott *et al.*, 1997) which requires a minimum PAR of 400 MJ m^{-2}; which is 15% of the incident radiation. In this study, the incident radiation was greater than 20 % of incident radiation at any determination occasion. During rainy seasons when soil water is freely available (e.g. El Nino rains), crop yield was greater under the canopy than in the open, implying that tree shading had little effect on maize yields and that soil water had greater impact on crop yield. Previous studies (Howard, 1997) reported that interception of 76% of incident light did not reduce maize yield significantly compared to open plots. Similarly, Jonsson *et al.* (1999) reported that interception of 80% of incident radiation by *Parkia biglobosa* did not also significantly reduce millet yields under the canopies compared to the open fields. In contrast, Corlett *et al.* (1992) found that millet growth in the early stages of development under trees were significantly greater than that of sole crop but by 59 days after sowing the trend reversed and by 90 DAS the millet growth in the open was greater than that shaded by the trees. From these observations, it implies that, suppressed maize growth in the tree plots was not caused by shading alone but other below ground factors are involved too.

When soil moisture is freely available e.g. El Nino rains, *Melia* trees have no negative effect on the crop yields, in fact improved maize cob yield occurred close to the trees than in the open. The yield under the *Melia* tree canopies was 18% greater than that in the open. The reverse occurred during the maize 3 season when soil moisture was limiting. The unexpected results of improved maize yields under the tree canopies were probably caused by improved soil nutrient under the canopy associated with litter fall. The researcher counted an average of 80 pods per m^2 per tree from a sample of five *Melia* trees. Litter fall under tree canopy was reported to improved crop yield, e.g. Rao *et al.* (1998) reported improved millet yield under *Parkia biglobosa* trees compared to that in the open because of enhanced soil nutrients under the trees. To validate the assumption of soil fertility improvement by leaves and pods falling under *Melia* trees, soil samples collected under and outwith canopy from isolated trees on the farmers fields at Kitui, Embu and Machakos were used to raise maize in pots at nursery (trial 7). The results of the pot experiment (Table 7.6.1) highlighted that there was a significantly greater maize dry biomass in the soils collected from under the tree canopy than that from the open when soil water was not limiting.

In addition, while evaluating maize grain yields in the farmers' fields, results further indicated that the tree size greatly influenced the yields within their proximity (Fig. 7.5.2). That, the bigger the trees, the lower the yields obtained close to them and their influence extended beyond 15 m from trees.

Generally, there was no difference in crop growth and yield between provenances. This was explained by the fact that there were no differences in shading, soil water, sap flow and crop yield between provenances during the investigation period. Furthermore, there was no difference in yields when *Melia* was compared with other species except close to *Senna* and *Gliricidia* where the dense shading effect was experienced (60 and 70% respectively).

CHAPTER EIGHT

8.0 GENERAL DISCUSSION AND CONCLUSIONS

Below ground tree-crop competition is an ever-changing phenomenon which is influenced by rainfall and tree age. This changeability was highlighted in this study, which commenced shortly after the El Nino rains, when soil moisture was much more freely available than normal. In this situation, no differences were found between *Melia volkensii* provenances or between species in their effects on either soil water or crop yields when soil moisture was freely available and when trees were young. While the current study found no differences in yield between species, previous studies (Odhiambo, 1999; Broadhead, 2000) reported differences in crop yields between species when soil water was limiting and when trees were 4-5 years of age. However, later, when soil water was limiting, the current study observed that there were differences in maize yields only between *Melia volkensii* and *Senna spectabilis*, and tree x distance interactions which affected crop yields beyond 9 m from 4 year old trees planted in rows, although much of the crop yields differences between the two species is attributed to the heavy shading effects of *Senna* on crops. At the same time, there were no differences in crop yields between provenances although trees had affected yields up to 9 m compared with control plots (Fig. 7.3.6.1). The tree impact was greater for mature isolated *Melia* trees where crop on farm studies indicated that yields were reduced as far as 15 m from the trees. Using similar species to those covered in this study (trial 2), Ong *et al.* (1999) and Odhiambo *et al.* (1999) reported that crop yields in the *Grevillea*, *Melia* and *Gliricidia* line plantings were affected in a zone which increased from 2 m to 6.5 m from trees when the trees were 2 and 4 years old respectively.

Although some farmers believe that *Melia* is not competitive with crops, results from on-farm experimental data clearly indicate otherwise. Isolated mature (= 8 years) *Melia* trees which were crown pruned at the start of each cropping season were found to reduce crop yields within a radius of 15 m from trees (Fig. 7.4.1b). In addition, tree impact on crop yields depended on tree size and therefore planting trees at high density on farms could have a devastating effect on crop yields as trees mature, contrary to what farmers currently believe. Furthermore, these data indicate that current pruning practices, which some farmers believe will reduce competition, are not effective.

Generally, even though *Melia* is competitive, there is great potential to expand *Melia* planting on farms, because it has a higher value than the maize crop it replaces and there is a demand for its timber. Some farmers own large fields and many are already practising *Melia* planting on fallow; a system which could be used by others to grow *Melia* to provide timber and other products instead of crops. Furthermore, results indicated that *Melia* trees improved soil fertility through litter fall which would be beneficial to crops once fallow lands are put back to crops. There are however, dangers of planting more trees on crop land because of the reductions in crop yields and farmers should consider cost-benefit issues. Four trees per hectare were able to compensate for the value of lost maize yields and still make a profit for farmers.

The CI method was not able to predict tree competitivity with crops when applied to closely spaced line tree plantings. This could have been because of the variability in CI between individuals (few trees) to predict crop yields in a large plot with many trees. Furthermore, while evaluating the root architecture method, an interesting observation occurred: the first order roots originating from the stem base which descended deeply (vertically) into the soil developed second order roots that grew towards the surface. This may have resulted in trees with smaller CI values becoming competitive as their second order roots exploited soil resources near the surface in the same way as did the first order shallow roots of trees with higher CI values.

Overall, tree size and root architecture were correlated with water use and crop yields in normal seasons when trees were grown separately. There was a significant relationship between CI values and crop yields where trees are planted separately, implying that shallow rooting reduced crop yields with isolated trees. Studies of plant propagation methods indicated that plants raised from cuttings were more shallow rooted than seedlings, such material might be undesirable in farmers' fields and therefore deeper rooting plants such as seedlings are recommended on croplands.

The main results of chapters of the study are summarised, and conclusions and recommendations are drawn in the following sections.

8.1 Summary of major results and conclusions

- With extreme conditions of soil moisture during the study period, and the failure of the young trees to exert significant impact on below ground resources, made an evaluation of tree-crop competition a difficult task.
- Although the on-farm survey indicated that farmers believed *Melia* is less competitive with crops, results of on-farm experiments within farmers' fields showed clearly that *Melia volkensii* is competitive with crops. Furthermore, pruned trees which farmers' assumed did not compete with crops was also found to compete with crops and therefore no basis was indicated in the study that made farmers to believe that *Melia* did not compete.
- Although *Melia* was found to be competitive with associated crops, particularly when soil water is limiting, many farmers leave a large number of trees on their farms willingly, knowing that the benefits they reap from *Melia* more than offset the value of crop forgone. Compared to other species such as cypress and pines, finished *Melia* timber products fetch at least 45% more cash.
- The relationship between tree competition indices and crop yield indicated that shallow rootedness increases crop yield reduction, and therefore plants with shallow root architecture such as cuttings are inappropriate on farmers' fields.
- The investigation into whether differences in crop yields reported by farmers in the survey were a result of variation between *Melia* provenances, indicated that there were no differences between *Melia* provenances on either CI values or root length at shallow depths or phenology. Furthermore, there were no differences in CI values between species except in one site (Kitui site) where *Melia* had a greater CI than *Grevillea robusta*, *Eucalyptus camaldulensis* and *Azadirachta indica*.
- The CI values varied greatly between individual trees of the same provenance or species and were inconsistent with tree size and because of this, it can be used to predict tree competivity with crops only for individual trees.
- Because the CI equation makes no allowance for tree size (which has a great impact on water demand), it is recommended that tree size is incorporated in the equation to improve the prediction of tree impact on crop yields.

- Results of the root architecture method indicated that some vertical roots possessed secondary roots which grew towards the soil surface, thus making deeply descending roots grow partly shallow.
- Results indicated that keeping trees on farms improves soil fertility through litter fall (e.g. fallows) and when such trees are removed, crop yield will improve greatly.

8.2 Recommendations

- Since seedlings have a deeper root architecture than cuttings, farmers are recommended to use seedlings to reduce competition. However, seed germination of *Melia volkensii* is a problem, this should be a research priority for seed scientists in Kenya.
- Also, this study only looked at young trees, and therefore there is need to see whether seedlings persist in having low CI value.
- The competition index (CI) method cannot replace other methods of studying root distribution and root architecture but should be used only to complement other methods in predicting tree-crop competition where trees occur in isolation. In addition, CI values should be standardized or modified to incorporate tree size in order to predict tree competivity with crops more accurately.
- Where fallow farming is practised, farmers should plant *Melia* trees in the fallow land to enhance overall farm productivity and avoid tree-crop competition.
- The cost-benefit analysis of planting *Melia* trees on farmers' fields needs further evaluation to include costings of planting and tending trees and crops and the value of other tree products (e.g. fodder, seeds, bee hives, hand tools, pesticides).
- Future research should focus on *Melia volkensii* tree management practices such as root and shoot pruning, and pollarding impact on timber growth and quality and crop yield.
- Future research is also suggested to determine the optimum rotation age at which *Melia volkensii* trees can be cut for timber without compromising quality through testing fibre quality at different ages.

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APPENDICES

APPENDIX 1: Questionnaire used in the survey

Household questionnaire

1. Household

Name of household head ---------------------
Name of repondent ---------------------
Relationship with household head ---------------------

Sublocation ---------------------
Location ---------------------
Division ---------------------
District ---------------------

Household record
Land size ---------------------

Source of income
(i) Farming ---------------------
(ii) Informal employment ---------------------
(iii) Formal employment ---------------------
(iv) Others (specify) ---------------------

Land ownership
(I) Inherited ---------------------
(ii) Bought ---------------------
(iii) Squatter ---------------------
(iv) others (specify) ---------------------

Land size under crops ---------------------
Farming system practiced ---------------------

2. Crops

Main food crops

1 ---------------------
2 ---------------------
3 ---------------------
4 ---------------------

Main cash crops

1 ---------------------
2 ---------------------
3 ---------------------
4 ---------------------

3. Tree planting

Tree species	Number on farm	Main uses
i.		
ii.		
iii.		
iv.		
v.		
vi.		
vii.		
viii.		

What tree products in order of importance do you purchase

Product	Species	Frequency
i.		
ii.		
iii.		
iv.		
v.		

Planting and use of *Melia*

Do have *Melia* on your farm? Yes / No ---------------------
If Yes, how many do you have on cropland ---------------------
If No, why ---------------------

4. Establishment

How do/did you establish your *Melias*
a) Left after clearing
b) Natural regeneration
c) Direct sowing
d) Seedlings
e) Cuttings

f) Coppicing
Any other (specify)

Do you know any other way of establishing *Melia*?,
but you did not apply. --

In you opinion which method is best of all that you know in
Melia volkensii establishment? --

Any particular reason of planting *Melia* trees where they are?

Do women participate in tree planting in this farm? Yes / No
Briefly explain --

What are main uses of *Melia* on this farm
i --------------------------------------
ii --------------------------------------
iii --------------------------------------
iv --------------------------------------

How do you compare tree and crop income wise?

How do you describe the interaction between your crops
and *Melia*? ---

What management practices do you apply to you
Melia trees?
i ------------------------
ii ------------------------
iii ------------------------
iv ------------------------
v.------------------------

What constraints do you face in growing *Melias*?
i ------------------------
ii ------------------------
iii ------------------------
iv ------------------------

Have you been assisted in tree planting? Yes / NO
If Yes, who ---

What are you future plans of growing *Melia* on farms?
Explain --

5. Marketing

Do you sell *Melia* trees? Yes / NO
If Yes, how do you price it --
If I wanted to buy single tree how much would you sell it? ----------------------

Do you sell any other *Melia* products? Yes / No
If Yes, what products --

Do you have any comments to make on the pricing of *Melia*?
If Yes, comment --

6. Merchants and timber dealers

Which timber species do you sell?
i ---------------------
ii ---------------------
iii ---------------------
iv ---------------------

Where do you get your *Melia* timber from?
i ---------------------
ii ---------------------
iii ---------------------

What timber products do you sell most
i ---------------------
ii ---------------------
iii ---------------------
iv ---------------------

What is price per unit of these products
i ---------------------
ii ---------------------
iii ---------------------
iv ---------------------

Name of interviewer --
Date --
Comments if any --

APPENDIX 2: Sap flow calculations from heat pulse

Basically, heat transfer through sapwood is based on a pulse of heat (maximum temperature) reaching equilibrium, which is determined by wood components (Edwardsand Warwick, 1984). The components of the conducting sapwood properties are accounted for in the equations used in the calculation of sap flux from heat pulse velocity.

To convert heat pulse velocity (V_h) to sap velocity (V_s), Marshall, (1958) suggested;

$$V_s = aV_h \qquad (1)$$

where a is lumen area of sapwood. Lumen wood can only be established by destructive sampling, and for this reason, Marshall proposed further amendments to equation (1),

$$V_s = (pc/p_s c_s)V_h \qquad (2)$$

where p is density of green wood, c is specific heat of wood, c_s is specific heat capacity of sap (water) and p_s is density of sap (water).

Equation (2) can be substituted by

$$V_s = V_h\,(p_b(c_w m_c c_s))/p_s c_s \qquad (3)$$

where p_b is density of dry wood, c_w is specific heat capacity of dry wood, m_c is moisture fraction of sapwood. Specific gravity of sap (p_s) is assumed to be 1000kg m^{-3} and specific gravity of wood is constant for a particular species e.g. 1530 kg m^{-3} for hardwood such as eucalyptus (Edwards and Warwick, 1984). The specific heat of sapwood is 1.38×10^6 kj kg^{-1} $°C^{-1}$) and specific heat of sap (water) is 4.186×10^6 kj kg^{-}

^{1} $°C^{-1}$. Thermal capacity of sapwood equals capacity of its components (Marshall, 1984). Substituting equation (3),

$$V_s = V_h\,(0.505F_m + F_l) \qquad (4)$$

where F_m is volume fraction of wood and F_l is volume fraction of water. To get the fractions of wood and water, cut tree pieces of sapwood are weighed as fresh weight, oven dried and the immersed water weight or volume of the sapwood sample.

The volume fraction of water (F_l) is:

$$F_l = (w_t +- w_d)/w_i \qquad (5)$$

and the wood volume fraction (F_m) is:

$$F_m = w_d/1.53w_i \qquad (6)$$

where w_f is the fresh weight, w_d is oven dried weight and w_i is immersed weight or volume of sapwood sample.

Most of the tree physiologists are not merely interested in sap flow velocity but rather on the volume of sap flow (sap flux) through the stem. For sap flux calculations, the cross sectional area of the conducting wood has to be determined (Edwards and Warwick, 1984). Sap flux (Q) can be expressed in gh^{-1} or litres per unit time (min, hr or day) and is a function of sap flow velocity and the area over which the flow takes place,

$$Q = V_sA \qquad (7)$$

where A is conducting wood area.

Because sap flow velocities vary spatially with depth into conducting wood and different loci on the stem, measuring sap flow in several points and then averaging the sap velocities is recommended (Hatton *et al.*, 1990; Swanson and Whitfield, 1981).