IMPACT OF TREES ON WATER AND NUTRIENTS DYNAMICS IN SMALLHOLDER MAIZE-BASED FARMING SYSTEMS IN TRANS-NZOIA, RIFT VALLEY, KENYA

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Impact of trees on water and nutrients dynamics in smallholder maize-based farming systems in Trans-Nzoia, Rift valley, Kenya

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DECLARATION

I, the undersigned, declare that this is my original work and has not been submitted to any university or institution for academic credit.

Signature……………………………… Date……………………

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This thesis has been submitted for examination with our approval as the appointed University supervisors.

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World Agroforestry Centre and Swedish University of Agricultural Sciences

DEDICATION

This work is dedicated to all those who have supported and encouraged me in my academic journey and most importantly my late dear Mum, Lydiah Wanjiru. This is for you!

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ABBREVIATIONS

AMMI	Additive main effect and multiplicative interaction
Al	Aluminium
Available P	Available phosphorus
B	Boron
C	Carbon
Ca	Calcium
cm	Centimeter
Cu	Copper
DAS	Days after sowing
DBH	Diameter at breast height
ECD	Electrical conductivity
FAO	Food and agriculture organization
Fe	Iron
g	Gram

GLM	General linear model
GLMM	General linear mixed model
H	The Shannon diversity index
ha	Hectare
ICRAF	World Agroforestry Centre
ICP	Inductively-coupled plasma
JKUAT	Jomo Kenyatta University of Agriculture and Technology
K	Potassium
Kg	Kilogram
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na	Sodium
P	Phosphorus
PSI	Phosphorus Sorption Index

S	Sulphur
SD	standard deviation
SE	Standard error
SLU	Swedish University of Agricultural Sciences
Total C	Total carbon
Total N	Total nitrogen
ExAc	Exchangeable acidity
ExBas	Exchangeable bases
WaNuLCAS	Water, Nutrient and Light Capture in Agroforestry System
WUE	Water use efficiency
VSWC	Volumetric soil water content
Zn	Zinc

ABSTRACT

With decreasing land size, caused by fragmentation as family size increases, competition for this scarce resource has led to prior consideration on what tree species to plant as complementarities to household economy or as an encouraged agroforestry intervention measure. Even though farmers can instinctively anticipate crop yield losses as trees grow, they would likely be unable to accurately predict the period of viable intercropping and their effects on soil resources. The current study hypothesizes that, the adoption and management of trees in agricultural fields is largely influenced by household resource endowment, land tenure and the period of occupation by current households. Farmers are also hypothesized to be able to detect differences in soil quality within their farms by using local soil quality indicators which can be confirmed by chemical soil analyses and they understand changes in soil resulting from the presence of trees on farm. In addition, different tree species at varying age/ stage of growth are hypothesized to have different contribution to an agroecosystem in terms of competition, complementarity or balanced off effects on below and above ground resources necessary for crop growth and productivity. The study evaluated agroforestry adoption and practices within smallholder farms in a former large-scale maize growing area of Trans-Nzoia County, Kenya to understand the structure, densities and utilization of tree populations in agricultural landscapes is useful in determining the species influencing agroecosystem functions. This was followed by investigating how household resource endowment, land tenure and time under current management affect the adoption and resulting agroforestry practices. Five settlement schemes which were formerly large estates dominated by maize mono-

cropping were selected for the current study. Tree inventories of the farms was obtained through transect walks across each settlement. A total of 123 farms were assessed representing households of different resource endowment levels, tenure and number of years under current management. Different analyses were carried out including farm size and tree number, tree density, species richness, tree diversity and utilization of the dominant tree species. This was followed by an assessment of water and nutrient dynamics in maize (*Zea mays*) and dominant tree species; (*Calliandra calothyrsus*, *Sesbania sesban*, *Grevillea robusta*, *Eucalyptus spp*, *Croton macrostachyus* and *Markhamia lutea*) intercrop in the smallholders' farms. The nature and extent of interaction was evaluated to establish the existing tree-crop relationships and effect on crop productivity in the farms. To understand the short and long-term effect of tree integration in the farms on soil crop productivity, water and nutrient availability, Water Nutrient Light Capture in Agroforestry **S**ystems (WaNuLCAS) model was parameterized and simulations run of three selected tree species (*Grevillea robusta*, *Croton macrostachyus* and *Markhamia lutea*). Finally, to better understand the soil fertility problem in the study area we assessed farmers knowledge on soil qualities in their farms, indicators used to detect changes in soil quality which was evaluated by comparing with scientific knowledge. Lastly, their perception of contribution of dominant tree species on soil quality was investigated. In total, the study identified 44 tree/shrub species, 24 of which were indigenous and the rest exotic. However, the exotic tree species dominated strongly in abundance with *Eucalyptus* spp being the most frequent taxon and constituting 34.6% of all trees. Species richness was found to be low compared to other agricultural landscapes in the region. Resource constrained households were found to prefer fruit tree species and maintained high tree diversity in the farms. Households with secure tenure had higher tree diversity than those without who had higher species richness and opted for fast growing fodder and fertilizer/firewood trees. Younger farms had fewer trees but highest species richness than older farms. Results showed that farmers possess the knowledge of the crops that best perform in each soil type they identified. Farmers also use plants as indicators of differences in soil quality in the farm. The smallholders' farmers have a wealth of experience on local indicators of soil quality and contribution of agroforestry trees in maize production systems. They know how to distinguish between fertile and infertile soils using visual and morphological soil characteristics. Farmers' perceptions of soil quality were substantiated through soil chemical analyses and pH, boron, ECd, ExAc, potassium and magnesium provided precise information on these differences. The ability of the trees to increase soil fertility through leaves decomposition, nitrogen fixing, erosion control and provision of minimal shade during dry seasons were the preferred attributes of agroforestry tree species. Great tree management diversity was exhibited among the farmers whereby they selectively prune trees perceived as competitive to crops but still want to maintain them in the farm such as *Eucalyptus spp* and *G. robusta*. The smallholder farmers in the study area remain important maize producers in Kenya with an average maize yield of 6.5 tons ha^{-1} recorded. Maize yield under the dominant tree species showed significant differences ($P < 0.001$) with leguminous species (*C. calothyrsus* and *S. sesban)* recording the highest amount of grain weight. Dominant tree species within the farms were also shown to significantly ($P < 0.001$) influence the spatial distribution of soil water. The study found that under *Eucalyptus spp* (exotic) and *S. sesban* (native) the amount of water was reduced compared to soil away from the tree influence while under *G. robusta* (exotic) and *C. macrostachyus* (native) soil moisture was increased under the trees. *S. sesban* (leguminous) and *C. macrostachyus* (non-leguminous) were shown to have highest turnover rate of plant residues compared to the rest of dominant tree species while *Eucalyptus spp* (non-leguminous) and *G. robusta* (non-leguminous) recorded lowest turnover rate. Agroforestry zones recorded significant difference in amount of soil pH ($P = 0.074$) and Mg ($P = 0.034$) under *S. sesban* which was not reported from other tree species. The nutrient concentrations decreased with distance from tree stems and with soil depth, a pattern caused by nutrient accumulation from litter fall below and high rate of residue decomposition around *S. sesban* canopy. Modelling using WaNuLCAS suggested that individual traits of tree species, management practices such as crop choices, tree selection, intercrop spacing and age are important factors affecting water use, nutrient availability and biomass production in smallholders' maize-based farms in Trans-Nzoia County. *M. lutea* was also shown to assist in P recycling in the farms. In contrast, there was increased water competition exhibited under *G. robusta* which in turn translated to low crop productivity under the tree. In conclusion, the study explains that; (1) the establishment of a diverse tree cover in the study area involves the simultaneous action of three main drivers, namely, household resource endowment, land tenure and time under current management, (2) farmers hold complex ecological knowledge or local knowledge on indicators of soil quality and contribution of agroforestry tree in their farms and they recognize the tradeoffs underlying a biodiverse agroforestry system. Their creative capability in the utilisation of local knowledge was also demonstrated, (3) differences in water availability and maize productivity under dominant tree species in smallholder farms was shown to be much more complex than in monocultural systems; and (4) different tree species contribute differently to soil nutrients in agroforestry systems therefore it is not always beneficial to grow intimate mixtures of trees and crops. Farmers should be encouraged to incorporate tree species that exhibited less competition with crops into their farms such as *S. sesban* while avoiding those exhibiting increased competition such as *Eucalyptus spp*. However, management of such tree species proved more important to the farmer than total elimination and the integration of local knowledge with scientific can be a good tool to enhance productivity of agroforestry systems.

CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Agriculture is the backbone of the economies of East African countries and is dominated by smallholder farmers who occupy much of the land and produce most of the crop and livestock products (Salami et al., 2010). In Kenya, 75% of national agricultural share contribution to economy in 2007 was from smallholder farmers with mean farm size of 2.5 hectares (FAOSTAT, 2009). This reality underpins the importance and prevalence of small-scale farming activities in the country whereby efforts aimed to increasing agricultural productivity is often directed to small-scale farmers.

One major challenge in managing the smallholder farms in the region is to meet the ever-growing demand for agricultural products while conserving biodiversity, providing critical ecosystem services, and maintaining rural livelihoods (Barrios, 2007; Harvey et al., 2008). However, agricultural landscapes where small-scale farming is significant have been noted for their potential for tree (Lengkeek et al., 2006; Kindt et al., 2007), soil biota (Barrios et al. 2012), bird (Komar, 2006), insect (Armbrecht et al., 2006; Perfecto *et al*., 1996), mammal (Gallina et al., 1996), and orchid (Solis-Montero et al., 2005) biodiversity conservation in the tropics.

Agroforestry is a common agricultural practice used by many farmers in sub-Saharan Africa practice agroforestry (Mbow et al., 2014; Prahbu et al., 2015). The adoption of agroforestry to replace monoculture practices has been driven by the multiple functions trees play in farmer's fields, namely, fuelwood supply (WRI, 2007; Nyaga et al., 2015), timber for income generation and construction purposes (Garrity, 2004; Nyaga et al., 2015), fruits provision to households and also for sale at the markets (Harvey et al., 2008; Nyaga et al., 2015), fodder shrubs for livestock (Garrity, 2004; Franzel et al., 2014), conservation of above-ground and below-ground biodiversity (Pauli et al., 2012; Barrios et al. 2012a), bolstering nutrient supply through nitrogen fixing and nutrient cycling (Barnes and Fagg, 2003; Giller et al., 2005), greater quantities of organic matter inputs (Barrios et al. 1997; Akinnifesi et al., 2007), improved soil structure and water infiltration (Chirwa et al., 2007; Fonte et al. 2010), increased carbon storage in the farms (Makumba et al., 2007), enhanced suppression of insect pests and weeds (Sileshi et al., 2006; Pumarino et al., 2015), medicine provision from selected species and even for ornamental purposes (Nyaga et al., 2015). Agroforestry is therefore considered a promising alternative to conventional agriculture that can both conserve bio- diversity and support local livelihoods (Valencia et al., 2014).

Agroforestry can be utilized as an integrated approach which combines sustainable agricultural production and biodiversity conservation (Pretty et al., 2006; Mbow, et al., 2014). It has also been recognized as a key natural resource management strategy in addressing the millennium development goals (Garrity, 2004). Despite the immense benefits that can be associated with introduction of trees in a farm, agroforestry design which is getting the right number of trees of the right species optimally distributed in space and time while maximising all the benefits of trees and minimising their disadvantages as reported by Abel et al. (1997), is proving to be too much of a complex situation for small-holder farmers.

The common practice of establishing trees as external boundaries around individual plots during the fragmentation process, at homesteads (mostly fruit trees) and at crop fields, has gradually contributed to transform predominantly monoculture systems into multi-use diversified systems (Nyaga et al., 2015). With decreasing farm size which in return increases the potential for tree-crop competition, agroforestry design is increasingly becoming an important consideration. Walker et al. (2008) showed in a model that the effectiveness of an agroforestry system to a large extent depends on the design of the system practised. They also showed that to maximise the gains of such systems, the design must be adapted to environmental factors such as access to water and nutrients.

1.1.1 Tree-crop interactions in an agroforestry system

Agroforestry systems are defined as a set of land use practices that involve the deliberate combination of woody perennials including trees, shrubs, palms and bamboos, with agricultural crops and/or animals on the same land management unit and arranged spatially or temporally leading to significant ecological and economic interactions between woody and non-woody components (Sinclair, 1999). In the current study the trees and/or shrubs in agroforestry systems are referred to as trees in agroforestry systems.

Agroforestry has also been demonstrated to increase crop yields in humid and semi humid tropics (Young, 1997; Barrios et al., 1998). This is mainly attributed to fertility improvement relative to negative effects of competition (Weber et al., 1995). Increases are rare in semi-arid tropics and in infertile acid soils due to immense competition for nutrient and water which outplays fertility improvement (Rao et al., 1998). Even though most of tree-crop interaction trials have reported increased yield (Young, 1997), early success or failure does not indicate the realistic long-term potential of the system. Effects of trees are likely to be cumulative and take longer time to stabilize (Rao et al., 1998).

Agroforestry practices where trees and crops co-exist (e.g. simultaneous agroforestry) usually experience competition for nutrients, water and light if not properly managed (Rao et al., 1998). The benefits obtained from interactions between woody and non-woody (annual crops) components are largely key to the success of all agroforestry systems (Rao et al., 1998). Therefore, a better understanding of these interactions provides a strong scientific basis for improvement of traditional as well as evolving agroforestry systems.

The presence of trees in a farm affects crop growth and yield particularly in water and nutrient limited environments (Muthuri et al., 2005). Interaction has been defined as the effect of one component of the system on the performance of another component and/or the overall system (Nair, 1993). Three distinct tree/crop interaction zones can be distinguished in intercropping and tree boundary systems (Figure 1.1): (i) a zone of light and root competition, mostly under the tree crown (A and B), ii) a zone of root competition, some area beyond the tree crown (C), and iii) open cropped areas that are relatively free from the interference of trees (D) (Van Noordwijk and Lusiana, 1999; Rao et al., 1998).

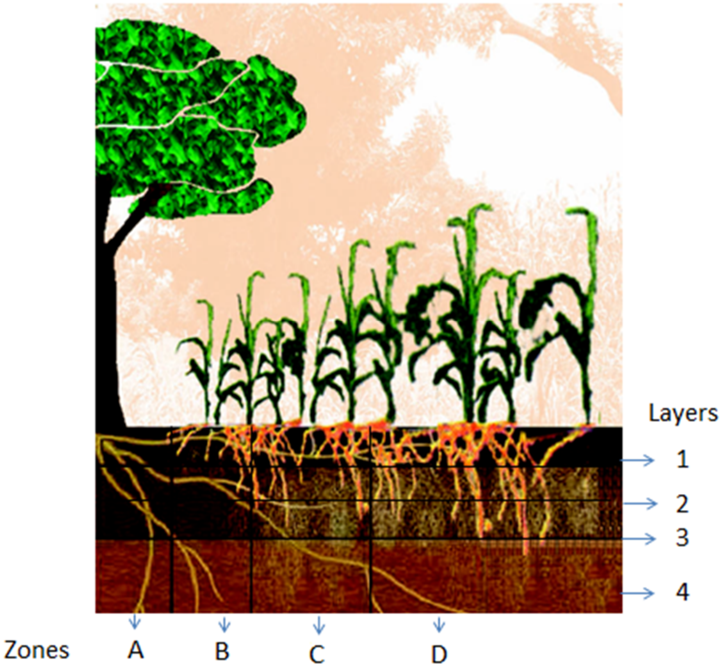

Figure 0.1: General layout of agroforestry zones and soil layers in WaNuLCAS showing different levels of tree-crop interactions (Van Noordwijk and Lusiana, 2000)

According to Young (1997) trees introduced into annual cropping systems help to overcome degraded soil conditions by (a) providing slowly decomposing litter layer that protects the soil from splash impacts of rainfall, reduces runoff and maximise water and nutrient resource use, (b) adding substantial amounts of organic matter through litter layer and root turnover, allowing for a gradual recovery of soil structure, and (c) capturing nutrients from deeper soil layers or intercepting current leaching losses, depending on their root distribution.

1.1.2 Biophysical dynamics in an agroforestry system

In simultaneous systems, interactions between component species are essentially responses of one species to the environment as modified by the presence of the other species (Akinnifesi et al., 1999a, 2004). Depending on the management, and or environmental and physiological factors controlling plant growth and functioning, one species may gain at the expense of the other, causing one species to be a winner (strong competitor) and the other a loser (weak competitor) (van Noordwijk et al., 1996a).

These interactions may have competitive (deleterious), complementary (beneficial) or balanced-off (neutral) overall effects. Competition occurs when species must share the resources from a limited pool and understanding and managing competitions is crucial for the success and sustainability of any simultaneous agroforestry systems (Schroth, 1999; Akinnifesi et al., 2004). According to Huxley (1999) trees must represent direct as well as indirect economic value, to offset their resource capture in competition with annual crops.

Capture of the limiting resource depends on the number, surface area, distribution and effectiveness of the individual elements within the canopy or root system of the species or mixtures involved.

1.1.2.1 Water

The addition of trees to conventional annual cropping systems may increase water use by using water which cannot be accessed by annual crops (Ong et al., 2000). The presence of trees may also modify microclimatic conditions in ways which improve the water use efficiency (WUE) of understorey crops. This is especially true for agroforestry systems, as these offer substantial scope for spatial and temporal complementarity of water use resulting from improved exploitation of soil water reserves and offseason rainfall. Significant complementarity of water use is obtained when the component species have different rooting patterns or exhibit contrasting temporal characteristics (Ong et al., 2000). However, as most tree species promoted for use in agroforestry have root systems whose vertical distribution is similar to agronomic crops (Akinnifesi et al., 1999a; Rowe et al., 1999), they may compete with associated crops.

To minimise competition for water especially when supplies are limited, the temporal patterns of below-ground activity by trees may be modified through management of their above-ground components (Schroth, 1999).

Pruning the tree canopy before the start of the growing season may allow annual crops to exploit available water in the surface horizons by reducing demand by the trees. Trees may also be able to tap water reserves in the deeper soil horizons as their canopy re-grows during the latter stages of the season (Droppelmann et al., 2000). However, some studies suggest that trees subjected to repeated shoot pruning may develop more extensive lateral rooting systems, thereby reducing spatial complementarity (van Noordwijk and Purnomosidhi, 1995; Ong and Leakey, 1999).

In systems where the crop does not provide complete ground cover during the growing season, evaporation from the soil surface may account for 30–60% of the annual rainfall (Wallace 1991, 1996). Ong et al. (1992) showed that, although the most effective cropping systems in semi-arid India used 40% of the annual rainfall, up to 33% of the annual rainfall was lost as run-off and deep drainage. Black & Ong (2000) suggested that the benefits of intercropping in such environments may result primarily from improvements in WUE rather than total seasonal water use.

Water is essential for many physiological processes of plants such as photosynthesis and transpiration. The response of photosynthesis to drought is controlled by both stomatal and non-stomatal factors. Stomata regulate photosynthesis by controlling the balance between water loss and carbon gain. Water stress decreases photosynthesis by limiting CO_2 diffusion into the leaf (Chaves et al., 2002). A good understanding of how plants utilize water is a prerequisite for choosing the best species/ cultivars and management practices to optimally exploit natural resources.

1.1.2.2 Soil nutrients

Pools of nutrients are located both above-ground biomass of live trees and crops, plant residues, soil fauna, soil organic matter (both labile and stable fractions) and available nutrients in soil solution. Flows within the system (uptake and return or recycling) include the decomposition of plant residues and soil organic matter, and plant uptake. Attiwill & Leeper (1987) and Young (1989) provide details of the major pathways of nutrient cycling which consists of stores and flows as well as gains and losses within the system. Gains and losses are external to the system and the former consist mainly of nitrogen fixation and fertilizer additions, rainfall and dry deposition while losses are while the latter include leaching, erosion and product removal (Young, 1997). Nutrients in litterfall, fine roots and pruning (unless added from off-site) represent recycled nutrients and not additions to the system. Litter is a central nutrient resource and litterfall is an important pathway for the return and recycling of dead organic matter and nutrients from plants to soils (Lian and Zhang, 1998; Martius et al., 2004). The amount of nutrients annually transferred depends on the amount of litterfall and the nutrients concentration in the litterfall.

Biomass from nitrogen-fixing legume trees (Mafongoya et al., 2006; Akinnifesi et al., 2007) and green manure/cover crops has been widely used to improve maize yields in Africa (Sileshi et al., 2008a). These legumes, when integrated into maize cropping systems either as rotational fallows or relay intercrops, have been shown to provide considerable amounts of organic matter and nitrogen to the soil (Barrios et al., 1997; Mafongoya et al., 2006; Mubiru and Coyne, 2009; Sileshi et al., 2008a). The organic matter thus added increases structural stability of the soil, resistance to rainfall impact, infiltration rates, and faunal and microbial activities (Mafongoya et al., 2006; Sileshi et al., 2008b). However, the success of this is dependent on farm management practices such as mulching and incorporation of crop residues.

Even though nitrogen is the most important nutrient limiting crop production, many soils of Africa are severely N deficient. This is mostly attributed by fact that inorganic fertilizers are unaffordable for most subsistence farmers (Ariga et al., 2006). Rotations and intercrops of legumes with crops may alleviate N deficiency through biological N_2 fixation and redistribution of subsoil N to the surface (Ikerra et al., 1999). Studies from Africa confirm the importance of N nutrition in maize yields, and the potential for use of soil inorganic N and N mineralization as predictors of yields. For example, Barrios et al. (1998) obtained strong correlations in eastern Zambia between maize grain yields following 3-yr-old tree fallows and both preseason inorganic N in surface soil and soil N mineralization potential. In Uganda, Stephen (1967) reported that soil nitrate N within one month of planting was highly correlated with maize and cotton yields, and Weber et al. (1995) in northern Nigeria obtained a highly significant relationship between maize grain yields and soil nitrate-N at 2 to 8 weeks after planting. Establishment of similar relationships in other agro-ecological zones can provide better means of predicting crop yields where soil N is the limiting nutrient.

Phosphorus is the second most important nutrient that is frequently deficient in African soils and more so in western Kenya (Kwabiah et al., 2003). Soil P can be unavailable to plants due to many factors such as the nature of mother rock, P fixation by oxides of aluminium, iron, clay and removal of crop residues (Iyamuremye et al., 1996). In sub-Saharan Africa, organic materials continue to be a major source of plant nutrients in smallholder farming cropping systems (Baijukya and de Steenhuijsen Piters, 1998). However, traditional crop residues, cattle manure and green manure that would otherwise substitute inorganic P fertilisers are usually not available in sufficient quantities on most farms. If available, these organic materials are very low in nutrients such as P. In addition, there is competition between farming and livestock for the same organic materials (Palm et al., 1997; Jama et al., 2000).

One way to overcome P depletion is the use of mineral P fertilisers. Unfortunately, inorganic fertilisers in Africa cost two to six times the price in Europe, North America, and Asia making them inaccessible to resource poor farmers (Sanchez, 2002). Therefore, supplementation of organic materials with moderate levels of inorganic P may be more affordable to farmers as a possible solution to reduce P deficiency and increase maize yields.

Alternative soil fertility amendment practices such as utilisation of mycorrhizal fungi and beneficial bacteria (Nyaga et al., 2015a), manure application (Nyaga et., 2014), composting, mulching and conservation agriculture methods have been incorporated into farming systems to supplement use of inorganic amendments with promising results in crop performance.

1.1.3 Agroforestry tree species under study

1.1.3.1 *Calliandra calothyrsus* Benth.

Calliandra calothyrsus, a tree legume native to Mexico and Central America, was first introduced to the Central Highlands of Kenya in 1987, and has since been widely promoted and adopted as a supplement to Napier grass (Wambugu et al., 2001). It is a very fast growing small tree/shrub reaching approximately 12 m in height at maturity. The leaves are suitable for forage and out-yield other shrub legumes, especially when grown on acid soil (Maghembe and Prins, 1994). The promotion of *C. calothyrsus* was initially based primarily on its promising agronomic attributes which include, in addition to nitrogen fixation, fast growth and high biomass production of both foliage and wood even during the dry season, tolerance of repeated lopping, and tolerance of acidic soils and/or high aluminium saturation (Palmer et al., 1994; Chamberlain, 2001). The plant does grow well in soil sufficiently permeable to allow root penetration and water infiltration. The plant does not tolerate water logging and the soil pH should be 6-8 (Hu et al., 1983).

C. calothyrsus has a dense, extensive and deep root system, making it suitable for erosion control on slopes and stabilization of soil and water conservation structures (ICRAF, 2001). The deep root system plays a recognizable role in holding soil together if planted along soil conservation structures such as terraces at a close spacing of 0.5 m. It can also be combined with Napier grass on terraces (Angima et al., 2001, ICRAF, 2001), for example by planting adjacent to lines of napier grass terraces (ICRAF, 2001). Rosecrance et al. (1992) also reported that four years of mulch application from *C. calothyrsus* hedges to crop rows measurably improved soil water holding capacity and bulk density.

Improved fallows or rotational woodlots of *C. calothyrsus* grown for two years have also been observed to replenish soil fertility, and subsequently to increase crop yields on degraded terrace sections (Mafongoya, 1995). In contrast, *C. calothyrsus* has been reported as a bad fallow species because of a slow decomposition rate and slow nutrient release, caused by high levels of polyphenolics (Handayato et al., 1994; Lehmann et al., 1995).

C. calothyrsus is fast growing even on poor soils, and has the ability to improve soil fertility, but it does not do well on acidic soils (Franzel et al., 2001). It lives in symbiosis with rhizobium, which forms nodules on the roots to fix nitrogen from the air, which is transferred to the *C. calothyrsus* plant. This helps the *C. calothyrsus* to grow fast, and leaves the soil more fertile than before by releasing nitrogen in the soil (ICRAF, 2001). *C. calothyrsus* competes with crops if pruning is neglected (Gerrits, 2000) and this is attributed to extensive root system that can result in competition with crop plants for water and nutrients. Annual or seasonal harvesting can also deplete nutrients from the soil.

1.1.3.2 *Croton macrostachyus* Hochst. ex Del.

Croton macrostachyus is a multipurpose, medium sized, drought-deciduous pioneer tree that belongs to the Euphorbiaceae, a family that contains large numbers of plant species. It is estimated that there are 8–10 thousand species, contained within 300 genera of the Euphorbiaceae. While Euphorbiaceae is commonly known as the ‘spurge’ family, *C. macrostachyus* is called ‘rushfoil’ or ‘broad-leaved croton’. The species regenerates naturally in less productive sites including forest edges, mountain slopes and waste grounds under a wide range of ecological conditions (Negash, 2010). When not degraded (e.g., through lopping or de-branching), and when grown in the open field, *C. macrostachyus* typically has rounded crown, medium-sized trunk that is studded with relatively long and spreading branches (Negash, 2010). Under the open field conditions, isolated trees are quite short with thick trunks, but can attain heights of over 25 m when growing in fairly crowded forests. According to Negash (2010), one very important morphological and/or develop- mental attribute responsible for the tree's rapid establishment and growth is the possession (by young trees) of leaf blades that are fairly broad and droopy, collectively covering a space of 360°. If there is no shading by other plants, this type of leaf arrangement and orientation helps the young tree maximize the capture and transformation of sun's light (by means of photosynthesis) throughout the 360° space. This is an important evolutionary adaptation for harvesting as much light energy as possible for photosynthesis during the rainy season, when environmental conditions are favorable for growth.

The species is competitive; with distinctive morphological and physiological characteristics that include rapid production of large numbers of leaves and flowers during the rainy season and shedding these during the dry season. The tree is quite persistent, regenerating large numbers of coppices or shoots, even when it is repeatedly lopped or degraded (Negash, 2010). Provided that environmental and soil conditions are favorable, *C. macrostachyus* does establish well and can grow quite fast on reasonably good and well-drained soils, but prefers red or loam soils to vertisols (Negash, 2010).

1.1.3.3 *Eucalyptus* spp L'Hér.

Eucalyptus spp is an exotic evergreen tree of Myrtaceae family. The leaves are leathery and hang obliquely or vertically. The flower petals cohere to form a cap when the flower expands. The fruit is surrounded by a woody, cup-shaped receptacle and contains numerous minute seeds.

Eucalyptus spp plantations are easily established and fast growing, and can be highly profitable, even in areas that are traditionally poor in timber production. The area under *Eucalyptus spp* species in Kenya was estimated to be about 100,000 hectares of plantations, 15,000 ha in gazetted forests, about 35,000 ha planted by private companies and 50,000 ha by farmers in 2009 (KFS, 2009). The main reason for the introduction of eucalypts was its fast growth, ability to re-sprout and the straight nature of its stems. The wide range of products such as firewood, charcoal, building materials, fencing posts, transmission poles, pulpwood, timber and plywood obtained from *Eucalyptus spp* have made the genus very versatile (KFS, 2009).

However, there are negative environmental impacts in planting Eucalyptus, such as loss of biodiversity in the understory and soil degradation (Forrester et al., 2006; Wang et al., 2010). *Eucalyptus spp* has also been reported to deplete water from surrounding soils leading to increased competition for water with crops growing in that area (Kidanu et al., 2004; Gindaba et al., 2007) and therefore the widespread establishment of *Eucalyptus spp* plantations for the commercial production of timber and fiber products has generated worldwide controversy (Tang et al., 2007; Zhao et al., 2007).

Recently, there have been concerns in Kenya about *Eucalyptus spp* trees that are depleting water from rivers and springs, and the perceived negative effects on crops. Not surprisingly, *Eucalyptus spp* is usually planted in small woodlots or on farm boundaries to minimise competition with crops (Jagger et al., 2005). In dry areas, the species is reported to transpire more water than the average rainfall recorded over the same period

(Jagger and Pender, 2005). In humid areas, *Eucalyptus spp* does not transpire large amounts of water when soil water is not limiting (Myers et al., 1996).

1.1.3.4 *Grevillea robusta* A. Cunn.ex. R.Br.

Grevillea robusta (family Proteaceae), a tree native to eastern Australia, has been widely planted in subtropical and tropical highland environments of eastern and central Africa, south and central America, and south Asia (Harwood 1992). In the East African Highlands is popular at altitudes of 850–2500 m in areas with annual rainfall of 850–1500 mm and mean annual temperatures of 13°C to 21°C (Muthuri et al., 2009). In Kenya, it was introduced as a shade tree for coffee and tea from 1910 and is well accepted in Western (Otieno, 1992) and Central (Muthuri et al., 2009) Kenya.

The species performs best on well drained fertile soils but also grows moderately well on medium textured soils (loam, clay-loam to light sandy soils). However, it does not tolerate water logged soils. *G. robusta* is a fast-growing tree. On suitable sites, *G. robusta* can attain a height of 20 m and diameter of up to 25 cm in 15 to 20 years (Njuguna et al., 2014). *G. robusta* is mainly used for timber, poles/posts and fuelwood. Other uses include bee forage, fodder, mulch, soil conservation, wind break, shade for coffee and other crops, ornamental and to demarcate farm boundaries (Muthuri et al., 2009; Njuguna et al., 2014).

A maize (*Zea mays* L.) and *G. robusta* agroforestry system is common in Kenya. *G. robusta* can harvest water in the deeper horizons beneath the crop's rooting zone and to develop a cluster of roots that acquire nutrients from the soils deficient of phosphorus

(Lott et al., 2000). Dead leaves and twigs serve as manure in the topsoil layer (Raju 1992). *G. robusta* is also easy to propagate and not significantly affected by pests and diseases. It does not compete much with the agricultural crops and may even enhance yields of some crops (Akycampong et al., 1999), however, the tree can greatly reduce the above ground biomass and grain yield of maize (Lott et al., 2000). Minimized competition is attributed to its relatively light crown and deep rooting habit (Harwood and Booth 1992; Muchiri, 2004). The level of competition may also be regulated because *G. robusta* tolerates heavy stem pruning, pollarding and trimming of lateral roots (Muchiri, 2004). The trees are arranged on farms in rows or irregularly. The relationship between maize plants and *G. robusta* may vary in one field from no competition to very high competition.

1.1.3.5 *Markhamia lutea* (Benth.) K. Schum.

Markhamia lutea is an upright evergreen broadleaved tree which belongs to the tropical family of Bignoniaceae. It is abundant throughout the East African countries and occurs naturally in riverine, evergreen forests, forest edges and occasionally in savannah woodlands. *M. lutea* grows well in areas receiving 700-1700 mm of rainfall per year with a bimodal rainfall regime. The dry season months should not exceed more than 3 to 5 months. Furthermore, it can be found at elevations between 700 and 2400 m above sea level. The tree grows best on deep, well drained red loams but also on gravy loams or sandy soils. It tolerates acid conditions but is not adapted to water logging. The tree coppices extremely well and remains vital for many years. Another characteristic which makes the use very attractive especially for the rural population is its resistance against termites and its tolerance against relatively infertile soils. Farmers plant it on external boundaries, around homesteads, scattered within fields and in woodlots. Particularly among resource–poor farmers the wood is used for poles, firewood, the making of traditional stools, bows and other handles. The timber is highly valued for hut constructions due to its termite resistance.

M. lutea has less competitive roots with crops in agroforestry systems which is relatively comparable to *G. robusta* (Wajja-Musukwe et al., 2008). The tree competes with crops with its large fibrous roots and the rather dense shade caused by its crown. The shade from the tree can be reduced by pruning and its multipurpose use nature makes it desirable for use in agroforestry systems.

1.1.3.6 *Sesbania sesban* (L.) Merr.

Sesbania sesban has been widely promoted as improved short-fallow species in southern and East Africa. It is a nitrogen-fixing tree that can be used for firewood, construction, fodder, soil conservation and a promising agroforestry alternative to traditional fallows for increasing the fertility of nutrient-depleted soils. *Sesbania* species are generally preferred because of their greater effects on the yield with improved N input and its availability and subsequent crops and provision of fuelwood (Kwesiga et al., 1999).

High yields after *Sesbania sesban* improved fallows, for example, have been recorded and mainly attributed to increased soil inorganic nitrogen generated during decomposition and mineralization of N-rich organic residues (Barrios et al., 1998; Chirwa et al., 2004;

Sjögren et al., 2010). This has been attributed to low shading to associated crops given its low specific leaf area and, it's nitrogen fixing nature.

Equally important, *S. sesban* can store 10.1 ton C ha^{-1} above and below ground in a 12-month old fallow and 23.5 ton C $ha^{-}1$ in a 22-month old fallow (Verchot et al., 2007). *S. sesban* fallow increased the soil-water storage in the soil profile and drainage below the maximum crop root zone compared with the conventionally tilled non-fertilized maize (Phiri et al., 2003). However, *S. sesban* has certain drawbacks in that it is severely attacked by pests including *Mesoplatys ochroptera* Stäl. (Sileshi et al., 2000) and root-knot nematodes (Desaeger and Rao, 2000) and it should not be grown in the same field as crops sensitive to nematodes, such as bananas or potatoes (Maundu and Tengnäs, 2005).

1.1.4 Maize

Maize (*Zea mays* L.) is the most important agricultural commodity in Kenya contributing more than 25% of agricultural employment and 20% of total agricultural production (Government of Kenya, 2001) and providing about 40% of the populations' caloric requirements (Wekesa et al., 2003).

Despite the key role maize plays in food security and income generation in Trans-Nzoia district, and the whole country at large, its productivity has not been adequate especially in the past four decades during which stagnation/decline in maize yield led to frequent food security problems. Yields however remain low at approximately 1.3 ton ha^{-1} against a potential of 6.0 ton ha^{-1}. The total country production volumes were below the projected consumption level of 36.0 million bags in 2009, thus necessitating imports to cover the deficit (MOA, 2010). Ariga et al. (2006) have attributed maize yield decline to two main reasons: (i) declining soil fertility and (ii) increase in world fertilizer prices. The situation has been exacerbated by maize price fluctuation and occasional importation of cheap maize grains.

1.1.5 Use of models in agroforestry

Process-based models are essential to understand interactions in agroforestry land use systems, which are considerably more complex than the usual agronomic experimental designs. The model should be simple but summarising parameters of constituent interactions and experiments (van Noordiwijk, 1996b). This will help to highlight the interactions and surveys of real world variation in a farmer developed agroforestry system and possible components.

Modelling approaches have been used in recent years to address important agroforestry concerns in the African context. For example, by using the Water, Nutrient and Light Capture in Agroforestry System (WaNuLCAS) model Muthuri et al. (2000) addressed the contribution of leafing phenology to growth and water use of selected tree species in semi-arid Kenya. More recently, Bayala et al. (2008) used the WaNuLCAS model to infer the amount of water redistributed based on soil water potential from two native tree species of agroforestry parklands of West Africa and also Walker et al. (2008), modelled planted legumes fallows in Western Kenya to evaluate productivity and sustainability of simulated management practices.

To assess possible agroforestry scenarios the tree-soil-crop interaction model in agroforestry systems (WaNuLCAS 4.0) was used in the current study. WaNulCAS is a model of tree-crop interaction in agroforestry system that allow user to explore interactions among various agroforestry options available to farmers, as well as evaluating the combinations of components that are most likely to meet their expectations.

The model is formulated in the STELLA research modelling environment. The key features of the model are the description of uptake of water and nutrients based on root length densities of both the tree and the crop, plant demand factors and effective supply by diffusion at a given soil water content (van Noordwijk et al., 2004b). The model represents a four-layer soil profile (vertical), with four spatial zones (horizontal), (Figure 1) water and nitrogen balance and uptake by a crop and a tree. The user can define the width and depth of each zone and adjust it to the type of system simulated. The model can be used both for simultaneous and sequential agroforestry systems and may help to understand the continuum of options ranging from improved fallow via relay planting of tree fallow to rotational and simultaneous forms of hedgerow intercropping. The model explicitly incorporates management options such as tree spacing, choice of species and pruning regime. The model includes various tree characteristics, such as (dynamic) root distribution (over the 16 cells; four layers by four zones), canopy shape (above the four spatial zones), litter quality and maximum growth rate. If applied to hedgerow intercropping, the model allows for the evaluation of crop growth at different tree spacing, densities or fertilizer application rates (van Noordwijk and Lusiana, 1999). Soils are represented in four layers, the depth of which can be chosen, with specified soil physical properties and initial water and nitrogen contents, for all sixteen cells (van Noordwijk et al., 2004b).

1.2 Statement of the problem

Smallholder farmers are introducing trees in their traditional farming system mainly driven by the need to obtain new product diversification for direct cash value such as wood, pulp and oil which may provide new source of income to farmers to buffer against the downturns in profitability of other farm enterprises. Also, farmers incorporate trees into farms to enhance existing enterprises such as provision of fodder shrubs to fill a seasonal feeding gap, wind break to protect crops or tree planting to alleviate water logging in low-lying land. There is also the urgency for resource protection i.e. resource base such as quality of soil and water of the farm must be protected and enhanced so that traditional farming enterprises may survive which influence tree planting. Lastly, trees are planted to make landscape more pleasing for human habitation and provide new niches for other plants and animals as conservation and/or beauty purposes.

Growing trees is different from other farm enterprises because the tree exerts an influence at a considerable distance and depth away from where it is planted. For instance, trees explore layers of soil 1-5 m or more below the rooting depth of annual crop and pasture species. Secondly, tree shade or compete for water and nutrients with crops growing tens of metres away and lastly, trees modify microclimates hundreds of metres away and can reduce soil erosion. As observed, introduction of trees in the farms has the potential to allow agricultural practice that successfully addresses the problems associated with intensive farming and maintaining the provision of other ecosystem services, however, scientific knowledge on how to minimize negative effects of trees-crop interaction and how to optimize the positive ones is missing.

1.3 Justification of the study

The current study enhances greater understanding of how to optimize tree-soil biota interactions that improve agroecosystems function and soil health. This is through studying the impact of tree spatial arrangements and management that minimize competition and favors complementarities and facilitative interactions among trees and associated crops in terms of biomass production, nutrient and water use efficiency, and how these in turn influence the abundance, diversity and activity of key soil biota.

Tree-crop interaction mainly through water and nutrient competition and subsequent effect on maize production will be evaluated through a modelling approach that synthesizes the complexities found in agroforestry systems. The study will therefore contribute to knowledge that is valuable to farmers, advisors and policy makers in making decisions such as tree species to plant, density and management in consideration of anticipated aging of agroforestry systems.

1.4 Hypotheses

The study hypothesized that:

i. The adoption and management of trees in agricultural fields is largely influenced by household resource endowment, land tenure and the period of occupation by current households;
ii. Farmers can detect differences in soil quality within their farms by using local soil quality indicators which can be confirmed by chemical soil analyses. Farmers can also detect changes in soil resulting from the presence of trees on farm;
iii. The pattern of water availability resulting from the presence of tree species has a significant influence on crop yield and biomass;
iv. Dominant tree species in smallholder farms have different influence on the spatial distribution of soil nutrient;
v. Spatial-temporal arrangement of dominant tree species as modified by age and density affect crop yield, water, nutrient availability in smallholder maize-based agroforestry systems.

1.5 General objective

To investigate the impacts of trees on water and nutrient dynamics in smallholder's maize-based agroforestry systems in Trans-Nzoia County.

1.6 Specific objectives

i. To determine how the presence and use of dominant tree species in selected smallholder farms in Trans-Nzoia County is affected by household resource endowment, land tenure and the period of occupation by current households.
ii. To evaluate the farmers' local knowledge on the spatial distribution of local soil quality classes in their farms, identify local indicators used by smallholder farmers to assess differences in soil quality, characterize the local soil quality classes using soil chemical analyses, and assess the spatial distribution of dominant agroforestry tree species on local soil quality classes and their perceived effects on soil quality within smallholder farms in Trans-Nzoia County.
iii. To investigate the effect of dominant tree species of various ages, under various densities and spatial-temporal arrangements on water availability and maize performance.
iv. To determine the spatial effect of dominant tree species on nutrient availability and soil organic C within smallholder farms in Trans-Nzoia County.
v. To model the impacts of the dominant trees species, as modified by their age, density and spatial-temporal arrangements on soil organic C, water and nutrient availability, and maize productivity using the WaNuLCAS model.

1.7 Scope of the study

To understand the presence and utilization of trees in agricultural landscapes the study evaluated agroforestry adoption and practices within smallholder farms in a former large-scale maize growing area of Trans-Nzoia County, Rift Valley Province, Kenya. A total of 123 farms were assessed representing households of different resource endowment levels, tenure and number of years under current management in five selected settlement schemes in the County. Different analyses were carried out including farm size and tree number, tree density, species richness, tree diversity and utilization of the dominant tree species. This was followed by an assessment of water and nutrient dynamics in maize (*Zea mays*) and dominant tree species; (*C. calothyrsus*, *S. sesban*, *G. robusta*, *Eucalyptus spp*, *C. macrostachyus* and *M. lutea*) intercrop in the smallholders' farms in the year 2012 and 2013. The nature and extent of interaction in a total of 30 agroforestry plots was evaluated to establish the existing tree-crop relationships and effect on crop productivity in the farms. To evaluate the short and long-term effect of tree integration in the farms on soil crop productivity, water and nutrient availability, WaNuLCAS model was parameterized and simulations run of three selected tree species (*G. robusta*, *C. macrostachyus* and *M. lutea*) for a period of 10 years. Parameterization of the three species was carried out at an on-station experiment established at Vi Agroforestry demonstration farm in Kitale and monitoring of tree growth done for two seasons/years (2012 and 2013). Finally, to better understand the soil fertility problem in the study area we assessed farmers knowledge on soil qualities in their farms, indicators used to detect changes in soil quality and the spatial distribution of dominant agroforestry tree species on local soil quality classes and their perceived effects on soil quality.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

This chapter presents a review of the literature related to the following specific objectives: 1) the presence and use of dominant tree species in selected smallholder farms; 2) effects of dominant tree species of various ages, under various densities and spatial-temporal arrangements on water availability and associated crop performance; 3) spatial effect of dominant tree species on nutrient availability; 4) modelling the impacts of the dominant trees species, as modified by their age, density and spatial-temporal arrangements on soil organic C, water and nutrient availability, and maize productivity using the WaNuLCAS model; and 5) the farmers' local knowledge on trees contribution to soil water/nutrient availability and biological activity within smallholder farms in Trans-Nzoia County.

2.2 Agroforestry practices and factors influencing agroforestry adoption within smallholder farms

The decisions to adopt resource-conserving practices like agroforestry are largely driven by expected contributions to increased productivity, output stability through risk reduction, and enhanced economic viability compared to other land management alternatives (Mercer, 2004). The pattern of resource availability and allocation to different activities, however, is determined by household resource endowment and depend on household priorities and production strategies (Tittonell et al., 2005).

Land insecurity is a major problem in many countries in Sub Saharan Africa (Namubiru-Mwaura & Place, 2013). The constraints related to the tenure system, such as insecurity of land tenure, unequal access to land and lack of a mechanism to transfer rights and consolidate plots, have resulted in under-developed agriculture, high landlessness, food insecurity, and degradation of natural resources in East Africa (Salami et al., 2010). However, farmers have been reported to initiate long-term investments in farms such as tree planting where individualized rights are established (Deininger and Ali, 2007).

Furthermore, the available land in East Africa is overly subdivided into small and uneconomic units, resulting generally in fragmented production systems and low productivity (Salami et al., 2010). The fragmentation is an on-going process where settling of new landowners leads to differences in period of occupation by current household. This process is driven by population growth, local inheritance systems or / and government policy on land resettlement. As observed by Lengkeek et al. (2006), few studies are documenting the variation in number, diversity and utility of trees maintained on-farm during the development of agroforestry systems. Such information is important in supporting the design of agroforestry systems that are better adapted to face changing environmental challenges and farmer requirements.

The adoption and management of trees in agricultural field is therefore hypothesized to be largely influenced by household resource endowment, land tenure and the period of occupation by current households. Differences in adoption levels are expected to contribute to various agroforestry configurations characterized by the number, density, diversity and utility of trees maintained on farms.

2.3 Water and nutrient availability under dominant agroforestry trees within smallholder farms

Studies on tree-soil interactions have clearly shown that trees significantly influence soil nutrients. Trees improve soil fertility in cultivated land by increasing nutrient inputs from organic matter via litter fall, root decay and biological N fixation (Barrios et al., 1997; Akinnifesi et al., 2006). Specifically, legumes in alleys and fallows increase SOM, SOC, inorganic N, K, plant-available P, exchangeable bases (Ca, K, Mg) and maintain higher soil pH than natural grass fallows or continuous maize cultivation (Kang et al., 1999; Bünemann et al., 2004). In parklands, the concentrations of SOC, SOM and nutrients such as N, P, and K greater beneath tree canopies than on open ground between trees has been reported (Bayala et al., 2002; Dick et al., 2006). In contrast, trees have also been reported to reduce certain soil nutrients in relation to continuous cropping. Low concentrations of exchangeable bases (Ca, K, and Mg) have been reported particularly in alley cropping with leguminous trees (Schroth et al., 1995; Kang et al., 1999). Other parameters recorded in lower quantities in agroforestry treatments as compared to mono-cropping are total soil C and N, and plant available P (Olsen P) (Kang et al., 1999; Makumba et al., 2009). These cases of low concentration of nutrients in the soil were presumably because of nutrient uptake by trees (Isaac et al., 2007). Therefore, to minimize trade-off and maximize synergies resulting from increased tree-crop interactions it is critical to better understand tree attributes influencing soil nutrient availability (Barrios et al., 2015).

Adoption of agroforestry is believed to alter the hydrological cycle which affects both the levels of water use and the total irrigation requirement (Ilstedt et al., 2007). This is largely because of being perennial, having greater total evaporative leaf surface, their ability to exploit a larger volume of soil to extract moisture and increased rainfall interception (Zomer et al., 2007). The soil water content is extremely important for crop growth and the soil water storage before sowing of an annual crop plays an essential role in crop performance and yield (Muthuri, 2004).

Presence of semi-deciduous (*Alnus acuminata*) trees in a farm was found to positively affects crop growth and yield in water and nutrient limited environments while evergreen species (*G. robusta*) recorded reduced yield under similar environmental conditions (Muthuri et al., 2005). Competition for soil moisture has also been reported to reduce stem diameter, plant height and yield in maize in agroforestry systems relative to sole crops (Muthuri, 2005).

In conclusion, the relationship between tree cover and water supply is not straight forward which necessitates further studies especially with incorporation of crops in the systems which as expected would contribute to enhanced competition (Ong et al., 2014; Ilstedt et al., 2016).

2.4 Maize productivity under dominant agroforestry practices within smallholder farms

The introduction or maintenance of trees in farmland has the potential to allow agricultural practice that successfully addresses land degradation problems associated with intensive farming while at the same time maintaining the provision of other ecosystem services (Barrios *et al.*, 2012a). This at the same time offers a unique opportunity for most rural poor whose individual land holding is becoming too small because of land fragmentation processes driven by inheritance customary laws (Nyaga et al., 2015b). Moreover, as human and domesticated livestock populations increase and the size of land-holdings decreases, the possibility of incorporating trees into farmlands becomes increasingly attractive (Muthuri et al., 2005). In addition, agroforestry offers a promising option for productive and sustainable use of land (Pretty et al., 2006; Chirwa et al., 2007; Garrity et al., 2010; Mbow, et al., 2014).

Agroforestry practices vary in the density and configuration of trees in farming landscapes from a few scattered trees or line plantings to dense and complex agroforests (Sinclair, 1999). Muthuri et al. (2005, 2009) observed that characterization of component interactions in agroforestry practices is crucial in determining the extent of competition and complementarity between trees and crops and therefore tree species selection and spatial arrangement of trees are key factors in determining the resource use efficiency of agroforestry systems.

Maize production in the County in on a decrease which is also magnified by the fact that population continues to increase annually at a rate of about 2.9% leading to decreasing per capita consumption. The combined effect of increasing human population and poor maize yields on the country's capacity to feed the population is then accelerated annually (Government of Kenya, 2001; and 2004). Other reasons including continuous cropping, degradation of land as natural resource, low investment in soil fertility, inappropriate production technologies, and episodes of bad weather have been cited for the stagnation in maize production in Kenya (Kedera et al., 1999; Kamidi et al., 2000; Mwangi et al., 2001).

To improve maize production in smallholders' farms research is required on various problems constraining maize production such as diminishing land size compounded by introduction of other farming activities in the same plots which leads to growth resources competition. The research should also address the long-term solutions in consideration of time and money limitations with an aim of proper farming practices policies development.

2.5 Modelling possible maize-based agroforestry scenarios using selected dominant tree species

Agroforestry systems are more complex assemblages of ecosystem components and to carryout robust impact projection renewed effort in process-based agroforestry modelling is required (van Noordiwijk, 1996b; Luedeling et al., 2014). This importance is compounded by the short-term nature of funding for research projects, the complexity associated with agroecosystem processes, the corresponding expense of measuring every significant variable and the expense of investigating the effects of changing these variables in diverse and complex systems (Matthews and Stephens, 2002). As a solution, computer modelling can yield cost effective, quickly generated, predictions over short and long term (Walker et al., 2008). The utilization of an existing simulation model to explore interactions among various agroforestry options available to farmers, as well as evaluating the combinations of components that are most likely to meet their expectations, comes as a logical alternative.

WaNuLCAS 4.0 model (van Noordwijk et al., 2011) was used in this study to investigate short term and long-term impacts of selected dominant tree species, as modified by density and spatial-temporal arrangements on crop productivity, soil water and nutrient availability in smallholders' maize production systems in Trans-Nzoia County. WaNuLCAS is a generic plant-plant interaction model based on the capture of above- and below-ground resources (van Noordwijk and Lusiana, 1999). WaNuLCAS is an advanced prototype model which does not yet include all possible soil-tree-crop interactions, but does incorporate established core relationships (Van Noordwijk and Lusiana, 1999).

2.5.1 Model description

WaNuLCAS was developed to simulate interactions between trees, soil and crops at plot level (Van Noordwijk et al., 2004). Agroforestry systems are defined in WaNuLCAS based on four horizontally distributed spatial zones and four soil layers in which water, nitrogen and phosphorus balances and uptake by crop may be examined on a daily basis.

The model can be viewed as a “null model” which can be used as a null hypothesis, providing a background against which specific datasets can be tested (Van Noordwijk and Lusiana, 1999). This open framework allows users to add other relationships as required, making the model sufficiently broad to include a wide range of parameters while still able to cater for specific needs. These features were particularly attractive as they allowed differences in effects on nutrient and water to be incorporated, important issues when comparing tree-crop interaction of dominant tree species examined in the present study. In addition, the model makes use of “zones” and “layers” to take account of the spatial variation in resource capture which occurs around trees and thus covers an essential aspect of real agroforestry systems in the field.

Soils are represented in four layers, the depth of which can be chosen, with specified soil physical properties and initial water and nitrogen contents, for all sixteen cells (van Noordwijk et al., 2011). The model needs the relationship between water potential and soil water content, to derive the soil water content equivalent to certain root water potential (van Genuchten, 1980). As the relationships are not measured for all soils, pedotransfer functions are used (Arah and Hodnett, 1997). Soil physical parameters included into the model are derived via a pedotransfer function from soil texture, bulk density and soil organic matter content from field data (Suprayago et al., 2003). WaNuLCAS pedotransfer functions for hydraulic properties of soils are adapted for Wosten et al. (1998).

The nitrogen balance of the model includes inputs from fertilizer (specified by amount and time of application), atmospheric N fixation and mineralization of soil organic matter and fresh residues (van Noordwijk et al., 2011). Uptake by crop and tree is allocated over yields and recycled residues. Leaching of mineral N (nitrate) is driven by the water balance, the N concentrations and apparent adsorption constant for nitrate in each layer. Decomposition of soil organic matter is represented by a three-pool model, following the terminology and concepts of the Century model (Parton et al., 1994).

Growth of crop and tree is calculated on a daily basis by multiplying potential growth (which depends on climate and current plant size) with the minimum of four stress factors: one for shading, one for water limitation, one for nitrogen and one for stress history. Uptake of both water and nutrients by the tree and crops is driven by demand but within limits set by a zero-sink uptake model (de Willigen and van Noordwijk, 1994). Competition is based on sharing the potential uptake rate for both (based on the combined root length densities) on the basis of relative root length multiplied by relative demand (van Noordwijk et al., 2011).

Trees can be grown in one of the outer zones (zone 1 to 4). This structure allows monitoring below and aboveground competition for growth factors such as water, nutrients (N and P) and light between trees and crops over a wide range of production systems. The soil is represented as four horizons (layers), the depth of which can be defined within the model, together with specified soil physical properties and initial water and nitrogen contents for each of the sixteen compartments. The model incorporates standard management regimes, such as the choice of tree/crop species, spacing, tree-pruning and fertilizer rates. Zone width and layer depth can be adapted to experimental set up.

2.5.2 Model inputs

WaNuLCAS was created in the Stella® modelling environment (ISEE systems Inc., Lebanon, NH, USA) and linked to Excel® spreadsheets for input and output data (Van Noordwijk and Lusiana, 1999). Inputs entered in the WaNuLCAS Excel file include: i) climatic data i.e. rainfall, soil temperature and potential evapotranspiration; ii) soil data i.e. N, P, percent C, clay and silt contents, bulk density and soil texture for each soil layer; iii) management schedule, including planting and weeding dates, fertilizer input and pruning; and iv) crop and tree parameters such as the length of the vegetative cycle and water requirements.

2.6 Linking local and scientific indicators of soil quality to contributions of agroforestry trees in smallholders' maize production systems

Soil fertility decline is considered a major limiting factor for achieving household food security in sub Saharan Africa (Bationo et al., 2004). The general lack or limited application of nutrient inputs during cultivation has led to soil degradation through a process known as nutrient mining (Vanlauwe et al., 2010). Increasing concern about agricultural sustainability has promoted the development of indicators of soil quality to monitor changes resulting from land use and soil management (Arshad and Martin, 2002).

Smallholder farmers in Sub-Saharan Africa are introducing agroforestry practices into their farms in their effort to improve soil fertility (Barrios et al., 1997; Kwesiga et al., 2003; Akinnifesi et al., 2010, Barrios et al., 2012a), and other household demands (Nyaga et al. 2015b). Farm management decisions in localities with poor extension services are largely guided by local knowledge (Berkes et al., 2000; Barrios and Trejo 2003). Local knowledge is defined here as a result of the intuitive integration of local agroecosystems responses to climate, land-use and soil management through time by land managers (Barrios et al., 1994; Berkes, 1999; Barrios and Trejo, 2003; Barrera-Bassols and Toledo, 2005).

The use of local knowledge has been recommended as a way of improving the sustainability of natural resource management at the local level (Berkes et al., 2000; Moller et al., 2004; Fairhead and Scoones, 2005; Rist and Dahdouh-Guebas, 2006; Pauli et al., 2012). Various studies have been carried out utilizing local knowledge on soil and indicators of soil quality (Barrios and Trejo, 2003; Oudwater and Martin, 2003; Mairura et al., 2008; Dawoe et al., 2012). There are several soil quality indicators that are important to farmers and may include biological and/or physical soil fertility parameters (Doran & Jones, 1996). Farmers have been reported to use local plants and soil biota as key indicators of differences in soil quality (Barrios and Trejo, 2003; Mairura et al., 2007; Pauli et al., 2012).

Local knowledge can be integrated with global scientific knowledge through knowledge sharing methodologies aiming to generate ‘hybrid knowledge’ (Barrios et al., 2006;

Barrios et al., 2012b). Integration of local and scientific soil knowledge is important in that it adds to the general body of knowledge about soil health, in other instances, farmers in the study area may have different perceptions of what makes a soil ‘good’ compared to researchers (Gray and Morant, 2003).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Site selection and description

The study was carried out on selected settlements in Trans-Nzoia County, Rift Valley, Kenya (Figure 3.1). The settlements were formerly large-scale farms under a single owner which were later subdivided and dedicate to smallholder farms under different management options during and after Kenya independence, 1964. Trans-Nzoia is one of the highland areas where ex-soldier settlement schemes were established after World War I and World War II. A total of 28,000 acres were distributed to individuals who participated in the East African campaign, cooperative societies or government. At independence, most of the white farmers in Trans-Nzoia were displaced and there were basically three ways in which the land ended up in the hands of new owners; (1) Kenyan individuals bought whole farms; (2) cooperatives societies bought the land collectively and divided it among their members; and (3) government bought the farms, some of which was put under the Agricultural Development Corporation (ADC) farms or sub-divided for smallholder settlement schemes (Soini, 2007).

Five settlements were selected following preliminary survey using interviews with County and village officers, field tours and agroecological maps. The settlements are: i) Botwa (0º 57′N; 35º06′E), ii) Hututu (1º 00′N; 35º09′E), iii) Sinoko (0º 57′N; 35º09′E), iv) Wehoya (0º 57′N; 35º04′E) and v) Yuya (1º 00′N; 35º06′E). All settlements selected are within a 10km radius, have similar altitude, soil type and rainfall pattern, representative of current land use, share historical land use of being changed from large-scale farming to subdivision into small-scale farms to ensure representative. Botwa, Sinoko, Wehoya and Yuya settlements were the result of redistribution processes led by cooperative societies while Hututu was part of a government resettlement initiative.

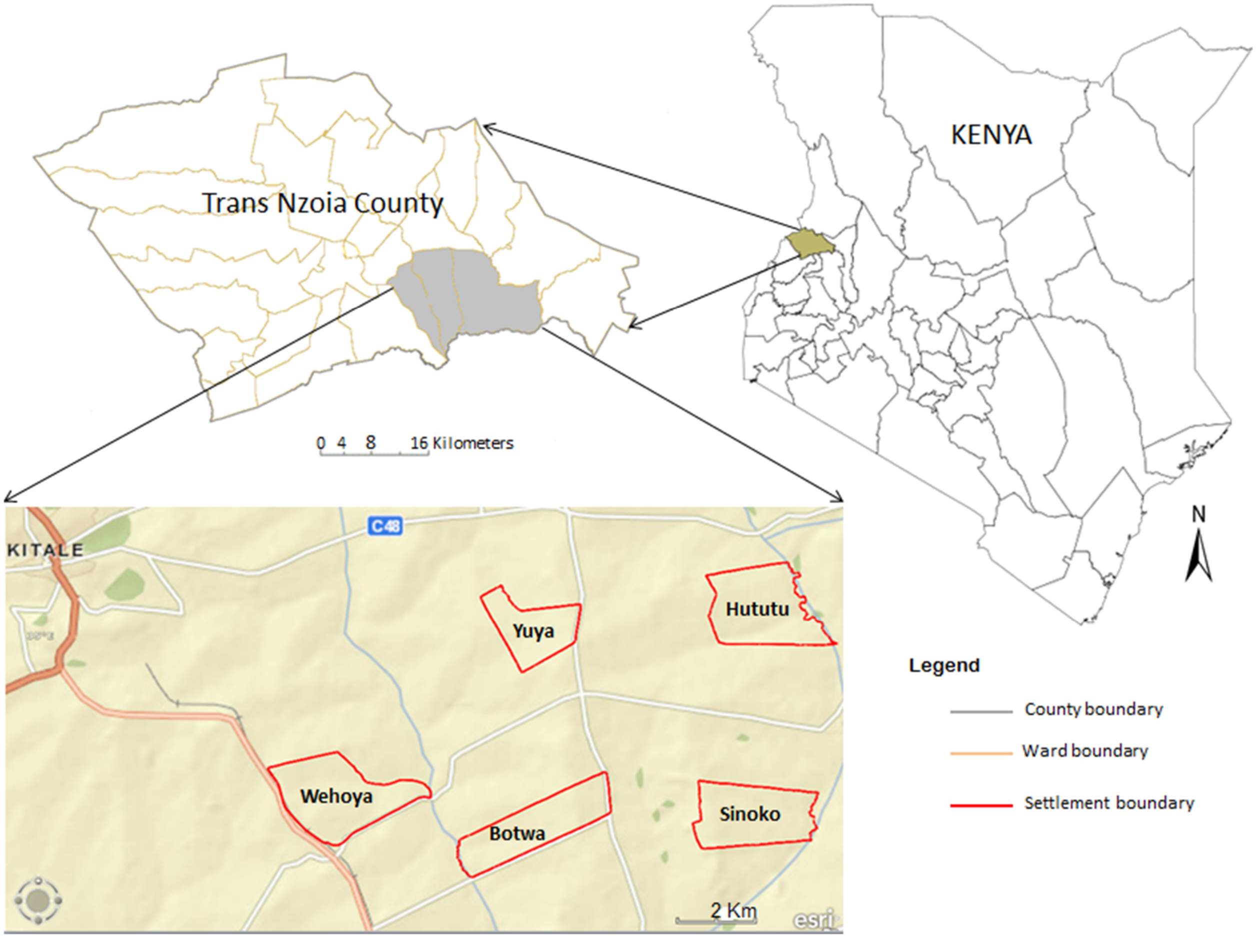

Figure 0.1: Map of the study site of showing the five settlements in Trans-Nzoia County, Kenya.

Trans-Nzoia County is traditionally considered as the food basket of Kenya with major production of maize seconded by beans (Horváth, 2006). The County is under agro-ecological zone 4 corresponding to upper midlands (FAO, 1996), characterized by 1800-1900 m altitude, a cool and temperate climate with average annual temperatures ranging between 10 and 27°C. The area receives 1000-1200 mm precipitation annually falling between end of March and November (Jaetzold and Schmidt, 1983). Trans-Nzoia lies in a basement system with mainly sedimentary rocks or claystones; the dominant soil types are Andosols and Nitisols (Horváth 2006).

The County has a high population density of more than 328 persons km^{-2} according to 2009 national census (KNBS, 2010) with 50% of the population living below the poverty line (KNBS, 2005/2006). The average farm size ranges between 0.5 and 1 hectare per household (Francis, 2000; Mango, 2002).

During the large-scale farming period, before 1964, maize (*Zea mays* L.) monocropping was practiced in rotations of 2-3 years with beans (*Phaseolus vulgaris* L.) or wheat (*Triticum aestivum* L.). Livestock was also an important farming practice in each settlement which involved paddocking as well as cultivation of livestock fodder such as napier (*Pennisetum purpureum* Schumack) and Boma Rhode (*Chloris gayana* Kunth) grasses, and sunflower (*Helianthus annuus* L.). Currently, livestock still forms an important part of the smallholder farming and include cattle and sheep. The cattle are free-ranging during maize off-season and controlled during maize season. Some farmers feed the livestock exclusively within their own plots while others take them to feed outside their plots.

3.2 Sampling Design

Transects were laid out across each settlement, with the help of a settlement elder and key informants, to ensure representative selection of study farms. Transect walks were organized with local guides during sampling of households. Farms with non-existing homestead were skipped as well as those without a household member to respond to questionnaire, or non-cooperative farmers. GPS coordinates for each sampled homestead were recorded. A total of 123 farms were sampled in the five settlements (Botwa=24, Hututu=21, Sinoko=25, Wehoya=34 and Yuya=19). Crop field is defined here as comprising of the cropping areas, the boundary planting around cropping areas, and the woodlot area of the farm.

Tree species richness analysis was conducted on-farm to identify the most common species found intercropped with maize in crop fields and assess farmers' preferences on agroforestry tree attributes. Overall, from the top ten list, the order of importance of trees at crop field was *Eucalyptus spp* > *S. sesban* > *G. robusta* > *C. calothyrsus* > *M. lutea* > *C. macrostachyus* with the rest found growing at homestead area (Nyaga et al., 2015b). In order to evaluate the effect of dominant tree species on crop yield in addition to contribution of water and nutrient availability in the soil smallholder farmers intercropping maize with one or more of the six (6) listed trees at crop field were selected.

The dominant tree species represented 76.2% of the total tree cover in the study. The study selected one (1) tree individual in each of the five (5) settlements thus every species was replicated five (5) times. Therefore, the six dominant tree species were each replicated five (5) times thus resulting in 30 agroforestry plots sampled. Tree were selected in smallholders' farms guided by number of factors which include; 1) farm size between 0.5 to 3 acres; 2) farmers willing to collaborate; 3) a farmer intercropping maize with one or more of selected tree species; 4) areas not affected by flooding; and 5) farm within a former large-scale maize land use with a continuous history of management by current owners.

To study farmers' preferences on agroforestry tree attributes contributing to soil quality the study focused on their practice of intercropping maize with one or more of the top six (6) listed trees at crop fields. From each of the five (5) settlements, three (3) tree replicates of each of the six (6) selected agroforestry trees were included adding up to ninety (90) agroforestry trees. Since several the selected farmers retained more than one of the selected trees species, the 90 agroforestry trees were found in 47 study farms.

3.2.1 On-station experiment

To enable quantification of tree effect on maize performance in a controlled environment, an on-station experiment was established at Kitale Vi-agroforestry demonstration farm. The experiment was also used to monitor tree growth. Seedlings for three selected tree species *M. lutea*, *G. robusta* and *C. macrostachyus* were transplanted to established plot. The plot was 75m by 17m in measurement and had existing mature *M. lutea* and *C. macrostachyus*. The two species were established at a spacing of 8m by 6m with the initial planting done in 1995. Most of the first-generation trees have been cut down and replaced with new ones. In consideration to available land, 3 blocks were set with each block measuring of 15m by 25m. In each block 20 treatment/trees (4 treatments replicated 5 times) were established. The treatments are *G. robusta, M. lutea, C. macrostachyus* and control (maize alone).

The experiment was laid in a completely randomized block design. This considered historical differences in the plot management along its length. Tree seedlings were established in 5 metres spacing whereby planting of new seedling and their monitoring allowed WaNuLCAS parametarization. The plots had already mature species which allowed monitoring of tree-crop interaction and planting of new seedlings was synchronized with already existing mature trees. Seedlings and maize planting in the plot was carried out in April 2012 and 2013. Hybrid 614 which is the common maize variety among farmers within the County was planted. The spacing of maize was done at 75 cm by 25cm with two seeds per hole whereby thinning was done after germination to one seed per hole. Maize growth measurements like those carried out in on-farm experiments and tree growths measurements were done which include basal diameter and height.

3.3 Data collection procedures

3.3.1 Inventory of current trees grown on farms and measurement of their physical attributes

The number of trees, species present and their utilization at each farm was identified and quantified using ground based method and semi-structured questionnaires. All trees i.e. woody perennials growing to over 1.5 m (Beentje, 1994) with diameter at breast height (DBH) greater than or equal to 5 cm were enumerated. Tree were identified to species level and local names recorded.

DBH was measured at 1.3 m above the ground using measuring tape. Crown diameter was measured crosswise with measuring tape as adopted from Kuyah et al. (2012); the largest diameter and the diameter perpendicular to it. Crown area (ca) in m^2 was calculated assuming an elliptical crown shape using the formula: $ca = \pi\{(l/2) \times (w/2)\}$ where (l) is the largest diameter and (w) is the diameter perpendicular the largest diameter. Total height and height to the first leaf (m) of standing trees was estimated using a hypsometer (vertex III and transponder T3) (Table 3.1).

Using semi-structured interviews, the land size owned by each farmer and nature of tenure was recorded. House characteristics was observed about size and quality (permanent, semi-permanent or grass thatched). Livestock ownership was also recorded in terms of type, number and whether local or improved breed are present. In crop production, the farmyard manure use, amount of fertilizer used during planting and at top-dressing and frequency of use was also recorded. Employment status of household members was recorded and categorized into formal or casual employment and the frequency of seeking casual employment. Other off-farm earnings such as children remittance were recorded.

During household level semi-structures interviews, information on land tenure and time under current management was obtained for each household. Two land tenure categories were identified based on possession or not of a title deed which is the legal assurance of ownership to land in paper form and is loosely referred to as the certificate to land ownership in Kenya. The time since the current household started to farm their present land was classified into three (3) age categories; short-term (1 to 15 years), medium-term (16 to 30 years), and long-term (over 30 years).

Table 0.1: Physical attributes of selected tree species. **Trees specifically sampled for soil moisture determination are indicated in bold letters.**

Site	Farmer	Tree	Tree age (years)	Tree height (m)	DBH[1] (cm)	Height to 1st leaf (m)	Crown area (m^2)
Botwa	William Wamalwa	*C. calothyrsus*	10	3.5	6.4	0.05	0.20
Yuya	David Kisaka	*C. calothyrsus*	10	4.3	13.1	0.1	0.20
Yuya	Patrick Wanjala	*C. calothyrsus*	10	3.7	7.3	0.2	3.25
Hututu	**Patrick Muchuta**	***C. calothyrsus***	**22**	**3.3**	**5.7**	**0.2**	**23.08**
Wehoya	Evans Kamadi	*C. calothyrsus*	7	1.7	3.8	0.1	23.08
Yuya	Kaitano Mukhebi	*C. macrostachyus*	2	4.1	5.1	2.65	13.16
Yuya	Joyce Simiyu	*C. macrostachyus*	8	11.7	24.5	3.5	51.43
Hututu	Isaac Juma	*C. macrostachyus*	11	7.5	17.8	3.2	18.78
Wehoya	Evans Kamadi	*C. macrostachyus*	4	3	4.5	1.7	16.96
Sinoko	**Irario Barasa**	***C. macrostachyus***	**8**	**6.4**	**15.3**	**1.9**	**30.51**
Botwa	Francis Wandabwa	*Eucalyptus spp*	3	8.6	7.6	2.7	19.97
Yuya	Alfred Opwaka	*Eucalyptus spp*	17	10.9	16.2	1	15.89
Wehoya	Dismus Wanyama	*Eucalyptus spp*	18	16.6	49.0	3.3	36.58
Sinoko	**Convic Mbali**	***Eucalyptus spp***	**39**	**26**	**143.3**	**6**	**81.17**
Sinoko	Alex Juma	*Eucalyptus spp*	10	16.2	67.2	5	30.14
Botwa	Francis Wandabwa	*G. robusta*	4	6.6	5.1	2.4	14.08
Yuya	Joseph Situma	*G. robusta*	6	8.5	15.9	2.75	20.82
Hututu	**Linus Juma**	***G. robusta***	**23**	**14.7**	**31.2**	**2.5**	**43.52**
Hututu	Isaac Juma	*G. robusta*	11	15.3	21.0	3.5	28.26
Sinoko	Alex Juma	*G. robusta*	6	8.9	13.7	2.8	9.88
Botwa	Maurice Majimbo	*M. lutea*	14	9.2	23.2	2.5	8.71
Yuya	Peter Juma	*M. lutea*	12	8.8	11.1	2.2	10.94
Hututu	John Makali	*M. lutea*	20	8.7	20.4	3.3	19.08
Hututu	Isaac Juma	*M. lutea*	11	12.1	13.7	5.4	20.02
Sinoko	**Convic Mbali**	***M. lutea***	**19**	**15**	**74.2**	**2.5**	**32.97**
Hututu	Patrick Muchuta	*S. sesban*	2	4.6	9.9	2.1	23.31
Hututu	Isaac Juma	*S. sesban*	3	7.9	7.6	2	15.07
Hututu	Martin Shikuku	*S. sesban*	3	1.6	8.9	2.8	15.70

Sinoko	**Irario Barasa**	***S. sesban***	**3**	**5**	**5.1**	**2.3**	**6.99**
Sinoko	Alex Juma	*S. sesban*	3	7	6.4	2	20.80

[1]DBH-Diameter at breast height (1.3m)

3.3.2 Indicators and ranking of household resource endowment

Socio-economic information of each farm was collected in Section 3.3.1 was used to characterize household resource endowment together with information from key informants.

The key informants were selected elderly people, village/settlement heads and other knowledge holders who had lived in the area for a period greater than 40 years. They were selected after informal discussions with settlement inhabitants. Wealth ranking was carried out by adapting the technique of Crowley (1997). At every settlement, the key informants were requested to list and prioritize wealth indicators that could be used during classification of household resource endowment. The indicators selected were: 1) land area owned, 2) house quality and size (permanent, semi-permanent or grass thatched), 3) form of employment; formal or casual off-farm employment, and also the frequency of seeking casual employment, 4) amount of annual crop production; yield and ability to purchase inputs such as fertilizer, 5) Livestock/cattle ownership; quantity, improved or local breeds, and 6) other off-farm earnings such as children remittance.

A combination of two methodological approaches was used to differentiate and group farmers according to resource endowment. First, information obtained from farmers during the household level semi-structures interviews (e.g. Section 3.3.1) was compared with the household resource endowment indicators described in this section and used to distribute each farmer into one of the 3 established resource endowment categories: high, medium or low. Second, at each settlement, the chairman and the key informants were requested to rank the farmers according to their own criteria and also taking into account the existing list of prioritized household resource endowment indicators. The two sets of results were then integrated to obtain the final ranking.

3.3.3 Local knowledge data collection and participatory soil sampling

Detailed, semi-structured interviews adapted from Barrios et al. (2012b) (Appendix 1) were undertaken with the 47 smallholder farmers in November and December 2012. Interview questions covered local soil classes, local indicators of soil quality used to separate local soil classes, and agroforestry tree attributes recognized to influence soil quality. During interviews farmers were asked to orally describe the characteristics of the local soil classes that occurred in their land. Farmers also gave a tour of their farms, pointing out distinguishing farm features such as visual soil characteristics, soil animals, plant species or other components of their farms.

At every farm, soil sampling was guided by local soil classes and soil qualities recognized by the respective farmer. Twenty-seven (27) out of 117 fields were classified as intermediate between productive (good) and non-productive (poor) soil. Soil sampling was conducted at the center point at each local soil quality class identified, and 4 additional samples were taken in four directions (i.e. N, S, E and W) from the center point avoiding coming close to the edge of the next soil quality class when more than one was present at the study farm. A sampling depth of 0-20cm was maintained because most farmers classify their soil considering the arable portion of the soil and do not consider the deeper soil profile. A composite sample of 500 g was collected from each local soil quality class by thoroughly mixing the five sub samples on a polythene sheet. Soil analysis was also carried out at ICRAF Soil-Plant Spectral Diagnostic Laboratory as described in Section 3.3.7 below.

3.3.4 Crop establishment, growth and yield measurements

The land was ploughed, harrowed and planting done in April 2012 and 2013 though at different dates for different farms. The distance of maize establishment as related to each experimental tree was measured and recorded to establish the zones of tree influence. Most farmers plant the late maturing H614D and H6213 maize varieties which grow for a period of 7 months between mid-April and mid-November of every year. Two (2) maize plants per row were labeled with tape on opposing sides of the tree to facilitate repeated measurements of basal stem diameter, height to the tip of the youngest leaf, and height to the top of the canopy. Harvesting was done when leaves had dried uniformly at crop maturity and measurement done. The above-ground dry weights (stover biomass) were measured at four (4) distances set for each tree individual and determined on two plants per row on a row by row basis. The two plants per row were also used to assess maize yield, giving a total of 16 plants per plot. Maize yield (cob weight and grain dry weight) of each plot was assessed at the end of the cropping season on a row-by-row basis. The cobs were separated from the stover and weighed separately. Grain dry weight was determined after shelling the cobs.

3.3.5 Determination of volumetric soil moisture content (VSWC)

A Delta-T Profile Probe type PR1/6 (Delta-T Devices Ltd, Cambridge, UK) (PR1) was used for VSWC determination and the access tubes were installed at four distances away from the tree (Table 2). Three distinct tree/crop interaction zones can be distinguished in intercropping and include: i) a zone of light and root competition, mostly under the tree crown (A & B), ii) a zone of root competition, some area beyond the tree crown (C), and iii) open cropped areas that are relatively free from the interference of trees (D) (Rao et al., 1998; Van Noordwijk and Lusiana 1999; Muthuri, 2004). These zones were used as reference when establishing distances for access tubes installation and crop performance measurements under and outside the tree canopy. Zone A, B and C are also together described as ‘under’ the tree canopy while zone D is ‘outside’ tree canopy.

A total of Four (4) access tubes were installed at the different agroforestry zones for each of the 6 selected tree species without replication (Table 3.2). Access tubes under *Eucalyptus spp* and *M. lutea* were installed on the same farm under similar management similar to *C. macrostachyus* and *S. sesban*. Gouge and spiral augers were used to make clean, vertical holes, 28 mm in diameter and 1.11 m in depth within the soil profile. The depths of the holes were dug accurately to avoid any void beneath the tip of the tubes. The access tubes extended 50 mm above the soil surface and were wrapped with polythene papers over the top of the tubes and tightly taped. This was to prevent their base from being flushed with the surface soil and to deflect rain away from the sides of the access tube and avoid errors associated with differential flow down the side of the tube. A moisture meter type HH2 attached to the probe was used to record volumetric water content simultaneously at 10, 20, 30, 40, 60, and 100 cm depths. Repeated monthly measurements were carried out between May to December 2013.

Table 0.2: Table showing the list of farms, trees and distances in meters (Zone A: Distance 1; Zone B: Distance 2; Zone C: Distance 3; and Zone D: Distance 4) from tree trunk where access tubes were installed.

			Distance in metres			
Tree selected	Farmer	Settlement	Zone A	Zone B	Zone C	Zone D
Calliandra calothyrsus	Patrick Muchuta	Hututu	0.9	1.8	2.7	5.4
Croton macrostachyus	Irario Barasa	Sinoko	0.9	1.8	2.7	5.4
Eucalyptus spp	Convic Mbali	Sinoko	2.2	5.2	10.2	13.2
Grevillea robusta	Linus Juma	Hututu	1.25	2.5	5	8.75
Markhamia lutea	Convic Mbali	Sinoko	1.25	2.5	5	8.75
Sesbania sesban	Irario Barasa	Sinoko	0.9	1.8	2.7	5.4

3.3.6 Soil sampling under agroforestry zones and depths

Concentric zoning approach (Bayala et al., 2015) was used to collect soil samples for nutrient availability analysis as affected by distance from the tree trunk. At each agroforestry plot level, the area around each tree was subdivided into four concentric tree influence zones; 0-1 m from the trunk (zone A), from 1 m to half diameter of the tree crown (zone B), from half diameter to the edge of the crown (zone C), and from the edge of the crown to 3 m outside of the crown (zone D). This approach allowed comparing influence zones from trees with different horizontal radius of the tree crown (Table 3.3).

Fifteen (15) soil pits were dug across the 5 settlements to characterize the soil profiles. Analysis of depth of horizon zones showed little variation between settlements and locations and thus a common average depth for each soil horizon was calculated from the 15 measurements and adopted in soil sampling protocol at each agroforestry plot. Four standard soil layers were defined as follows: 0-20 cm (layer 1), 21-35 cm (layer 2), 36-60 cm (layer 3), and 61-90 cm (layer 4) (Table 3.4).

Four sub samples in opposing sides (at right angles) were collected and pooled at each layer and zone. Approximately 500g samples were collected and immediately transferred to tightly fitting zip lock polythene bags. Samples were air-dried before transportation to the Laboratory.

Table 0.3: Width (m) of the agroforestry zones designated for soil sampling under dominant tree species in Trans-Nzoia County.

Zone	*C. macrostachyus*	*G. robusta*	*M. lutea*
A	1.25	1.25	1.25
B	2.5	2.5	2.5
C	5.0	5.0	5.0
D	8.75	8.75	8.75
Total Zone	*17.5*	*17.5*	*17.5*

Table 0.4: Soil layer thickness (m) in the agroforestry zones at Trans-Nzoia County.

Layers	Depth
1	20
2	15
3	25
4	40
Total depth	*100*

3.3.7 Analysis of soil samples

Air-dried soil samples were crushed to pass a 2mm sieve and 20 g subsamples were submitted to ICRAF Soil-Plant Spectral Diagnostic Laboratory for analysis by mid-infrared diffuse reflectance spectroscopy (MIR) and other specialized analyses. To generate reference samples for prediction purposes, 48 (10%) soil samples from n= 480 were selected (Kennard and Stone, 1969) and were subjected to Carbon (C) and Nitrogen (N) and wet chemistry based on MIR Spectra diversity.

Fine ground soil samples were loaded into four replicate wells, each scanned 32 times, using Bruker, Tensor 27 Fourier-Transform spectrometer attached to a High-Throughput Screening (HTS-XT) extension unit with robotic arm, Bruker Optics, Karlsruhe, Germany (Shepherd and Walsh, 2007). The four spectra were averaged to account for within-sample variability and differences in particle size and packing density. The measured wavebands ranged from 4000 to 600 cm^{-1} with a resolution of 4 cm^{-1} and zero filling of 2. The resulting spectral and reference values were read into R statistics software for computation of the partial least squares (PLS) model. All the spectral data were pre-processed using the first derivatives.

For chemical analysis soil samples were ground for a minute to 0.5mm size using Retsch RM 200 mill prior to carbon (C) analysis. Total carbon was then analyzed by thermal oxidation (Skjemstad and Baldock, 2008) using a CN-Analyzer (Flash EA 1112 NC, CE Instrument, Thermo-quest). Soil pH was measured in soil/water suspension consisting of

20 g air-dried soil and 40 milliliters of demineralized water by use of pH meter (Anderson and Ingram, 1993). Mehlich 3 extraction method was used to analyze for exchangeable bases and available P, because it allowed analyses of multiple elements from one extractant using inductively-coupled plasma spectroscopy (ICP) (Mehlich, 1984).

3.3.8 Determination of bulk density

Using a machete, an undisturbed flat horizontal surface in the soil was prepared at the depth four (4) depths previously identified in profile pits description (Section 3.3.7). Labelled steel ring was gently hammered into the soil using a wooden block to protect the ring. Care was taken to avoid pushing the ring in too far thereby preventing the soil compaction. Excavation around the ring without disturbing or loosening the soil it contains was done to carefully remove it with the soil intact. Any excess soil from the outside the ring was removed. The soil was poured into the plastic bag and sealed.

Bulk density was determined as follows;

$$\textit{Bulk density } (g/cm^3) = \textit{Dry soil weight } (g) \,/\, \textit{Soil volume } (cm^3) \qquad \textit{Equation 1}$$

To obtain the soil dry weight an ovenproof container was measured in grams (W_1). All soil from the bag was removed into the container and oven dried at 105ºC for 2 hours. The samples were weighed after (W_2) and dry soil weight was determined as follows;

$$\textit{Dry soil weight } (g) = W_2 - W1 \qquad \textit{Equation 2}$$

Soil volume was estimated from the ring volume as the product of the ring height, square of the ring radius and *pi* (3.14).

3.3.9 Calculations and statistical analysis

Recorded tree species information was tabulated into an ecological data matrix. This was subjected to diversity analysis using BiodiversityR (Kindt and Coe, 2005), based on R statistical software version 2.11.1 (R Development Core Team 2010). The Shannon-Wiener (H) and Simpsons's (D) diversity indices were calculated as described by Magurran (2004). In order to keep consistency among diversity indices (e.g. the bigger the value the greater the diversity), the inverse Simpson's diversity index (D) was used.

The Shannon-Wiener diversity index was created to effectively deliver a message concerning species richness and evenness in a given plant community. The Shannon diversity index (H) calculated as follows (Equation 3), (Magurran, 2004):

$$H = \sum_{i=1} - (P_i * \ln P_i) \qquad \textit{Equation 3}$$

Where P_i is the fraction of the entire population made up of species i.

Shannon index provides information on the species density and distribution among all the species in the community. High values of H would be representative of more diverse communities with evenly distributed species while a community with only one species would have an H value of 0 because P_i would equal 1 and be multiplied by ln P_i which would equal zero. If the species are evenly distributed then the H value would be high. So, the H value allows us to know not only the number of species but how the abundance of the species is distributed among all the species in the community. Shannon-Wiener indices obtained were converted to effective number of species or true diversity by taking the exponential of Shannon diversity index.

Shannon-Wiener index values are between 0 to 5 and results are generally between 1.5 – 3.5, and it very rarely exceeds 4.5. The values above 3.0 indicate that the structure of habitat is stable and balanced; the values under 1.0 indicate that the habitat structure is unstable (Mandaville 2002) as a result of disturbances or degradation.

The Simpson's diversity index (D) is most sensitive to changes in the more abundant species. Simpson's diversity index considers the number of species present, as well as the abundance of each species. The value of this index starts with 0 as the lowest possible figure. When using the Simpsons index (Equation 4), the number you will calculate should be a value between zero and one with $0 < D \leq 1$. Values near zero indicate a highly diverse (heterogeneous) ecosystem and values near one indicate a less diverse (homogeneous) ecosystem. The Simpson index was calculated as follows:

$$D = \frac{\sum n(n-1)}{N(N-1)}$$

Equation 4

D = diversity

N = total number of individuals

n = numbers of each different species (relative abundance of each species)

The value of D ranges from 0 to 1. With this index, 0 represents infinite diversity and, 1, no diversity. That is, the bigger the value the lower the diversity. This does not seem intuitive or logical, so in current study we use derivations of the index; the inverse (1/D).

Tree counts corresponding to homestead or crop field respectively are reported as trees per farm because of missing information on their relative farm area cover. Nevertheless, all other data (e.g. farm size, tree density, species richness, number of exotic or indigenous species, utility groups and number of dominant trees species) were expressed on a per hectare basis to allow unbiased comparison between the smallholder farms. Normality test (Shapiro-Wilk) on the raw data showed that the samples did not follow a normal distribution. Therefore, a non-parametric test, Kruskall-Wallis test, was performed for more than 2 independent samples while Mann-Whitney (U) test was carried out for 2 independent samples using SPSS version 23 (IBM Corp. Released (2014). Pairwise Mann-Whitney Test was carried out where significant difference was obtained through Kruskall-Wallis test. Significance levels of $P \leq 0.05$ were used unless stated otherwise.

Response variables (farm size, tree density, number of trees in homestead/crop fields, number of exotic/native trees, number of trees according to utility group, and abundance of the 10 most dominant species in the farms) were modeled to evaluate the additive effect of the three explanatory variables (resource endowment, land tenure and time under current management) using the generalized linear model (GLM) described in the Tree Diversity Analysis Manual (Kindt and Coe, 2005). Generalized linear model were picked for use in current analysis as the response variables were in form of count data. Estimated dispersion parameters/deviance explained were found to be low for all models indicating that the individuals are not randomly distributed but were clumped. Diagnostic plots also provided evidence to this and quasi-Poisson generalized linear model was more appropriate than Poisson model in this situation. Generalized linear models (GLM) using R statistical software version 3.0.3 (2014) were developed as described in Tree diversity analysis manual (Kindt and Coe, 2005). The significance levels were results of type-II ANOVA Chi^2-test which is based on deletions of variables from the model. It investigates whether there is evidence that removing one variable would result in a significantly lower deviance that is explained by the simplified model. If P-value is significant it means that the predictor/independent/explanatory variable helps predict the occurrence of response variable.

Normality test (Shapiro-Wilk) on raw maize performance data showed that the samples did not follow a normal distribution therefore, non-parametric tests were carried out. Kruskall-Wallis test was performed for more than 2 independent samples while Mann-Whitney (U) test was carried out for 2 independent samples using SPSS version 23 (IBM Corp. Released (2014). Where a significant difference was obtained through Kruskal-Wallis test, results were subjected to pairwise Mann-Whitney test. Standard Error (SE) was calculated to show distribution of data around the mean.

Nitrogen fixation ability defined by the production of root nodules, and decomposability of organic inputs (e.g. (Lignin + Polyphenol)/N ratio), were also included as key tree attributes linked to soil nutrient availability (Barrios et al. 1997). To estimate the decomposability rate/ N-mineralisation of different tree residues (foliage, litter and root samples), we calculated (lignin + polyphenol)/N ratios and used them as indicators of organic resource quality and decomposability. Analysis of Variance (ANOVA) between decomposability of the dominant tree species was performed using SPSS version 23 (IBM, Corp. Released 2014).

Two methods were used to compare soil nutrient availability at different distances from the tree trunk and soil depths beneath dominant tree species in smallholder farms. First, a general linear mixed model (GLMM) was used to test the effects of tree species, agroforestry zones and soil sampling depth on soil properties (Model formulas: factor ~ Tree species + Error (replication: tree species) + zone + tree species × zone + layer + tree species × layer + tree species × zone × layer. This was subjected to analysis using nlme package (Pinheiro et al., 2009) based on R statistical software version 3.1.1 (R Development Core Team., 2014). Values on soil nutrients were square root-transformed to improve normality before GLMM. Lastly, Kruskall-Wallis test was performed for more than 2 independent samples while Mann-Whitney (U) test was carried out for 2 independent samples using SPSS version 23 (IBM, Corp. Released 2014). Normality test (Shapiro-Wilk) performed on the raw data showed that the samples did not follow a normal distribution and non-parametric test were opted. Pairwise Mann-Whitney Test was carried out where significant difference was obtained through Kruskall-Wallis test.

We used a general linear mixed model (GLMM) to test the effects of tree species, agroforestry zones and soil layer on soil water (Model formulas: 1) factor ~ tree species + soil depth + tree species × soil depth and including tree replicate as a random factor, and 2) factor ~ tree species + agroforestry zone + tree species × agroforestry zone and including tree replicate as a random factor in volumetric soil water content and different sampling dates for VSWC analysis). This was subjected to analysis using nlme (linear and nonlinear mixed effects of models) package (Pinheiro et al., 2009) based on R statistical software version 3.1.1 (R Development Core Team., 2014). The effect of distance from the tree trunk was considered by performing the same GLMM separately for each distance hereby referred as zones. Values on VSWC were log-transformed to improve normality before GLMM.

In order to identify factors explaining crop productivity, AMMI model (Additive Main effects and Multiplicative Interaction) was used. The AMMI model is one of the most widely used statistical tools in the analysis of multiple-environment trials. It has two purposes, namely understanding complex genotype by environment interaction (GEI) and increasing accuracy. Nevertheless, the AMMI model is a widely used tool for the analysis of multiple-environment trials, where the data are represented by a two-way table of GEI means. In the complete tables, least squares estimation for the AMMI model is equivalent to fitting an additive two-way ANOVA model for the main effects and applying a singular value decomposition to the interaction residuals. It assumes equal weights for all GEI means implicitly. The AMMI model identified the best combinations of tree species and agroforestry zones with respect to maize yield as the response variable.

Usually the environmental (agroforestry zones) and genotype (tree species) scores of the first and second bilinear terms are plotted. The distance between two genotype vectors (their end points) is indicative of the amount of interaction between the genotypes. The cosine of the angle between two genotype (or environment) vectors approximates the correlation between the genotypes (or environments) with respect to their interaction. Acute angles indicate positive correlation, with parallel vectors (in exactly the same directions) representing a correlation of 1. Obtuse angles represent negative correlations, with opposite directions indicating a correlation of -1. Perpendicularity of directions indicates a correlation of zero. The relative amounts of interaction for a particular genotype over environments can be obtained from orthogonal projections of the environmental vectors on the line determined by the direction of the corresponding genotype vector. Environmental vectors having the same direction as the genotype vectors have positive interactions (that is these environments favored these genotypes), whereas vectors in the opposite direction have negative interactions.

Pearson's correlation analysis was also performed on the data of soil nutrients availability and maize yield under each of the six dominant tree species. This was carried out in order to investigate the differential impact of spatial distribution of soil nutrients under the dominant tree species on maize yield.

Quantitative data on local knowledge was subjected to descriptive analysis of simple proportions using the SPSS version 23 (IBM Corp. Released (2014). Farmers' answers to questions in the semi-structured interviews were categorised and the number of responses falling into each category was expressed as a proportion of the total number of farmers interviewed.

Three different analyses were performed on the data. First, an unbalanced one-way analysis of variance (ANOVA) was performed on soil properties measured in the laboratory. The three farmers' soil quality classes (good, intermediate and poor) were used as the grouping variable. Secondly, to distinguish between inherent differences in soil type from those that result from past land management, we analyzed effect of land use history, land tenure, age of small-scale farming and time under current management for soil chemical properties showing significant differences in the different soil quality classes. Non-parametric tests were performed, Kruskall-Wallis test, for more than 2 independent samples and Mann-Whitney (U) test for 2 independent samples. Lastly, results from chemical analyses conducted (pH, Al, B, Cu, Fe, Mn, P, S, Zn, PSI, Na, Ca, Mg, K, ExBas, ECd, ExAc, Total N, Total C, Acidified N and Acidified C) were associated with the respective local soil quality classes. This was followed by a calculation of the proportion of farmers accurately predicting the soil chemical data during their discrimination of local soil quality classes (e.g. good, intermediate, poor) at their respective farms. In order to increase robustness of the identification of local indicators of soil quality we used triangulation rationale i.e. at least 3 votes supporting an indicator/context interaction to be included in our analysis (Patton, 2015).

Significance levels of $P \leq 0.05$ were used unless stated otherwise.

3.3.10 Parameterization of WaNuLCAS model

Zone A represents the horizontal distance occupied by trees within the model. Zones B and C include both the tree and crop components and represent the zones where the tree canopy and roots influence the crop to an extent which varies depending on distance from the tree row. The crop predominantly occupies zone D, with few or no tree roots being present. The zones defined for the three dominant tree species differed to due differences in canopy diameter.

Crop management data covering key activities such as crop planting and fertilizer application (Table 3.5) were entered in WaNuLCAS.

Table 0.5: Management practices of selected tree species in Trans-Nzoia County.

Farmer	Tree	Fertilizer application (g m^{-2})	Top dressing (g m^{-2})
Isaac Juma	*C. macrostachyus*	6.87	6.87
Isaac Juma	*G. robusta*	6.87	6.87
Isaac Juma	*M. lutea*	6.87	6.87

Three rain gauge kits (Brannan, UK) and three minimum-maximum thermometers were installed at Wehoya, Botwa and Hututu settlements. Temperature recordings were carried out thrice in a day; morning, mid-morning and evening while daily records of rainfall were made every morning. The daily rainfall recording was entered into weather section of excel file of the model. Model default soil temperature was used for the simulation due to lack of data in this respect. The water balance of the system includes rainfall, with the option of exchange between the tree zones by run-on and run-off, surface evaporation, uptake by the crop and tree and leaching. For the description of the soil water balance in soil plant models a number of processes should be combined which act on different time scales (van Noordwijk and Lusiana, 2011).

Maize was selected as the crop for intercrop scenarios because is the most preferred food and cash crop among farmers in the study area. No changes were made in the default parameters for maize from WaNuLCAS 4.0 crop library. One cropping season per year was set for model simulation according to farmers practices based on field observation.

The WanFBA model (van Noordwijk and Mulia, 2002) was used in the study to develop allometric equations to estimate aboveground biomass for *C. macrostachyus, G. robusta* and *M. lutea* and results were included into the set of WaNuLCAS 4.0 inputs parameters. The survey incorporates knowledge of tree growth, canopy, light capture, rain interception, tree water, N fixation, N and P concentration, litterfall and litter quality (Table 3.7 and 3.8). Litter quality from litterfall, pruned biomass and root of the three dominant tree species were also assessed and details used in tree parameterization (Table 3.6). Measured tree growth parameters at Table 3.7 and 3.8 were used in the survey to develop allometric equations to estimate aboveground biomass for selected tree species.

Table 0.6: Litter quality inputs for *C. macrostachyus, G. robusta* and *M. lutea* used in simulations.

	Litterfall		Pruned biomass		Root	
Tree species	Lignin fraction	Polyphenols fraction	Lignin fraction	Polyphenols fraction	Lignin fraction	Polyphenols fraction
Croton macrostachyus	0.21	0.04	0.08	0.03	0.16	0.01
Grevillea robusta	0.19	0.04	0.19	0.07	0.24	0.04

Markhamia lutea	0.15	0.06	0.35	0.06	0.14	0.02

Table 0.7: Tree growth parameters used in WaNuLCAS tree parameterization using WanFBA model.

Tree species	Wood density (>10 cm) g cm^{-3}	Branch density (2-10 cm) g cm^{-3}	Twig density (< 2 cm) g cm^{-3}	Area of a single leaf (cm^2)	Leaf dry weight (g)	Specific leaf area (cm g^{-1})
Croton macrostachyus	0.434	0.457	0.458	168.46	4.03	700
Grevillea robusta	0.616	0.571	0.543	230.02	4.01	57.36
Markhamia lutea	0.700	0.579	0.540	223.04	0.36	619.56

Table 0.8: Physical attributes of *C. macrostachyus, G. robusta* and *M. lutea* in Trans-Nzoia County selected for WaNuLCAS simulation.

Farmer	Tree	Tree age(years)	Tree height (m)	DBH^1 (m)	RCD^2 (m)	Crown diameter (m)	Crown area (m^2)	Height to 1st leaf (m)	Canopy Height (m)	Radius/height (ratio)
Isaac Juma	*Grevillea robusta*	11	15.3	0.66	0.99	6.0	23.26	3.5	11.8	0.25
Isaac Juma	*Markhamia lutea*	11	12.1	0.43	0.74	5.05	20.02	5.4	6.7	0.38
Isaac Juma	*Croton macrostachyus*	11	7.5	0.56	1.92	4.9	18.78	3.2	4.3	0.57

1DBH-Diameter at breast height (1.3m); 2RCD-Root Collar Diameter

3.3.10.1 Soil profile

Soil physical and chemical properties were based on analysis of samples collected from four soil layers and four zones (Section 3.3.6 and 3.3.7). Results of amount of soil N and P (Table 3.11) was used to parameterize soil nutrients in WaNuLCAS 4.0. Other soil physical and chemical characteristics were derived via WaNuLCAS 4.0 pedotransfer functions from soil texture (Table 3.9), bulk density (Table 3.9), soil organic matter content (Table 3.11), soil pH and soil CEC (Table 3.10) obtained from field data collected. Fertilizer inputs (specified by amount and time of application), atmospheric N fixation were specified in the model and they represent the nutrient balance part of the model.

Table 0.9: Values of soil physical used in the pedotransfer functions in the WaNuLCAS core module.

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})	Soil texture
0-20	61.6	18.2	22.8	1.39	Sandy clay loam
21-35	58.1	18.1	24.5	1.44	Sandy clay loam
36-60	55.2	17.4	26.3	1.42	Sandy clay loam
61-100	53.1	16.9	28.7	1.40	Sandy clay loam

Table 0.10: Soil CEC and pH inputs under C. *macrostachyus, G. robusta* and *M. lutea* used in WaNuLCAS pedotransfer function.

	Depth 1		Depth 2		Depth 3		Depth 4	
Tree species	pH	CEC	pH	CEC	pH	CEC	pH	CEC
Croton macrostachyus	5.935	9.87	5.831	9.52	5.979	8.85	6.120	5.98
Grevillea robusta	5.948	11.6	6.033	7.85	6.227	7.90	6.251	8.86
Markhamia lutea	6.262	7.09	6.132	7.09	6.005	6.46	6.072	6.46

Table 0.11: Measured soil organic carbon, N and P inputs under *C. macrostachyus, G. robusta* and *M. lutea* used in pedotransfer function in WaNuLCAS.

		Agroforestry zones											
		A			B			C			D		
		N (mg cm^{-3})	P (mg cm^{-3})	Organic C (%)	N (mg cm^{-3})	P (mg cm^{-3})	Organic C (%)	N (mg cm^{-3})	P (mg cm^{-3})	Organic C (%)	N (mg cm^{-3})	P (mg cm^{-3})	Organic C (%)
Croton macrostachyus	Depth 1	1.101	0.159	1.48	1.02	0.082	1.52	1.008	0.061	1.54	0.972	0.063	1.38
	Depth 2	0.882	0.05	1.28	0.868	0.029	1.33	0.828	0.031	1.18	0.756	0.025	1.07
	Depth 3	0.633	0.007	0.85	0.663	0.008	0.98	0.608	0.009	0.81	0.643	0.014	0.79
	Depth 4	0.627	0.01	0.82	0.584	0.004	0.84	0.568	0.009	0.77	0.53	0.005	0.65
Grevillea robusta	Depth 1	0.94	0.02	1.53	0.969	0.029	1.56	0.973	0.021	1.62	0.882	0.021	1.36
	Depth 2	0.723	0.006	1.13	0.736	0.008	1.18	0.662	0.003	1.11	0.615	0.003	0.95
	Depth 3	0.534	0.001	0.85	0.603	0.003	0.98	0.554	0.002	0.88	0.597	0.005	0.74
	Depth 4	0.492	0.001	0.72	0.466	0.001	0.79	0.471	0.001	0.72	0.425	0	0.8
Markhamia lutea	Depth 1	0.808	0.01	1.19	0.967	0.023	1.52	0.922	0.017	1.45	0.961	0.024	1.53
	Depth 2	0.641	0.002	1.01	0.662	0.003	1.05	0.702	0.004	1.05	0.821	0.011	1.25
	Depth 3	0.553	0.001	0.88	0.588	0.002	0.85	0.529	0.001	0.78	0.589	0.001	0.98
	Depth 4	0.464	0	0.67	0.51	0.001	0.7	0.431	0	0.62	0.485	0.001	0.76

3.3.10.2 Model simulations

Each tree species was run for 2 years period in a tree monoculture simulation and predicted results were compared with empirical field plantations measurements. Three (3) possible land use scenarios were characterized and simulated into the model for comparison purposes: (i) maize monocropping; (ii) tree-maize intercropping; and (iii) tree monoculture. The model was run at five different tree densities (50, 100, 200, 400, 800 trees/ha) to evaluate effect of tree density on crop production. To evaluate effect of agroforestry practices on soil water and nutrients the model was simulated for 100-year period. The scenarios simulated for each of the three species are summed up in Figure 3.2.

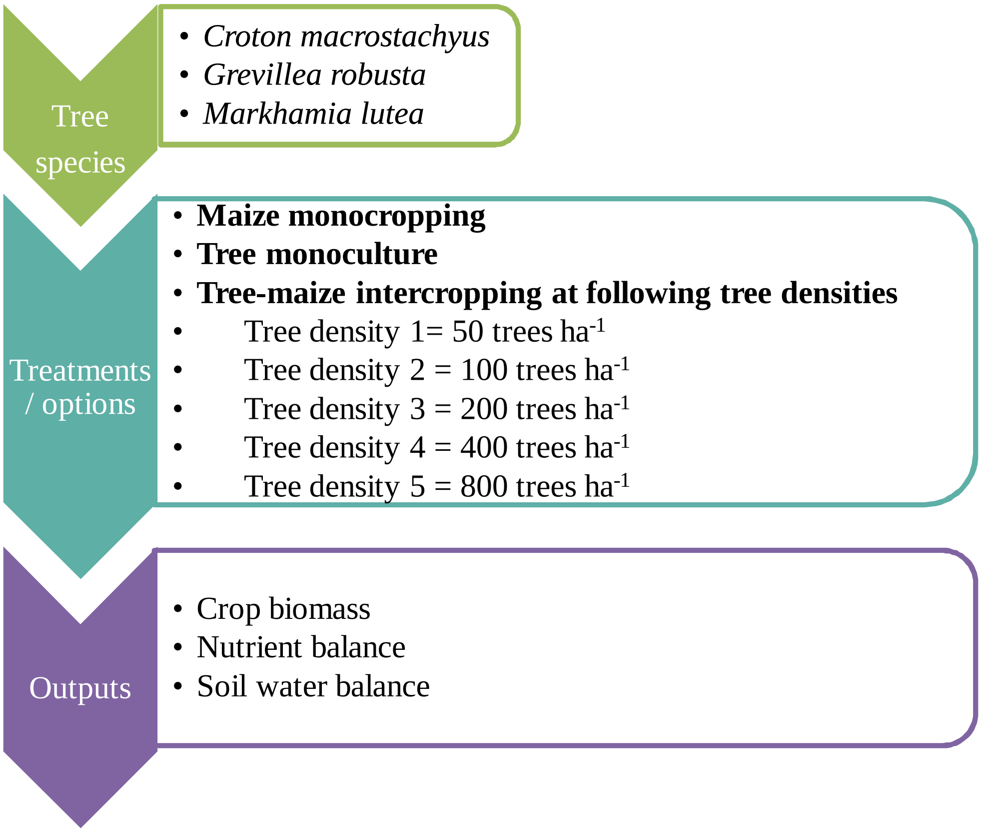

Figure 0.2: Flow chart illustrating scenarios simulated at Trans-Nzoia County.

Each tree species was subjected to all tree and crop planting scenarios and outputs were compared. An Excel table was therefore created within the model into which the daily information for the stem diameter and biomass of the trees generated during the simulations was copied; this was then used to provide the graphical outputs.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 General Information

4.1.1 Farm characteristics within the settlements

Thirty-one (66%) of the interviewed farmers were female and held primary responsibility in sowing and harvesting. Most of the farms in the surveyed area are small with a mean farm size of 0.89 ha (range = 0.04-8.09 ha) (Table 4.1). Surveyed farms on average hold 80 trees while the mean species richness per farm was 7.8 (range = 5.1-9.0). Many of the farms surveyed, 71 (58%) had a tree density of <100 trees ha^{-1}. Maize and livestock farming forms an integral part of economic activities of the farmers. All farmers grow maize on their farms and also a majority (98%) also intercrop maize and beans during the cropping season. 90% of farmers apply inorganic fertilizers during planting or for top dressing. 80% of farmers keep cattle with an average of 2.4 cows per household. Farmers also use cow manure for maize cultivation with 75% of farmers reporting the practice. The Shannon diversity index decreased in the following order Wehoya>Hututu>Botwa>Yuya>Sinoko. The Inverse-Simpson diversity index was largely consistent with the Shannon index and showed the following trend Hututu>Wehoya>Botwa>Yuya>Sinoko (Table 4.1).

Table 0.1: Main characteristics of typical smallholder farms discriminated by settlements studied in Trans-Nzoia, Kenya. Number in parenthesis represent range under farm size.

Variable	Unit	Settlement (n)				
		Botwa (24)	Hututu (21)	Sinoko (25)	Wehoya (34)	Yuya (19)
Year of subdivision into smallholder farms		1980	1977	1974	1982	1981
Total area	hectares	420	474	435	486	281
Number of households		1000	650	1000	1600	1000
Average farm size (range)	hectares	1.0 (0.2-8.1)	0.79 (0.04-8.1)	1.1 (0.04-6.9)	0.78 (0.04-6.1)	0.74 (0.04-2.0)
Maize cultivation	% farmers	100	100	100	100	100
Intercropping	% farmers	96	100	100	94	100
Fertilizer use	% farmers	67	81	100	94	90
Manure use	% farmers	54	71	72	50	60
		Sum (mean)				
Trees count	Settlement^{-1}(farm^{-1})	2189 (91)	2028 (97)	2000 (80)	2132 (63)	1336 (70)
Tree density	hectare^{-1}	102	139	116	132	150
Tree density >100 trees ha^{-1}	% farmers	42	52	44	32	40
Species richness	hectare^{-1}	9.0	8.7	8.5	7.6	5.1
Shannon index *H'*		2.07	2.28	1.83	2.31	1.84
Inverse-Simpson's *D*		4.99	7.54	3.67	5.79	4.48
Number of cows	farm^{-1}	2.7	2.6	2.3	1.4	2.8

n = number of farms studied per settlement

All the farmers surveyed had ownership over the land they farmed either through land inheritance or purchase and average farm age is 20.5 years. The typical set up of each household is partial cultivation of the land leaving around 22% of total land area fallowing as part of the homestead area. In the homestead area various farming enterprises are initiated which include tree planting, grazing and livestock handling area (Figure 4.1). Forest occupies 12% of the total land and is inclusive of agroforestry systems such as woodlots, intercropping and boundary plantings. Maize and beans are the most common crops with all farmers surveyed growing maize-bean intercrops representing on average closer to 60% of total farm area. 43% of interviewed farmers reported cultivating cassava in average of 0.1% of total farm area while 26% and 23% of farmers reported cultivating banana and sweet potato respectively in similar average land size of 0.1% of total farm size. 0.1 % of total farmers had sown additional crops including sorghum millet, sugarcane and vegetables in average of 0.1 % of total farm size.

Livestock keeping is a common practice in the surveyed farms with 86% of respondents keeping cow (87%), poultry (77%), sheep (26%) and goat (2%) with an average ownership of 3.3, 12.5, 3.6 and 3 per household respectively. In previous years, most farmers (60%) burnt their farms for a number of reasons ranging from easing ploughing process, belief that ash made the farm more fertile and also an explanation that they lacked cows to feed on the farm residues. Currently farmers do not carry out the burning stating that it lowers crop production and also makes soil less fertile. Majority of farmers (96%) use inorganic fertilizer to address crop nutrient demands. Close to 40% of interviewed farmers used pesticides application is in the studied farms.

The majority of households consist of married adults (96%) with a mean age of 53 years who currently bear adult sons and daughters and in most cases numerous grandchildren which explain the high number of household members. Farming is the main occupation activities for majority (43%) of the respondents while those working as casual labourers are 40% of all respondents.

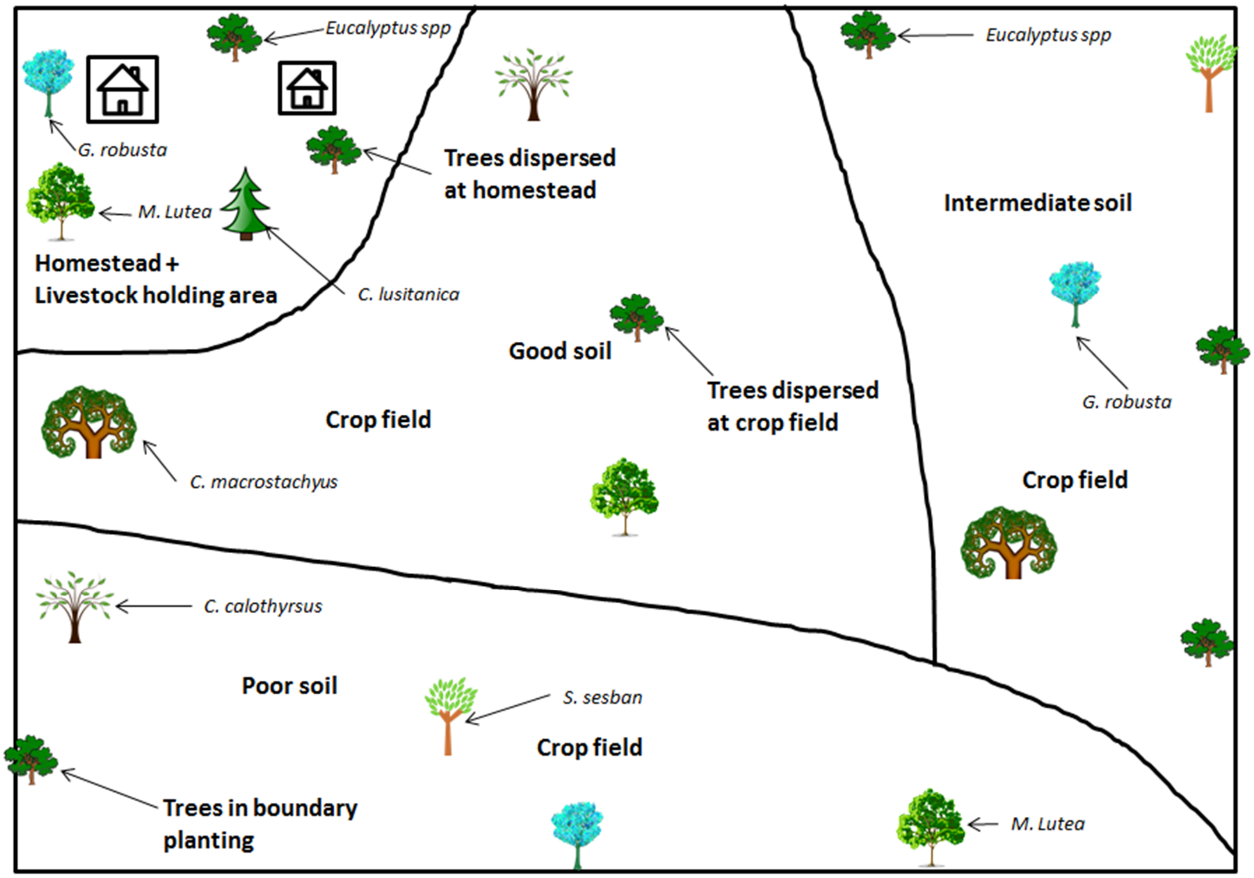

Figure 0.1: Typical farm layout showing the homestead which also acts as a livestock handling area and the rest of the farm which acts as crop field. Different tree species are found dispersed in the farm or planted as farm boundary. The dominant tree species at crop field in order of importance are *Eucalyptus* spp, *Sesbania* spp, *G. robusta*, *C. calothyrsus*, *M. lutea*, *C. macrostachyus* while at the homestead area are *Eucalyptus* spp, *C. lusitanica*, *G. robusta*, *M. lutea* in the order of importance.

4.1.2 Rainfall and temperature during the study period

The area recorded a cool and temperate climate throughout the study period (January-December 2013) with average annual temperatures ranging between 12.6 and 25.9°C and an average rainfall of 1418 mm (Figure 4.2). Precipitation was lowest in February, with an average of 25.3 mm. In August it reached its peak, with an average of 279.8 mm. At an average temperature of 20.1°C, March was the hottest month whereas August was the coldest month of the year with an average of 17.9°C.

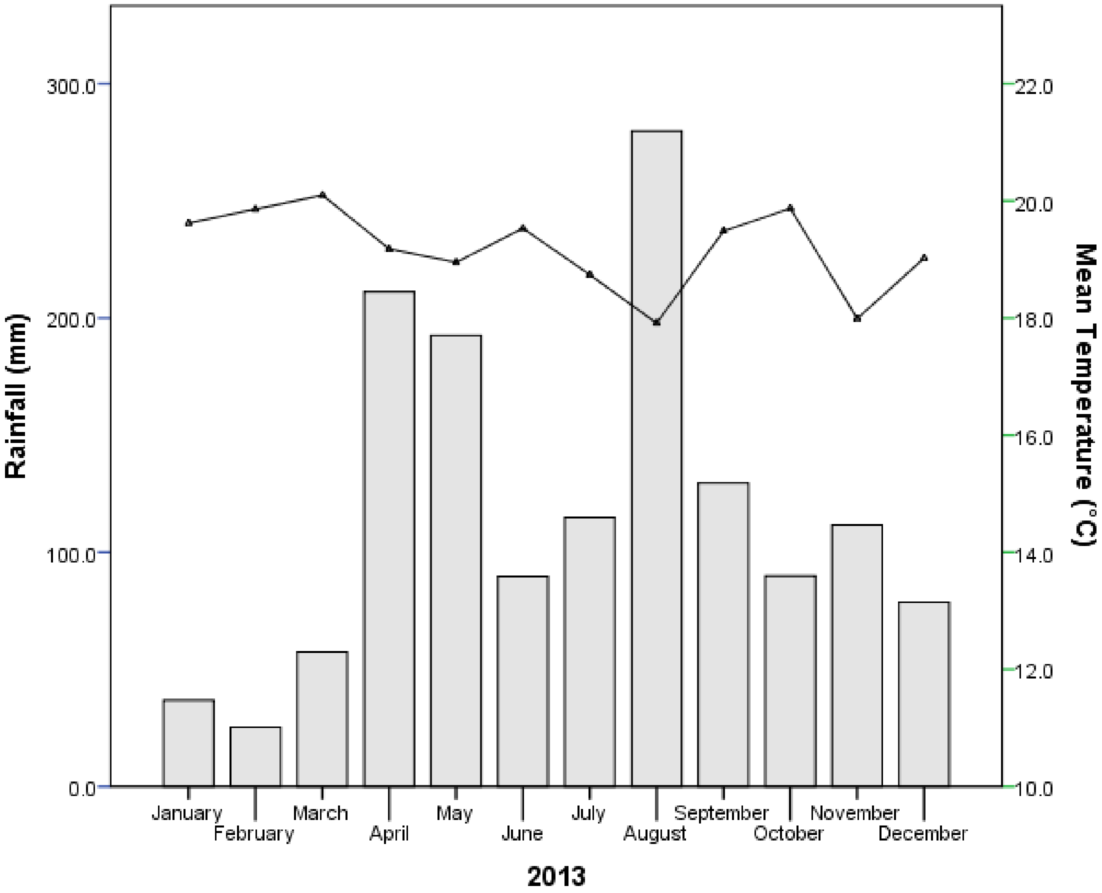

Figure 0.2: Monthly rainfall and mean monthly temperature of the study area.

4.1.3 Growth and management of dominant tree species in smallholder farms

The selected tree species are used by farmers as fuel wood through utilization of pruning usually obtained at onset of every cropping season (Table 4.2). Equally, farmers cut and use them as timber at maturity except for *S. sesban* and *C. calothyrsus* whose pruning are used as fodder. The dominant tree species are all evergreen except *C. macrostachyus* which is deciduous in nature. *S. sesban and C. calothyrsu*s are usually intercropped with maize while *Eucalyptus* spp is selectively maintained away from crop field. *C.*

macrostachyus, G. robusta, M. lutea are mostly found in external boundary but are also found dispersed in crop field although few.

Table 0.2: Growing characteristics and management practices of the dominant tree species in smallholder farms in Trans-Nzoia County.

Tree species	Management [a]	Phenology	Nitrogen fixing	Utilization by farmers [a]
Calliandra calothyrsus	Dispersed at crop field>external boundary>internal boundary at crop field	Evergreen	Leguminous	Fuel wood, fertilizer tree and fodder tree
Croton macrostachyus	External boundary planting>dispersed at crop field> dispersed at homestead	Evergreen	Non-leguminous	Fuel wood, timber
Eucalyptus spp	Woodlot> external boundary>dispersed at homestead	Evergreen	Non-leguminous	Fuel wood, timber
Grevillea robusta	External boundary>dispersed at homestead>woodlot planting>dispersed at crop field>internal boundary at crop field	Evergreen	Non-leguminous	Fuel wood, timber
Markhamia lutea	External boundary>dispersed at homestead>dispersed at crop field	Evergreen	Non-leguminous	Fuel wood, timber
Sesbania sesban	Dispersed at crop field>external boundary>woodlot planting>dispersed at homestead	Deciduous	Leguminous	Fuel wood, fertilizer tree and fodder tree

[a] Information adopted from Nyaga et al. 2015b

Eucalyptus spp recorded significantly ($P < 0.05$) the greatest mean height among the six dominant tree species in the smallholder farms (Figure 4.3). This was followed by *G. robusta* and *M. lutea* with approximate values of 12, 10 and 8 metres respectively. The mean height to the lowest leaf was also measured and was greatest for *G. robusta*, followed by *Eucalyptus* spp and *C. macrostachyus* respectively. *C. calothyrsus* recorded the lowest measurements of both heights and great root collar diameter which points to heavy pruning by famers. The canopy spread (area) was greatest under *C. macrostachyus* followed by M. lutea and *Eucalyptus* spp respectively while lowest under *C. calothyrsus*. The root collar diameter was greatest for *Eucalyptus* spp followed by *M. lutea* but lowest for *S. sesban*. Crown reduction in *C. macrostachyus* is minimal as farmers adopt crown raising to minimize tree shading as tree inherently has big canopy spread. Despite the great height, farmers hardly prune *M. lutea* which is evidenced by low hanging leaves and big canopy spread. *S. sesban* are eliminated from the farms after few years and this is evidenced by small root collar diameter and despite their small heights they exhibit great canopy spread.

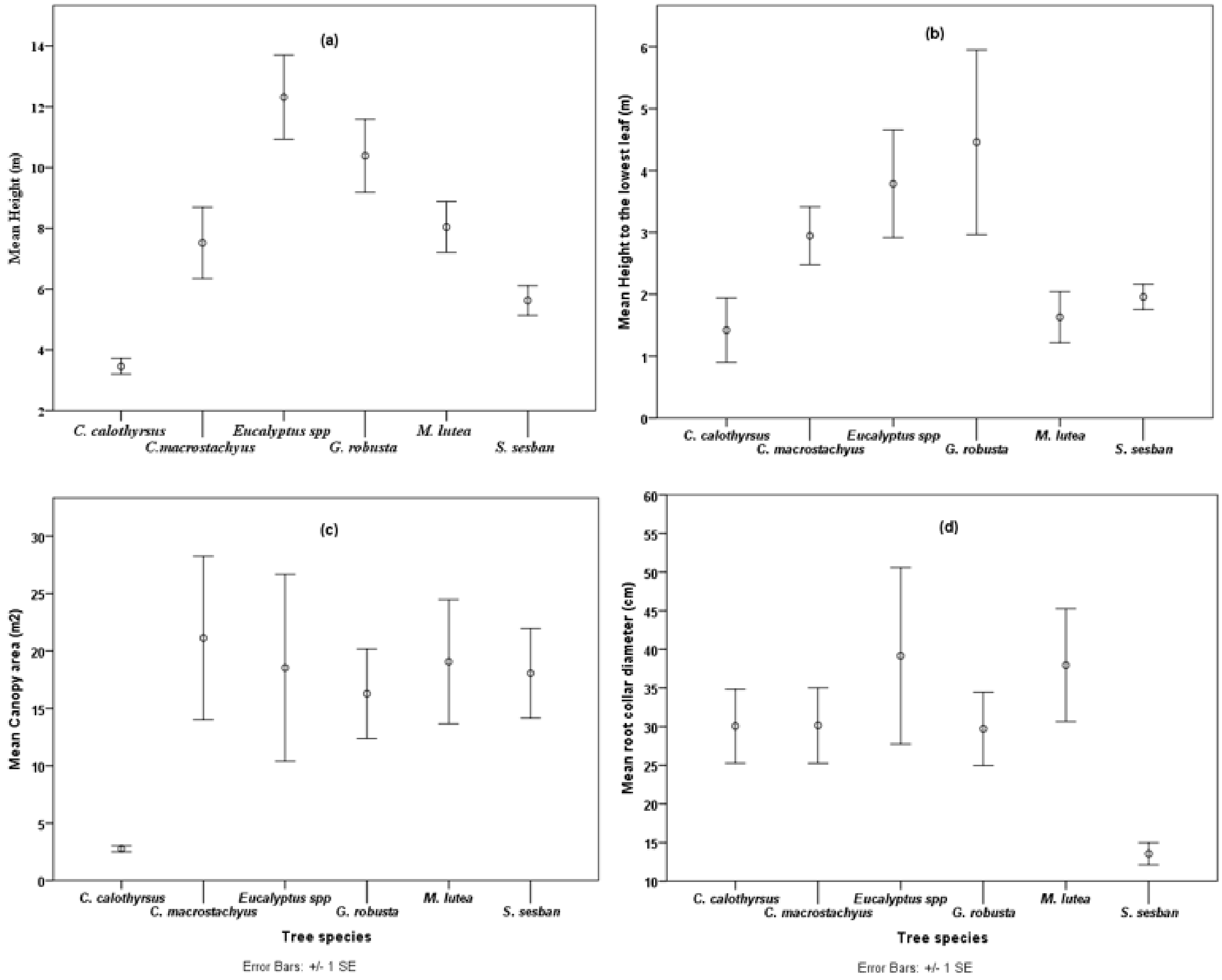

Figure 0.3: Mean height in centimeters (a), height to the lowest leaf in metres (b), canopy area in metre squared (c) and root collar diameter in centimeters of the dominant tree species in

smallholder farms in Trans-Nzoia County. The tree species are *Calliandra calothyrsus, Croton macrostachyus, Eucalyptus* spp*, Grevilea robusta, Markhamia lutea* and *Sesbania sesban*.

4.2 Agroforestry practices and factors influencing agroforestry adoption within smallholder farms

4.2.1 Tree number and density in smallholder farms studied

When combining results from all farms across settlements 44 tree species, 20 exotics and 24 indigenous were found (Table 4.3). The 10 most abundant species by ranking accounted for 94% of all trees on-farm. Most of the dominant species in the surveyed area are exotics with *Eucalyptus* spp, *G. robusta* and *C. lusitanica* ranking 1, 3 and 4 respectively, and representing about 65% of total tree counts. *Eucalyptus* spp was the most frequent tree; constituting 34.6% of the total tree counts (Table 4.3). Similarly, the most commonly grown indigenous tree species were *Sesbania* spp, *M. lutea* and *C. macrostachyus* ranking 2, 5 and 8; respectively, they (combined) represent about 25% of total tree counts (Table 4.3).

Table 0.3: Tree counts, species frequencies and on-farm location in representative settlements of Trans-Nzoia, Kenya. Native species are shown in bold letters

Species	Rank	Total counts	Frequencies of species (%)	On-farm location	
				Crop field (# trees farm^{-1})	Homestead (# trees farm^{-1})
Eucalyptus spp	1	3354	34.6	1413	1941

Sesbania spp	2	1461	15.1	1349	112
Grevillea robusta	3	1297	13.3	897	400
Cupressus lusitanica Mill.	4	1030	10.6	152	878
Markhamia lutea	5	511	5.3	282	229
Persea americana Mill.	6	389	4	174	215
Calliandra calothyrsus	7	386	4	367	19
Croton macrostachyus	8	378	3.9	248	130
Psidium guajava L.	9	204	2.1	52	152
Eriobotrya japonica (Thunb.) Lindl.	10	86	0.9	41	45
Casimiroa edulis La Llave.	11	71	0.7	23	48
Mangifera indica L.	12	47	0.5	24	23
Erythrina abyssinica Lam. ex DC.	13	45	0.5	37	8
Cordia africana Lam.	14	42	0.4	16	26
Croton megalocarpus Hutch.	15	41	0.4	14	27
Acacia abyssinica Lam. ex DC.	16	38	0.4	20	18
Morus alba L.	17	34	0.4	1	33
Syzygium guineense Wall.	18	30	0.3	17	13
Melia azedarach L.	19	29	0.3	15	14
Olea capensis L.	20	28	0.3	7	21
Spathodea campanulata P. Beauv.	21	28	0.3	6	22
Acacia mearnsii De Wild.	22	27	0.3	17	10
Casuarina equisetifolia L.	23	26	0.3	20	6
Annona squamosa L.	24	20	0.2	5	15
Jacaranda mimosifolia D. Don	25	19	0.2	1	18
Callistemon citrinus (Curtis) Skeels.	26	12	0.1	0	12
Citrus limon (L.) Burm.f.	27	9	0.1	7	2
Warbugia ugandensis Sprague	28	9	0.1	4	5
Podocarpus falcatus (Thunb.) C.N Page.	29	8	0.1	1	7
Prunus africana (Hook.f.) Kalkman.	30	7	0	5	2
Ficus sycomorus L.	31	5	0	3	2
Elaeodendron buchananii (Loes.) Loes.	32	4	0	3	1
Artocarpus heterophyllus Lam.	33	3	0	1	2
Rubus spp L.	34	3	0	1	2
Vernonia spp Schreb.	35	3	0	1	2
Citrus sinensis (L.) Osbeck.	36	2	0	0	2
Albizia coriaria Welw. Ex Oliv.	37	2	0	0	2
Piliostigma thonningii (Schum.) Milne-Redh.	38	2	0	1	1
Ziziphus abyssinica Hochst. ex A. Rich.	39	2	0	0	2

Acacia xanthophloea Benth.	40	1	0	0	1
Tamarindus indica L.	42	1	0	1	0
Solanecio mannii (Hook.f.) C. Jeffrey.	43	1	0	0	1
Trichilia emetica Vahl.	44	1	0	1	0

 # represent number of trees

Overall, from the top ten list, the order of importance of trees at crop field was *Eucalyptus* spp > *Sesbania* spp > *G. robusta* > *C. calothyrsus* > *M. lutea* > *C. macrostachyus*, while at the homestead area, the order of importance of trees was *Eucalyptus* spp >*C. lusitanica* >*G. robusta*>*M. lutea* >*P. americana* >*P. guajava* >*Sesbania* spp > *C. macrostachyus* (Table 4.3).

4.2.2 Utilization of dominant tree species and agroforestry practices within smallholder farms

Trees are planted or retained for specific uses or for multiple purposes. Seven utility groups for trees (fuel, timber, fruit, fodder, fertilizer, medicinal and ornamental) were identified by farmers (Figure 4.4). The most common uses of trees cited by farmers was as a source of fuel and this is evidenced by fact that all tree species in their farms were highlighted as sources of fuel. Tree as a source of timber was also an important reason given by farmers for the incorporation of trees in their farms. Among the dominant species, the N-fixing *C. calothyrsus* and *Sesbania* spp are the only species introduced by farmers for fodder given their high protein content, but they are also used as biofertilizer and for fuel purposes. *Eucalyptus* spp, *C. lusitanica,* G. *robusta, M. lutea* and *C. macrostachyus* are preferentially introduced by farmers for timber products. Fruit trees are also important in studied area and *Persea americana* (avocado) and *Psidium guajava* (guava) are the most common among the dominant species.

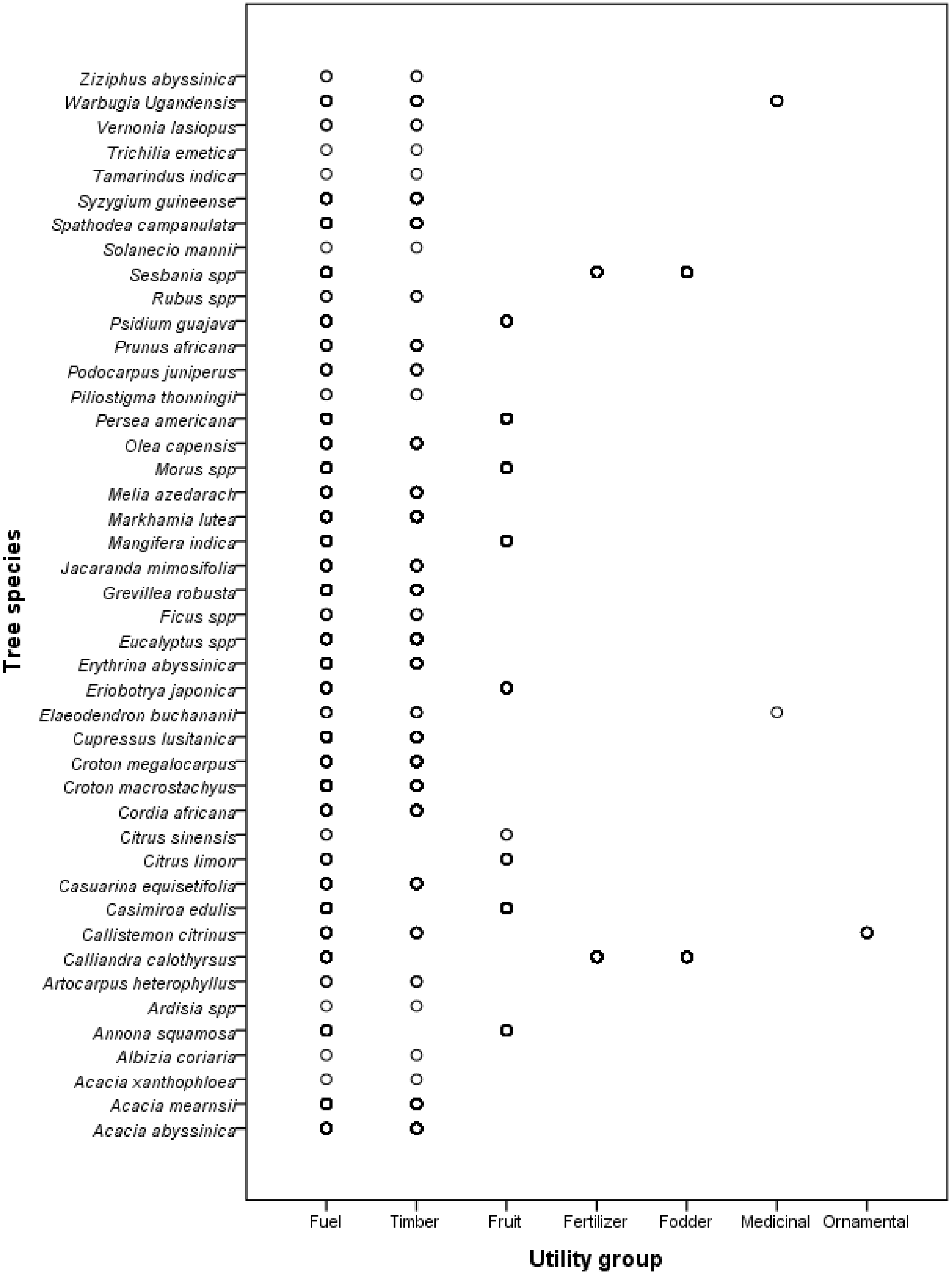
Tree species
Ziziphus abyssinica
Warbugia Ugandensis
Vernonia lasiopus
Trichilia emetica
Tamarindus indica
Syzygium guineense
Spathodea campanulata
Solanecio mannii
Sesbania spp
Rubus spp
Psidium guajava
Prunus africana
Podocarpus juniperus
Piliostigma thonningii
Persea americana
Olea capensis
Morus spp
Melia azedarach
Markhamia lutea
Mangifera indica
Jacaranda mimosifolia
Grevillea robusta
Ficus spp
Eucalyptus spp
Erythrina abyssinica
Eriobotrya japonica
Elaeodendron buchananii
Cupressus lusitanica
Croton megalocarpus
Croton macrostachyus
Cordia africana
Citrus sinensis
Citrus limon
Casuarina equisetifolia
Casimiroa edulis
Callistemon citrinus
Calliandra calothyrsus
Artocarpus heterophyllus
Ardisia spp
Annona squamosa
Albizia coriaria
Acacia xanthophloea
Acacia mearnsii
Acacia abyssinica
Fuel
Timber
Fruit
Fertilizer
Fodder
Medicinal
Ornamental
Utility group

Figure 0.4: Scatter diagram showing the distribution of recorded tree species into various utility groups in representative settlements of Trans-Nzoia, Kenya.

Different tree species are preferentially found under particular agroforestry practices (Figure 4.5). *Eucalyptus* spp and *C. lusitanica* are preferred in woodlots or in boundary planting. *Sesbania* spp and *C. macrostachyus* are commonly dispersed in crop fields or in boundary planting. There is a similar trend for *C. calothyrsus* although a small number are also found as hedgerows in crop fields. *M. lutea* is preferred as a boundary tree or dispersed on crop fields while *G. robusta* is most frequently found in boundary planting or dispersed in homesteads. Fruit trees such as *P. americana* and *P. guajava* are commonly found dispersed at homesteads and rarely at crop fields.

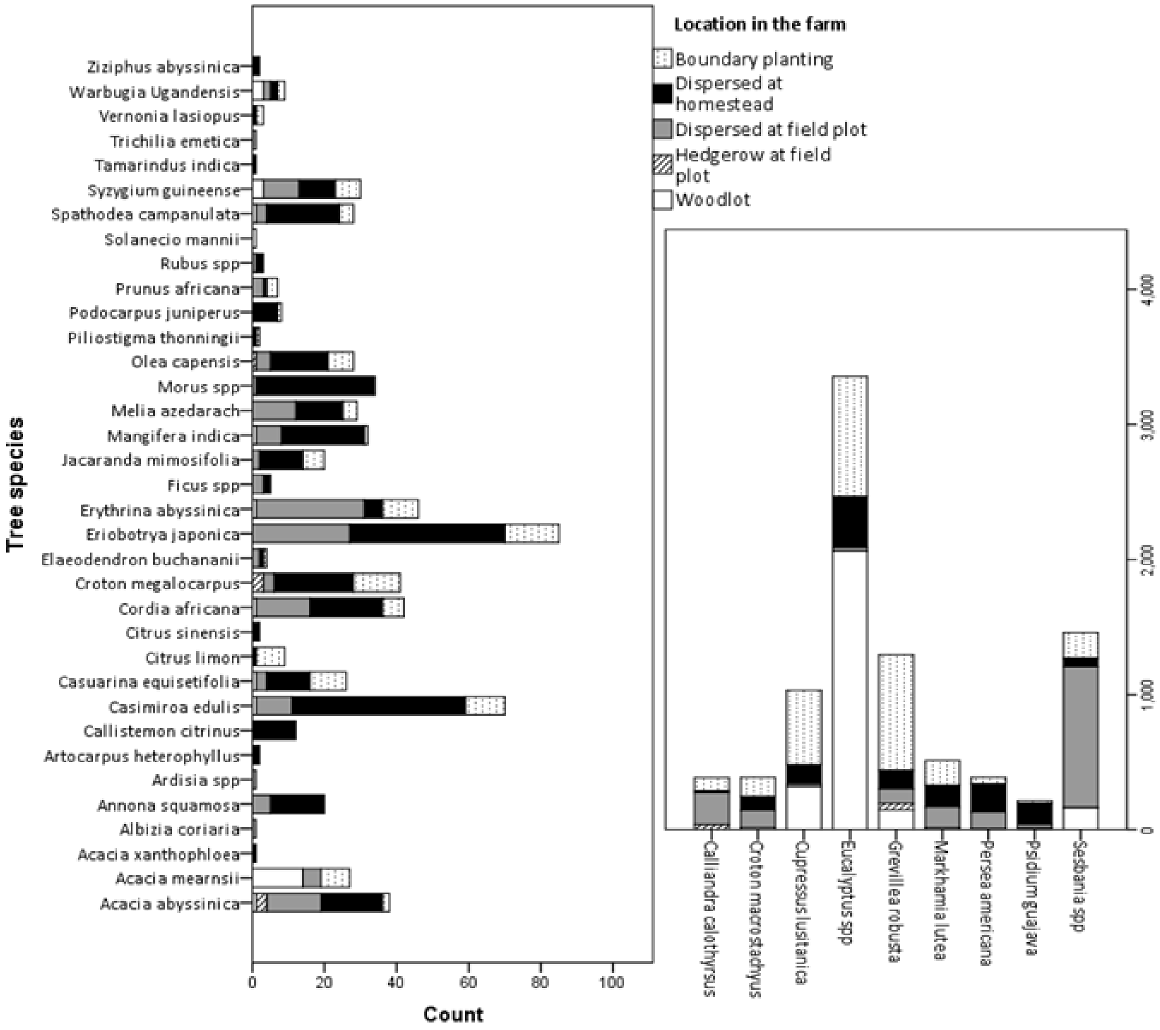

Figure 0.5: Histograms showing agroforestry practices of recorded tree species within the smallholder farms in representative settlements of Trans-Nzoia, Kenya.

4.2.3 Effect of household resource endowment on tree number, density, diversity and utility of dominant tree species

Household resource endowment had a significant effect on mean farm size, tree number, tree diversity (Table 4.4). Mean farm size in high resource endowed households was about three times larger than low resource endowed households. Number of trees growing at the homestead area per farm was statistically different between the resource endowment levels with farmers in the high category recording highest number followed by medium and low categories respectively. Species richness was also significantly different between the resource endowment levels but the highest number of species was recorded from the low category (26.2 species ha^{-1}) followed by medium (17.3 species ha^{-1}) and high (9.4 species ha^{-1}) categories. Tree density, number of tree planted at crop fields, number of exotic species and indigenous species were not significantly affected by resource endowment.

Among the utility groups only the number of fruit trees per hectare showed a significant difference between the resource endowment levels. The highest number of fruit trees was recorded from farmers in low category (18.6 trees ha^{-1}) followed by medium (16.3 trees ha^{-1}) and high (5.9 trees ha^{-1}) categories. The planting of timber, fodder and fertilizer trees species was not significantly different among households of different resource endowment.

Analysis of the 10-dominant species showed that, the number of *P. americana*, *C. calothyrsus* and *C. macrostachyus* planted per hectare were significantly affected by resource endowment levels. *P. americana* was most common among low resource endowed farmers, while *C. calothyrsus* and *C. macrostachyus* were most common among the medium resource endowed farmers.

Table 0.4: Mean number (and standard error of means) of tree number, density, diversity and utility in smallholder farms as affected by household resource endowment in Trans-Nzoia, Kenya.

Household resource endowment (n)	Low (n=38)	Medium (n=60)	High (n=25)	P values
Farm size (hectares)	0.5 ± 0.1^{c}	0.8 ± 0.1^{b}	1.7 ± 0.3^{a}	<0.001***
Tree density(ha^{-1})	155.8 ± 29.2	122.8 ± 12.8	99.1 ± 19.0	0.544^{NS}
Homestead (# trees farm^{-1})	18.4 ± 6.0^{c}	28.5 ± 5.4^{b}	71.1 ± 20.1^{a}	<0.001***
Crop fields (# trees farm^{-1})	36.1 ± 9.2	45.2 ± 7.7	53.1 ± 10.2	0.107^{NS}
Species richness (ha^{-1})	26.2 ± 4.7^{a}	17.3 ± 2.8^{b}	9.4 ± 2.3^{c}	<0.001***
Exotic species (# trees ha^{-1})	106.7 ± 24.4	83.9 ± 11.2	78.3 ± 16.3	0.978^{NS}
Indigenous species (# trees ha^{-1})	48.7 ± 12.5	37.9 ± 6.3	21.3 ± 4.8	0.394^{NS}
Fruit trees (# trees ha^{-1})	18.6 ± 4.3^{a}	16.3 ± 3.3^{a}	5.9 ± 1.9^{b}	0.055*
Fodder/fertilizer species (# trees ha^{-1})	38.4±11.6	27.1±5.7	12.7 ± 4.3	0.134^{NS}
Timber trees (# trees ha^{-1})	98.3 ± 24.7	76.0 ± 10.6	81.0 ± 14.7	0.498^{NS}
Eucalyptus spp (# trees ha^{-1})	28.5 ± 7.3	35.7 ± 6.9	29.8 ± 8.1	0.493^{NS}
Sesbania spp (# trees ha^{-1})	35.2 ± 11.5	22.7 ± 5.3	9.5 ± 3.4	0.087^{NS}
Grevillea robusta (# trees ha^{-1})	40.9 ± 18.4	14.8 ± 3.8	21.1 ± 10.2	0.339^{NS}
Cupressus lusitanica (# trees ha^{-1})	12.8 ± 6.8	12.1 ± 6.2	15.0 ± 6.3	0.098^{NS}
Markhamia lutea (# trees ha^{-1})	7.8 ± 3.4	7.1 ± 2.2	4.9 ± 2.6	0.891^{NS}

Persea americana (# trees ha^{-1})	8.5 ± 2.2^{a}	8.2 ± 1.8^{a}	2.8 ± 1.0^{b}	0.051*
Calliandra calothyrsus (# trees ha^{-1})	1.4 ± 1.3^{b}	4.3 ± 1.5^{a}	1.4 ± 0.7^{b}	0.026*
Croton macrostachyus (# trees ha^{-1})	2.0 ± 0.8^{b}	5.0 ± 1.3^{a}	4.2 ± 1.1^{a}	0.017*
Psidium guajava (# trees ha^{-1})	4.3 ± 1.3	3.1 ± 0.7	1.3 ± 0.4	0.512^{NS}
Eriobotrya japonica (# trees ha^{-1})	2.8 ± 1.3	1.4 ± 0.5	0.9 ± 0.4	0.628^{NS}

Low (poor farmers), medium (moderately wealthy farmers), high (wealthy farmers); *NS (not* significant); n-sample size. Significant differences within rows are indicated by * p<0.05, ** p<0.01 and *** p<0.001. Mean values in a row followed by the same letter are not significantly different at p<0.05.

Table 0.5: Tree species diversity indices in smallholder farms as affected by household resource endowment in Trans-Nzoia, Kenya

Diversity index	Low (38)	Medium (60)	High (25)
Shannon-Wiener *H'*	2.22	2.08	2.12
Inverse-Simpson's *D*	5.86	4.95	5.46

The conclusion of whether one community is more diverse than another can depend on the diversity measure used. This is explained by the fact that diversity indices weight species’ abundances differently; usually by treating rare species differently. Shannon-Wiener index is most sensitive to changes in the rare species in the community while Simpson’s index is most sensitive to changes in the more abundant species. Households in the low category consistently maintained highest tree diversity for the two diversity indicators used followed by those of high and medium resource endowment categories respectively (Table 4.5).

4.2.4 Influence of land tenure on tree number, density, diversity and utility of dominant tree species

A total of 51 households had secure land tenure with title deed as evidence of ownership while 71 lacked the same. Land tenure had a significant influence on mean farm size, tree number, diversity and agroforestry practices (Table 4.6). Households with secure tenure recorded close to 35% larger farm sizes than those without. Similar to farm size, farmers with secure tenure recorded tree count at their homesteads which was twice that in households with no secure tenure. Species richness was also significantly affected by land tenure. However, contrary to farm size and number of trees at homestead, higher species richness was found in households without secure tenure.

Among the utility groups only the number of fodder/fertilizer trees showed significant differences as a result of land tenure. Households without secure tenure had a higher number of fodder and fertilizer tree per hectare. Analysis of the 10-dominant species showed that, only the number of *Sesbania* spp and *C. macrostachyus* in the smallholder farms was significantly affected by land tenure status. While the number of *Sesbania* spp per hectare was higher for farmers without secure tenure, the number of *C. macrostachyus* recorded per hectare was higher from households with secure tenure.

Higher tree diversity was consistently registered in farms with tenure as indicated by the Shannon and Inverse-Simpson diversity indices (Table 4.7).

Table 0.6: Mean number (and standard error of means) of tree number, density, diversity, and utility in smallholder farms as affected land tenure in Trans-Nzoia, Kenya

Land tenure status (n)	Tenure (51)	No tenure (72)	P values
Farm size (hectares)	1.1 ± 0.1^a	0.7 ± 0.1^b	<0.001***
Tree density(ha^{-1})	122.8 ± 20.4	132.0 ± 13.9	0.156^{NS}
Homestead (# trees farm^{-1})	48.0 ± 11.2^a	24.1 ± 4.5^b	0.012*
Crop fields (# trees farm^{-1})	45.6 ± 6.9	42.9 ± 7.3	0.337^{NS}
Species richness (# trees ha^{-1})	14.7 ± 3.1^b	21.0 ± 2.6^a	0.006**
Exotic species (# trees ha^{-1})	95.5 ± 19.1	85.8 ± 10.1	0.400^{NS}
Indigenous species (# trees ha^{-1})	27.6 ± 5.6	45.1 ± 7.4	0.252^{NS}
Fruit trees (# trees ha^{-1})	11.6 ± 3.2	17.2 ± 2.8	0.418^{NS}
Fodder/fertilizer species (# trees ha^{-1})	16.1 ± 5.1^b	35.9 ± 7.0^a	0.018*
Timber trees (# trees ha^{-1})	92.4 ± 18.2	77.9 ± 10.3	0.898^{NS}
Eucalyptus spp (# trees ha^{-1})	30.6 ± 5.9	33.5 ± 6.2	0.622^{NS}
Sesbania spp (# trees ha^{-1})	14.2 ± 4.8^b	30.7 ± 6.7^a	0.034*
Grevillea robusta (# trees ha^{-1})	31.2 ± 13.5	19.2 ± 5.1	0.459^{NS}
Cupressus lusitanica (# trees ha^{-1})	19.8 ± 7.8	8.1 ± 3.6	0.084^{NS}
Markhamia lutea (# trees ha^{-1})	5.0 ± 1.5	8.3 ± 2.5	0.244^{NS}
Persea americana (# trees ha^{-1})	5.6 ± 1.7	8.3 ± 1.5	0.375^{NS}
Calliandra calothyrsus (# trees ha^{-1})	1.0 ± 0.4	4.1 ± 1.4	0.704^{NS}
Croton macrostachyus (# trees ha^{-1})	5.6 ± 1.3^b	2.8 ± 0.8^a	0.011*
Psidium guajava (# trees ha^{-1})	2.1 ± 0.5	3.8 ± 0.8	0.469^{NS}
Eriobotrya japonica (# trees ha^{-1})	1.8 ± 0.8	1.7 ± 0.6	0.874^{NS}

***NS* not significant; n-sample size; Significant differences within rows are indicated by * p<0.05, ** p<0.01 and ***p<0.001. Mean values in a row followed by the same letter are not significantly different at p<0.05.**

Table 0.7: Tree species diversity indices in smallholder farms as affected by land tenure in Trans-Nzoia, Kenya

Diversity index	Tenure (51)	No tenure (72)
Shannon-Wiener *H'*	0.83	0.80
inverse-Simpson's *D*	5.80	4.99

4.2.5 Influence of time under current farm management on tree number, density, diversity and utility of dominant tree species

The time interval a farm has been under current management was found to significantly influence mean farm size, tree number, tree diversity and utilization of trees in smallholder farms in the study area (Table 4.8). Households in the short-term category showed the lowest farm size followed by medium- and long-term categories respectively. During the first 15 years of farming, activities took place in significantly smaller areas that doubled in size with increased time under current management. The number of trees at both homestead and crop field were highest for the long-term category. Conversely, species richness was on average greatest for the short-term category (26 species ha^{-1}) followed by the medium- (15.9 species ha^{-1}) and long-term (13.4 species ha^{-1}) categories, respectively.

For the 10-dominant species, only the number of *P. guajava* and *Eriobotrya japonica* species showed significant differences among the different times of current farm management. The number of *P. guajava* trees maintained by farmers, was found to increase with increasing time under current management. However, the number of *E. japonica* maintained by farmers was highest in the medium-term category followed by long- and short-term categories respectively.

Households under long-term current management consistently recorded highest tree diversity (Table 4.9). The Shannon index showed that farms in the long-term category had the most diverse tree community followed by farms in the medium- and short-term categories respectively. The Inverse-Simpson index also found highest diversity in the long-term category.

Table 0.8: Mean number (and standard error of means) of tree number, density, diversity, and utility in smallholder farms as affected by time under current management in Trans-Nzoia, Kenya

Time under current management (n)	Short (41)	Medium (40)	Long (42)	P values
Farm size (hectares)	0.4 ± 0.1^{b}	1.1 ± 0.2^{a}	1.1 ± 0.1^{a}	<0.001***
Tree density(ha^{-1})	162.5 ± 28.4	109.4 ± 14.0	112.7 ± 14.2	0.717^{NS}
Homestead (# trees farm^{-1})	27.5 ± 12.6^{b}	32.3 ± 6.7^{a}	42.0 ± 7.8^{a}	0.001***
Crop fields (# trees farm^{-1})	29.6 ± 6.3^{b}	47.6 ± 10.4^{ab}	54.5 ± 9.2^{a}	0.027**

Species richness (ha^{-1})	26.0 ± 5.0^{a}	15.9 ± 2.8^{b}	13.4 ± 2.1^{b}	0.050*
Exotic species (# trees ha^{-1})	113.0 ± 24.8	77.1 ± 10.6	79.3 ± 11.8	0.983^{NS}
Indigenous species (# trees ha^{-1})	49.3 ± 11.8	30.3 ± 6.5	33.9 ± 6.6	0.310^{NS}
Fruit trees (# trees ha^{-1})	13.2 ± 3.9	16.6 ± 4.3	14.9 ± 3.0	0.166^{NS}
Fodder/fertilizer species (# trees ha^{-1})	37.7 ± 11.3	20.0 ± 5.4	25.1 ± 6.1	0.489^{NS}
Timber trees (# trees ha^{-1})	106.9 ± 24.5	70.7 ± 9.4	74.1 ± 11.9	0.957^{NS}
Eucalyptus spp (# trees ha^{-1})	28.1 ± 6.5	34.3 ± 7.7	34.4 ± 8.4	0.794^{NS}
Sesbania spp (# trees ha^{-1})	35.5 ± 11.2	16.8 ± 4.7	19.2 ± 5.7	0.385^{NS}
Grevillea robusta (# trees ha^{-1})	43.8 ± 17.4	15.4 ± 6.0	13.4 ± 4.3	0.842^{NS}
Cupressus lusitanica (# trees ha^{-1})	24.0 ± 10.7	5.9 ± 3.4	8.7 ± 2.9	0.410^{NS}
Markhamia lutea (# trees ha^{-1})	7.5 ± 3.1	4.5 ± 1.1	8.6 ± 3.3	0.224^{NS}
Persea americana (# trees ha^{-1})	7.5 ± 2.4	7.8 ± 2.1	6.3 ± 1.5	1.870 ^{NS}
Calliandra calothyrsus (# trees ha^{-1})	2.4 ± 1.4	3.0 ± 1.5	3.0 ± 1.6	0.372^{NS}
Croton macrostachyus (# trees ha^{-1})	3.7 ± 1.0	5.3 ± 1.9	2.9 ± 0.6	0.644^{NS}
Psidium guajava (# trees ha^{-1})	1.7 ± 0.7^{b}	2.1 ± 0.5^{a}	5.3 ± 1.3^{a}	<0.001***
Eriobotrya japonica (# trees ha^{-1})	1.1 ± 0.6^{b}	2.6 ± 1.2^{a}	1.6 ± 0.5^{a}	0.022**

Short (1-15 yrs), medium (16-30 yrs), long (over 30 yrs); *NS* not significant; n-sample size. Significant differences within rows are indicated by * p<0.05, ** p<0.01 and *** p<0.001. Mean values in a row followed by the same letter are not significantly different at p<0.05.

Table 0.9: Tree species diversity indices in smallholder farms as affected by time under current management in Trans-Nzoia, Kenya

Diversity index	Short (41)	Medium (40)	Long (42)
Shannon-Wiener *H'*	1.95	2.08	2.29
inverse-Simpson's *D*	5.08	4.80	6.19

4.2.6 Influence of household resource endowment, land tenure and time **under current management on tree density, number, diversity and utility of dominant tree species**

Modeled effects of the 3 explanatory variables predicted tree density, tree number, tree diversity and utilization of tree species in smallholder farms in different ways (Table 4.10). Among the three explanatory variables only time under current management predicted tree density. Tree density was highest in farms in the short-term category, with an average of 1.5 times greater tree density than farms in the medium-term category, that is not significantly different from the long-term category. The number of trees at homesteads was only predicted by resource endowment and was greatest in farms in the high category with an average of 2.2 times greater number of trees than other resource endowment categories. Number of trees at homesteads was lowest in farms in the low category with an average of 1.5 times lower than other resource endowment categories. On the other hand, the number of trees at crop fields per farm was only predicted by time under current management and was lowest in farms in the short-term category with an average of 1.7 times lower than farms in the medium-term category, which is not significantly different from the long-term category.

Both resource endowment and time under current management were found to predict species richness in the smallholder farms studied. The number of tree species per hectare was highest in the low resource endowment category with an average of 1.5 times greater tree species count than farms in the medium category, which is not significantly different from the high category. In addition, the number of tree species was also highest in farms in the short-term category, with an average of 1.5 times greater number of tree species than farms in medium-term category, which is not significantly different from the long-term category.

Table 0.10: Tree number, density, diversity and utility predictors in Trans-Nzoia, Kenya, showing estimated coefficients and impact direction

	Predictor label				
	Resource endowment	Resource endowment	Land tenure (tenure)	Time under current management	Time under current management
Response variables	1=High	2=low		1=long	2=short
Tree density(ha^{-1})	ns	ns	ns	ns	+1.45*
Homestead (# trees farm^{-1})	+2.2**	-1.5**	ns	ns	ns
Crop fields (# trees farm^{-1})	ns	ns	ns	ns	-1.7*
Species richness (ha^{-1})	ns	+1.5*	ns	ns	+1.5**
Fruit trees (# trees ha^{-1})	-2.8*	ns	ns	ns	ns
Fodder/fertilizer species (# trees ha^{-1})	ns	ns	-1.9*	ns	ns
Grevillea robusta (# trees ha^{-1})	ns	ns	ns	ns	+2.9**
Cupressus lusitanica (# trees ha^{-1})	ns	ns	+2.5*	ns	+4.4**
Persea americana (# trees ha^{-1})	-2.8*	ns	ns	ns	ns
Calliandra calothyrsus (# trees ha^{-1})	ns	ns	-4.1*	ns	ns
Croton macrostachyus (# trees ha^{-1})	ns	ns	+1.9*	ns	ns
Psidium guajava (# trees ha^{-1})	-2.8*	ns	ns	+2.6**	ns

ns= not significant; Resource endowment: Low (poor farmers), medium (moderately wealthy farmers), high (wealthy farmers); Time under current management: Short (1-15 yrs), medium (16-30 yrs), long (over 30 yrs); Land tenure: yes (tenure), no (no tenure). The base (parameter=0) level for resource endowment and time under current management is fixed at medium level/category.

Quasi-Poisson multiple regressions; where variables showed significance effect on the response the regression estimate (λ_j) is provided and also the direction of the impact (+/-). The significance levels are results of type-11 ANOVA Chi^2-test *$P \leq 0.1$ and **$P \leq 0.05$. Because log link was used, the means in log scale obtained were converted back to correct magnitudes using the exponential function.

Among the three explanatory variables only resource endowment predicted the number of fruit trees maintained by smallholder farmers in the study area. The number of fruit trees was lowest in farms in the high category with an average of 2.8 times less fruit trees than farms in the medium category, which is not significantly different from the low category. Land tenure alone was found to predict the number of fodder and fertilizer trees found in the smallholder farms. The number of fodder and fertilizer trees was about twice greater in farms without secure tenure compared to farms with secure tenure.

Among the three explanatory variables only time under current management predicted the number of *G. robusta* maintained in the smallholder farms. The number of *G. robusta* was highest in farms in the short-term category, with an average of 2.9 times more *G. robusta* trees than farms in the medium-term category, which is not significantly different from the long-term category. Both land tenure and time under current management predicted the number of *C. lusitanica* found in the farms. The number of *C. lusitanica* was highest in farms with secure tenure with an average of 2.5 times more *C. lusitanica* trees than farms without. Furthermore, the number of *C. lusitanica* was highest in farms in the short-term category, with an average of 4.4 times more *C. lusitanica* trees than farms in the medium-term category, which is not significantly different from the long-term category.

Among the three explanatory variables only household resource endowment predicted the number of *P. americana* found in the farms. The number of *P. americana* was lowest in the high resource endowment category with an average of 2.8 times less *P. americana* trees than farms in the medium category, which is not significantly different from the low category. Land tenure, on the other hand, was shown to predict the number of *C. calothyrsus* and *C. macrostachyus* maintained in the farms. The number of *C. calothyrsus* was lower in farms with secure tenure with an average of as much as 4.1 times less *C. calothyrsus* trees than farms without. In contrast, the number of *C. macrostachyus* was higher in farms with tenure with an average of as much as 1.9 times more *C. macrostachyus* trees than farms without tenure. Both resource endowment and time under current management were found to predict the number of *P. guajava* maintained by the smallholder farmers. The number of *P. guajava* was lowest in the high resource endowment category with an average of 2.8 times less *P. guajava* trees than farms in the medium category, which is not significantly different from the low category. The number of *P. guajava* was highest in farms in the long-term category with an average of 2.6 times more *P. guajava* trees than farms in the medium-term category, which is not significantly different from the short-term category.

4.3 Local and scientific indicators of soil quality

4.3.1 Local soil classes

Farmers' criteria considered important for distinguishing soil types in the field included soil colour, texture, how easy it is to plough, and water retention capability. Farmers recognized 3 soil types that are locally named in vernacular as follows: *Lukusii* (brown soil), *Olondo I* (Red soil) and *Olondo II* (reddish brown soil) (Table 4.11). Colour was the most important indicator used to characterize each of the local soil classes compared to texture and stoniness, water retention capability and characteristics of top soil. 83

percent of farmers acknowledged existences of different soil types in their farms while the rest reported homogeneity in soil types within their farms. *Lukusii* was the most mentioned by farmers at 76% among whom 93% mentioned that it was fertile soil. In comparison 91% of farmers who mentioned *Olondo* attributed it to infertility or bad quality soil. *Olondo II* was slightly better-quality soil than *Olondo I*.

Farmers' observed that *Lukusii* was best suited to grow maize, beans, sweet potato, banana, Irish potatoes and leafy vegetables and generally was not bad for growing any crop. In contrast, majority of farmers observed that *Olondo* was best to grow beans and millet/ sorghum and sweet potato and was reported by some to be bad for growing maize.

The differences in soil quality was also attributed to farm management practices and farms topography which include; a) differences in the application rate of household litters to areas close to the house, b) heterogeneity in application of fertiliser and manure; for example, it is common practice to initiate applications of nutrient inputs on the upper side of the farm or where farmers perceive the soil is better and expect high yield. In such situation, the other parts of the farms receive lower amount of nutrient input or none depending on the amount available in the cropping season, c) flooding also contributes to soil quality differences, and d) previous land use is recognized as an important factor; for example, soils under *Eucalyptus* spp or *Lantana camara* are recognized as generally poorer or promoting greater soil quality heterogeneity within the farm.

Table 0.11: Characteristics of local soil classes identified by smallholder farmers in Trans-Nzoia County, Kenya.

Values in parenthesis are number or percentage of respondents.

Soil class	Colour	Local name	Number of farmers who recognize the soil class in their farms (%)	Fertility classification by respondents	Good for growing following crop (observations)
1	Brown	*Lukusii*	(76%)	Fertile (93%), Infertile (7%)	Maize (34), bean (24), cassava (1), banana (6), millet (3), sweet potato (3), vegetables (3)
2	Red	*Olondo I*	(53%)	Fertile (9%), Infertile (91%)	Maize (7), bean (9), cassava (2)
3	Reddish brown	*Olondo II*	(5%)	Fertile (25%), Infertile (75%)	Beans (2), Maize (1)

The number of farmers identifying a particular soil type is followed by the percent (%) of farmers interviewed who recognized that soil type in parenthesis. The soil types and crops grown by soil type in the table above were recognized by at least three of 47 farmers interviewed. Vegetables include cowpea (kunde), *Crotalaria brevidens*

4.3.2 Local indicators of soil quality

Effort was made to obtain local indicators of soil quality which are visible to farmers such as plant and soil macrofauna species. Most farmers could distinguish and characterize fields as either of good or poor soil quality using the abundance and diversity of tree and weed species and the presence of soil macro fauna. Farmers named four native trees and nine weed species as reflecting soil quality status, crop growth or farming activities (Table 4.12). There was a consensus among farmers on the negative or positive attributes of different tree species as indicators of soil quality. *C. macrostachyus, Sesbania,* and *M. lutea* were considered by farmers to have more positive than negative attributes (Table 4.12). *A. abyssinica* was highlighted as having more negative attributes than positive ones.

Among the weed species, *Bidens pilosa* L. was the most frequently identified (28) species used as an indicator of soil quality and most cases of good soil (Table 4.12). This was followed respectively by *Commelina benghalenss* L. (23) and *Digitaria scalarum* (Schweinf.) Chiov./ *Limbuka*/Coach grass (19). *Tagetes minuta* L. (12), *Omondi* weed (14), and *Embululwe* (9) are also commonly used as indicators of soil quality. While, most farmers use the above weed species as indicator of good soils there were a few farmers using the same species as indicators of poor soils. However, *Commelina benghalensis* when in reddish, thin and less leafy growing condition was unanimously named by farmers as indicator of poor soils.

Table 0.12: Plant species utilized by farmers as indicators of fertile and poor soil for growing crops in Trans-Nzoia County.

	Presence of the plant in soil indicates	
Scientific/common/local name	Fertile soil attributes	Poor soil attributes
Indicator trees species		
Croton macrostachyus.	-fertile soils (5) -good litter (4) -good litter and minimal competition (1)	-
Sesbania spp	-fertile soil/land (11) -good litter (3) -minimal competition (1) -add or contribute to soil fertility (1)	-
Markhamia lutea	-fertile soil/land (7) -good litter (1) -minimal competition (1) -good litter and control soil erosion (1)	-
Acacia abyssinica	-	-infertile soil (3)
Indicator weed species		

Bidens pilosa L. (*Makoe*)	-Fertile soil/land (26), -good litter (1)	-Infertile soil (1)
Commelina benghalensis L. (*Silulu*)	(Green and leafy) -Fertile soil/land (22), -good litter (1)	(reddish, thin and less leafy) -Infertile soil (7) -contribute to high salinity/acidity in the farm (1)
Digitaria scalarum/ *Lumbuku*/Coach grass	-Fertile soil/land (2)	-Infertile soil (12) -high competition from roots and through shading (2) -contribute to high salinity/acidity in the farm (1) -infertile soil/land and difficult to control (1) -soil is very fine and dries very fast becoming too hard (1)
Tagetes minuta L./ *Nanjaka*	-Fertile soil/land (11)	-Infertile soil (1)
Kumuchokoni/Omondi weed/ *kimilandang'ombe*	-	-Infertile soil (10) -high competition from roots and through shading (3) -infertile soil and difficult to control (1) -infertile soil and negative allelopathy (1)
Embululwe/khafululu	-Fertile soil/land (3)	-Infertile soil (6)
Galinsoga parviflora/ *Lufuta*	-Fertile soil/land (8)	-Infertile soil (2)
pink grass/weed 3	-	-Infertile soil (3)

Ageratum conyzoides L./ *Liyongo*	-	-Infertile soil (3)

The number of farmers identifying a particular plant as indicator of soil quality is followed by the percent (%) of farmers interviewed who recognized that plant indicator in parenthesis. Species shown above were named by at least three of 47 farmers interviewed. Triangulation rationale i.e. at least 3 votes supporting an indicator/context interaction to be considered valid was applied.

Farmers interviewed named 14 commonly recognized, distinct soil macrofauna taxa used as indicators of soil quality (Table 4.13). In general, farmers highlighted that presence of more and different types of soil macrofauna (abundance and diversity) is a clear indicator of fertile soil.

Beetles and earthworms were the two most commonly named bio indicators of fertile fields. 64 per cent of the interviewed farmers use beetles as indicators of fertile soil while 55% acknowledged using earthworm as well. Millipedes were named as indicators of fertile fields by 11% interviewed farmers.

Ants (black ants, safari/red ants and termites) were also frequently mentioned by farmers but with diverse opinions on whether they indicate fertile or poor soils (Table 4.13). The abilities of the ants of to convert crop waste into manure, mixing up of soil which farmers noted that it brings about improved soil fertility were noted. However, other farmers were of opinion that ants indicate poor soils and this is purely on their ability to destroy crops in the field or seeds before onset of the rains.

Table 0.13: Soil macrofauna groups utilized by smallholder farmers as indicators of soil quality in Trans-Nzoia County.

		Farmers opinion (percentage) about macrofauna as an indicator of		Attributes of macrofauna highlighted by farmers	
Macrofauna	Local name	Fertile soil	Poor soil	Beneficial	Detrimental
Beetles (white grubs)	*Masivili*	30 (63.8)	0	-Contribute to soil fertility (9) -Mix the soil up bringing about nutrients (3)	-Cut plant or seedlings or destroy leaves of crops and vegetables (3)
Earthworms	*Makhani*	26 (55.3)	0	-Contribute to soil fertility (10) -Converts crop wastes into manure (4) -Associated with fertile soil and water availability (4) -Beneficial but farmers do not understand how (4)	
Black ants	*Mamonyo*	8 (17.0)	4 (8.5)	- Contribute to soil fertility (3) -Mix the soil up bringing about nutrients (3) -Aerates soil (3)	- Cut plant or seedlings or destroy leaves of crops and vegetables (6) - Saliva poisonous to maize and beans (1)
Termites	White ants	11 (23.4)	3 (6.4)	-Converts crop wastes into manure (5) - Contribute to soil fertility (3)	- Cut plant or seedlings or destroy leaves of crops and vegetables (7) -Mould soil together leading to reduced yield (5) -Destroy crop at harvest (3)

Safari ants	5 (10.6)	6 (12.8)	-	- Cut plant or seedlings or destroy leaves of crops and vegetables (8) -Eat planted maize seed before onset of rain (4) -Destroy crop at harvest/growth (4)
Millipedes	5 (10.6)	0		

The number of farmers identifying a particular attribute is followed by the percent (%) of farmers interviewed who recognized that attribute in parenthesis. Macrofauna above were named by at least three of 47 farmers interviewed. Attributes shown above were named by at least three farmers.

4.3.3 Scientific assessment of local soil quality classes

Twenty-seven (27) out of 117 fields were classified as intermediate (transitional) between productive (good) and non-productive (poor) soil. Farmers indicating good soils were found to refer to *lukusii* (brown soil) while poor and intermediate soils were *olondo II (red)* and *olondo I (reddish-brown)* respectively. To substantiate farmers' perception of soil quality common soil chemical analyses on local soil classes identified by local farmers on the 47 study farms was carried out (Table 4.14).

Table 0.14: Mean soil chemical properties from good, intermediate and poor soil quality classes in 47 selected smallholder farms of Trans-Nzoia County.

	Farmers' categories of soil quality			
Soil properties	Good	Intermediate	Poor	P-Values
pH	5.91 ± 0.045	5.78 ± 0.051	5.79 ± 0.040	***0.070****
Al (mg kg^{-1})	995.9 ± 10.3	1013 ± 14.9	1020 ± 9.24	*0.231*
Total C (g kg^{-1})	17.30 ± 0.350	16.57 ± 0.454	16.58 ± 0.330	*0.253*
Total N (g kg^{-1})	1.16 ± 0.028	1.10 ± 0.033	1.11 ± 0.027	*0.330*
Available P (mg kg^{-1})	28.52 ± 1.57	27.07 ± 1.57	27.1 ± 1.38	*0.729*
PSI	98.5 ± 2.12	100.5 ± 3.36	100.8 ± 2.42	*0.770*
K (mg kg^{-1})	0.822 ± 0.020	0.762 ± 0.021	0.765 ± 0.017	***0.041*****
Ca (mg kg^{-1})	5.46 ± 0.203	4.81 ± 0.267	4.99 ± 0.190	***0.092****
Mg (mg kg^{-1})	1.71 ± 0.048	1.55 ± 0.075	1.56 ± 0.049	***0.075****
ExAc (cmol$_c$kg^{-1})	0.143 ± 0.006	0.164 ± 0.008	0.169 ± 0.008	***0.019*****
ExBas (cmol$_c$kg^{-1})	8.01 ± 0.229	7.38 ± 0.316	7.46 ± 0.212	*0.137*
B (mg kg^{-1})	0.488 ± 0.012	0.457 ± 0.013	0.452 ± 0.009	***0.039*****
Cu (mg kg^{-1})	3.83 ± 0.127	3.74 ± 0.197	3.74 ± 0.144	*0.883*
Fe (mg kg^{-1})	106.4 ± 1.72	104.9 ± 2.16	106.3 ± 1.96	*0.859*
Mn (mg kg^{-1})	209.1 ± 6.11	200.5 ± 9.41	198.6 ± 7.51	*0.534*
Na (mg kg^{-1})	0.172 ± 0.003	0.171 ± 0.005	0.17 ± 0.005	*0.929*
S (mg kg^{-1})	15.80 ± 0.222	16.0 ± 0.228	15.80 ± 0.164	*0.740*
Zn (mg kg^{-1})	11.0 ± 0.403	10.3 ± 0.350	10.10 ± 0.243	*0.136*
Ecd (cmol$_c$kg^{-1})	0.109 ± 0.003	0.10 ± 0.003	0.10 ± 0.002	***0.028*****

Ecd=Electrical Conductivity; Bold p-values indicate significant effects at * p<0.10, ** p<0.05

Laboratory tests of soils corroborate respective farmers' perceived soil qualities. Good soils had higher amount of all soil nutrients except Al and PSI compared to poor soils. Significant difference in amount recorded from different soil quality classes was obtained for pH, Ca, K, Mg, B, ECd and ExAc.

To distinguish between inherent differences of soils and those that result from past land management analysis on whether the significant value observed in Table 4.14 could be explained by land tenure, land use history, age of small-scale farming or time under current management was carried out. The amount of pH, ECd and ExAc in the soil could not be explained by land tenure, land use history, age of small-scale farming or time under current management in either of the 3 soil quality classes (Table 4.15). The amount of B in the soil was found to be affected by land tenure under good soil quality class with highest amount recorded in farms with tenure compared to those without. The number of years the studied farms have been under small-scale farming also affected the amount of B in the soil with the amount in the soil increasing with an increase with number of years the farm is under small-scale farming. The amount of Ca in the soil was found to be significantly affected by land tenure under both good and poor soil quality classes with highest amount recorded in the farms with tenure compared to those without. Land use history was also found to significantly affect the amount of Ca in the soil in the good soil quality class and highest amount was recorded from farms which had maize growing history compared to non -maize growing farms. The amount of K in the soil was shown to be significantly affected by land tenure in the poor soils quality class and highest amount was recorded in the farms with tenure compared to those without. The amount of

Mg in the soil was also shown to be affected by land tenure and land use history for both good and poor soil quality classes. Farmers with tenure and maize growing history recorded higher amount of Mg in the soil than those without tenure and non-maize growing history respectively.

Table 0.15: Mean soil chemical properties of reported significant parameters from soil quality classes as alienated by land tenure, land use history, age of small-scale farming and time under current management of 47 selected smallholder farms of Trans-Nzoia County.

Soil quality classes	Farm characteristics		Soil nutrients						
			pH	B	Ca	K	Mg	ECd	ExAc
Good soil	Land tenure	Tenure	5.94 ± 0.049	0.492 ± 0.009	5.63 ± 0.190	0.825 ± 0.018	1.76 ± 0.042	0.109 ± 0.003	0.142 ± 0.006
		No tenure	5.78 ± 0.110	0.472 ± 0.060	4.68 ± 0.703	0.806 ± 0.077	1.46 ± 0.170	0.109 ± 0.013	0.146 ± 0.016
		P-value	*0.153*	*0.063*	***0.011***	*0.259*	***0.002***	*0.405*	*0.347*
	Land use history	Maize	5.94 ± 0.051	0.491 ± 0.014	5.61 ± 0.227	0.822 ± 0.023	1.74 ± 0.054	0.108 ± 0.004	0.143 ± 0.006
		Non-maize	5.77 ± 0.069	0.475 ± 0.017	4.67 ± 0.300	0.823 ± 0.013	1.51 ± 0.062	0.114 ± 0.004	0.140 ± 0.014
		P-value	*0.301*	*0.988*	*0.082*	*0.613*	***0.030***	*0.157*	*0.748*
	Age of small-scale farming (years)	10-20	5.77 ± 0.092	0.480 ± 0.017	4.73 ± 0.311	0.796 ± 0.028	1.62 ± 0.082	0.109 ± 0.004	0.146 ± 0.019
		21-30	5.76 ± 0.085	0.470 ±0.010	4.94 ± 0.349	0.778 ± 0.027	1.63 ± 0.054	0.106 ±0.004	0.159 ± 0.014
		31-40	5.98 ± 0.056	0.495 ±0.017	5.74 ± 0.262	0.838 ± 0.027	1.74 ± 0.066	0.110 ±0.004	0.138 ± 0.006
		P-value	*0.125*	*0.526*	*0.131*	*0.447*	*0.396*	*0.881*	*0.511*
	Time under current management (years)	Short-term	5.98 ± 0.131	0.502 ± 0.030	5.43 ± 0.510	0.878 ± 0.054	1.71 ± 0.122	0.117 ± 0.008	0.152 ± 0.018
		Medium-term	5.86 ±0.053	0.486 ± 0.018	5.39 ± 0.275	0.804 ± 0.026	1.71 ± 0.060	0.109 ± 0.004	0.140 ± 0.007
		Long-term	5.97 ±0.095	0.483 ± 0.018	5.66 ± 0.382	0.817 ± 0.029	1.70 ± 0.109	0.103 ± 0.005	0.143 ± 0.007
		P-value	*0.636*	*0.719*	*0.746*	*0.232*	*0.839*	*0.350*	*0.856*
	Land tenure	Tenure	5.79 ± 0.056	0.466 ± 0.012	4.91 ± 0.300	0.768 ± 0.021	1.60 ± 0.079	0.101 ± 0.004	0.166 ± 0.010
		No tenure	5.77 ± 0.131	0.424 ± 0.039	4.44 ± 0.609	0.741 ± 0.067	1.40 ± 0.192	0.098 ± 0.008	0.156 ± 0.016
		P-value	*0.798*	*0.125*	*0.289*	*0.441*	*0.195*	*0.629*	*0.842*
	Land use history	Maize	5.79 ± 0.057	0.459 ± 0.014	4.91 ± 0.292	0.764 ± 0.024	1.59 ± 0.080	0.101 ± 0.004	0.167 ± 0.009
		Non-maize	5.69 ± 0.019	0.442 ± 0.006	3.99 ± 0.287	0.740 ± 0.031	1.26 ± 0.122	0.096 ± 0.003	0.142 ± 0.006
		P-value	*0.856*	*0.583*	*0.313*	*0.743*	*0.139*	*0.999*	*0.532*
	Age of small-scale farming (years)	10-20	5.82 ± 0.131	0.462 ± 0.036	5.03 ± 0.642	0.745 ± 0.017	1.57 ± 0.133	0.106 ± 0.011	0.140 ± 0.005
		21-30	5.70 ± 0.051	0.457 ± 0.012	4.72 ± 0.326	0.767 ± 0.030	1.58 ± 0.072	0.105 ± 0.005	0.162 ± 0.015
		31-40	5.80 ± 0.076	0.455 ± 0.018	4.77 ± 0.399	0.765 ± 0.035	1.53 ± 0.119	0.096 ± 0.004	0.172 ± 0.013
		P-value	*0.923*	*0.928*	*0.700*	*0.893*	*0.879*	*0.277*	*0.601*
		Short-term	5.89 ± 0.137	0.489 ± 0.026	5.31 ± 0.608	0.804 ± 0.027	1.66 ± 0.119	0.108 ± 0.009	0.160 ± 0.020

Intermediate soil	Time under current management (years)	Medium-term	5.73 ± 0.055	0.451 ± 0.015	4.68 ± 0.273	0.765 ± 0.028	1.54 ± 0.084	0.990 ± 0.003	0.161 ± 0.011
		Long-term	5.82 ± 0.146	0.439 ± 0.039	4.59 ± 0.975	0.702 ± 0.066	1.47 ± 0.290	0.930 ± 0.010	0.178 ± 0.022
		P-value	*0.676*	*0.374*	*0.350*	*0.371*	*0.450*	*0.323*	*0.717*
Poor soil	Land tenure	Tenure	5.81 ± 0.044	0.464 ± 0.008	5.18 ± 0.203	0.776 ± 0.016	1.63 ± 0.046	0.101 ± 0.002	0.166 ± 0.009
		No tenure	5.67 ± 0.091	0.393 ± 0.027	4.10 ± 0.393	0.715 ± 0.055	1.22 ± 0.121	0.096 ± 0.006	0.184 ± 0.021
		P-value	*0.161*	***0.003***	***0.047***	*0.088*	***0.002***	*0.171*	*0.357*
	Land use history	Maize	5.79 ± 0.044	0.455 ± 0.010	5.07 ± 0.209	0.769 ± 0.019	1.60 ± 0.053	0.100 ± 0.002	0.171 ± 0.009
		Non-maize	5.78 ± 0.110	0.430 ± 0.017	4.50 ± 0.407	0.744 ± 0.029	1.31 ± 0.089	0.101 ± 0.002	0.155 ± 0.012
		P-value	*0.807*	*0.217*	*0.350*	*0.483*	***0.016***	*0.637*	*0.637*
	Age of small-scale farming (years)	10-20	5.79 ± 0.152	0.409 ± 0.020	4.75 ± 0.628	0.714 ± 0.017	1.37 ± 0.119	0.104 ± 0.003	0.151 ± 0.016
		21-30	5.63 ± 0.051	0.449 ± 0.015	4.74 ± 0.349	0.779 ± 0.023	1.62 ± 0.074	0.102 ± 0.002	0.194 ± 0.028
		31-40	5.83 ± 0.048	0.461 ± 0.012	5.10 ± 0.235	0.772 ± 0.023	1.58 ± 0.064	0.099 ± 0.003	0.166 ± 0.008
		P-value	*0.216*	*0.082*	*0.647*	*0.270*	*0.183*	*0.362*	*0.484*
	Time under current management (years)	Short-term	5.86 ± 0.108	0.435 ± 0.021	4.91 ± 0.448	0.732 ± 0.022	1.45 ± 0.108	0.101 ± 0.004	0.148 ± 0.012
		Medium-term	5.74 ± 0.048	0.449 ± 0.012	4.85 ± 0.257	0.757 ± 0.023	1.56 ± 0.065	0.099 ± 0.003	0.183 ± 0.011
		Long-term	5.86 ±0.089	0.474 ± 0.017	5.43 ± 0.358	0.816 ± 0.038	1.67 ± 0.103	0.103 ± 0.004	0.152 ± 0.013
		P-value	*0.350*	*0.235*	*0.392*	*0.126*	*0.215*	*0.802*	*0.145*

P-value obtained through Mann-Whitney U test for 2 independent samples and Kruskall-Wallis test for more than 2 independent samples. Bold values indicate significant effects at p<0.05.

4.3.3.1 Estimating accuracy during description of soil quality classes

The percent of farmers accurately predicting soil to contain highest (good), intermediate, and lowest (poor) amount of soil macro and micro nutrients was calculated (Table 4.16). For the soil quality classes, prediction of good or poor soils was more precise than prediction of intermediate soils. Among the soil nutrients, prediction of Mn, Mg and K was the most precise with mean accuracy of 56.1%, 55.3% and 55.3% respectively. Prediction of S was least precise with 35.1 % mean accuracy. Soil pH was shown to be the most accurately predicted soil chemical property for the good or poor soils quality classes with 72.7% accuracy. It is therefore evident that effects of changes in soil pH soil quality indicators are the most prevalently used by farmers to monitor soil quality changes.

Table 0.16: Percent of farmers accurately predicting soil macro- and micro nutrients in good or poor and intermediate soil qualities in Trans-Nzoia County.

	Percentage accuracy		
Soil nutrients	Good/Poor	Intermediate	Mean accuracy (%)
pH	72.7	34.5	53.6
Al (mg kg^{-1})	40.9	38.5	39.7
Total C (g kg^{-1})	56.8	46.2	51.6
Total N (g kg^{-1})	59.1	50.0	54.6
Available P (mg kg^{-1})	56.8	46.2	51.5
PSI	52.3	34.6	43.5
K (mg kg^{-1})	68.2	42.3	55.3
Ca (mg kg^{-1})	68.2	38.4	53.3
Mg (mg kg^{-1})	68.2	42.3	55.3
ExAc ($cmol_c kg^{-1}$)	40.9	38.4	39.7
ExBas ($cmol_c kg^{-1}$)	65.9	34.6	50.3
B (mg kg^{-1})	68.2	38.5	53.4
Cu (mg kg^{-1})	59.1	38.4	48.8
Fe (mg kg^{-1})	63.6	42.3	53.0
Mn (mg kg^{-1})	65.9	46.2	56.1
Na (mg kg^{-1})	47.7	30.7	39.2
S (mg kg^{-1})	43.2	26.9	35.1
Zn (mg kg^{-1})	50.0	26.9	38.5
Ecd ($cmol_c kg^{-1}$)	63.6	46.2	54.9
Acidified N (g kg^{-1})	63.6	38.5	51.1
Acidified C (g kg^{-1})	68.2	38.5	53.4

4.3.4 Attributes of local tree species and their perceived effects on soil quality

When asked to explain attributes associated with presence of plants in an area, farmers named a diverse range of negative or positive attributes indicated by plant species presence (Table 4.17). These included soil fertility characteristics (such as competition levels for soil nutrients, competition for water, high soil pH, increased soil salinity, good litter, soil erosion control, easiness of working on the soil below), tree canopy and root characteristics (such as competition through roots and shading intensity).

Farmers interviewed named 33 tree species as having a particular impact on soil quality, farming activities or crop growth (Table 4.17). There was a general concordance among farmers on the beneficial and detrimental tree species. The preferred tree attribute cited by farmers in order of importance were, increase of soil fertility through leaves decomposition, soil erosion control, provision of shade to growing crops and nitrogen fixation. Comparatively, the less favored attributes were contribution of tree to dried ground, allelopathy, increased competition for water and nutrients, and too much shading. Seven out of the ten most commonly named tree species were favored / beneficial according to the farmers and include *G. robusta, C. macrostachyus, Sesbania* spp, *M. lutea, C. calothyrsus, F. sycomorus* and *P. Americana.* Four out of the seven beneficial tree species were native in origin while 2 (*Sesbania spp* and *C. calothyrsus*) were leguminous species, which can fix atmospheric nitrogen through a symbiotic relationship with rhizobia in root nodules. The three out of the ten commonly named tree species were less favored according to the interviewed farmers and they include *Eucalyptus* spp, *C. lusitanica* and *A. abyssinica*.

Table 0.17: Farmers' perception of contribution of various agroforestry tree and shrub species to soil quality in Trans-Nzoia County.

A similar triangulation approach was used when describing perceptions of tree impacts/rationale for impacts on soil quality.

	Farmers opinion about tree in percentage (# farmers)		Tree attributes enumerated by farmers	
Scientific name	Beneficial	Detrimental	Positive	Negative
Eucalyptus spp	-	45 (95.7)	-	-Dries the soil around it because the roots are too high thus less water for crops (18) -Leaves decomposition or tree presence increase acidity in the soil and also consumes a lot of water (6) -Increase soil acidity leading to low productivity (5) -Roots are shallow or over competes the crop (4) -Allelopathic effect and consumes a lot of water (3) -Allelopathic effect (2) -Leaves decay slowly and roots extend too far increasing competition (2) -The crops near the tree have stunted growth (1) -Too much shade and also depletes water for crops (1)

				- Consumes water and then compacts the soil leading to nutrient loss (1) **-**Takes up a lot of water and nutrients than crop and also increase acidity to the soil (1) **-**Reason not given (1)
Grevillea robusta	33 (70.2)	**-**	**-**Increase soil fertility through leaves decomposition (19) **-**Increase soil fertility through leaves decomposition and prevent soil erosion by compacting soil together (5) **-**Leaves forms good litter and compete minimally with crops (3) **-**Minimal or no competition with crops (2) **-**Shade the crop from too much sunlight (1) **-**The area below the tree do not dry very much/ acts as a wind breaker and also leaves form good litter (1) **-**Acts as a wind breaker (1)	**-**

			-Reason not given (1)	
Croton macrostachyus	17 (6.2)	2 (4.3)	-Increase soil fertility through leaves decomposition (9) -Increase soil fertility through leaves decomposition and prevent soil erosion by compacting soil together (4) -The area below the tree do not dry very much/ acts as a wind breaker and also leaves form good litter (1) -Crops perform better below it (1) -Shed leaves so less competition and leaves decay into nutrients (1) -Control soil erosion and the associated crop is not interfered with during rainy season (1)	-The adjacent area is too dry when the tree is not pruned (1) -Too much shade and also depletes water for crops (1)
***Sesbania* spp**	28 (59.6)	1 (2.1)	-Increase soil fertility through leaves decomposition (7) -Leaves forms good litter and compete minimally with crops (4) -Increase soil fertility through leaves decomposition and prevent soil erosion by compacting soil together (3) -The area around the tree has more nutrients (3) -Minimal or no competition with crops (2) -Control soil erosion and the associated crop is not interfered with during rainy season (2) -Crops perform better below it (2)	-Roots are shallow or over competes the crop (1)

			-Nitrogen fixing (1) -The area below the tree do not dry very much/ acts as a wind breaker and also leaves form good litter (1) -Increase soil fertility through leaves decomposition and nitrogen fixing (1) -The area around the base has more nutrients and water (1) -No reason given (1)	
Markhamia lutea	26 (55.3)	-	-Increase soil fertility through leaves decomposition (17) -Leaves forms good litter and compete minimally with crops (2) -Increase soil fertility through leaves decomposition and prevent soil erosion by compacting soil together (2) -The area below the tree do not dry very much/ acts as a wind breaker and also leaves form good litter (2) -Crops perform better below it (1) -Minimal or no competition with crops (1) -Control soil erosion and the associated crop is not interfered with during rainy season (1)	-
Cupressus lusitanica	-	18 (38.3)	-	- Dries the soil around it because the roots are too high thus less water for crops (4)

				-Roots are shallow or over competes the crop (2) -Kills soil microorganisms and crops around it (2) -Too much shade and also depletes water for crops (2) -Roots are shallow or the tree over compete the crops (1) -Allelopathic effect and consumes a lot of water (1) -Allelopathic effect (1) -Leaves decay slowly and roots extend too far increasing competition (1) -The crops near the tree have stunted growth (1) -Too much shade decreasing crop productivity (1) -Too much shade as the tree do not shed leaves and roots are also found competing at top soil (1) -Reason not given (1)
Calliandra calothyrsus	16 (34.0)	-	-Increase soil fertility through leaves decomposition (7) -Leaves forms good litter and compete minimally with crops (1) -Increase soil fertility through leaves decomposition and prevent soil erosion by compacting soil together (4)	-

			-The area around the tree has more nutrients (1) -The area below the tree do not dry very much/ acts as a wind breaker and also leaves form good litter (1) -The area around the base has more nutrients and water (1) -Do not destroy soil (1)	
Persea americana	10.6 (5)	2.1 (1)	-Increase soil fertility through leaves decomposition (4) -The area below the tree do not dry very much/ acts as a wind breaker and also leaves form good litter (1)	-Too much shade decreasing crop productivity below (1)
Acacia mearnsii	-	12.8 (6)	-	- Dries the soil around it because the roots are too high thus less water for crops (1) -Too much shade as the tree do not shed leaves and roots are also found competing at top soil (1) -Allelopathic effect and consumes a lot of water (1) -Increase soil acidity leading to low productivity (1) -Takes up a lot of water and nutrients than crop and also increase acidity to the soil (1) -Adds salinity to the soil leading to low productivity (1)
Cordia africana Lam.	8.5 (4)	-	-Increase soil fertility through leaves decomposition (4)	-
Ricinus communis	6.4 (3)	-	-Increase soil fertility through leaves decomposition (2) -The area below the tree do not dry very much/ acts as a wind breaker and also leaves form good litter (1)	-

The 47 interviewed farmers named 33 different tree species as having a particular impact on soil quality or farming activities. The number in brackets after the attributes refers to the number of farmers who named that attribute. Native species are shown in bold letters. The tree species in the table above were named by at least three of 47 farmers interviewed.

4.3.5 Preferential incorporation of dominant agroforestry trees as guided by perceived local soil quality

About 73% of *C. calothyrsus* individuals were found growing at intermediate soils and 26% of *C. macrostachyus* individuals are found planted in good soils of soil. 57% of *Eucalyptus* spp trees are incorporated in good soils and 62% of *G. robusta* trees are found in good soils. *M. lutea* are found in good soils and intermediate soils at 40 % each while 57 % of *S. sesban* are in good soil and the rest in intermediate soils (Table 4.18).

Table 0.18: Location of planted six dominant tree species as related to farmer perception of soil type and soil quality.

		Number of trees					
Soil type	Local soil quality classes	*Calliandra calothyrsus*	*Croton macrostachyus*	*Eucalyptus* spp	*Grevillea robusta*	*Markhamia lutea*	*Sesbania* sesban
1	Good	1	1	2	2	2	1
	Intermediate	3	3	0	2	1	1
	Poor	0	0	2	0	0	0
2	Good	2	2	4	4	4	7
	Intermediate	4	1	0	1	2	3
	Poor	0	4	1	0	2	0
3	Good	0	2	2	2	0	0
	Intermediate	4	1	1	1	2	2
	Poor	1	0	2	1	1	0
	Total trees	15	14	14	13	14	14
	#Trees/good soil	20%	36%	57%	62%	43%	57%
	#Trees/intermediate soil	73%	36%	7%	31%	36%	43%
	#Trees/poor soil	7%	28%	36%	7%	21%	0%

Less preferential planting of *C. calothyrsus, Eucalyptus* spp. and *G. robusta* for a particular soil can be an indicator of greater adaptability of the trees or high value placed on the tree by the farmers that allows them to risk planting them even in good soil. *C. macrostachyus, M. lutea* and *S. sesban* were preferentially found in poor soil and this may be an indicator that farmers may try to use the trees to improve soil quality (for the case of *S. sesban*) or as an effort to look for alternative tree products where crop growth is not optimal.

4.4 Water and nutrient availability under dominant agroforestry trees within smallholder farms

4.4.1 Spatial distribution of soil nutrients around area of influence of dominant tree species

The overall effect of tree species on the horizontal and vertical dimensions consistently affected all soil nutrients (total C, total N, available P, PSI, K, Ca, ExBas, Al and pH) except Mg in soil of studied farms (Table 4.19).

Table 0.19: General linear mixed model (GLMM) showing effects of tree species, soil layer and their interactions with soil chemical properties under different agroforestry zones in smallholder farms of Trans Nzoia County.

Effects	Tree species	Zone	Layer	Tree*Zone	Tree*Layer	Tree*Zone *Layer
Total C (g kg^{-1})	**0.016***	0.383	**<0.001*****	0.648	0.701	1.000
Total N (g kg^{-1})	**0.007***	0.552	**<0.001*****	0.713	0.796	1.000
Available P (mg kg^{-1})	**0.004***	0.185	**<0.001*****	0.624	**0.022***	0.919
PSI	**<0.001*****	0.131	**<0.001*****	0.936	**0.037***	1.000
K (mg kg^{-1})	**<0.001*****	**0.021***	**<0.001*****	0.788	0.169	1.000
Ca (mg kg^{-1})	**<0.001*****	0.165	**0.048***	0.442	0.453	1.000
Mg (mg kg^{-1})	0.136	**0.087**$^{\#}$	**0.019***	0.337	0.716	1.000
ExBas ($cmol_c kg^{-1}$)	**<0.001*****	**0.096**$^{\#}$	**0.083**$^{\#}$	0.315	0.278	0.979
Al (mg kg^{-1})	**<0.001*****	**0.039***	**<0.001*****	0.993	0.529	1.000
pH	**0.018***	0.118	**0.001****	0.405	0.780	1.000

PSI = Phosphorus Sorption Index, ns = not significant; Bold values indicate significant effects at $^{\#}<0.1$, $^{*}p<0.05$, $^{**}p<0.001$, $^{***}p<0.0001$, respectively.

Zone (distance from tree trunk) was found to affect the amount of K, Mg, ExBas and Al in the soil while soil layer recorded effect on availability of all soil nutrients. Interaction between tree species and zone was shown to not affect availability any soil nutrient in the farms while the interaction between tree species and layer influenced availability of soil P and PSI.

4.4.1.1 Soil nutrients as affected by distance from the tree trunk

Among the soil nutrients tested only Mg availability and soil pH recorded significant difference under the dominant tree species when discriminated by zone (Table 4.20). Equally, among the dominant tree species in smallholder farms significant difference in Mg availability was only recorded under *S. sesban*. The amount of Mg was significantly higher under *S. sesban* (Zone A, B and C) than amount recorded in zone D (zone away from tree influence). Soil acidity under *S. sesban* marginally but significantly increased with an increase in distance from the tree trunk where the amount in the three zones under the tree influence was statistically different from the amount recorded at zone D.

4.4.1.2 Soil nutrients as affected by soil depth/layer

All soil nutrients recorded significant differences in availability in the soil amongst the dominant tree species when discriminated by layer (Table 4.21). The amount of C and N in the soil under all tree species significantly decreased with an increase in depth of layer.

Analysis of effect of layer under all the tree species showed significant difference in the amount of P in the soil where the amount in top layer was significantly higher than the amount recorded in the bottom layer for all tree species. The PSI, K significantly reduced with an increase in depth of layer for all tree species with amount in top layer significantly higher to amount in the bottom layer. The amount of Ca in the soil under *C. calothyrsus* significantly decreased with an increase in depth of layer when comparing the two top depths with two lower depths. Under *Eucalyptus spp*, *G. robusta, M. lutea* and *S. sesban* the amount of Ca in the soil decreased significantly with an increase in depth of layers. The amount of Mg in the soil was only significantly different amongst the layers only under *G. robusta* with significantly higher amount recorded in lowest layer compared to upper layer. In contrast to majority of other soil nutrients, the amount of Al in the soil increased with an increase in depth of layer for all the tree species. The amount of ExBas in the soil decreased with an increase in depth of layer under all tree species. Soil pH significantly decreased with an increase in depth of layer under *C. calothyrsus* and *G. robusta*

Table 0.20: Spatial pattern of soil chemical properties under *C. calothyrsus, C. macrostachyus, Eucalyptus spp, G. robusta, M. lutea* and *S. sesban* as affected by different zones in smallholder farms of Trans-Nzoia County.

	Zone	Total C (g kg^{-1})	Total N (g kg^{-1})	PSI	P (mg kg^{-1})	ExBas (cmol$_c$kg^{-1})	Al (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	K (mg kg^{-1})	pH
Calliandra calothyrsus	A	12.22 ± 0.89	0.88 ± 0.06	36.34 ± 2.1	2.74 ± 0.72	6.85 ± 0.37	1139 ± 27.3	801.7 ± 63.4	204.0 ± 8.0	222.7 ± 15.3	5.91 ± 0.07
	B	11.77 ± 0.71	0.85 ± 0.05	36.76 ± 1.9	3.15 ± 1.03	6.82 ± 0.30	1125 ± 27.5	803.4 ± 48.7	205.7 ± 6.6	212.9 ± 12.6	5.96 ± 0.06
	C	11.53 ± 0.78	0.83 ± 0.06	36.09 ± 2.1	3.37 ± 1.23	6.66 ± 0.29	1143 ±27.8	783.4 ± 32.0	201.4 ± 6.9	210.2 ± 14.5	5.92 ± 0.05
	D	11.03 ± 0.68	0.80 ±0.05	35.68 ± 2.1	2.13 ± 0.62	6.62 ± 0.28	1149 ± 26.3	840.3 ± 49.6	204.7 ± 8.7	201.7 ± 11.0	5.96 ± 0.07
P-value		*0.766*	*0.705*	*0.787*	*0.935*	*0.935*	*0.829*	*0.978*	*0.787*	*0.705*	*0.499*
Croton macrostachyus	A	11.39 ± 0.92	0.84 ± 0.07	39.21 ± 1.98	3.64 ± 1.27	8.19 ± 1.04	1085 ± 42.7	1065 ± 167	218.1 ± 17.1	222.2 ± 13.7	6.06 ± 0.15
	B	11.40 ±0.85	0.85 ± 0.06	40.96 ± 2.93	3.41 ± 0.96	12.33 ±3.45	1072 ± 57.4	1654 ± 496	250.6 ± 35.1	253.4 ± 22.7	6.20 ±0.25
	C	11.24 ± 0.85	0.82 ± 0.06	40.98 ± 2.41	3.16 ± 1.00	10.11 ±2.39	1058 ± 47.9	1333 ± 388	235.3 ± 25.5	237.2 ± 19.8	6.17 ±0.19
	D	11.57 ± 0.77	0.86 ± 0.06	37.99 ± 1.96	3.78 ± 1.14	6.22 ±0.27	1137 ± 27.7	753.7 ± 46.4	188.2 ± 5.1	209.4 ± 11.0	5.83 ± 0.05
P-value		*0.986*	*0.962*	*0.878*	*0.980*	*0.304*	*0.844*	*0.521*	*0.584*	*0.627*	*0.549*
Eucalyptus spp	A	11.95 ± 0.85	0.89 ± 0.06	40.42 ± 2.42	9.23 ± 5.32	6.81 ± 0.32	1110 ± 29.9	857.0 ± 71.0	203.5 ± 6.68	222.3 ± 17.9	5.97 ± 0.06
	B	11.94 ± 0.85	0.87 ± 0.07	39.40 ± 2.22	4.90 ± 2.16	6.93 ± 0.31	1111 ± 31.9	866.9 ± 67.5	214.5 ± 8.94	208.9 ± 14.7	6.04 ± 0.07
	C	11.68 ± 0.77	0.86 ± 0.06	38.06 ± 2.07	2.60 ± 0.68	6.75 ± 0.29	1122 ± 32.4	816.5 ± 67.3	205.9 ± 4.54	204.8 ± 14.1	5.99 ± 0.05
	D	11.62 ± 0.69	0.86 ± 0.06	37.58 ± 2.18	2.87 ± 0.99	6.71 ± 0.23	1143 ± 31.4	773.7. ± 47.1	203.1 ± 5.83	206.6 ± 12.7	5.94 ± 0.06
P-value		*0.997*	*0.994*	*0.799*	*0.967*	*0.938*	*0.852*	*0.753*	*0.717*	*0.960*	*0.657*
Grevillea robusta	A	11.23 ± 0.84	0.83 ±0.07	34.12 ± 1.58	3.34 ± 1.74	6.23 ± 0.28	1181 ± 27.9	789.0 ± 56.4	203.3 ± 5.90	199.6 ± 14.7	5.95 ±0.06
	B	11.23 ± 0.69	0.83 ±0.06	33.30 ± 1.53	3.11 ± 1.66	6.21 ± 0.20	1189 ± 30.9	710.3 ± 41.3	204.0 ± 4.81	202.8 ± 12.7	5.93 ± 0.06
	C	11.09 ± 0.78	0.82 ± 0.06	33.65 ± 1.37	2.01 ± 0.87	6.10 ± 0.26	1190 ± 26.1	726.4 ± 52.7	200.0 ± 5.28	193.9 ± 12.9	5.92 ±0.06
	D	11.08 ± 0.71	0.81 ± 0.06	34.15 ± 1.49	1.84 ± 0.51	6.15 ± 0.27	1206 ± 30.6	723.9 ± 51.7	202.2 ± 6.41	194.6 ± 11.6	5.91 ±0.05
P-value		*0.980*	*0.988*	*0.977*	*0.896*	*0.961*	*0.923*	*0.792*	*0.899*	*0.909*	*0.963*
Markhamia lutea	A	12.22 ± 1.09	0.86 ± 0.08	36.06 ± 2.37	3.53 ± 1.97	6.68 ± 0.41	1134 ± 28.4	755.1 ± 72.7	213.2 ± 7.05	223.5 ± 16.6	6.01 ± 0.06
	B	11.86 ± 0.99	0.83 ± 0.07	34.72 ± 2.06	1.86 ± 0.89	6.51 ± 0.38	1141 ± 25.3	734.5 ± 67.5	211.6 ± 5.99	213.2 ± 14.2	6.00 ± 0.05
	C	11.26 ± 0.76	0.78 ± 0.06	33.31 ± 1.80	0.96 ± 0.34	6.35 ± 0.28	1153 ± 25.6	695.5 ± 45.4	217.2 ± 5.39	203.0 ± 11.9	6.06 ± 0.05
	D	10.65 ± 0.79	0.75 ± 0.05	33.52 ± 1.82	0.85 ± 0.26	5.93 ± 0.31	1165 ± 27.7	653.1 ± 52.0	206.8 ± 5.29	197.1 ± 12.4	6.01 ± 0.05
P-value		*0.755*	*0.828*	*0.878*	*0.895*	*0.471*	*0.872*	*0.776*	*0.785*	*0.715*	*0.921*
Sesbania sesban	A	10.49 ± 0.94	0.75 ± 0.07	41.79 ± 2.33	4.51 ± 1.68	8.47 ± 1.09	981.6 ± 44.1	1179 ± 223	241.2 ± 13.6a	223.7 ± 15.6	6.37 ± 0.13a
	B	10.56 ± 0.75	0.77 ± 0.05	42.02 ± 2.33	4.91 ± 1.77	7.86 ± 0.88	1004 ± 43.1	1032 ± 163	218.1 ± 13.8ab	231.7 ± 13.9	6.15 ± 0.12ab
	C	11.04 ± 0.78	0.81 ± 0.06	41.62 ± 2.37	5.68 ± 2.17	6.99 ± 0.44	1028 ± 39.7	962.7 ± 112	204.7 ± 6.71ab	221.9 ± 14.3	6.04 ± 0.07ab
	D	11.19 ± 0.63	0.82 ± 0.05	40.01 ± 2.11	5.73 ± 1.89	6.35 ± 0.27	1053 ± 31.3	839.7 ± 66.1	197.7 ± 5.66b	215.1 ± 14.7	5.96 ± 0.06b
P-value		*0.624*	*0.512*	*0.965*	*0.568*	*0.656*	*0.640*	*0.955*	***0.034****	*0.819*	***0.074***

PSI = Phosphorus Sorption Index; Standard error of the difference in means (SED) reported with means. Mean values in a column followed by the same letter in zone or layer category are not significantly different at p<0.05. The overall mean is reported for Zone given lack of significant differences. Bold p-values indicate significant effects at **<0.1, ***p<0.05.

Table 0.21: Spatial pattern of soil chemical properties under *C. calothyrsus, C. macrostachyus, Eucalyptus spp, G. robusta, M. lutea* and *S. sesban* as affected by different sampling depths in smallholder farms of Trans-Nzoia County.

	Layer	Total C	Total N	P	PSI	K	Ca	Mg	Al	ExBas	pH
	(cm)	(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})		(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(cmol$_c$kg^{-1})	
Calliandra calothyrsus	0-20	16.08 ± 0.42a	1.16 ± 0.03a	7.20 ± 1.2a	47.80 ± 1.3a	286.4 ± 9.8a	978.8 ± 51.4a	200.9 ± 5.8	1013 ± 18.7a	8.00 ± 0.31a	5.90 ± 0.05ab
	21-35	12.98 ± 0.25b	0.94 ± 0.02b	2.99 ± 0.62b	38.86 ± 1.2b	226.5 ± 8.3b	874.3 ± 42.3a	201.6 ± 7.0	1099 ± 20.8b	6.98 ± 0.25b	5.90 ± 0.06ab
	36-60	9.48 ± 0.19c	0.69 ± 0.01c	0.81 ± 0.19b	30.89 ± 0.7c	176.6 ± 4.9c	723.6 ± 34.3b	193.8 ± 6.9	1209 ± 16.6c	5.97 ± 0.21c	5.86 ± 0.06a
	61-90	8.01 ± 0.21d	0.57 ± 0.02d	0.39 ± 0.12b	27.32 ± 0.6c	157.9 ± 5.0c	652.3 ± 30.8b	219.6 ± 9.1	1234 ± 16.6c	6.00 ± 0.22c	6.09 ± 0.07b
	p-value	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	_0.189_	___<0.001***___	___<0.001***___	___0.050***___
Croton macrostachyus	0-20	15.55 ± 0.61a	1.14 ± 0.04a	8.59 ± 1.44a	47.45 ± 1.05a	275.4 ± 7.59a	1023 ± 71.9ab	198.9 ± 7.91	1012 ± 24.6a	7.92 ± 0.38b	5.88 ± 0.08
	21-35	12.73 ± 0.61b	0.95 ± 0.04b	3.89 ± 0.75b	42.34 ± 1.72ab	249.5 ± 12.8a	1145 ± 293ab	203.7 ± 17.5	1074 ± 37.4b	8.63 ± 1.67b	5.90 ± 0.14
	36-60	9.43 ± 0.49c	0.70 ± 0.03c	1.03 ± 0.18bc	37.26 ± 2.65bc	218.0 ± 24.8ab	1653 ± 552a	247.6 ± 34.8	1103 ± 55.8c	12.17 ± 3.78a	6.23 ± 0.24
	61-90	7.89 ± 0.28c	0.58 ± 0.02c	0.48 ± 0.09c	32.08 ± 2.11c	179.3 ± 13.0b	984.0 ± 195b	241.9 ± 25.2	1163 ± 51.3d	8.12 ± 1.41b	6.25 ± 0.19
	p-value	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	___0.015***___	_0.159_	___0.001***___	___0.021***___	_0.081_
Eucalyptus spp	0-20	16.55 ± 0.43a	1.23 ± 0.04a	15.52 ± 5.21a	52.63 ± 1.14a	296.6 ± 9.68a	1043 ± 69.2a	207.1 ± 5.17	964.6 ± 17.8a	8.39 ± 0.14a	5.97 ± 0.06
	21-35	12.68 ± 0.39b	0.94 ± 0.03b	3.16 ± 0.80b	41.02 ± 1.04b	225.2 ± 8.68b	898.3 ± 60.5ab	203.9 ± 6.51	1086 ± 23.0a	7.02 ± 0.20b	5.96 ± 0.06
	36-60	9.69 ± 0.13c	0.71 ± 0.01c	0.65 ± 0.08b	32.71 ± 0.55c	172.0 ± 5.73c	710.7 ± 39.2bc	205.3 ± 8.50	1197 ± 21.2b	6.04 ± 0.13c	5.96 ± 0.07
	61-90	8.26 ± 0.20d	0.61 ± 0.01d	0.29 ± 0.04b	29.09 ± 0.42d	148.8 ± 4.94c	661.8 ± 41.9c	210.6 ± 6.41	1240 ± 17.4c	5.75 ± 0.20c	6.04 ± 0.05
	p-value	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	_0.791_	___<0.001***___	___<0.001***___	_0.735_
Grevillea robusta	0-20	15.69 ± 0.48a	1.16 ± 0.05a	8.16 ± 2.15a	43.07 ± 0.69a	271.1 ± 12.4a	885.0 ± 50.9a	194.6 ± 4.62b	1079 ± 20.2c	7.24 ± 0.23a	5.81 ± 0.05b
	21-35	11.57 ± 0.46b	0.85 ± 0.03b	1.25 ± 0.15b	34.62 ± 0.49b	196.2 ± 5.77b	751.3 ± 42.7ab	191.7 ± 4.06b	1175 ± 21.6b	6.03 ± 0.23b	5.84 ± 0.04b
	36-60	9.27 ± 0.26c	0.68 ± 0.02c	0.63 ± 0.15b	30.32 ± 0.57c	172.9 ± 5.80bc	662.3 ± 41.7b	201.3 ± 5.18b	1234 ± 26.0ab	5.71 ±0.18b	5.95 ± 0.05ab
	61-90	8.09 ± 0.16c	0.58 ± 0.02c	0.25 ± 0.05b	27.22 ± 0.64d	150.9 ± 5.09c	651.0 ± 50.2b	221.9 ± 5.81a	1277 ± 25.8a	5.70 ± 0.20b	6.11 ± 0.06a
	p-value	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	___0.004***___	___0.002***___	___<0.001***___	___<0.001***___	___<0.001***___
Markhamia lutea	0-20	16.31 ± 0.79a	1.14 ± 0.06a	5.38 ± 2.00a	45.85 ± 1.57a	284.5 ± 9.98a	920.2 ± 64.8a	212.9 ± 5.44	1009 ± 19.8c	7.71 ± 0.31a	6.00 ± 0.06
	21-35	12.72 ± 0.58b	0.90 ± 0.05b	1.50 ± 0.39b	36.75 ± 1.13b	230.0 ± 9.22b	707.6 ± 45.7b	206.9 ± 5.34	1112 ± 17.5b	6.50 ± 0.27b	5.96 ± 0.06
	36-60	9.17 ± 0.29c	0.65 ± 0.02c	0.24 ± 0.04b	28.96 ± 0.55c	172.2 ± 4.15c	608.1 ± 39.3b	208.8 ± 4.02	1212 ± 14.5a	5.63 ± 0.24b	6.02 ± 0.03
	61-90	7.78 ± 0.27c	0.54 ± 0.02c	0.09 ± 0.02b	26.05 ± 0.44c	150.1 ± 4.32c	602.3 ± 60.0b	220.2 ± 8.11	1260 ± 11.8a	5.63 ± 0.35b	6.10 ± 0.06
	p-value	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	___<0.001***___	___0.001***___	_0.491_	___<0.001***___	___<0.001***___	_0.327_
	0-20	14.90 ± 0.69a	1.09 ± 0.05a	14.76 ± 2.49a	52.50 ± 1.52a	289.8 ± 10.4a	1156 ± 112a	209.6 ± 8.61	913.2 ± 23.3b	8.17 ± 0.33a	6.06 ± 0.09
	21-35	11.45 ± 0.58b	0.83 ± 0.83b	4.13 ± 1.10b	43.54 ± 1.52b	233.3 ± 11.0b	1036 ± 144a	217.4 ± 11.0	980.2 ± 36.4ab	7.49 ± 0.58b	6.16 ± 0.11

Sesbania sesban	36-60	8.87 ± 0.31c	0.65 ± 0.65c	1.11 ± 0.19b	36.69 ± 1.54c	187.3 ± 8.86c	914.7 ± 150a	209.6 ± 9.85	1075 ± 39.9a	6.74 ± 0.72c	6.11 ± 0.09
	61-90	8.06 ± 0.23c	0.58 ±0.02c	0.83 ± 0.17b	32.71 ± 1.49c	182.0 ± 12.6c	906.9 ± 195a	225.1 ± 14.4	1097 ± 43.6a	7.28 ± 1.16b	6.20 ± 0.13
	p-value	***<0.001****	***<0.001****	***<0.001****	***<0.001****	***<0.001****	***0.012****	*0.851*	***<0.001****	***<0.001****	*0.855*

PSI = Phosphorus Sorption Index; Standard error of the difference in means (SED) reported with means. Mean values in a column followed by the same letter in layer category are not significantly different at $p<0.05$. The overall mean is reported for Zone given lack of significant differences. Bold p-values indicate significant effects at **<0.1, ***$p<0.05$.

4.4.1.3 Decomposability of tree organic inputs

Foliage, litter and root decomposability showed significant differences among dominant tree species (Table 4.22). The (lignin+polyphenol)/N ratio for foliage followed the trend *S. sesban* < *C. macrostachyus* < *M. lutea* < *C. calothyrsus* < *Eucalyptus sp.* < *G. robusta* while the leaf litter followed the trend *S. sesban* < *C. macrostachyus* < *M. lutea* < *C. calothyrsus* < *G. robusta* < *Eucalyptus sp*. Lastly, the (lignin+polyphenol)/N ratio for tree roots followed the trend *C. macrostachyus* < *M. lutea* < *S. sesban* < *C. calothyrsus* < *G. robusta* < *Eucalyptus sp*. The (lignin+polyphenol)/N ratio was generally lowest for leaves, followed by leaf litter and roots, in the case of *M. lutea*, values for leaf and leaf litter where not significantly different (Table 4.22).

Table 0.22: Relative decomposability of foliage, litter and root samples based on the (lignin+polyphenol)/N ratio from the dominant tree species in Trans Nzoia County.

	(Lignin + polyphenol)/N ratios			
Tree species	Foliage	Litter	Root	*P-value*
C. calothyrsus	$0.938^{b\ (A)}$	$1.272^{b\ (B)}$	$2.065^{c\ (C)}$	***<0.0001***
C. macrostachyus	$0.431^{cd\ (A)}$	$0.722^{c\ (B)}$	$0.623^{e\ (AB)}$	***0.032***
Eucalyptus spp	$1.213^{ab\ (A)}$	$2.012^{a\ (B)}$	$3.675^{a\ (C)}$	***<0.0001***
G. robusta	$1.478^{a\ (A)}$	$1.871^{a\ (A)}$	$2.730^{b\ (B)}$	***<0.0001***
M. lutea	0.885^{bc}	0.900^{bc}	1.067^{de}	*0.587*
S. sesban	$0.352^{d\ (A)}$	$0.484^{c\ (B)}$	$1.350^{d\ (C)}$	***<0.002***
P-value	***<0.0001***	***<0.0001***	***<0.0001***	

Bold p-values indicate significant effects at $p<0.05$. Mean values in a row followed by the same uppercase letter are not significantly different at $p<0.05$ while values in a column followed by same lowercase letter are not significantly different at $p<0.05$.

4.4.2 Spatial effect of agroforestry zones and sampling depths on volumetric soil water content among the dominant tree species

VSWC showed a distinct pattern depending on tree species at zone A, B, C, and D (Table 4.23). Also, all agroforestry zones showed distinct patterns on VSWC depending on sampling depth. VSWC showed a distinct pattern depending on tree species for all sampling depths. Agroforestry zones contribution to changes in VSWC was only significant at sampling depth 4. The interaction between tree species and sampling depth showed distinct pattern on VSWC at zone A, B and C and none at zone D. In comparison, the interaction of tree species and agroforestry zones showed a distinct pattern of VSWC at all sampling depths.

Table 0.23: General linear mixed model showing effects of tree species agroforestry zones and sampling depth on volumetric soil water content (m^3m^{-3}).

Distance	Tree	Depth	Interaction
Zone A	**11.05*****	**4.22****	**5.22*****
Zone B	**22.18*****	**7.92*****	**2.38***
Zone C	**20.04*****	**5.09****	**1.65***
Zone D	**42.02*****	**10.60*****	1.49
Depth	Tree	Zone	Interaction
Depth 1 (10cm)	**19.55*****	1.69	**2.11***
Depth 2 (20cm)	**21.39*****	0.80	**2.08***
Depth 3 (30cm)	**16.23*****	1.89	**3.68*****
Depth 4 (40cm)	**10.39*****	**8.54*****	**3.70*****
Depth 5 (60cm)	**10.14*****	0.19	**3.22****
Depth 6 (100cm)	**10.72*****	1.03	**4.06*****

Values indicate F-value. Bold values indicate significant effects at *$p<0.05$, **$p<0.001$, ***$p<0.0001$, respectively. Zone A= 1m from the tree trunk; Zone B= half diameter of the tree crown; Zone C= the edge of tree crown; and Zone D= 3m outside edge of the crown.

Mann-Whitney U test showed that VSWC was significantly different under various trees canopies compared to away from tree canopies. *C. macrostachyus, Eucalyptus spp, G.*

robusta and *S. sesban* significantly affect the amount of moisture in the soil (Table 4.24). There was a decrease in VSWC under *Eucalyptus spp* and *S. sesban* compared to away from the tree influence with 7 and 12% reduction recorded respectively. High level in amount of water under the tree was recorded from *C. macrostachyus* and *G. robusta* compared to away from the tree influence with 7 and 20% increment respectively (Table 4.24).

Table 0.24: Mean rank obtained after Mann-Whitney test on volumetric soil water content (VSWC) under and away from influence of dominant tree species in smallholder farms in Trans-Nzoia County during 2012-2013 cropping seasons.

Tree species	Average VSWC (m^3m^{-3})		Percentage change in VSWC	Asymptotic significance (2-tailed) p-value
	Under	Away		
Calliandra calothyrsus	0.11692	0.1169	+0.04	*0.123*
Croton macrostachyus	0.3287	0.3086	+6.50	***0.051***
Eucalyptus spp	0.3146	0.3367	-6.60	***0.034***
Grevillea robusta	0.2355	0.1971	+19.50	***0.029***
Markhamia lutea	0.2841	0.2905	-2.20	*0.646*
Sesbania sesban	0.2511	0.2850	-11.90	***0.005***

Analysis of VSWC considering agroforestry zones registered significant differences under *C. macrostachyus, Eucalyptus spp* and *S. sesban* (Table 4.25). Further, when considering sampling depths significant VSWC differences were identified under *C. calothyrsus, C. macrostachyus*, *Eucalyptus spp* and *S. sesban* (Table 4.25). Under *C. macrostachyus,* VSWC was significantly higher at zone B compared to amount at zone D (control). In contrast, under *Eucalyptus spp* the amount at zone A was significantly lower than the amount in other zones while under *S. sesban*, the amount at zone C was lower than amount in zone D. VSWC was significantly higher at depth 4 compared to depth 6 under *C. calothyrsus*. Under *C. macrostachyus,* the amount in the top 3 depths was significantly higher than amount at depth 4 and 6. Under *Eucalyptus spp*, VSWC was high at depth 2, 3 and 4 and the amount was significantly different from that at lowest depth. In comparison, under *S. sesban* where the highest amount was recorded at depth 2 with the value being significantly higher than the amount at lowest depth.

Table 0.25: Mean rank obtained after Kruskal-Wallis Test of VSWC - volumetric soil water content (m^{3}m^{-3}) within the different agroforestry zones and sampling depths as affected by dominant tree species in Trans-Nzoia County

	Calliandra calothyrsus	*Croton macrostachyus*	*Eucalyptus spp*	*Grevillea robusta*	*Markhamia lutea*	*Sesbania sesban*
Zone A	110.9	104.9^{ab}	59.9^{a}	86.0	86.5	96.5^{ab}
Zone B	117.2	115.4^{a}	105.8^{b}	85.5	104.3	96.0^{ab}
Zone C	124.6	85.7^{ab}	114.0^{b}	95.9	100.3	77.2^{b}
Zone D	95.1	79.9^{b}	116.3^{b}	70.6	94.9	116.3^{a}
p-value	*0.086*	***0.005***	***<0.001***	*0.123*	*0.428*	***0.008***
Depth 1 (10cm)	108.6^{ab}	116.3^{a}	78.1^{ab}	74.1	101.8	103.7^{ab}
Depth 2 (20cm)	109.9^{ab}	130.0^{a}	103.7^{a}	91.6	100.5	105.4^{a}
Depth 3 (30cm)	122.2^{ab}	126.7^{a}	103.8^{a}	86.7	91.2	103.6^{ab}
Depth 4 (40cm)	127.3^{a}	71.0^{bc}	126.0^{a}	91.6	95.6	99.7^{ab}
Depth 5 (60cm)	118.5^{ab}	95.0^{ab}	100.9^{ab}	93.0	103.3	102.1^{ab}
Depth 6 (100cm)	82.5^{b}	40.1^{c}	66.5^{b}	69.9	86.6	64.4^{b}
p-value	***0.045***	***<0.001***	***<0.001***	*0.315*	*0.812*	***0.023***

^{a,b,c}Mean values in a column followed by the same letter in zone or depth category are not significantly different at p<0.05. Bold p-values indicate significant effects at p<0.05. Zone A= 1m from the tree trunk; Zone B= half diameter of the tree crown; Zone C= the edge of tree crown; and Zone D= 3m outside edge of the crown.

4.4.3 Relationship between tree species, soil nutrient availability and maize productivity

A weak negative linear relationship between the amount of Ca and ExBas in the soil and maize yield was recorded under *C. calothyrsus*. Thus, an increase in amount of Ca and ExBas in the soil under *C. calothyrsus* results in decreased maize yield or vice versa (Table 4.26). Moderate negative linear relationship between Al (strong), C (moderate) and N (moderate) availability and maize yield under *C. macrostachyus* was reported. As Al, C and N increases under the tree, reduced crop yield was recorded. In contrast, moderate positive linear relationship between pH (moderate), PSI (moderate), K (weak), Mg (weak), Ca (weak) and ExBas (weak) levels and availability in the soil with maize yield under *C. macrostachyus* was recorded. As the soil pH and PSI increases maize yield improved. This is also true to amount of K, Mg, Ca and ExBas in the soil under *C. macrostachyus* (Table 4.26).

A weak positive correlation between soil pH and maize yield under *Eucalyptus spp* was recorded. As soil pH improved under the tree, results implied there was improved maize yield. A weak negative correlation between Ca and Mg availability under *G. robusta* and maize yield was recorded. As the amount of Ca and Mg availability in the soil increased analysis implied there was reduced maize yield. A negative correlation between ExBas (strong), Ca (strong), C (weak), N (weak) and K (weak) availability in the soil and maize yield under *M. lutea* was recorded. As the amount of ExBas, Ca, C, K and N increases under *M. lutea* a reduced crop yield was reported (Table 4.26). In contrast, a weak positive correlation between soil pH and maize yield under *M. lutea* was recorded which implies that with increased soil pH under the tree, analysis implied there was improved maize yield.

A very strong positive correlation (r=0.831) was recorded between amount of Ca in the soil and maize yield under *S. sesban*. A strong positive correlation was recorded between soil pH (r=762), ExBas (r=0.741), Mg (r=0.757) and maize yield under *S. sesban*. As the amount of Ca, Mg, pH and ExBas in the soil increases analysis showed improved maize yield. A negative correlation between Al (moderate), C (weak) and N (weak) availability under *S. sesban* and crop yield was recorded. As amount of Al, C and N increased in the soil, analysis implied crop yield decreased too (Table 4.26).

Table 0.26: Correlation matrix (Pearson) showing correlation coefficient (r) between soil nutrient availability and maize yield under each of the dominant tree species in Trans-Nzoia County.

		Soil nutrients									
	Tree species	C	N	P	PSI	K	Ca	Mg	Al	ExBas	pH
Maize Yield	*Calliandra calothyrsus*	0.009	-0.022	0.053	-0.110	-0.114	**-0.340****	-0.090	0.112	**-0.289***	-0.124
	Croton macrostachyus	**-0.417****	**-0.442*****	0.056	**0.455*****	**0.346****	**0.296***	**0.369****	**-0.643*****	**0.269***	**0.481*****
	Eucalyptus spp	-0.105	-0.152	-0.160	-0.019	0.181	-0.210	0.186	-0.182	0.018	**0.256***
	Grevillea robusta	-0.093	-0.132	-0.106	-0.043	-0.093	**-0.322***	**-0.309***	-0.188	-0.183	-0.171
	Markhamia lutea	**-0.342****	**-0.365****	-0.167	-0.132	**-0.306***	**-0.606*****	-0.038	-0.172	**-0.627*****	**0.319***
	Sesbania sesban	**-0.345****	**-0.352****	-0.149	0.222	0.240	**0.831*****	**0.757*****	**-0.578*****	**0.743*****	**0.762*****

PSI = Phosphorus Sorption Index; Values in bold are significantly different from zero with a significance level at *p<0.05, **p<0.001, ***p<0.0001, respectively.

Analysis of contribution of dominant tree species on nutrient availability showed a significant interaction between tree species and agroforestry zones on maize yield. The biplot shows that the first two components can explain 95.3% of the total variability and therefore the biplot can provide information about tree species-agroforestry zone interaction (Figure 4.6).

In zone A, maize yield was better under *S. sesban* than the rest of tree species; that is, maize production under *S. sesban* was better performing at Zone A. Under *C. calothyrsus* maize production is adapted to Zone B. Maize production under *C. macrostachyus* has specific adaptation to Zone C while under *Eucalyptus spp* maize production is higher at Zone D (Figure 4.6).

Among the tree species *G. robusta* is the nearest to the origin which mean maize production under the tree was the most stable and in consequence the yield across all zones are similar. On the other hand, maize productivity under *C. calothyrsus, S. sesban* and *M.*

lutea were the most unstable; that is, these had specific adaptations, because they were more distant from biplot origin.

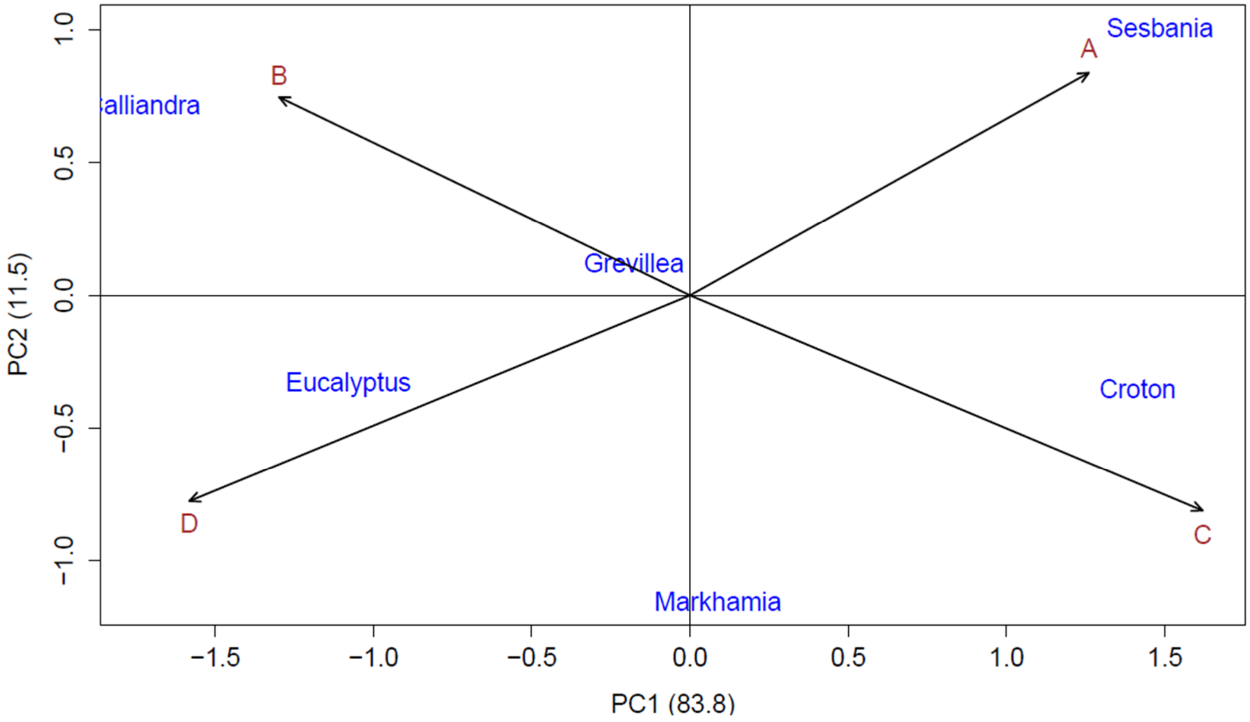

Figure 0.6: AMMI biplot showing the first two principle axes of interaction (PC1 vs. PC2) for maize yield (tons ha-1) variable under 6 dominant tree species evaluated in 4 agroforestry zones of smallholders' farms in Trans-Nzoia County.

4.5 Maize productivity under dominant agroforestry practices within smallholder farms

4.5.1 Effect of trees on maize performance, biomass and yield at on-station

Effect of two agroforestry tree species (*C. macrostachyus* and *M. lutea*) on maize performance was evaluated at on-station experiment as described in Section 3.2.1. There was no existing mature *G. robusta* species at the on-station site and therefore they were excluded in analysis of tree-crop interactions discussed in this section. A significant difference in maize basal diameter and height was recorded between the two species at 50 DAS (Days after sowing) (Figure 4.7). Maize performance was better under *C. macrostachyus*. In subsequent measurement there was no significance difference in maize performance recorded although the maize height and diameter under *C. macrostachyus* was consistently higher and larger than under *M. lutea*.

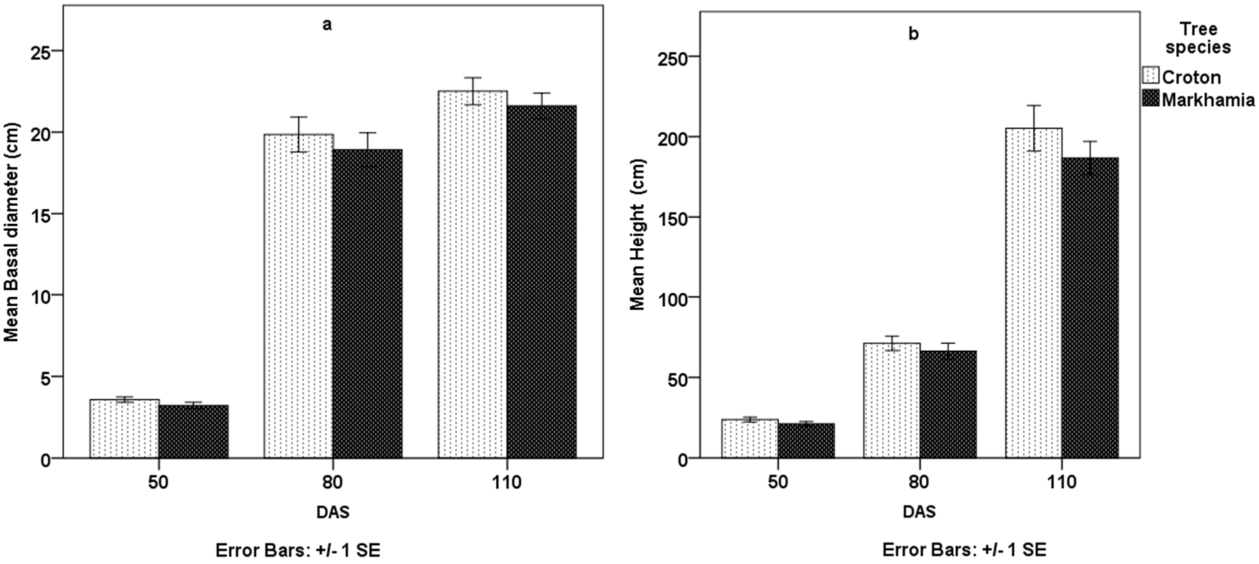

Figure 0.7: Average maize basal diameter (a) and height (b) recorded under *C. macrostachyus* and *M. lutea* at different days after sowing (DAS) in an on-station experiment in Vi-agroforestry demonstration farm in Kitale.

At 50 DAS, Zone A recorded significantly higher maize height under *C. macrostachyus* compared to Zone D but the difference diminished with subsequent measurements (Figure 4.8). At 110 DAS, significantly lower maize height was recorded at Zone B compared to

Zone D. Under *M. lutea*, higher average maize height was recorded at Zone D and the amount was significantly different from height at Zone C (Figure 4.8). However, no such difference was recorded between Zone D and Zone A.

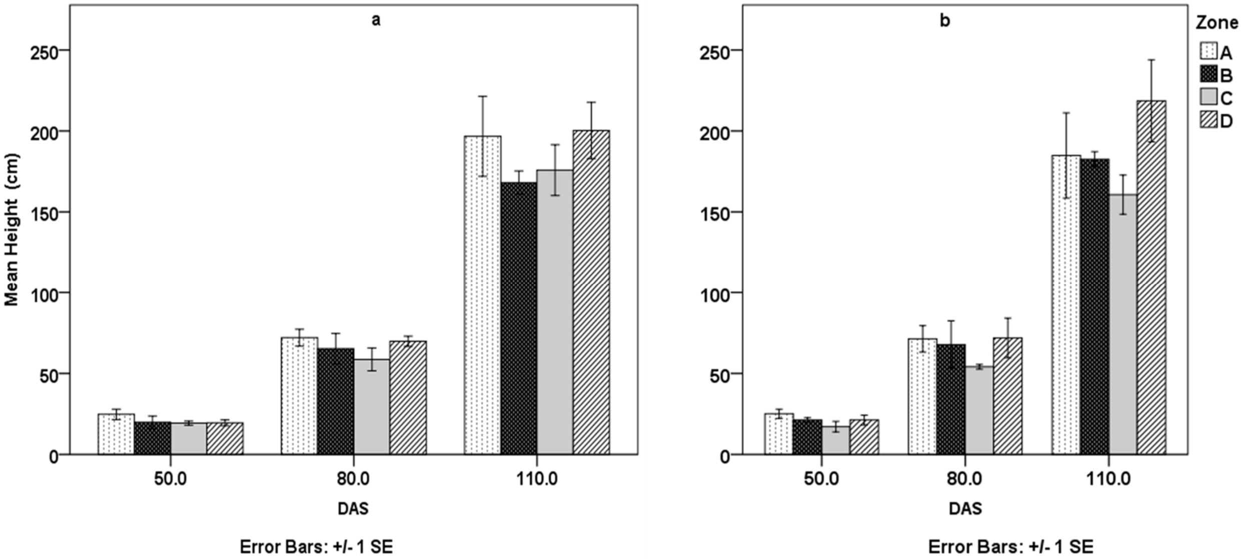

Figure 0.8: Average maize height recorded at different agroforestry zones under *C. macrostachyus* (a) and *M. lutea* (b) at different days after sowing (DAS) in an on-station experiment in Vi-agroforestry demonstration farm in Kitale.

Biomass production under the two species plus control (maize alone) ranged from 29.4 to 32.2 tons ha^{-1} but did not record significance difference between them and between different agroforestry zones within individual species. A pattern was however observed of increased biomass production with an increase with distance from tree trunk (agroforestry zones) for both species except under control (Figure 4.9).

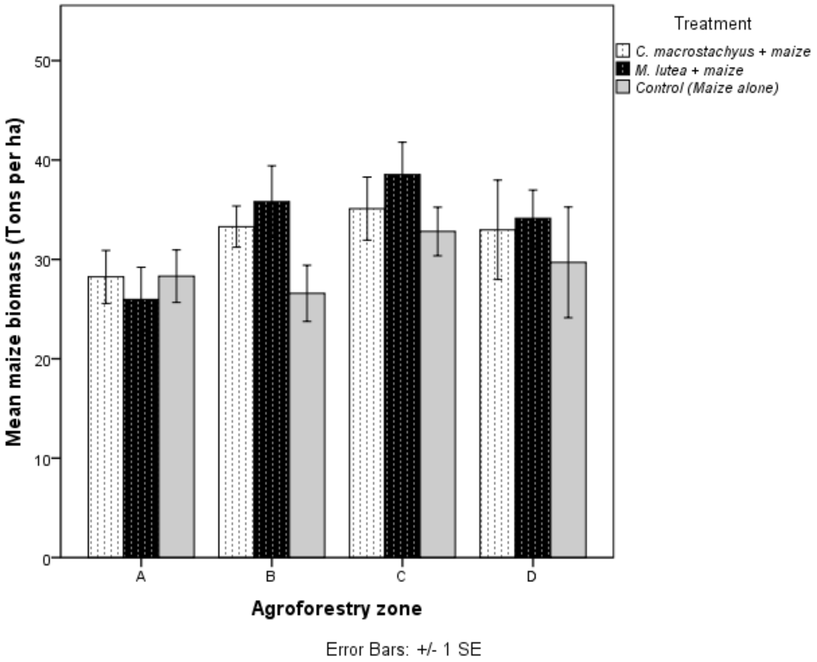

Figure 0.9: Average maize biomass (tonnes per hectare) at four agroforestry zones (A, B, C and D) under *C. macrostachyus, M. lutea* and control treatments at an on-station experiment in Vi-agroforestry demonstration farm in Kitale. Zone A= 1m from the tree trunk; Zone B= half diameter of the tree crown; Zone C= the edge of tree crown; and Zone D= 3m outside edge of the crown.

The grain weight was significant between species with highest amount of yield recorded under *C. macrostachyus* followed by *M. lutea* treatment with mean yield of 10.5 and 8.07 tons ha^{-1} respectively (Figure 4.10). Kruskal-Wallis test on grain weight under different treatments recorded significant difference (asymptotic significance, P = 0.003) with maize under *C. macrostachyus* showing stochastic dominance.

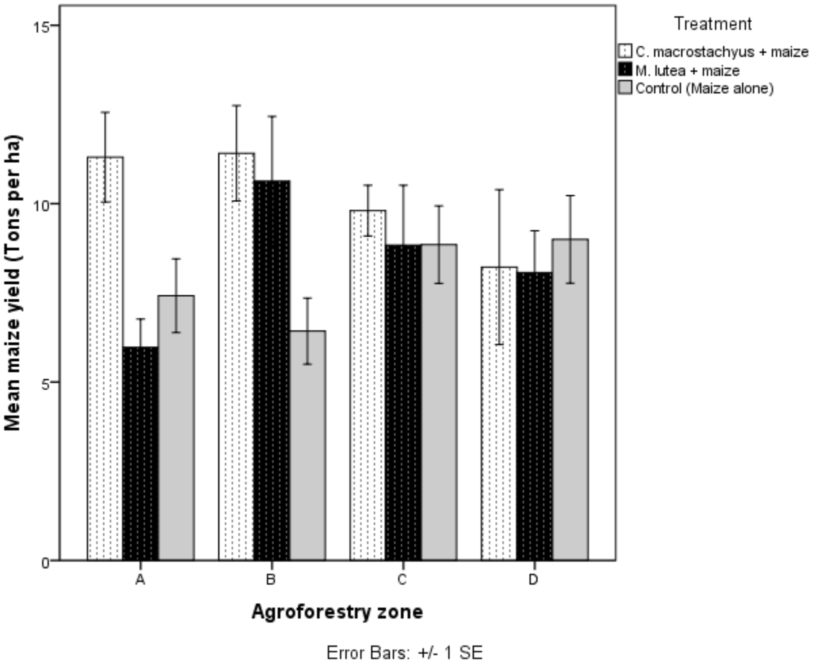

Figure 0.10: Average maize grain weight (tonnes per hectare) at four agroforestry zones (A, B, C and D) under *C. macrostachyus, M. lutea* and control treatments at an on-station experiment in Vi-agroforestry demonstration farm in Kitale. Zone A= 1m from the tree trunk; Zone B= half diameter of the tree crown; Zone C= the edge of tree crown; and Zone D= 3m outside edge of the crown.

4.5.2 Spatial effect of trees on maize performance at smallholders' farms

Spatial effect of agroforestry zones on maize performance, biomass and crop yield at on-farm. The height and basal diameter of maize growing under *Eucalyptus spp* and *G. robusta* recorded significantly greater height than maize growing outside the canopies by the third month of crop growth (Table 4.22). Under all tree species, the height of maize tended to be higher away from the tree canopy.

Table 0.27: Mean maize height (centimeters) at the first 90 days after planting under and outside tree canopies of six dominant tree species in Trans Nzoia County.

Measurements (cm)	Species	Tree influence	Time (days) after sowing			Average
			30	60	90	
Height	*Calliandra calothyrsus*	Under	58.6 ± 7.7	71.6 ± 8.8	177.1 ± 23.7	109.2 ± 13.0
		Away	62.7 ± 17.6	92.1 ± 21.0	204.8 ± 57.1	128 ± 28.3
		P-value	*0.727*	*0.275*	*0.827*	*0.533*
	Croton macrostachyus	Under	48.6 ± 5.7	110.8 ± 13.7	165.7 ± 11.2	112.7 ± 9.7
		Away	54.4 ± 12.0	116.7 ± 27.7	174.5 ± 21.3	119.5 ± 17.9
		p-value	*0.716*	*0.793*	*0.631*	*0.755*
	Eucalyptus spp	Under	51.5 ± 4.4	86.3 ± 14.1	160.0 ± 10.0	99.3 ± 9.0
		Away	56.7 ± 8.3	108.2 ± 32.8	201.8 ± 20.9	122.3 ± 20.2
		p-value	*0.541*	*0.541*	***0.089****	*0.275*
	Grevillea robusta	Under	45.6 ± 4.4	93.3 ± 15.1	186.5 ± 7.5	108.5 ± 10.5
		Away	54.5 ± 4.7	111.5 ± 34.7	214.8 ± 8.8	126.9 ± 20.9
		p-value	*0.150*	*0.694*	***0.032*****	*0.318*
	Markhamia lutea	Under	42.9 ± 4.2	108.2 ± 10.8	164.8 ± 8.9	105.3 ± 8.9
		Away	46.8 ± 7.9	117.8 ± 24.6	176.9 ± 20.6	113.0 ± 17.5
		p-value	*0.570*	*0.512*	*0.694*	*0.591*
	Sesbania sesban	Under	60.4 ± 6.4	123.3 ± 16.9	166.9 ± 19.1	120.9 ± 11.2
		Away	71.5 ± 5.1	139.3 ± 26.3	178.6 ± 31.4	133.9 ± 18.1
		p-value	*0.467*	*0.513*	*0.827*	*0.472*

P-value obtained through Mann-Whitney U test. Bold values indicate significant effects at *p<0.1, **p<0.05.

The overall maize height under the six dominant tree species showed significantly reduced maize height at zone A under *Eucalyptus spp* compared to other tree species (Figure 4.11). Maize height was highest under *M. lutea* followed by *C. calothyrsus* at zone A. At zone B, height of maize under *Eucalyptus spp* and *C. macrostachyus* were significantly lower than the height recorded under *C. calothyrsus*, *G. robusta* and *M. lutea*. Average maize height under *C. macrostachyus* at zone B was lower than the height recorded from zone D. Under *Eucalyptus spp*, the height at zone A was significantly lower than those in subsequent agroforestry zones (B, C and D). Under *M. lutea*, maize height at zone A, B and C, was significantly lower than that recorded in zone D.

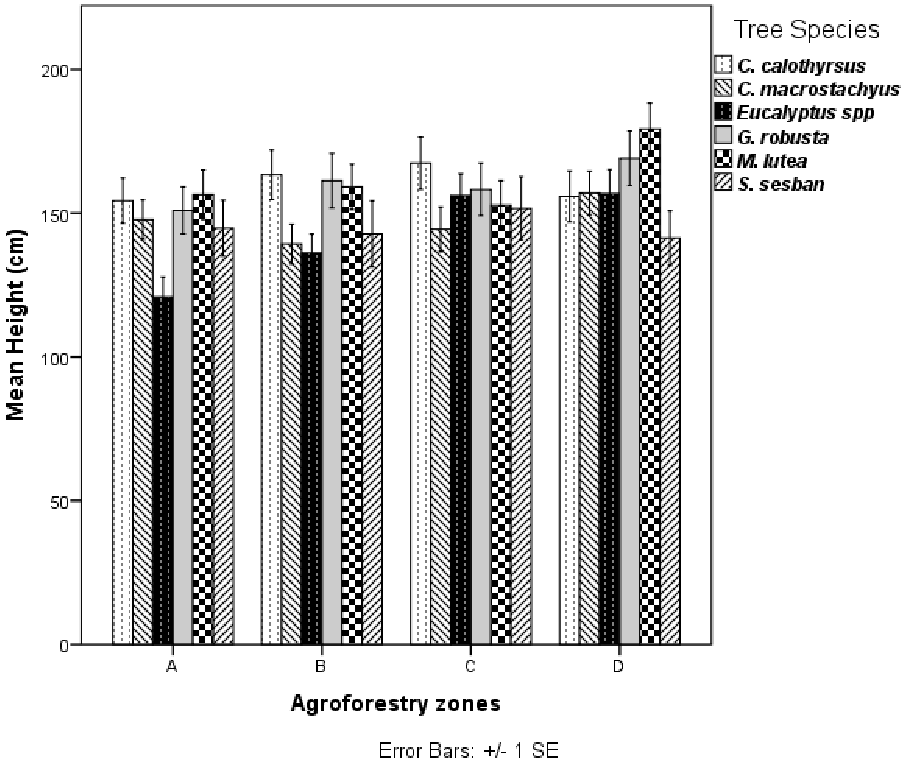

Figure 0.11: Average maize height in centimeters at the four agroforestry zones (A, B, C and D) under the six dominant tree species in smallholder maize farms (on-farm) in Trans Nzoia County. Zone A= 1m from the tree trunk; Zone B= half diameter of the tree crown; Zone C= the edge of tree crown; and Zone D= 3m outside edge of the crown.

The amount of grain weight measured under the dominant tree species showed significant differences (asymptotic significance of $P < 0.001$) between various tree species with highest amount recorded under *C. calothyrsus* with a value of 10.1 tons ha^{-1} (Figure 4.12). The second highest amount of grain weight was recorded under *S. sesban* and lowest amount under *G. robusta* with an average of 7.9 and 3.6 tons ha^{-1} respectively.

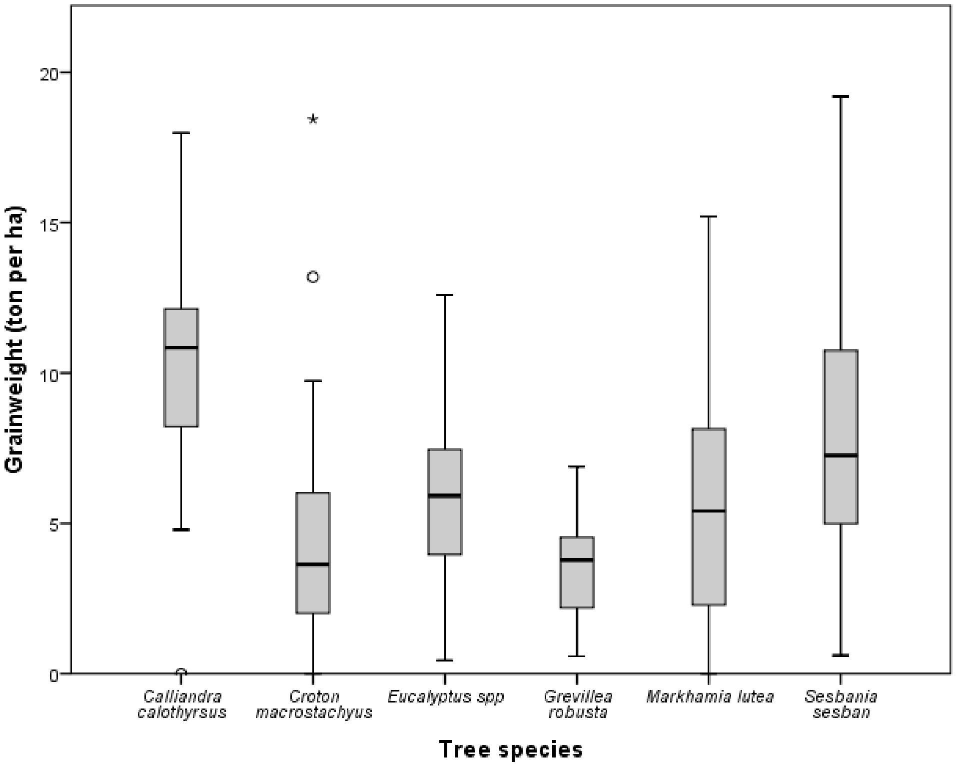

Figure 0.12: Box plots showing distribution of maize grain weights in tonnes per hectare under dominant tree species within smallholder farms in Trans-Nzoia County in 2013 cropping season.

Maize grain weight measured from different agroforestry zones in smallholder farms in Trans Nzoia county recorded significant difference under *C. macrostachyus* and *S. sesban* only (Figure 4.13). The lowest amount of grain yield (1.7 tons ha^{-1}) was recorded in zone A under *C. macrostachyus* with a pattern of increased crop yield observed with an increase in distance away from the tree trunk whereby zone C recorded yield of 5.9 tons ha^{-1}. Under *S. sesban,* significance difference in maize grain yield was recorded between zone B and C and no specific pattern of crop yield was observed between zones.

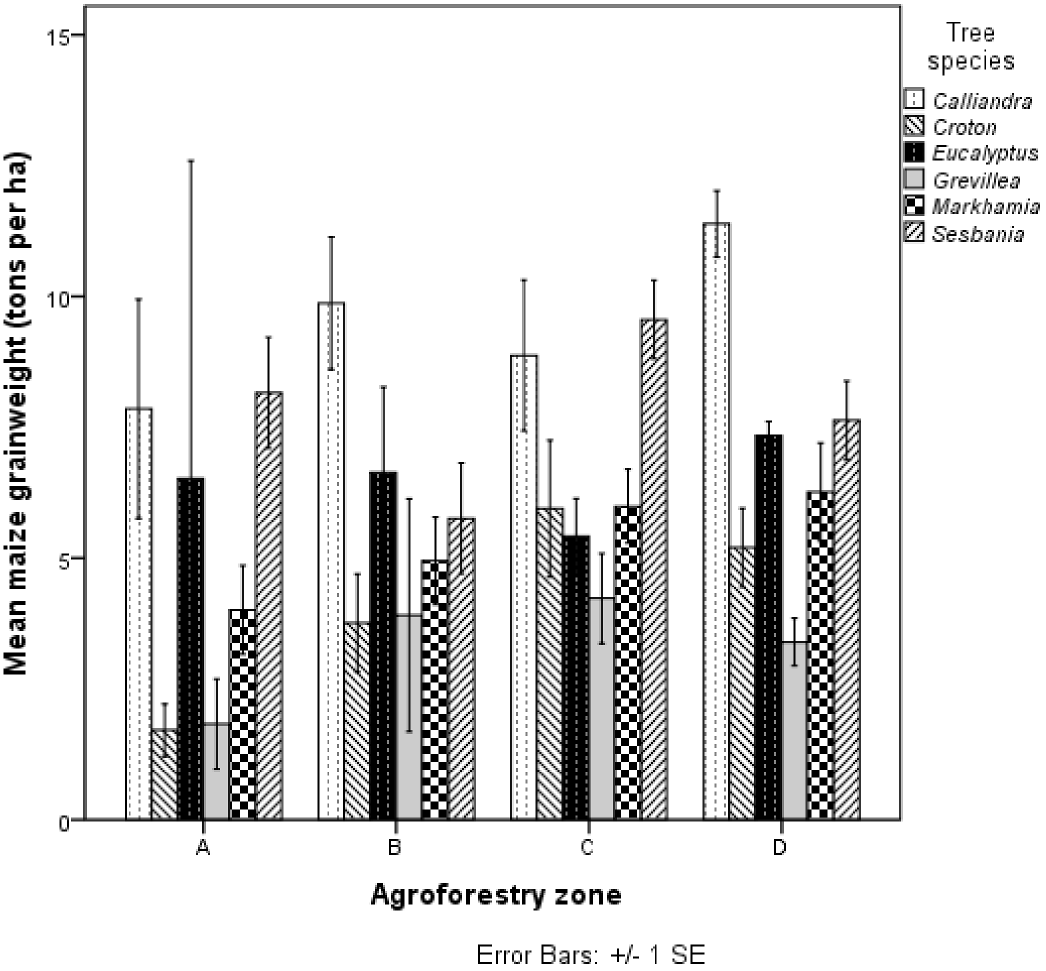

Figure 0.13: Average maize grain yield in tonnes per hectare under the six dominant tree species at the four agroforestry zones (A, B, C and D) in smallholder maize farms in Trans-Nzoia County. Zone A= 1m from the tree trunk; Zone B= half diameter of the tree crown; Zone C= the edge of tree crown; and Zone D= 3m outside edge of the crown.

4.6 Modelling possible maize-based agroforestry scenarios using selected dominant tree species

4.6.1 Tree growth

Tree species (*C. macrostachyus, G. robusta* and *M. lutea*) growth was simulated for a period of 10 years and compared with observed tree parameters from the field. Simulation done with annual tree pruning after 5 years was shown to more accurately predict tree parameters in the field (Figure 4.14). Annual tree pruning is common before onset of cropping season in the study area. Growth of *C. macrostachyus* was shown to be greatest followed by *G. robusta*.

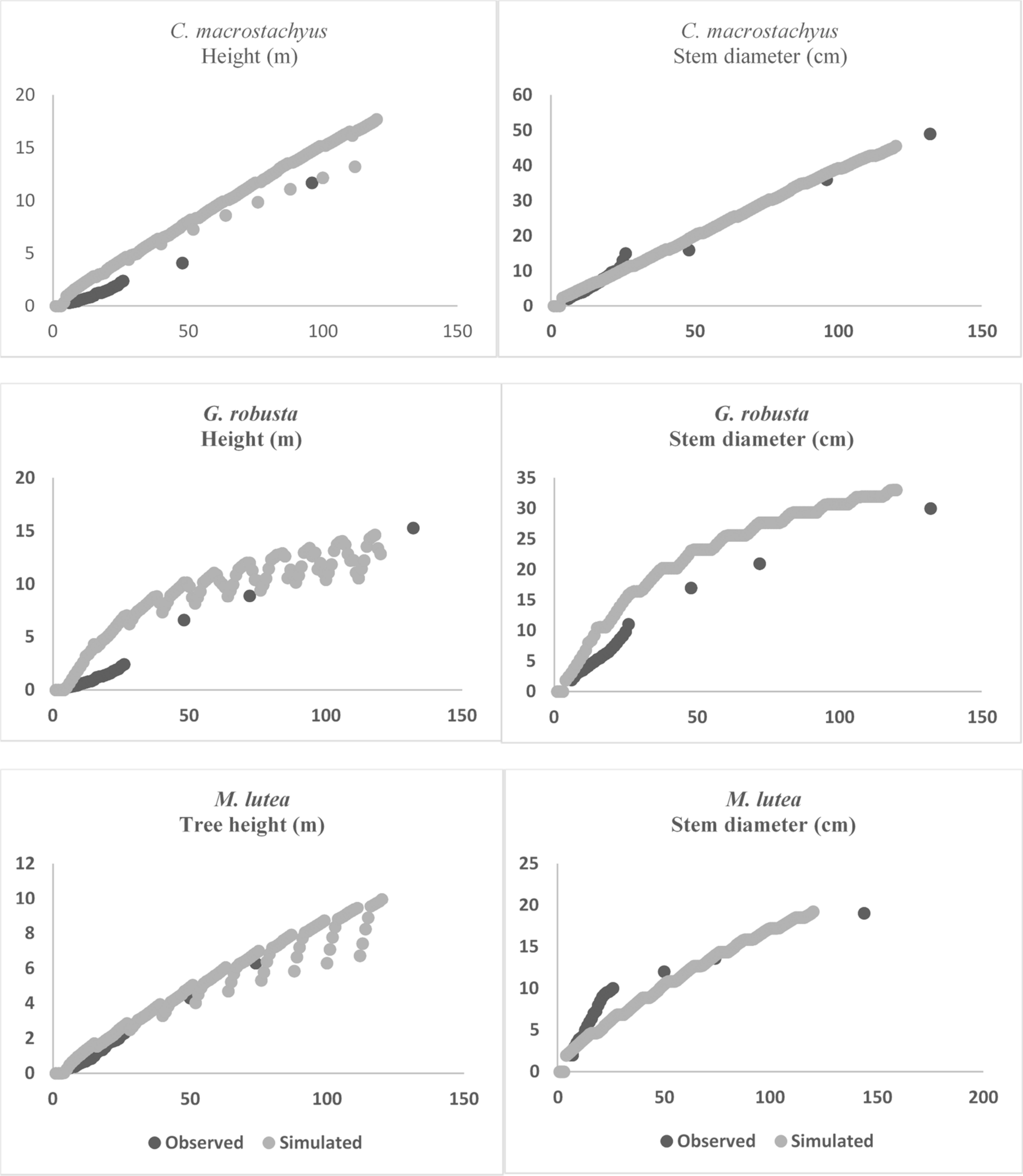

Figure 0.14: Comparison between simulated (10 years) and observed tree height and stem diameter for *C. macrostachyus*, *G. robusta* and *M. lutea* in Trans-Nzoia County. X-axis represent time in months while Y-axis represents tree height or tree stem diameter.

4.6.2 Crop growth

Crop biomass at the three agroforestry zones (Zone B, Zone C and Zone D) under each of the tree species (*C. macrostachyus, G. robusta* and *M. lutea*) were simulated for a period of 10 years. At Zone B, the highest crop biomass production was under monocrop scenario (Figure 4.15). This is the zone under root and light competition and thus under tree-crop intercrop scenario increased competition for growth resources is expected which in return reduce crop biomass. Increased tree density per hectare also reduced the crop biomass under *C. macrostachyus* and *M. lutea*. Under *G. robusta* the crop biomass at Zone B increased with an increase in tree density up to 400 trees ha^{-1} but reduced with subsequent increase in tree density. Significant difference in crop biomass production was recorded between monocrop and intercrop. Biomass production under *G. robusta* was also significantly lower than the amount recorded under *C. macrostachyus* and *M. lutea*.

At Zone C, similar observations as those made under Zone B were made (Figure 4.16). Significant difference between monocrop and intercrop scenarios was also observed but biomass production between species did not register significance difference as observed at Zone A. At Zone D, the crop biomass remained unchanged with an increase with tree density under all tree species (Figure 4.17). This was expected observation as Zone D represent zone away from tree influence.

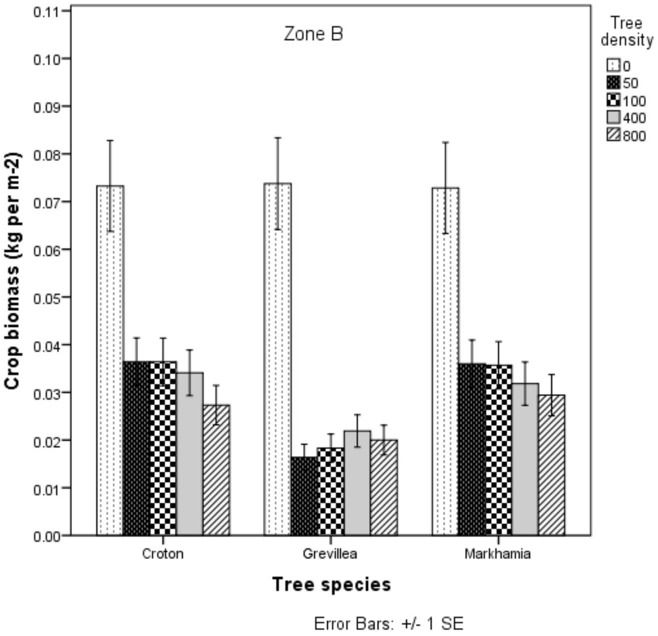

Figure 0.15: Simulated values of crop biomass at Zone B under *C. macrostachyus*, *G. robusta* and *M. lutea* in a ten-year simulation involving different mono-cropping (zero density) and increasing tree densities at 50, 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

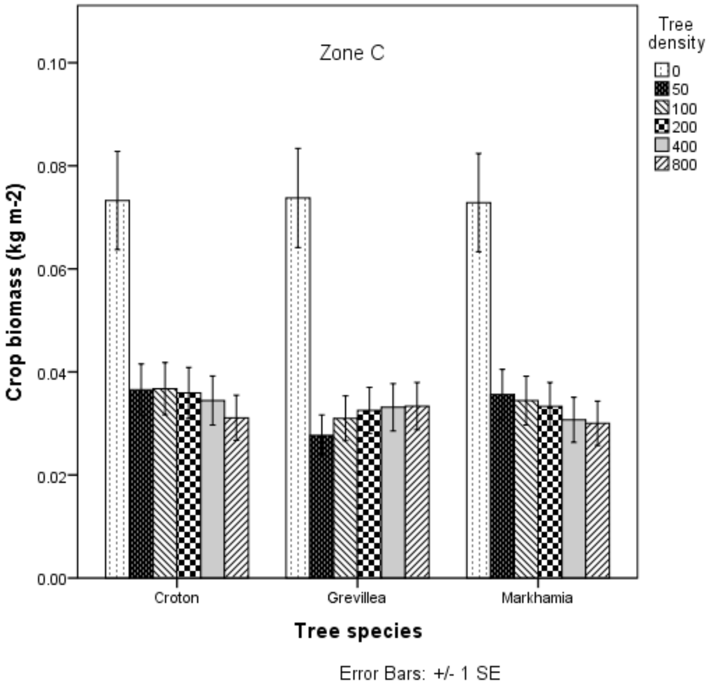

Figure 0.16: Simulated values of crop biomass at Zone C under *C. macrostachyus, G. robusta* and *M. lutea* in a ten-year simulation involving different mono-cropping (zero density) and increasing tree densities at 50, 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

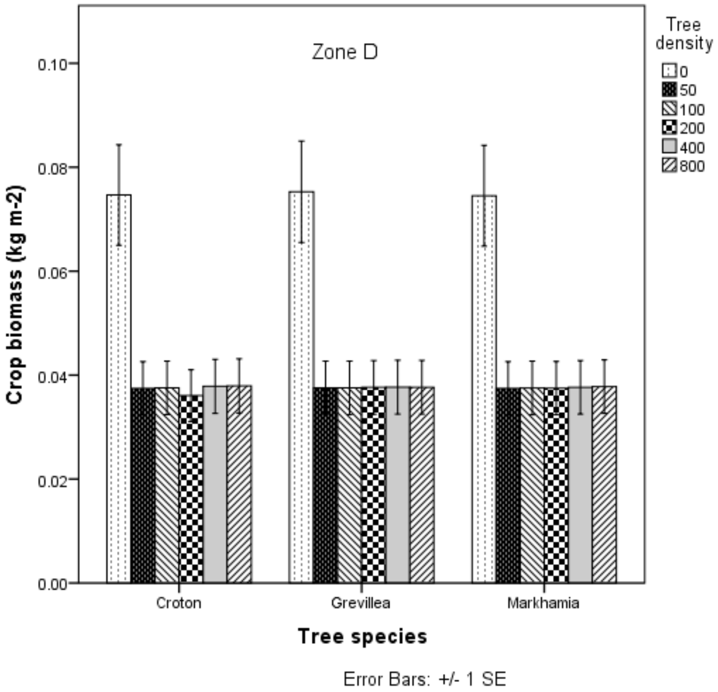

Figure 0.17: Simulated values of crop biomass at Zone D under *C. macrostachyus, G. robusta* and *M. lutea* in a ten-year simulation involving different mono-cropping (zero density) and increasing tree densities at 50, 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

4.6.3 Nutrient balance

Nitrogen and phosphorus, (N and P) under each of agroforestry zones were analyzed for the three species and under different tree planting densities. Under *C. macrostachyus,* the amount of N stock (inorganic N in the soil) at each agroforestry zone increased with increase in distance from the tree trunk (Figure 4.18). At zone A, the amount of N stock diminishes under all intercrop scenarios. A significant difference in amount of N stock in the soil at Zone B was recorded compared to Zone C.

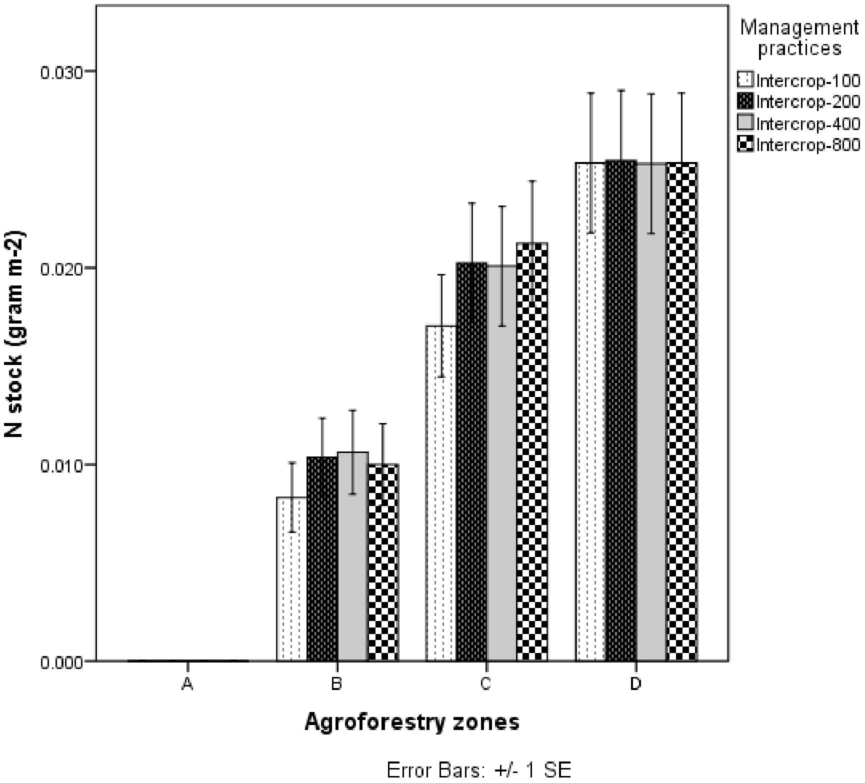

Figure 0.18: Simulated values of nitrogen (N) stock at different agroforestry zones under *C. macrostachyus* in a ten-year simulation involving different tree densities of 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

Under *C. macrostachyus,* P stock in the soil recorded significant difference between agroforestry zones (Figure 4.19). Zone A recorded significantly lower soil P balances in the soil compared to Zone B, C and D. Similar pattern of P stock (inorganic P in the soil) was observed as that of N stock in the soil.

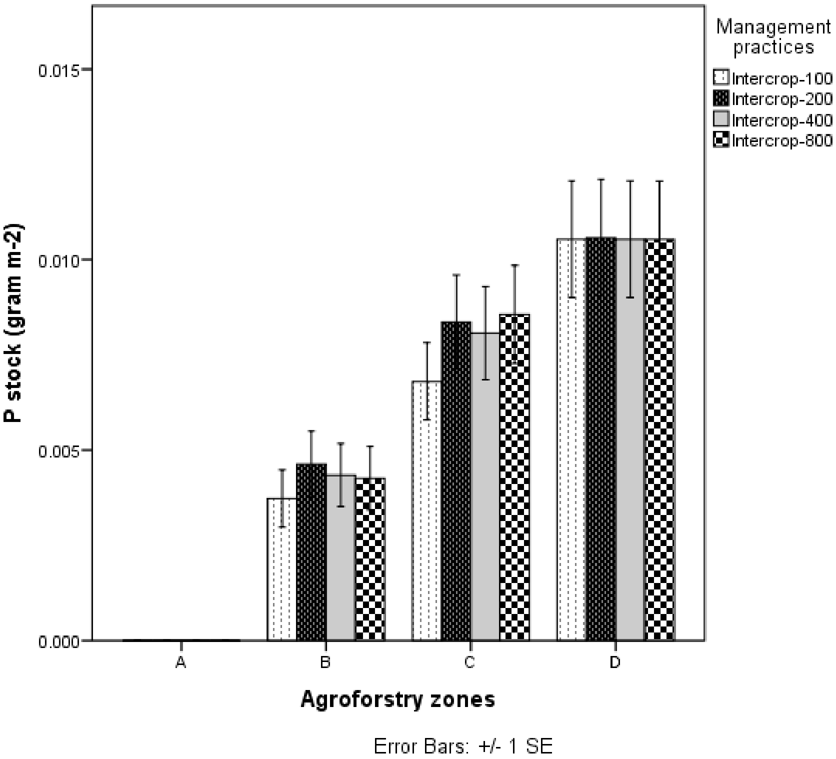

Figure 0.19: Simulated values of phosphorus (P) stock at different agroforestry zones under *C. macrostachyus* in a ten-year simulation involving different tree densities of 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

The amount on N uptake by crop under the tree showed a pattern of decreasing with an increase in tree density at Zone B (Figure 4.20). At Zone C, N uptake by crop decreased with an increase in tree density up to 400 trees ha^{-1} but the pattern was not observed at 800 trees ha^{-1}.

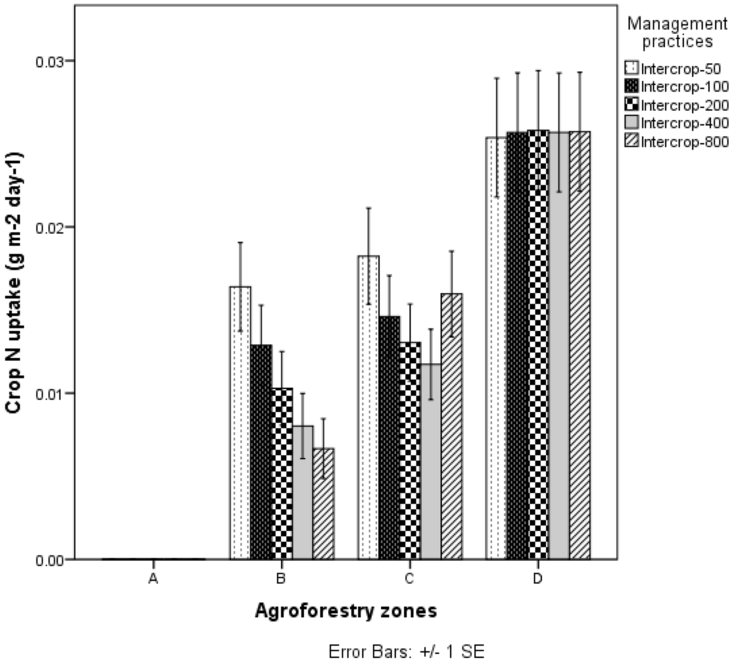

Figure 0.20: Simulated values of crop nitrogen (N) uptake at different agroforestry zones under *C. macrostachyus* in a ten-year simulation involving different tree densities of 50, 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

Similar observation to those of N crop uptake was made in crop P uptake under the tree (Figure 4.21)

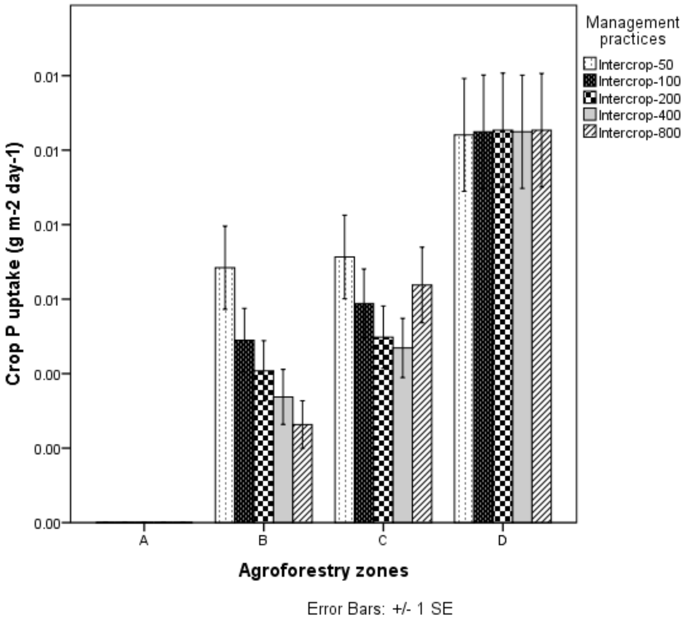

Figure 0.21: Simulated values of crop phosphorus (P) uptake at different agroforestry zones under *C. macrostachyus* in a ten-year simulation involving different tree densities of 50, 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

Similar observations to those under *C. macrostachyus* on N stock in the soil was made under *G. robusta* (Figure 4.22). A significant difference in amount of soil N was recorded between agroforestry zones with the amount reducing with a decrease in distance from tree trunk.

The amount of soil P under the tree was also found to be significantly different between the zones with highest amount recorded away from the tree (Figure 4.23).

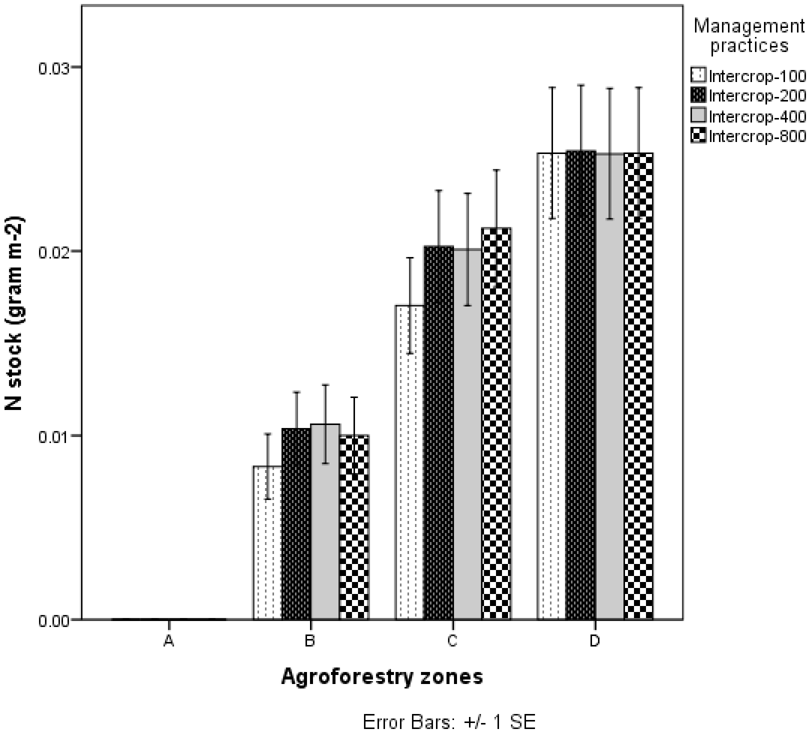

Figure 0.22: Simulated values of nitrogen (N) stock at different agroforestry zones under *G. robusta* in a ten-year simulation involving different tree densities of 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

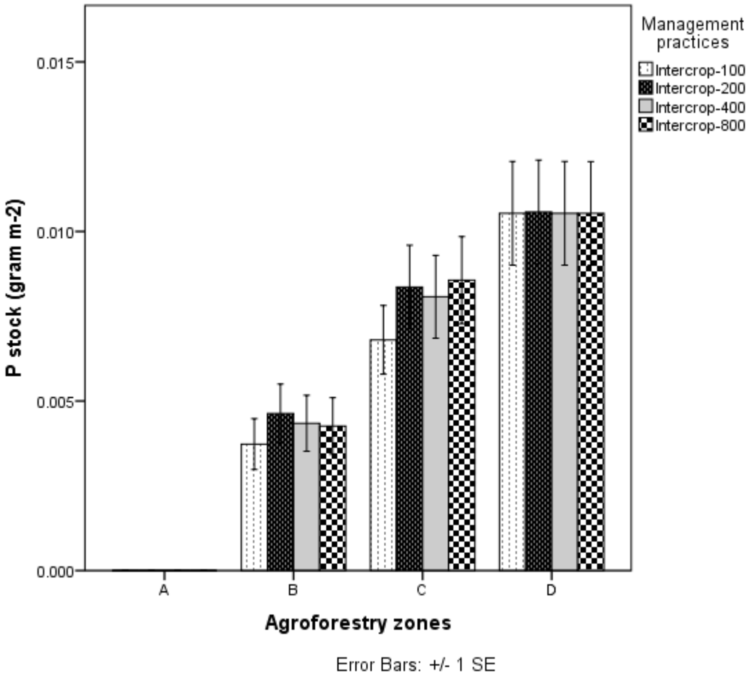

Figure 0.23: Simulated values of phosphorus (P) stock at different agroforestry zones under *G. robusta* in a ten-year simulation involving different tree densities of 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

N crop uptake under *G. robusta* showed a pattern of increase with an increase in tree density at Zone B and C (Figure 4.24).

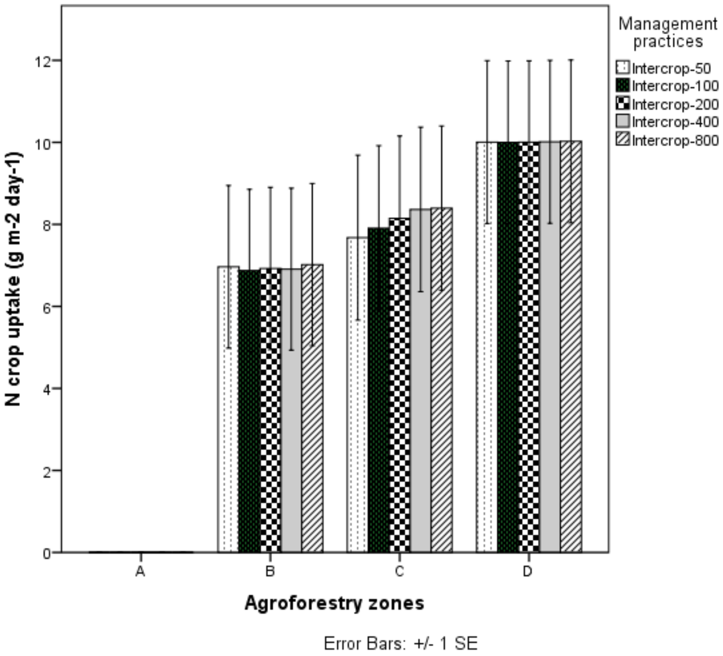

Figure 0.24: Simulated values of crop nitrogen (N) uptake at different agroforestry zones under *G. robusta* in a ten-year simulation involving different tree densities of 50, 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

Crop P uptake at Zone B showed a decreasing pattern with an increase in tree density for up to 400 trees ha^{-1} (Figure 4.25). Zone C and D did not record any pattern with increasing tree density.

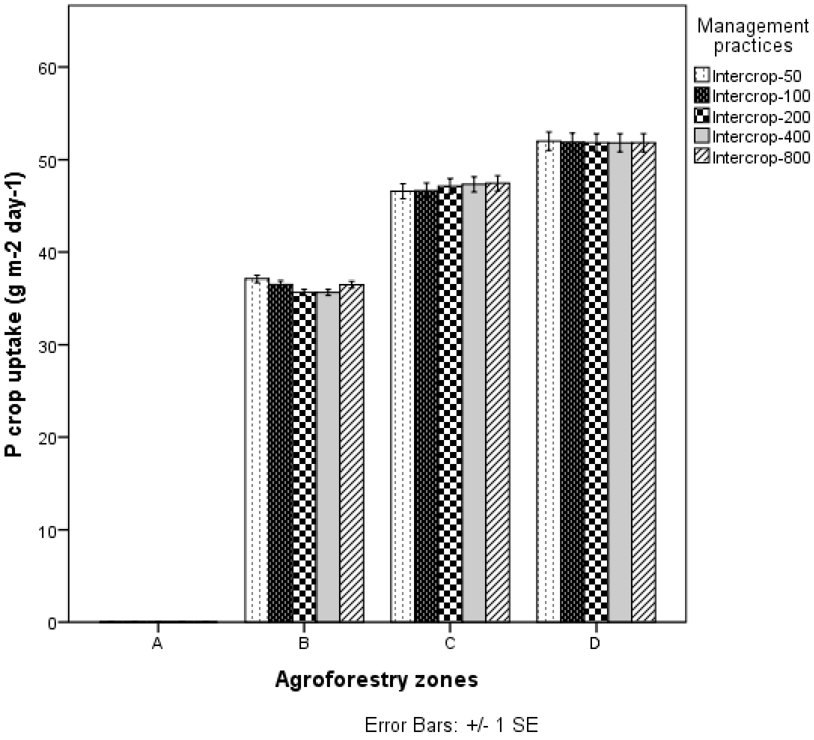

Figure 0.25: Simulated values of crop phosphorus (P) uptake at different agroforestry zones under G. robusta in a ten-year simulation involving different tree densities of 50, 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

N stock under *M. lutea* at zone A, B and C recorded significant reduction compared to Zone D (Figure 4.26). At zone A, B and C, a pattern of reduced N stock with an increase in tree density was observed. Zone A also recorded significant amount of N stock compared to *C. macrostachyus* and *G. robusta.*

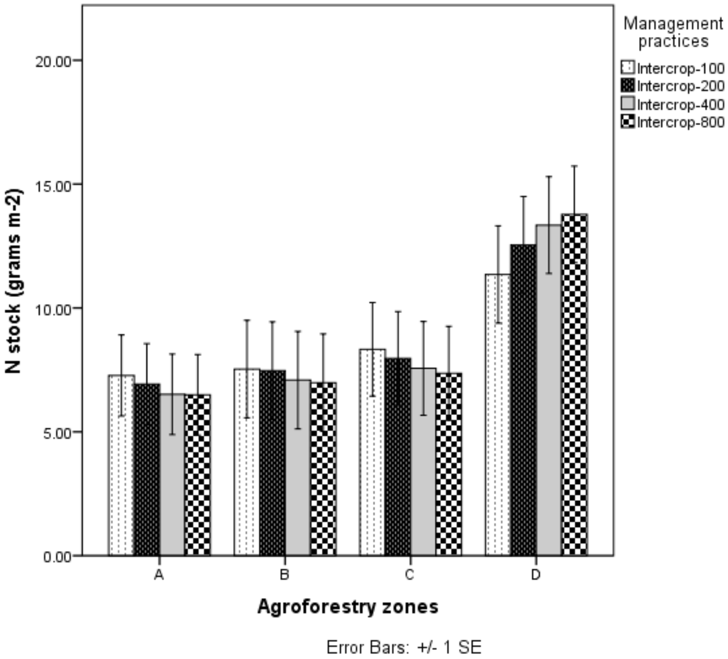

Figure 0.26: Simulated values of nitrogen (N) stock at different agroforestry zones under *M. lutea* in a ten-year simulation involving different tree densities of 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

P stock under *M. lutea* significantly increased at Zone A and D with an increase in tree density while a reduction was recorded at Zone C and B (Figure 4.27).

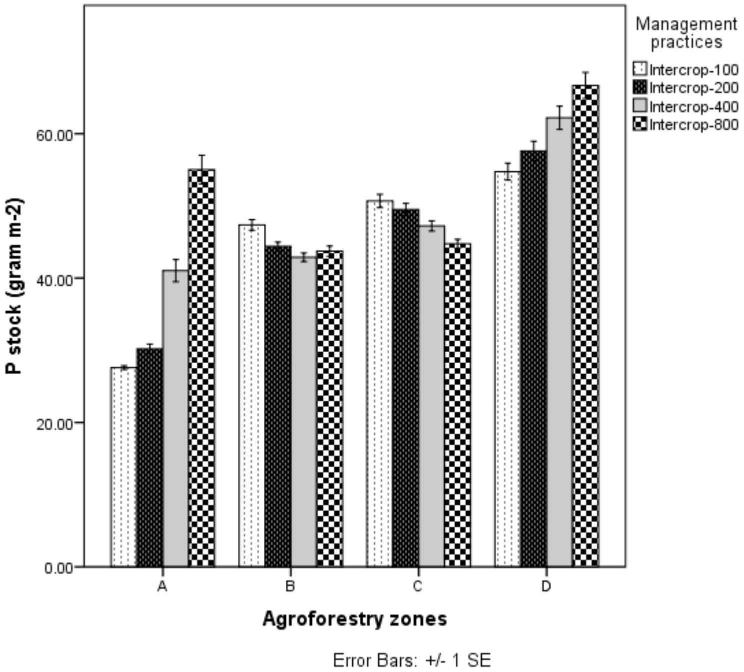

Figure 0.27: Simulated values of phosphorus (P) stock at different agroforestry zones under *M. lutea* in a ten-year simulation involving different tree densities of 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

N uptake by crop under *M. lutea* recorded a reducing pattern with an increase in tree density at Zone B and C (Figure 4.28). A similar observation was made with P uptake under the two zones (Figure 4.29).

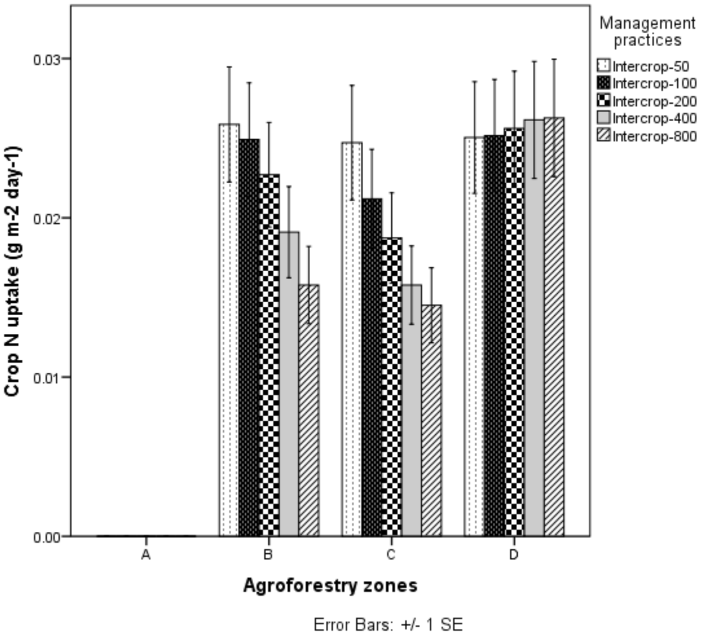

Figure 0.28: Simulated values of crop nitrogen (N) uptake at different agroforestry zones under *M. lutea in* a ten-year simulation involving different tree densities of 50, 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

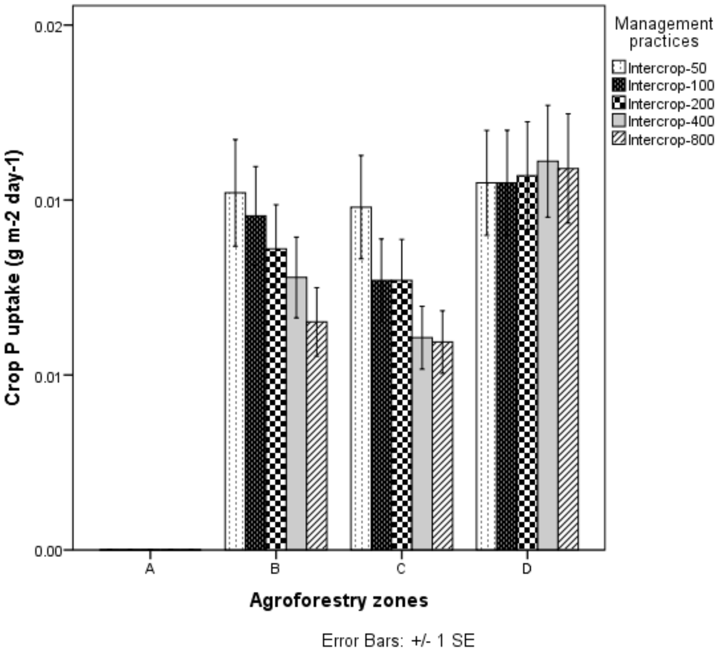

Figure 0.29: Simulated values of crop phosphorus (P) uptake at different agroforestry zones under *M. lutea* in a ten-year simulation involving different tree densities of 50, 100, 200, 400 and 800 trees ha^{-1} at Trans-Nzoia County.

4.6.4 Soil water balance

The components of water balance, soil evaporation, rainfall interception, drainage, runoff and water uptake by the trees and crops were obtained from 10 years simulations using the three species (*C. macrostachyus*, *G. robusta* and *M. lutea*) (Figure 4.30). The simulations suggest that a substantial proportion of water balance was attributable to soil evaporation and drainage. Also, the amount attributable to interception losses was also higher for *G. robusta*. Water losses attributable to drainage and runoff was significantly higher under *G. robusta* compared to rest of species. Water loss through evaporation was highest under *M. lutea*. Water uptake by crop was highest under *M. lutea* while tree water uptake was highest under *C. macrostachyus* followed by *G. robusta* and *M. lutea* respectively.

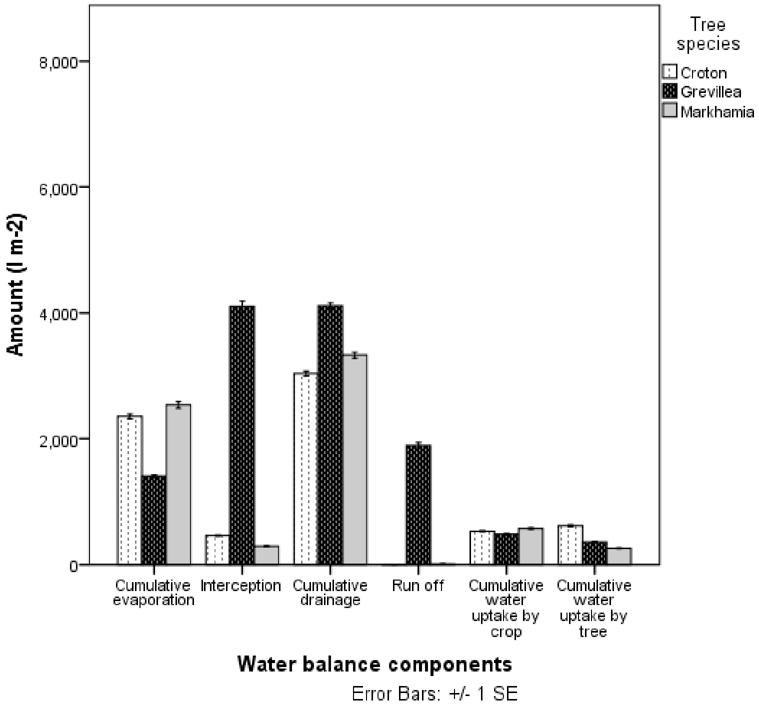

Figure 0.30: Values of water balance under *C. macrostachyus, G. robusta* and *M. lutea* in a ten-year simulation involving smallholder agroforestry systems at Trans-Nzoia County.

4.7 Agroforestry practices and factors influencing agroforestry adoption within smallholder farms

4.7.1 Agroforestry practices in smallholder farms

Small-scale farmers in the studied settlements invested in trees and gradually contributed to transform monoculture systems into multi-use diversified systems. Overall, the 10 most abundant species accounts for 94% of available trees in the farms. This high percentage can be explained by the historical elimination of natural vegetation during large-scale farming and currently, the landscape is dominated by those species preferred by smallholder farmers. The small abundances of indigenous species could indicate that genetic diversity and population sizes could be too low to be sustained within the agroecosystems if their abundance is not increased (Atta-Krah et al., 2004). Soini (2007) reported that firewood is a major motivation for tree planting in Trans-Nzoia County and this explains the high demand and planting of readily available seedlings of *Eucalyptus* spp, *Sesbania* spp and *G. robusta*. Also, dwindling returns caused by market induced changes in maize production, which has been the major source of income in Trans-Nzoia, have also accelerated the preference of farmers towards fast growing exotics**.** In Kenya, *Eucalyptus* was introduced in 1902 to provide fuelwood for the Kenya-Uganda railway. Currently, *Eucalyptus* are used for fuelwood, timber, plywood, electricity transmission poles, pulp, building materials, fencing posts and windbreaks. A ready market for *Eucalyptus* products has motivated farmers to grow the species to improve their livelihoods through increased income (Oballa et al., 2010). The two *Eucalyptus* species planted in Trans-Nzoia include *E. grandis* and *E. saligna.*

The smallholder farms in the study area have low species richness compared to other areas in Kenya. While in Kenyan natural forests tree diversity can reach as much as 280 species (Mutangah, et al., 1993), tree diversity in agricultural landscapes is often considerably reduced. For example, Carsan (2012) recorded 165 tree species on smallholder coffee farms in Central Kenya with mean species richness of 17 species per farm. Kehlenbeck et al. (2011) found a mean tree species richness of 17 per farm and Lengkeek et al. (2005) observed a mean of 54 species per farm. The species richness of 44 we found in our study area and a mean of 8 tree species per farm are therefore relatively low compared to other studies in agricultural landscapes of Kenya. The low species count in Trans-Nzoia County can be attributed to first, the limited time since land use conversion from large-scale to small-scale crop farming took place. The current owners initiated tree planting in the area about 23 years ago within the period after the subdivision of large-scale to small-scale farms. Secondly, there is lack of connectivity of the current farms to natural forests which suggests loss of indigenous plant populations. Lastly, low diversity can be the result of planting only the dominant species based on the farmers' preference which may be guided by availability of planting material, time to maturity, economic value attached to the tree among other factors. For instance, while the presence of indigenous species on-farm account for 55% of the recorded species, their frequency of distribution is low representing 27% of all tree counts. Only *Sesbania* spp, *M. lutea* and *C. macrostachyus* are ranked among the 10 most abundant tree species in the farms studied. This observation is consistent to results obtained from western and central Kenya (Lengkeek et al., 2005; Kindt et al., 2006; Kehlenbeck et al., 2011) whereby exotic species had tree count compared to indigenous species but lower species count. The existence of high abundance of exotics demonstrates deliberate planting and choice (Simons and Leakey, 2004).

Despite the high abundance of *Eucalyptus* spp and *C. lusitanica* in the agricultural landscape, farmers usually establish them as woodlots to maintain the benefit and minimize negative interaction with crops. This indicates knowledge about trees that is locally derived through observation and experience and can be referred as local knowledge (Sinclair and Joshi, 2000; Smith et al., 2014). The establishment of woodlots in croplands is also an effort by farmers to respond to the high demand for wood (WRI, 2007).

Homestead areas, remain important locations for the preferential establishment of fruit trees. The reason for this practice is largely to allow farmers to protect these valuable trees to maturity as well as protecting the fruits from theft once they mature. Furthermore, preference for homestead planting of fruit trees can also be because soils are generally richer than fields away from home. This is supported by previous studies in sub-Saharan Africa by Tittonell et al. (2005) and Zingore et al. (2007) which identified soil fertility gradients within farms and where homesteads have more favorable growing conditions. Farmers also establish fruit trees in locations where they can nurture them when young by watering (Bucagu et al., 2012). The preference to plant fruit trees near the homes clearly indicates the value attached to fruit trees in the study area.

Fuel and timber are the major products and largely the reason for tree planting in the study area. About 89 % of rural Kenya relies on firewood for their energy needs and about 84

% of firewood supplies come from agroforestry systems and on-farm sources (WRI, 2007). The reliance on tree for fuel and timber is also common among other sub-Saharan African countries like Ethiopia (Assefa and RudolfBork, 2014). Timber is utilized for construction purposes or as a source of income through direct sales. As earlier observed by Scherr (1995) in western Kenya, farmers consider tree planting as a way of increasing the value of assets in their farms and this also explains the high number of timber trees.

Integration of nitrogen fixing species in the farming system was found to be common with utilization of *Sesbania* spp and *C. calothyrsus* species. The practice has been recognised as important in increasing biomass production in the farming system with richer sources of organically bound nutrients to complement inorganic fertilizer used by smallholder farmers (Barrios et al., 1997; Barrios and Cobo, 2004; Garrity et al., 2010). *C. calothyrsus* was commonly found as hedgerows in crop fields while *Sesbania* spp was predominantly dispersed/ intercropped in crop fields as an improved fallow species. *C. calothyrsus* and *Sesbania* spp are also common fodder tree species. The use of trees and shrubs for fodder was introduced in the late 1980’s in Southern Africa and East African highlands as a low-cost technology, relatively easy to use, effective in raising milk yields and available for use as a substitute for expensive dairy feed concentrates (Kwesiga et al., 2003; Pye-Smith, 2010; Franzel et al., 2014).

4.7.2 Effects of household resource endowment on agroforestry practices in smallholder farms

Households with low resource endowment were found to integrate more fruit trees as well as more tree species in their farms to supplement their income and family nutrition. This contrasts with the notion that poorer farmers are the main reason behind tree cover loss (Fisher, 2010). Many smallholder farmers in Sub-Saharan Africa practice agroforestry which has been shown to provide many livelihood benefits such as; improving the asset base of poor households with farm-grown trees, enhancing soil fertility and livestock productivity on farms and also linking poor households to markets for high-value fruits, oils, cash crops and medicines among other benefits (Mbow et al., 2014). Furthermore, the study highlights the importance of low resource endowed farmers in climate change mitigation efforts whereby by adopting agroforestry and planting more tree species, they also contribute to store carbon in the soil and in the woody biomass and may also reduce soil greenhouse gas emissions.

Households with high resource endowment showed a positive relationship with number of trees growing in the homestead. This can be explained by farm size which was larger among the farmers in the high household resource endowment category, and resulted in larger homesteads which allowed the establishment of a greater number of trees. Farmers in the low resource endowment category, however, were found to integrate more tree species into their farms. Diversification is a well-recognized strategy for managing risks in highly uncertain economic environments which suggests that farmers plant several species for the same use to reduce risks of losing a valuable tree benefit and meet a range of site and management conditions (Scherr, 1995; Jerneck and Olsson, 2013).

The negative relationship found between the high resource endowment category and the abundance of fruit trees on-farm could indicate that resource endowed households prefer to purchase this product rather than to produce it themselves as highlighted by Kindt et al. (2006). Conversely, planting and maintaining fruit trees could also represent a survival mechanism among the low resource endowed households to ensure the supply of nutritious products that are too expensive to be purchased. This observation is supported by the significantly high number of *P. americana* trees recorded in low resource endowed households in the study area and is also consistent with findings from a study in Haiti by Bannister and Nair (2003).

4.7.3 Effects of land tenure on agroforestry practices in smallholder farms

Households with secure land tenure were found to increase the number of trees growing at their homesteads, as well as the number of *C. lusitanica* and *C. macrostachyus* in the farms. This is consistent with the notion that where individualized rights are established on agricultural land, farmers invest in longer-term improvements such as tree planting (Otsuka and Place, 2014; Holden and Otsuka, 2014; Deininger et al., 2011). Where land holdings are insecure, farmers are often reluctant to invest in the long-term endeavor of establishing trees that may benefit the next owner of their land rather than themselves (Mbow et al., 2014). This is also consistent with studies in Ghana (Besley, 1995), Ethiopia

(Deninger et al., 2003) and Uganda (Petracco, 2009) largely reporting higher investments into smallholders farming with tenure security. *C. lusitanica* and *C. macrostachyus* are also slow growing trees and thus linked to more stable forms of tenure.

Species richness increased in farms without secure tenure despite a decrease in the number of representatives of each species. As explained by Scherr (1995), diversification as a strategy for managing risk of losing a valuable tree benefit may have influenced farmers to adopt fast growing multipurpose trees to address fodder, soil fertility and firewood demands. This notion is supported by our results as fodder/fertilizer tree species, largely *C. calothyrsus and Sesbania* spp, were lower in number where farmers own the land and higher where farmers lack tenure. In addition, farmers gain local recognition of their ownership by planting trees whether they have legal document or not showing they own the land (Baland et al., 1999). The increased fragmentation of farms with time and the frequent establishment of live fences partly explain the increased number of trees in the studied farms and agricultural landscapes (Harvey et al., 2005). While it is commonly thought that owning land would lead farmers to managing farms better through the adoption of trees, there are also studies reporting neutral or negative impacts of trees (Clay et al., 1998; Neil and Lee, 1999). Nevertheless, this could simply be a result of using the wrong tree species in the wrong context and lack or limited diversity of tree interventions as highlighted by Coe et al. (2014).

4.7.4 Effects of time under current management on agroforestry practices in smallholder farms

Finding greater number of trees in both homesteads and crop fields in farms with greater time under current management could be explained by the observed co-occurring trend of increasing farm size which allowed greater area for establishing trees compared to other time interval categories. Nevertheless, our results also showed that the number of tree species count per hectare was greatest amongst farms in the short-term category. This finding could be interpreted as an indication of high farmer reliance on benefits provided by trees to support their livelihoods particularly early in the process of conversion from monoculture to multi-use diversified systems. During literature review we found no references considering the effect of time under current management on agroforestry adoption and practices and this limited a comparative analysis.

The finding that *P. guajava* and *E. japonica* were more common among farms with more than 15 years under current management could be explained by a change in farmer demand in recent years. This could be a result, for example, of difficulties to find planting material of good quality, lack of proper maintenance of these trees by farmers and/or diminishing importance usually attached to the two species. On the other hand, while timber trees were not predicted by time under current management, newly established farms had a higher number of *G. robusta* and *C. lusitanica* than older farms. Thus, the planting of these two species is a relatively new phenomenon in the area. As explained by Bannister and Nair (2003), agroforestry practices evolve over time as farmers experience increases and matures, and characteristics of their fields change. The change in tree composition observed with time under current management demonstrates farmer's preference and an increased reliance on trees as sources of income from traditional maize farming.

4.8 Water and nutrient availability under dominant agroforestry trees within smallholder farms

4.8.1 Spatial distribution of soil nutrients in the area of influence under dominant tree species

The litter turnover from agroforestry trees in tropical agroecosystems is important in determining nutrient supply. Residue quality and environmental conditions regulate the rate and extent of decomposition of organic materials by soil organisms (Trinsoutrot et al., 2000; Cobo et al., 2002). Thus, higher residue N and P contents enhance decomposition (Mafongoya et al., 2000) while C, lignin and polyphenol contents reduce decomposition rates (Palm and Sanchez, 1991) thus the lower the (lignin + polyphenols) / N ratio, the higher the turnover rate of plant residues (Mafongoya et al., 1998; Hadas et al., 2004). Both *S. sesban* (leguminous) and *C. macrostachyus* (non-leguminous) were shown to have highest turnover rate of plant residues compared to the rest of dominant tree species while *Eucalyptus spp* (non-leguminous) and *G. robusta* (non-leguminous) recorded lowest turnover rate.

Trees contribute to the flow of macro- and micro-nutrients in agricultural landscapes. Agroforestry zones recorded significant difference in amount of soil pH and Mg under *S.*

sesban. This is evidence to significant contribution of tree residue contribution to soil pH and Mg under the tree. The (lignin + polyphenols) / N ratio was also lowest under the tree compared to other species which is indicative of higher turnover rate of plant residues. The nutrient concentrations decreased with distance from tree stems and with soil depth, a pattern caused by nutrient accumulation from litter fall below and high rate of residue decomposition around *S. sesban* canopy. In parklands, greater concentrations of SOC (soil organic carbon), SOM (soil organic matter) and nutrients such as N, P, and K beneath tree canopies than on open ground between trees has previously been reported (Boffa et al., 2000; Bayala et al., 2002).

The amount of Total C, Total N, ExBas, Ca, K, PSI and available P in the soil decreased with an increase in depth of soil layer under all dominant tree species, this indicates direct inputs of soil nutrients under the tree from the residues. This is an expected observation given the pattern caused by nutrients accumulation from litter fall below and agrees with other studies by Kho et al. (2001) and Dick et al. (2006). Certain tree species increase nutrient cycling by retrieving sub-soil inorganic N and P from deep soils and cycling these to crops through decomposing biomass (Aweto and Iyanda, 2003; Gindaba et al., 2005). Trees improve soil fertility in cultivated land by increasing nutrient inputs from organic matter via litter fall, root decay and biological N fixation (Barrios et al., 1997; Aihou et al., 1999; Ganunga et al., 2005; Akinnifesi et al., 2006). Other trees reduce loss of nutrients by reducing soil erosion (Angima et al., 2002; Kinama et al., 2007) and improving soil physical properties (Mlambo et al., 2005). Specifically, legumes in alleys and fallows frequently increase SOM, SOC, inorganic-N, K, plant-available P, exchangeable bases

(Ca, K, Mg) and maintain higher soil pH than natural grass fallows or continuous maize cultivation (Ikerra et al., 1999; Kang et al., 1999; Bünemann et al., 2004).

Trees sometimes reduced certain soil nutrients in relation to continuous cropping. In the current study, amount of Al in the soil increased with soil depth under all dominant tree species while amount of Mg in the soil also increased with soil depth but only under *G. robusta*. Also, soil pH significantly increased with increase in soil depth under *C. calothyrsus* and *G. robusta*. Previously, low concentrations of exchangeable bases (Ca, K, and Mg) have been reported particularly in alley cropping with leguminous trees (Schroth et al., 1995; Kang et al., 1999). Other parameters also reported in low quantities in agroforestry treatments as compared to cereal mono-cropping are total soil C and N, and plant available P (Schroth et al., 1995; Mathuva et al., 1998; Kang et al., 1999; Isaac et al., 2007; Makumba et al., 2009). These cases of low concentration of nutrients in the soil were presumably because of nutrient uptake by trees (Isaac et al., 2007), competition with crops or leaching.

4.8.2 Spatial effect of dominant tree species on soil water status within smallholder farms

The on-farm trees used for the study of volumetric soil moisture content (VSWC) varied in age, DBH, crown diameter and height; and this made it difficult to draw strong conclusions on the impact of tree species on VSWC. Efforts to minimize differences in area of tree influence included having different zones (distance away from the tree) for access tubes installation.

The interaction of tree species and depth or zone had distinct pattern in VSWC except at zone D (control). This implies the dominant tree species significantly affect water availability in the farms and more importantly the agroforestry zones identified in the current study had a working control (zone D). Adoption of agroforestry is believed to alter the hydrological cycle which affects both the levels of water use and the total irrigation requirement (Ong et al. 2006). Trees have been observed to consume more water than other shorter stature vegetation growing under the same environmental conditions, largely because of being perennial, having greater total evaporative leaf surface, their ability to exploit a larger volume of soil to extract moisture and increased rainfall interception (Zomer et al., 2007).

Van Noordwijk et al. (2015) stated that the general concepts that all trees are deep rooted is greatly overstated as differences in species, sites and the horizontal scavenging ability of tree roots exists. The study showed distinct pattern in VSWC with introduction of tree species at all sampling depths and thus studied tree species affects VSWC from 0-100cm. This highlights the need to analyze water and nutrient uptake at species level as opposed to a mixed species and taking into account different depths and prevailing environmental conditions. Distribution of roots is determined by various factors, including species, management and soil conditions and as observed by Van Noordwijk et al. (2015), it is their activity in the cropping zone that determines the extent to which trees compete with crops below ground. Analysis of the effect of agroforestry zones on VSWC recorded distinct pattern at sampling depth 4 (40cm). This is the level where tree-crop interactions contribution to water in the soil can be attributed to agroforestry zones in the study area.

Eucalyptus spp and *S. sesban* was shown to reduce the amount of water under the tree while under *G. robusta* and *C. macrostachyus* soil moisture increased. Under *Eucalyptus spp*, the lowest amount of soil moisture was recorded under the zone next to the tree (one meter away from tree trunk) while under *S. sesban* the zone at the edge of tree canopy had the lowest soil moisture. There was a significant reduction in amount of soil moisture in the top soil layer under *Eucalyptus spp* which was not reported under *S. sesban*. These observations are consistent with studies by Kidanu et al. (2004) and Gindaba et al. (2007) who observed that *Eucalyptus spp* depleted water from surrounding soils leading to increased competition for water with crops growing in that area. Other similar cases, in which trees in simultaneous agroforestry practices showed competition with crops for water resources, resulting in lower amounts of soil water close to trees than in continuous cropping or natural grass fallows, or at greater distances from trees (Hartemink et al., 1996; Odhiambo et al., 2001; Livesley et al., 2004) have previously been reported. This can be attributed to soil water uptake by trees, increased transpiration from the tree and possible reduced input of rainfall through canopy interception.

Increased soil moisture under *C. macrostachyus* is explained by both differences in available soil moisture per soil sampling depths and agroforestry zones (distances from tree trunk). The zone at the middle of the tree canopy and 20cm sampling depth recorded the highest amount of soil moisture. The tree is broad leaved which would explain increased shading during the period of leaf cover and flushing which reduces evapotranspiration. During dry season the tree sheds all leaves leaving behind only a few thick and highly reduced terminal leaves. This allows disposing off of surfaces with large number of stomata (Negash, 2010). Wakjira and Negash. (2013) observed that the ability of *C. macrostachyus* to conserve water was critical for sustainable agriculture in agroforestry systems. Increased soil moisture under *G. robusta* was recorded when comparing the amount under and away from the tree. Due to high rainfall in the study area, the tree canopy is able to protect a significant amount of water from evapotranspiration as compared to zone outside tree canopy. Root competition for water is also reduced which equally protects the water under tree canopy. Soil water content has been previously reported to be higher on farms with, rather than without trees, and this was attributed to increased infiltration rate (Chirwa et al., 2003; Chirwa et al., 2004; Makumba et al., 2005; Nyamadzawo et al., 2007) and reduced soil evaporation and transpiration (Adejuyigbe et al., 1999; Boffa et al., 2000; Sanou et al., 2010). Another positive effect of trees on soil water dynamics reported is hydraulic lift and redistribution in some tree and shrub species (Burgess et al., 1998; Bayala et al., 2008; Kizito et al., 2012).

4.8.3 Relationship between tree species, spatial nutrient availability and maize productivity in smallholders' farms

The study showed that competition in agroforestry systems is complex and multifaceted because of different levels of tree-crop interactions; belowground and aboveground. In this study, maize yield was better under *S. sesban* than the rest of tree species at zone A with better yield reported at Zone A. Crop yields under agroforestry systems increase due to improved microclimate, nutrient cycling and soil fertility (Kuyah et al., 2016). Additionally, as the amount of Ca, Mg, pH and ExBas in the soil increases there was improved maize yield. *S. sesban* generates low shading to associated crops given its low specific leaf area and this contributed to increased maize yield under tree-based systems. Results also showed that maize production to be adapted to Zone B under *C. calothyrsus*. These are nitrogen fixing shrubs has previously been reported to increase yields of intercropped or subsequent crops which is mainly attributed to increased soil inorganic nitrogen (Barrios et al., 1997; Barrios et al., 1998; Chirwa et al., 2004).

Despite high turnover rate of plant residues being recorded under *C. macrostachyus* the study showed no positive correlation between nutrients availability and maize yield. Maize production under the tree had specific adaptation to Zone C (zone of root competition). This is evidence of positive effects from plant residues but higher level of light competition under the tree. Stigter (2015) observed that in a simultaneous agroforestry system, above-ground competition for light between trees and crops is a major constraint to agroforestry under humid climatic conditions.

Trees on farm can in some cases also lead to reduced yields by competing with crops for nutrients, water and light. Maize production under *Eucalyptus* spp treatments was higher at Zone D (open cropped areas that are relatively free from the interference of trees). This negative competition between *Eucalyptus spp* and maize is not unique and has previously been reported. *Eucalyptus spp* negatively affect intercrops in agroforestry through reduced seedling emergence and maize growth parameters (EI-Khawas and Shehata, 2005), increased water competition (Kidanu et al., 2004; Gindaba et al., 2007), hydrophobicity of tree leaves (Abelho and Graca, 1996) among other factors. In the current study, soil pH was also shown to be an important constraining factor to better maize yield under *Eucalyptus* spp whereby higher pH was shown to result in improved maize yield.

Maize yield was consistently most stable under *G. robusta* thus suggesting a positive contribution to resilience in agricultural landscapes. The rate of litter and foliage decomposability was low compared to other species and positive contribution of the tree may be attributed to microclimate regulation (effect of mulching) as opposed to nutrient cycling. According to Akycampong et al. (1999), that *G. robusta* does not compete much with the agricultural crops and may even enhance yields of some crops. This explains why *G. robusta* has successfully been planted on farms because it provides economically viable products, tolerates heavy stem pruning, pollarding and trimming of lateral roots (Muthuri et al., 2005). This allows less competition with adjacent crop compared to other dominant tree species because of its relatively light crown and deep rooting habit. It also can harvest water in the deeper horizons beneath the crop's rooting zone and to develop a cluster of roots that acquire nutrients from the soils deficient of phosphorus (Harwood and Booth, 1992). Dead leaves and twigs serve as manure in the topsoil layer (Raju, 1992) although our study showed the turnover rate was low.

Increased soil pH under *M. lutea* resulted in higher maize yield and this was similar observation as that made under *Eucalyptus spp* Compared to *G. robusta*, no specific adaptation of maize production was observed under its agroforestry zones. *M. lutea* has less competitive roots with crops in agroforestry systems which is relatively comparable to *G. robusta* (Wajja-Musukwe et al., 2008). The tree competes with crops with its large fibrous roots and the rather dense shade caused by its crown. The shade from the tree can be reduced by pruning and its multipurpose use nature makes it desirable for use in agroforestry systems.

4.9 Maize productivity under dominant agroforestry practices within smallholder farms

The average maize yield of 6.5 tons ha^{-1} was high compared to countrywide average of 1.8 tons ha^{-1} and County average of 6 tons ha^{-1} but was lower than expected hybrid-614 variety average production potential of 8.5 tons ha^{-1}. The good harvest can be explained by the high mean rainfall received (1418 mm) in the study area in the year 2013 and was comparable to recorded long term values of 1,200–1,800 mm per year. Also, an average temperature of 19.3°C was recorded in the year 2013 which was equally comparable to long-term average of 19.2°C reported in literature as the annual temperature. In addition, 97% of the selected farmers applied DAP (diammonium phosphate) fertilizer during planting or CAN (calcium ammonium phosphate) during top dressing at an average rate of 94 kilograms per hectare (Nyaga et al., 2018a). These factors qualify the study site as a high potential maize growing area which explains the high average yield. However, the farm sizes are small at mean of 0.89 ha (range = 0.04-8.09 ha) (Nyaga et al., 2015b) and agroforestry offers a good opportunity to diversify household income which is dependent on agriculture from own farm.

Maize height under *G. robusta* and *Eucalyptus spp* was significantly reduced by the effect of the trees canopy. The significant impact of the presence of trees on crop performance has previously been reported depending on the species and distance from the tree trunk or size of canopy (Muthuri et al., 2005). For example, *G. robusta* has been reported to negatively affect maize production (Ong et al., 2000) and in the current study, the lowest amount of maize yield was recorded under the tree. However, the extent of this influence is site-dependent as shown in a study comparing two semi-arid sites in Kenya (Muthuri et al., 2005). Pruning of *G. robusta* was shown to be carried out in the study area by reducing and raising crown and this maybe an effort by farmers to minimize observed competition with crops. Management of competition under *G. robusta* is possible because the tree tolerates heavy stem pruning, pollarding and trimming of lateral roots (Muchiri, 2004). Previous studies have shown that *Eucalyptus spp* negatively affect intercrops in agroforestry through reduced seedling emergence and maize growth parameters (EI-Khawas and Shehata, 2005) and this study confirmed this negative interaction. The decomposability rate of the roots was slowest under *Eucalyptus spp* compared to other species which indicate reduced nutrient cycling belowground. In addition, there have been concerns recently in Kenya about *Eucalyptus spp* trees that are depleting water from rivers and springs, and the perceived negative effects on crops. Studied farmers' shows great innovations in adopting *Eucalyptus spp* in the farms which include sustained pruning to reduce and raise tree crown which in current study resulted in crop yield under the tree remaining un-affected. This is in addition to establishing them in woodlots, external boundaries, at homestead areas as opposed to integrating them with crops in most cases (Nyaga et al., 2015b; Nyaga et., 2018b). The main reason for the introduction of eucalypts was its fast growth, ability to re-sprout and the straight nature of its stems. The wide range of products such as firewood, charcoal, building materials, fencing posts, transmission poles, pulpwood, timber and plywood obtained from *Eucalyptus spp* have made the genus very versatile (KFS, 2009).

Under *C. macrostachyus,* maize height recorded from zone D was significantly higher than the maize height recorded from zone B (on-farm experiment) and zone C (on-station experiment). Amount of grain yield recorded from zone A under *C. macrostachyus* was lowest amongst different tree species in smallholder farms with a pattern of increased crop yield observed with an increase in distance away from the tree trunk. Zone B which represents zone of root and light competition while zone C is zone of light competition and reduced maize height identifies *C. macrostachyus* as a competitive tree species which is attributed to light competition. The tree has rapid production of large number broad-leaves and flowers during rainy season and young leaves possess leaf blades that are fairly broad and droopy, collectively covering a space of 360° (Negash, 2010). The leaf arrangement and orientation helps the tree maximize the capture of sunlight throughout

360° space. Maize, having the C_4 photosynthetic pathway, is sensitive to shading due to competition for light (Chirko et al., 1996). Light availability and/or intensity have been reported to have a large effect on plants biomass production than water level (Kotowskil et al., 2000).

Maize height was highest under *M. lutea* followed by *C. calothyrsus* at Zone A. In addition, the amount of grain weight measured at different zones under the dominant tree species in smallholder farms showed significant differences between various tree species with highest amount recorded under *C. calothyrsus* which highlights it as an important agroforestry species. The tree can improve soil fertility through symbiosis with rhizobium, which forms nodules on the roots to fix nitrogen from the air, which is transferred to the tree. This helps the *C. calothyrsus* to grow fast, and leaves the soil more fertile than before by releasing nitrogen in the soil (ICRAF, 2001). Improved fallows or rotational woodlots of *C. calothyrsus* can be grown to replenish soil fertility while still suppressing weeds with an aim of increasing crop yields (Nolte et al., 2007). In addition, farmers in the study area prune *C. calothyrsus* before the start of cropping season which minimizes competition with crop. The decomposability rate of *C. calothyrsus* was also the highest among the dominant tree species and this highlights the great contribution of the tree to belowground nutrients cycling.

Improved maize performance under *M. lutea* at Zone A is an indication of reduced competitiveness nature of the tree has which has also been reported in agroforestry systems (Wajja-Musukwe et al., 2008). At on-station experiment, maize performance under *M. lutea* recorded no difference at various distances from tree trunk attributed to minimal tree influence to crop growth. The tree is also very attractive to rural population as it grows best on deep, well drained red loams, coppices extremely well and remains vital for many years, produces highly valued timber which are resistance against termites' attack and is tolerant against relatively infertile soils (Nyaga et al., 2017). The farmer in the study area were found to hardly prune *M. lutea* and this is can be an area of consideration to allow improved tree-crop interaction.

Maize grain yield in smallholder farms was second highest under *S. sesban* which also highlights its importance as an agroforestry species. *S. sesban* is a nitrogen fixing shrub that generates low shading to associated crops given its low specific leaf area and this contributed to increased maize yield under tree-based systems compared to tree-less systems (Nyaga et al., 2017). The rate of litter and foliage decomposability was high under *S. sesban* which would also greatly improve nutrient cycling under the tree. High yields after *S. sesban* improved fallows, for example, have been recorded and mainly attributed to increased soil inorganic nitrogen generated during decomposition and mineralization of N-rich organic residues (Barrios et al., 1998; Chirwa et al., 2004; Sjögren et al., 2010). Farmers in the study area do not prune the tree which was evidenced by great canopy area.

4.10 Modelling possible maize-based agroforestry scenarios using selected dominant tree species

WaNuLCAS proved sensitive to changes in planting density and distance from the tree trunk, as the two were shown to greatly affect crop biomass, nutrients and water uptake. The effects of tree species, planting density, management practices and agroforestry zones was captured by the model simulations outputs.

Trees on-farm were shown to have negative long-term effect on crop productivity and is influenced by density and spatial arrangement. This was also partially supported by simulations results and was shown to be influenced by tree species whereby a significant difference in crop biomass with an increase in distance away from tree trunk was only recorded under *G. robusta*. Significant difference in crop biomass production was however recorded between monocrop and intercrop and there was a difference in biomass production between experimental trees with production under *G. robusta* being significantly lower than the amount recorded under *C. macrostachyus* and *M. lutea*. It is therefore evident that agroforestry species should have appropriate crown shapes which allow an optimal balance among trees and crops for both ecosystem and agricultural purpose. The competition for growth nutrients proved to be a key factor in the current study in tree effect on crop productivity as evidenced under *G. robusta*. There was increased water competition under the tree and this is reflected in reduced crop productivity under the tree. Competition for soil moisture occurs when tree and crop roots are actively taking up water from the same rooting zone. This may happen during the entire year but is particularly detrimental at the start of the rainy season when woody species with their perennial roots are at a competitive advantage to use soil moisture over annual species, which may struggle to establish as a result of this. Other similar cases of trees in simultaneous agroforestry practices showing competition with crops for water resources, resulting in lower amounts of soil water close to trees than in continuous cropping or natural grass fallows, or at greater distances from trees (Hartemink et al., 1996; Odhiambo et al., 2001; Livesley et al., 2004) has previously been reported.

Higher tree density result in reduced soil nutrients near the tree compared to low tree density but was shown to be dependent of tree species and soil nutrient being evaluated. N and P stock in the soil increased significantly with an increase in distance from tree trunk and this was true under *C. macrostachyus* and *G. robusta*. This highlights competition between trees and crop for resources near the tree species which is a drawback to introducing trees into systems of crop production. Competition between trees and crops results when exploitation of a resource by trees, for example, reduces its availability to levels that limit growth and productivity of the crop (Anderson and Sinclair, 1993; Smith et al., 1999). To increase the productive in an agroforestry system there is need to use resources in a way that ensure that the trees and crop exploit different resource pools, particularly at times when the availability of a resource is potentially limiting (Ong et al., 1996). Maintenance of adequate distance from the tree trunk would in allow smallholders' farmers minimize losses due to competition near the tree.

Water uptake was shown to be a factor of tree density but most importantly studied tree species. An increased proportion of the available water was attributed to evaporation in the simulated agroforestry systems, runoff (under *G. robusta*) and drainage across all tree species. This concurs with observations that agroforestry may improve water use efficiency by reducing the unproductive components of water balance i.e. run-off, soil evaporation and drainage (Ong et al., 2002; Muthuri et al., 2004). Increases in the drainage component facilitates the recharging of the water table and consequent replenishment of groundwater reserves, which may in turn increase stream flow. Therefore, although agroforestry offers considerable potential for exploiting residual water supplies within the soil profile and deeper reserves beyond the maximum rooting depth of annual crops (Black and Ong, 2000; Lott et al., 2003), it is essential to achieve a satisfactory balance between recharge and exploitation of groundwater. The amount of water loss through interception, drainage and run-off was higher under *G. robusta* compared to *C. macrostachyus* and *M. lutea*. The difference can be explained by differences in leafing phenology between the species whereby *G. robusta* is evergreen and the rest are deciduous in nature. *G. robusta* recorded a lower water use compared to *C. macrostachyus* and therefore increased stream flow is expected under the tree. Muthuri et al. (2004) also reported that deciduous habit of tree species reduces water demand as compared to evergreen tree species under similar growing conditions.

Differences in water balances under *G. robusta* compared to the *C. macrostachyus* and *M. lutea* is expected compared to the two other tree species which are indigenous and possibly deep-rooted allowing complementarity in their water use with crops. Spatial complementarity in soil moisture capture arises (a) through the differences in rooting architecture of trees and annual crops, which enable trees to access deeper water resources than crops, or (b) when trees and crops are grown separately, as in woodlots. Temporal complementarity occurs when trees use soil moisture outside the growing season of the crops, when 20–30% of annual rainfall may occur (Ong et al., 1991), or when trees are grown as part of rotational fallows.

The differences in water balance is also reflected in differences in crop growth under the trees which provide evidence of increased competition under *G. robusta*. The tree has previously been reported to share rooting space with annual crops which do not allow complementarity in their water use where the only available source of water is rainfall (Smith et al., 1999).

WaNulCAS 4.0 model was used to fill the gap that exists with lack of scientific information and records on native and exotic tree species in sub Saharan Africa agricultural landscapes. This allowed long-term predictions about suitability of these tree species for agroforestry systems under different management practices. Any of the results mentioned here would vary with parameters such as soil texture, soil depth, tree canopy characteristics, tree management practices, tree rooting pattern but the overall pattern of response to climate zones would remain determined by resource availability. The model can be viewed as a “null model” which can be used as a null hypothesis, providing a background against which specific datasets can be tested (Van Noordwijk and Lusiana, 2000).

4.11 Local and scientific indicators of soil quality

4.11.1 Role of local biological indicators in assessment of differences in soil quality

Farmers had detailed knowledge of plant species as bio-indicators of soil quality and their influence on farming activities. Similar suggestion was made by Suarez et al. (2001) and use of weed species was found to be a common practice. The reports by farmers for C. *bengalensis* as a good fertility indicator agrees with Barrios et al. (2000) and Tengö & Belfrage (2004) while *B. pilosa* and C. *bengalensis* were reported by Mairura et al. (2007) and (Barrios & Trejo, 2003).

Some tree species such as *Sesbania* spp, *A. abyssinica*, *B. pilosa*, *D. scalarum*, *T. minuta*, Embululwe and *G. parviflora* were named by different farmers as bio-indicators. The opinion of majority of farmers of farmers was considered in such situations to get overall classification of the tree as an indicator of fertile or poor soils. In a related situation, farmers at times utilize same plant species to indicate differences in soil quality by observing their performance in the farm. For example, farmers interviewed observed that the growth vigour of C. *bengalensis* determines the soil quality status in the soil. They reported that green and leafy C. *bengalensis* indicates fertile soil and when growing with reddish stem and less leafy it indicates poor soils. It is equally important to note that farmers mainly associate the succulent species with fertile soils and this is consistent with observation made by Mairura et al. (2007).

Farmers associated invading species and grasses with infertile soils. These include grasses like *D. scalarum, Nakhanyushi* and invading species locally known as *Kumuchokoni.* Species also disliked by farmers were found to be associated with infertile soils. A likely example is the report on *O. sinuatum* who's spiky and prickly characteristic make it nuisance to farmers and this may explain why the farmers associate them with infertile soils. It is therefore necessary for researchers to differentiate the nuisance nature and the indicator nature of involved plant species according to farmers in order to accurately pick actual plant indicators of soil quality.

With agroforestry systems being a common practice in the smallholder's farms in Rift Valley Kenya (Nyaga et al., 2015b), farmers have also adopted various tree species through which they are able to identify fertile or poor soils or fields. This is linked to tree attributes on whether they are competitive for water and nutrients and their litter quality. For those tree species named by more than three respondents, *C. macrostachyus, Sesbania* spp, and *M. lutea* presence in the farm indicate good area for growing crop. The attributes highlighted by farmers about the above species is the ability to provide good litter, minimal tree-crop competition and reduced soil erosion and overall this lead to fertile soil. Only native tree species were included in the local indicators list although farmers' recognition of tree species as indicators of fertile or infertile soils goes beyond their origin; native or exotic and this showed lack of information on tree origin by surveyed farmers.

Most of the farmers in the study area were found to be aware of macrofauna as bio-indicators and their activities. Earthworms and beetle larvae (white grub) were considered to be indicators of fertile soils by most farmers and similar results were obtained in other studies in tropical areas (Morales and Perfecto, 2000; Murage et al., 2000; Birang et al., 2003). It is therefore obvious that the two are very important bio-indicators that farmers recognize closely associated with agricultural activities and aspects of soil quality and not as a result of their large size as explained by Pauli et al. (2012). Farmers apparently are aware that earthworms and white grub are creators of fertile soils rather than the consequence. Similar results were obtained through a study by (Murage et al., 2000) on smallholder farmers in the central highlands of Kenya who regarded earthworms and beetle larvae as indicators of productive land. This belief also corroborates with results from southern Cameroon, which show that farmers believe that earthworms' concentrates plant nutrients in their surface cast which are usually richer than top soil (Norgrove and Hauser, 2000). The results however contrasts observation by Birang et al. (2003) in southern Cameroon who found out farmers believes that earthworms are the consequence rather than the creator of fertile soil. The beliefs by some interviewed farmers that earthworms and white grubs cut plant or seedlings/ destroy leaves of crops and vegetables, destroy crop at harvest, feed on soil leading to reduced productivity, feed on crop roots or feed on soil leading to reduced productivity needs to be addressed.

Soil macrofauna, particularly beetle larvae and millipedes were also relatively important as indicators of soil moisture for the farmers interviewed. The farmers use this to indicate the level of moisture in the soil as well as an indicator of the right time to plant crop. Two of interviewed farmers were quoted saying 'millipedes and beetles holds water and are only found in moist soils' and that, 'increased appearance of millipedes in the field indicate onset of rainy season for planting'.

Majority of interviewed farmers attributed ants to destruction of crops and regard them as detrimental in the soil. This was found to be linked to their feeding on drying maize which creates a major problem to interviewed farmers as they rely solely on maize production for food and cash crop. This observation may hinder farmers' appreciation of the role played by termites in soil fertility improvement and this is mostly elaborated by attributes recorded from farmers on safari ants/ red ants. The safari ants are biting making them nuisance to farmers and this may explain why the farmers recall only the negative attributes. However, many of interviewed farmers still regarded black ant and termites as being beneficial in the field and this was related to their ability to improve soil fertility in the field. Similar results were obtained in in West Africa by Black & Okwakol (1997) where changes in termites' community structure in forest areas were as indicators of soil fertility status.

4.11.2 Relationship between farmers' soil categories and scientific soil assessment

The current study found that small scale farmers' judgement of soil quality status was to be based on readily observed visible and tactile characteristics. Farmers' criteria for distinguishing soil types in the field included soil colour, texture, soil and water retention capability and the easiness to work on the soil. Soil colour is an important indicator reported by farmers often related to soil high organic matter content and an indicator of high productivity of the soil (Barrios and Trejo, 2003; Barrios et al., 2006; Mairura et al., 2007; Nath et al., 2015). The ability of farmers to use soil colour, texture and other visual appearances underscores the value of taking into consideration the visual and morphological soil characteristics used by farmers as key criteria in soil characterisation and management systems developed scientifically. It is evident that farmers associate darker soils with higher fertility compared to lighter soils here described as red soils. A study by Mairura et al. (2007) recorded similar observation in Gachoka division in Central Kenya whereby they also attributed the darker soils have more soil organic matter concentration than lighter soils.

Productive sites identified as good soils were used for production of high value crops such as maize, beans, potatoes, bananas and green vegetables. Maize and beans were intercropped in both good and poor soils and this highlights the importance of the crops to household diets and income. The results are congruent with study by Murage et al. (2000); Mairura et al. (2007) who observed farmers prioritize crops to be planted in fertile soils based on their importance to household diet and their economic value.

The results of soil analysis indicate that there was good agreement between assessment of soil fertility by farmers and scientific indicators of soil quality such as soil nutrient status and pH. Similar results have been found with other studies, for example, Mairura et al. (2007) found that soils collected from inherently fertile humic soils in Kenyan highlands were more fertile than those collected from lower agricultural potential areas in same country. Comparably, Murage et al. (2000) found that productive soils as classified by farmers had significantly higher soil pH, exchangeable cations, effective cation exchange capacity, extractable P, and total N and P than non-productive soils in central Kenya. In the current study, only pH, B, ECd, ExAc, K and Mg varied significantly between soils classified as good and poor by farmers.

4.11.3 Attributes of local tree species and their perceived effects on soil quality

The interviewed farmers from Trans-Nzoia County, Kenya perceive local tree species differently in their contribution to soil quality. Farmers considered tree species as beneficial if they are able to improve soil fertility through litter decomposition and nitrogen fixation. Comparatively, the competition for water and allelopathy were the least favored attributes of tree species. Even though farmers acknowledge existence of tree-crop competition with tree introduction in crop fields, they would prefer those species that are complementary to crops. Their selection of a tree species ensured that they continue maintaining crop growing with least disturbance from tree species.

Farmers' preference for tree species were at odds with the abundance of these species in the smallholders' farms in the studied area. *Eucalyptus* spp is the most frequent tree in the current study area constituting 34.6% of the total tree population. However, this species is recognized as having the least favored attributes leading to contradiction between farmer's perception and practice. Farmers plant *Eucalyptus* spp in highest number compared to other species despite acknowledging that they dislike most their attributes towards soil quality and results in Chapter 5 showed the species to highly compete for water. It is therefore obvious farmers will not always plant tree species with favorable attributes even when they possess the knowledge and farmers will consider multiple attributes of the tree plus the expected tree returns (farmer needs) in selection of tree species for agroforestry. The economic pressure makes farmers go beyond local knowledge rationale and engage in a sort of trade off analysis. Farmers were also found to selectively incorporate *Eucalyptus* in the good soil within the farm. A study of agroforestry systems of western Honduras found similar results where the number of farmers preferred species were around half of the total number of species commonly found within agroforestry plots (Pauli et al., 2012). Contrastingly, the authors highlighted that farmers still include less valuable species due to their contribution to ecosystem function and their role in ecological succession as the farmers rely on natural regeneration. In study area, farmers' carryout selective planting of preferred species as opposed to regeneration and therefore farmers may include trees with less favoured attributes towards soil quality for other reasons such as economic values associated with them. The question of economic value attached to tree species that lead to farmers selecting them over tree species with favored attributes is worthy further research.

Eucalyptus spp and *C. lusitanica* are the most cited tree species with least favoured attributes towards oil quality. A study from the same area by Nyaga et al. (2015b) reported that *Eucalyptus* spp and *C. lusitanica* are preferred in woodlots or in boundary planting. Therefore, in their effort to minimize negative effects accrued from the two species on soil quality and crop performance, farmers opt for arrangement method that offers minimal tree-crop interaction.

4.11.4 Implications of study findings

Farmers hold complex ecological knowledge or local knowledge on indicators of soil quality and contribution of agroforestry tree in their farms as presented in this study. There was a great variation in the kinds and depth of such knowledge. The choices made by individual farmers depends on their capacity to enact successful agricultural performances and to exploit an evolving range of opportunities (Osbahr and Allan (2003).

This study show that farmers recognize the tradeoffs underlying a biodiverse agroforestry system and their creative capability in the utilisation of local knowledge was demonstrated. Apart from being recognized as generators and co-producers of knowledge with the building of bridges between local and external knowledge systems as was reported by Munyua & Stilwell, (2013), farmers were found to quickly put the knowledge acquired into practice. Farmers draw upon varied ecological knowledge to make complex and dynamic management decisions thus local knowledge represents one part of the farmer’s strategy for managing soil fertility.

Farmers are increasingly being recognized as playing a major role as ecosystem managers (Cerdán et al., 2012) and provision of ecosystem services from agroforestry systems depends on their management decisions. It is therefore prudent to carry out further analysis of agroforestry management practices resulting from local knowledge in an effort to protect these ecosystems.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Agroforestry practices and factors influencing agroforestry adoption within smallholder farms

The study supports the notion that the establishment of a diverse tree cover in the study area involves the simultaneous action of three main drivers, namely, household resource endowment, land tenure and time under current management. Settlement schemes as a land redistribution system generally fostered greater number of trees on farm and the adoption of agroforestry practices. This process has been largely driven by the establishment of trees as external boundaries around individual plots as well as integration of selected tree species into crop growing areas. Farmers also reserve homesteads as an important area to raise fruit trees. This study has shown significant presence of exotics such as *Eucalyptus* spp, *G. robusta* and *C. lusitanica* which is indicative of farmer's preference. Although most tree species encountered were indigenous, their abundance was generally low for most species. Since genetic diversity is required for long-term survival of species, tree diversification with native species in agroforestry systems should be encouraged to allow their conservation *in-situ* as highlighted by Dawson et al. (2009).

This study confirms that planting of fruit trees is mainly conducted by low resource endowed farmers presumably as a means to supplement their family's nutrition and income. However, the planting of trees given the high demand for fuel wood and of high value timber trees to supplement household income was a common practice for all farmers irrespective of their resource endowment level. Low resource endowed farmers maintain significantly higher tree diversity in their farms despite their significantly smaller farm sizes compared to medium or high resource endowed farmers. This finding contradicts the discourse that poorer farmers are always the main reason behind deforestation.

This study supports the notion that households with land tenure increase longer term farm investment through increased tree cover, while lack of land tenure encouraged farmers to adopt fast growing multipurpose tree species. Further, even with an overall decrease in farm size as a result of fragmentation processes driven largely by population pressure, there is an increase in number of trees species that suggests a strong farmer reliance on tree products and other ecosystem services in the study area.

5.2 Maize productivity under dominant agroforestry practices within smallholder farms

The study hypothesized that dominant tree species and their associated agroforestry zones affect performance and productivity of associated maize. Maize height under *G. robusta* and *Eucalyptus spp* was significantly reduced which highlights their enhanced competition with the crop. *C. macrostachyus* exhibited increased light competition which can be minimized through tree pruning before crop planting. *M. lutea* showed no significance influence on crop performance while *C. calothyrsus* and *S. sesban* showed possibilities of improved yield in their agroforestry systems within the smallholders' farm.

The study clearly showed that different species contribute differently in agroforestry systems to tree-crop interactions therefore it is not always beneficial to grow intimate mixtures of trees and crops.

5.3 Water and nutrient availability under dominant agroforestry trees within smallholder farms

Dominant tree species in smallholder farms were found to differently influence the spatial distribution of soil nutrient which supported our hypothesis. The study also hypothesized that presence and management of dominant tree species in smallholder farms influences crop performance and water availability in the smallholder farms and this was supported by the study. First, presence of dominant tree species in smallholders' farms in the study area was shown to differently affect maize grain yield. Leguminous species such as *C. calothyrsus* and *S. sesban* which have capability to fix nitrogen were shown to compete more favorably with associated crops compared to non-leguminous species. Presence of *Eucalyptus* spp and *G. robusta* in the smallholder farms was shown to negatively affect maize performance in terms of crop height which presence of *C. macrostachyus* reduced grain yield obtained from under the tree. *M. lutea* was less competitive with associated crops despite being non-leguminous. Therefore, the current study highlights it as a suitable agroforestry species due to its ability to grow fast and produce highly valuable timber which can be an alternative source of income for smallholder farmers. Secondly, farmers were shown to differently manage trees on farms with different outcome of subsequent tree-crop interaction. The results also highlight the need to diversify management options for tree species on farm and better management of tree species can be advised to farmer’s especially pruning methods which will allow farmers to reduce tree-crop competition. Lastly, the amount of rainfall in the study area was adequate throughout the cropping season and its availability was not a limiting factor to crop productivity but dominant tree species in farms were shown to influence the spatial distribution of soil water. Therefore, designing of agroforestry systems should always consider effects on water especially in water limited zones. In conclusion, the study clearly showed that different species contribute differently in agroforestry systems to tree-crop interactions therefore it is not always beneficial to grow intimate mixtures of trees and crops.

5.4 Modelling possible maize-based agroforestry scenarios using selected dominant tree species

Modelling studies using WaNuLCAS suggested that individual traits of tree species, management practices such as crop choices, tree selection, intercrop spacing and age are important factors affecting water use, nutrient availability and biomass production in smallholders’ maize farms in Trans-Nzoia County. In contrast, there was increased water competition exhibited under *G. robusta* which in turn translated to low crop productivity under the tree. Trees are more robust and unlikely to die unless there are repeated long-lasting droughts. Thus, while trees may themselves reduce crop yields, their products can and do provide farmers with vital resources and a more resilient cropping system. With appropriate tree management practices such as pruning and spacing farmers can minimize competition and manipulate the trade-offs between the tree and crops, while also obtaining additional animal fodder or other useful biomass.

5.5 Local and scientific indicators of soil quality

The smallholders' farmers in Trans-Nzoia County, Kenya have a wealth of experience on local indicators of soil quality and contribution of agroforestry trees in maize production systems. They know how to distinguish between good and poor-quality soils using visual and morphological soil characteristics. Although the interviews generated a useful list of soil types as recognised by farmers, the range of these was rather limited and overlapping. There are also numerous bio-indicators; both plants and soil macrofauna, utilised by farmers to differentiate poor and fertile fields. Thus, farmers have better knowledge of their farming environment and can be termed as good specialists in pedology and soil biology which emphasizes the role of smallholder farmers in soil fertility management in the Sub-Saharan Africa. It is therefore necessary to find a realistic and common ground between scientific and local knowledge in order to implement a sustainable soil management programs. Farmers also have adequate knowledge on the contribution of agroforestry tree species to soil quality.

5.6 Recommendations for improvement in agroforestry

While the study achieved the objective to investigate the impacts of trees on water and nutrient dynamics in smallholder's maize-based agroforestry systems, the following recommendations are made to improve management of agroforestry systems in smallholders' farms.

The current study offers a significant insight on the opportunities and limitations of farmers using their knowledge and experience in their effort of using tree species to optimize farm production. Farmers should be encouraged to incorporate tree species that exhibited less competition with crops into their farms such as *S. sesban* while avoiding those exhibiting increased competition such as *Eucalyptus spp*. However, management of such tree species proved more important to the farmer than total elimination and the integration of local knowledge with scientific can be a good tool to enhance productivity of agroforestry systems. Incorporation of competitive tree species at homestead or as woodlots is a sure way to allow everyone benefits from ecosystem services provided by trees.

Low resource farmers are blamed for deforestation in many African contexts but the study showed otherwise and this forms an important step in integrating smallholder farmers in environmental management mainly through re-afforestation strategies as well as acknowledging their effort and roles they play in the same.

The farmer in the study area were found to hardly prune *M. lutea* and can be advised on to reduce the dense shade and improve complementarity between the tree and associated crops in agroforestry systems. Farmers in the study area should be advised on crown reduction together with crown raising as a pruning method which would allow reduction in competition under *C. macrostachyus* and management similar to those carried on *G. robusta* should be encouraged.

5.7 Areas of further studies

The influence of household resource endowment, land tenure and also the period of occupation by current households on adoption of agroforestry practices need to be tested in other areas in sub Saharan Africa as an effort to validate this new observation that resource constrained households prefer fruit tree species and maintained high tree diversity in the farms.

The question of economic value attached to individual tree species that farmers identified as detrimental to soil quality and crop production and nevertheless lead to farmers selecting them over tree species with favored attributes is worthy further research. The focus should also be on how to minimize negative effects as a way to advice farmers appropriately.

This study only evaluated simulations under *C. macrostachyus, G. robusta* and *M. lutea* but would be important to parameterize and simulate *Eucalyptus* spp*, S. sesban* and *C. calothyrsus* to understand their effects on soil water and nutrients and subsequent crop production.

Further studies to assess the trade-offs between trees and crops from a wide array of possible management options can be carried out by use of WaNuLCAS model. This will help in risk reduction in resource positioning amongst smallholder farmers. For example, whether the associate risks involved in growing tree differ from those for food crops. The financial, biophysical and social gains associated with crop yield should be compared to relative tree yield within the farms.

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APPENDICES

APPENDIX 1: QUESTIONNAIRE ON LOCAL KNOWLEDGE

World Agroforestry Centre
TRANSFORMING LIVES AND LANDSCAPES

JOMO KENYATTA UNIVERSITY OF AGRICULTURE AND TECHNOLOGY
Setting trends in Higher Education, Research and Innovation

A CASE STUDY ON LOCAL KNOWLEDGE ABOUT TREES, BIOLOGICAL ACTIVITIES AND THEIR INTERACTION IN AGROFORESTRY SYSTEMS

Introduction

My name is John Nyaga, a PhD student at Jomo Kenyatta University of Agriculture and Technology. This questionnaire is prepared to help gather information on local knowledge on soil quality and highlight indicators used by farmers to identify soil quality differences within their farms. The study main title of the study is, ‘Impact of trees on water and nutrients dynamics in smallholder maize-based farming systems in Trans-Nzoia, Kenya’.

You are kindly requested to respond to the following questions to the best of your ability since you are deemed a critical player in this research. Be assured that this information will only be used for the intended study.

Questionnaire Number ____________________________________

Name of the Farmer____

Country____

Province____

District____

Village____

Geo-reference____________________________________

Name of the Interviewer______________________________________

Date of Interview____

1. General information

Starting with the head of household, please tell me the number of people living in your household with you, their relationship to the head of household, sex, age, marital status, religion, level of education, occupation and type of work.

	Name	Relationship to HH	Sex 1=M 2=F	Age	Marital status	Religion	Level of Education	Occupational status	Type of work
1									
2									

3									
4									
5									

CODES:

Relationship to HH: 1= Household Head; 2=Spouse; 3=Son; 4=Daughter; 5=Brother/Sister; 6=Grandchild; 7= Other relatives; 8= Non- relatives

Education: 1=Not attended school; 2=Lower primary; 3=Upper primary; 4=Secondary; 5=College; 6=University; 7=Not applicable

Religion: 1=Catholic; 2=Protestant; 3=Adventists; 4=Muslim; 5=Traditionalist; 6=No religion; 7=Others (specify)

Occupational status: 1=Unemployed; 2=Temporary employment; 3=Permanent employment; 4=Business; 5=Not applicable

Type of work: 1=Farming; 2=Herding; 3=Business; 4=Casual employee; 5=Teacher; 6=Artisan; 7=Others (specify)

2. **Information about the farm:**

a) Do you own land? 1= Yes   2=No______________________________________

(If yes) How much land? ____

b) How long have you cultivated this farm? ________________________________

Is it all cultivated? Yes _______No ________

You cultivate_________% Fallow ________% Forest ___________%

History of the farm as long as you can recall?

____

____

____

c) Do you keep any livestock? Yes __________ No __________

If yes, how much land is left for the livestock? _______acres

If yes, which livestock do you keep and how many of each and their use?

Type of Livestock	**Number**	**Use (1=home; 2=sale; 3=both)**
Cows		
Sheep		
Goat		
Poultry		

Others		

History of the use of the various plots as long as you can recall?

____

____

____

____

____

d) How much land is allocated to?

Crop	**Size**	**Age**	**Other details**
Maize			
Beans			
Sweet potatoes			
Cassava			
Pasture			
Agroforestry			
Secondary Forest			

Nappier grass			
Other			

e) What quantity of the crops do you get?

Crop	**Quantity**
Maize	
Bean	
Sweet potatoes	
Cassava	
Others	

3. Soils

i. Are there varying soil types in the region and/ or on your farm?

____

____

ii. What kinds of soils do you have within your farm?

____

____

iii. What are the characteristics of each kind of the soil type?

(For example; colour, fertility, tree species, stones, depth, texture, water retention)

Soil Type	**Characteristics**

4. Farm participatory mapping

Prepare a map with the farmer showing the various types of soils (good-intermediate-poor), indicating slope, soils which dry fast or slowly, past and current use with regard to their location on the slope, location of cropping or fallow areas (geo-reference the uses), presence of weeds, soil organisms (e.g. ants, earthworms, termites, etc.) Use this map to conduct the rest of the interview while observing and sampling the various soil types.

i. Where is each type of soil found within your farm? Participatory mapping (help farmer draw a map of the distribution of different soil types in their farm).

Soil Type	**Where found**

ii. (For each soil type) Is this type of soil good or bad for growing crops, and why? Which crop grows best in (each type of soil)?

Soil Type	**Good or bad or in between, and why?**

5. **Trees**

i. For you, which plants or trees indicate an area would be good for growing crops?

Plant	**What does it indicate, and why?**

ii. Which plants or trees indicate that an area would not be good for growing crops?

Plant	**What does it indicate, and why?**

iii. Do the same types of trees grow in all parts of your farm, or are there different species in different parts of the farm?____

____

____

iv. Which trees have beneficial effects on crops? Why?

Tree species	**Effect and why?**

v. Which trees have detrimental effects on crops? Why?

Tree species	Effect and why?

vi. Which are the common tree species in the farm?

Type	Age	DBH	Total Count	Generation	Agroforestry practice

6. Soil Fauna

i. What kind of animals have you seen that live in the soil in your farm?

____

____

____

ii. (For each type named) Are they beneficial or detrimental to your crops, and why?

Type	Beneficial or Detrimental Why?

iii. Are there certain types of animals that indicate if land will be good or bad for growing crops?

Type	**What does it indicate, and why?**

iv. (For each of animal mentioned) Where do you find them in your farm?

Type	**Where found/ not found**	**Why**

v. Are there more soil animals during dry season or during rainy season? Why?

____

____

____

____Are there more animals near trees than far away from trees?

____

____

vi. Which trees have the largest number of soil animals in the soil around the base? Why, and which types of animal?

Tree	**Animal**	**Why**

7. Nutrients and management

a) Fertilizer Use

i. Do you use fertilizer in your farm?

____

____

ii. Which type of fertilizer do you use?

____

____

iii. When do you apply fertilizer?

____

____

iv. How do you apply fertilizer?

____

____

v. How much fertilizer do you usually use per acre?

____

____

vi. What do you think happens to the soil animals after applying fertilizer?

____

____

____

____

b) Pesticides

i. Do you use pesticides in your farm?

____

____

ii. Which type of pesticides do you use?

____

____

iii. When do you apply it?

____

____

iv. How do you apply pesticides?

____

____

v. How much pesticide do you usually use per acre?

____

____

vi. What do you think happens to soil animals after applying pesticides?

____

____

____

c) Burning

i. In previous years, did you burn your farm?

____

____

ii. How long ago did you stop?

____

____

iii. Why did you burn your farm?

____

____

iv. What effect did burning have on the soil? Trees? Soil organisms? Crops?

____

____

____

____

____

Thank you for your participation and co-operation.