NUTRIENT DYNAMICS, ALLELOPATHY LEVELS AND CROP PERFORMANCE UNDER *EUCALYPTUS GRANDIS* TREES IN KENYA

BY

STANLEY W. NADIR

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DECLARATION

DECLARATION BY STUDENT

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STANLEY W. NADIR **Signature: ……………..... Date: …......……..**

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DECLARATION BY SUPERVISORS

This thesis has been submitted with our approval as University supervisors

Prof. CALEB O. OTHIENO **Signature: ……………..... Date: …......……..**

Department of Soil Science,

School of Agriculture and Biotechnology,

University of Eldoret, Kenya.

Prof. WILSON K. NG'ETICH **Signature: ……………..... Date: …......……..**

Department of Soil Science,

School of Agriculture and Biotechnology,

University of Eldoret, Kenya.

DEDICATION

To God Almighty who has always guided me throughout my entire life, ever caring and watching over me.

ABSTRACT

Successful Eucalyptus-crop intercropping is limited by; soil nutrients and water dynamics, allellochemical accumulation in the soil and competition for light between trees and crops among other factors. A study with the objective to evaluate the effects of nutrient dynamics and allelopathy on performance of selected crops i.e. common beans (*Phaseolus vulguris*), Irish potatoes (*Solanum tuberosum* L.) and black Nightshade (*Solanum villosum*) under Eucalyptus trees was carried out. The study characterized and monitored changes in soil nutrients under *Eucalyptus grandis* tree stands at different ages (1.5, 3, 6, 12, 20 and 40 years) before and during intercropping. For allelopathy studies, the quantity of polyphenols in litter, fresh leaves and soils under trees were determined and tested for their effects on crop germination and soil water repellency. Radial cluster sampling in RCBD design was used for sampling soils and plant materials. Furthermore, the performance of crops under Eucalyptus (3 and 6 years) was evaluated. The crops were planted along rows of Eucalyptus in plot sizes of 4 m by 2 m adopting a factorial arrangement in RCBD where germination, photosynthetically active radiation (PAR), leaf area index (LAI) and yields were measured. Data analyses involved ANOVA, correlations and regressions. From the results; organic carbon, nitrogen and calcium in the soil significantly reduced with increasing soil depth under Eucalyptus trees. Soil available phosphorus, pH, iron, calcium, potassium and magnesium were reduced significantly as age of the stand increased. Crop cultivation under Eucalyptus trees reduced nitrogen and potassium in the soil while available phosphorus, pH, magnesium and manganese increased significantly. Soil organic carbon, exchangeable calcium and extractable iron were unchanged. Potassium, magnesium, manganese and organic carbon were above normal levels in the soil, Eucalyptus litter and its leaves. The soil polyphenol content was 50 to 100 times less than those present in the litter and leaves of Eucalyptus and increased with tree age and reduced down the soil profile. The polyphenol extract from litter and fresh leaves completely inhibited the seeds germination of common bean but not the soil extract (80% germination). Soil water repellency increased with Eucalyptus tree age, was severe during dry spells (less moisture) and reduced down the soil profile. Germination of crops under trees was high (beans 90%, potatoes 80%, and nightshade 100%) but did not differ when planted in the open field. The leaf area index (LAI) and yield of crops reduced under Eucalyptus trees ($p \leq .001$) except Nightshade. The age differences in Eucalyptus trees had no significant effect on the amount of PAR reaching the understory crops. In conclusion, phosphorus deficiency and manganese toxicity were the major limitations to optimum crop production under Eucalyptus trees. Soil soluble polyphenol and moisture contents influenced soil water repellency under Eucalyptus trees. It is recommended to continuously cultivate and mix litter with soils under Eucalyptus trees during intercropping to reduce soil water repellency. Nightshade vegetable performed well under Eucalyptus trees and should be adopted for intercropping.

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LIST OF ABBREVIATIONS AND ACRONYMS

C/N Carbon Nitrogen ratio

CRD Completely Randomized Design

EDTA Ethylene Di-amine Tetra-acetic Acid

Eucalypts Different species of Eucalyptus trees

FAO Food and Agricultural Organization

GenStat Statistical Package for General Statistics

HI Hydrophobicity Index

KALRO Kenya Agricultural and Livestock Research Organization

KARI Kenya Agricultural Research Institute

KEFRI Kenya Forestry Research Institute

LAI Leaf Area Index

PAR Photosynthetically Active Radiation

RCBD Randomized Complete Block Design

SP Species (singular)

SPP Species (plural)

WDPT Water Droplet Penetration Time

WRB World Resource Base for Soil Resources

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CHAPTER ONE

INTRODUCTION

1.1: Background

Competition for scarce land resources between food crops and trees has intensified hence there is need for a balance to accommodate both, either in rotation programs or in agroforestry systems. Population increase and change in the eating habits will cause an increment in world food requirements of 80–120% by 2050 (FAO (2006), hence there is need to close this gap through agroforestry as one of the solutions.

Successful intercropping of Eucalyptus trees with food crops is hindered by competition for light between trees and crops, the soil nutrient dynamics and the allelopathy effects from Eucalyptus trees (Alemie, 2009; Sasikumar *et al.,* 2002; Nair, 1993). Despite these challenges, recent studies by Chaturvedi *et al.,* (2017) and Mugunga (2016), suggest integration of Eucalyptus trees and crops is possible especially in spatially zoned agroforestry systems or as mixtures. Growing of Eucalyptus trees in Kenya has had a nationwide debate in the past (Kenya Forest Service (2009), raising concerns on the species' water utilization, allelopathy effect on biodiversity (Sasikumar *et al.,* 2002) and soil fertility problems. However, these challenges have not stopped the cultivation of the tree due to its enormous benefits, including provision of power transmission poles, cheap source of energy and high quality fiber for the pulp industry (Oballa *et al.,* 2010). Moreover, Eucalyptus tree is a chief driver of commercial forestry sub-sector providing income to farmers, (Kenya Forest Service, 2009). The tree is also a major component of forest cover and contributes to carbon sequestration which helps reduce climate change effects (Oballa *et al.,* 2010).

There is little information about the status of the nutrient dynamics in Eucalyptus plantations systems especially for the soil during intercropping with Eucalyptus trees with most of the past studies focusing mainly on comparing mono-cropping and Eucalyptus plantation systems separately. For instance, having long-term plantations of Eucalyptus trees on the land without intercropping have been reported to improve the soil fertility i.e. within a period of 8 to 10 years and with no significant differences in fertility when compared to soils under grass (Couto and Betters, 1995). Furthermore, soils under Eucalyptus trees have been associated with crop yield reduction due to nutrient depletion and production of toxic exudates or allelopathy (EI-Amin *et al.*, 2001). Studies on the effect of distance gradients from the Eucalyptus tree stand or canopies on soil fertility by Alemie (2009), reported a significant change in available phosphorus, exchangeable calcium, total nitrogen with no change in potassium concentration in the soil. Soil water content, soil hydrophobicity, light intensity and the density of the undergrowth are influenced by distance from tree stand (Alemie, 2009). Soil fertility depletion in soils previously under Eucalyptus plantations has been linked to nutrient mining and biomass export through harvesting of the trees (Zerfu, 2002), perhaps a problem for deep rooted crops only since mature trees extract nutrients deep down the soil profile.

The soils under *Eucalyptus* species contain allelochemicals which inhibit undergrowth regeneration (Sasikumar *et al.*, 2002), and negatively influence agricultural production especially in arable lands (Coder and Warnell, 1999). The allelopathic compounds present in *Eucalyptus* spp are of a wide spectrum ranging from non-polar to polar compounds including terpenes to soluble phenols with different abilities to accumulate and move through the soil system (Espinosa-García *et al.*, 2008).

Variable allelopathic effects are likely to be observed in different soil horizons due to different accumulation and movement potentials of the compounds down the profile (Singh, 1991). Although high rainfall is alleged to negate the allelopathic effects of these trees on crops (Kenya Forest Service, 2009), it's not very clear on which type of allelochemicals effect is negated. In addition, the allelopathic effects vary in terms of the affected species, their harmfulness and the conditions under which they grow (Espinosa-García, *et al.,* 2008). These compounds are inhibitory to plants and microbes e.g. phloroglucinols, grandinol and homograndinol from *E. grandis,* are potent photosynthetic inhibitors (Schumann *et al.,* 1995). For instance, the leave extracts of *E. grandis* and *E. urophylla* and their hybrids have shown to be allelopathic to certain crops. Intercropping of crops in plantations of *E. camaldulensis, E. grandis* and *E. tereticornis* have resulted in growth reduction and death of crop seedlings (Shivanna and Prassana, 1992). Allelopathic effects in *Eucalyptus* spp are masked by effects resulting from competition for water and nutrients (Shivanna and Prassana, 1992). Moreover it is not easy to separate the effects of competition for light or nutrients from those of allelochemicals, nor to know at what age of Eucalyptus is the effect of allelopathy maximum or minimum and the quantity present to permit successful intercropping. Furthermore, it has been shown that increased soil water repellency (hydrophobicity) of a soil due to accumulation of allelochemicals hinders infiltration affecting the understory crops despite the soil chemical or fertility aspect not limiting; a phenomenon easily confused with competition for light (Nair, 1993). In the ecosystem, phenolic compounds are the most important and common plant type of allelochemicals (Zeng *et al.,* 2008). The phenolic compounds are distributed in plants; commonly in plant decomposition products and they are important precursors of humic substances in soils and accumulate in the rhizosphere (Li *et al.,* 2010).

Therefore, information about soil and water dynamics together with allelochemical concentrations for different ages of Eucalyptus trees is important before introducing the crops under the canopies. These will provide a guideline on the aspects of the soil (chemical, physical or even biological) that needs amendments to enable successful cropping under the Eucalyptus trees.

Light interception by different components of a multi-layered agroforestry systems like the Eucalyptus-crop mixtures and the distribution of the photosynthetically active radiation (PAR) within the canopy units, are the key factors influencing the productivity of tree-crop mixtures (Nair, 1979; 1983; Loomis and Connor, 2002). To modify existing or create new agroforestry systems, information on newly created patterns for light capture is required (Johar *et al.,* 2017; Whiting, 2011). Therefore, it is important to estimate the PAR intercepted by each component of the systems at any given time, and to integrate it to reflect the time they occupy in space (Nair, 1993). The productivity of crop canopies has been quantified using concepts of Leaf Area Index (LAI) and the Crop Growth Rate (CGR) as estimators of the crop's ability to capture light energy available for plant growth (Campillo *et al.,* 2012; Gardner *et al.,* 1985), therefore necessary tools used to assess productivity in this study. Selection of crop species to be used in agroforestry systems is based on cultural, economic as well as environmental factors (Monteith, 1978; Nair, 1993). However, photosynthetic pathways are useful when choosing crop species. In permanent woody over-story systems with C_3 trees having significant shading; the understory preference should be for C_3 plants as they have a greater efficiency of CO_2 uptake at lower irradiance levels than C_4 plants (Monteith, 1978; Tieszen, 1983).

The outputs from the interactions between trees and crops cannot easily be predicted as the interactions are influenced by many factors including environmental conditions and plant species (Sheley and James, 2014). Therefore, more research is needed to screen more crop varieties for their specific responses, and to understand the mechanisms of such responses under Eucalyptus trees canopies for easy management practices to cope with the dynamics of water and soil fertility coupled with allelopathic effects.

1.2: Statement of the Problem

Successful intercropping of Eucalyptus trees with food crops is limited by; the soil and water dynamics, and allellochemical accumulation in the soils under the tree canopy. The other limiting factor is the issue of competition for light between trees and crops. The status of the soil (chemical, physical and biological) under Eucalyptus trees is less understood or has not been adequately studied especially for the different ages of the trees. While the soils under *Eucalyptus* species have been found to contain allelochemicals (Sasikumar *et al.,* 2002) which negatively influence crop production especially in arable lands, it's not clear what quantity or which crop species are affected since the effects vary in terms of the species, their harmfulness and the conditions under which they grow. The allelopathic effects in *Eucalyptus* spp are masked by effects resulting from competition for light and nutrients although it is evident that most of the studies have not been able to separate the effects of competition for light, water or nutrients from those of allelochemicals. Moreover, it is not clear at what stage of Eucalyptus tree growth is the effect of allelopathy, maximum or minimum, to permit successful intercropping or the minimum quantity of the active allelochemical present in the soil to cause crop failure. For successful intercropping, the soil fertility status under Eucalyptus trees needs to be understood adequately.

The performance of crops under reduced light conditions in the tree-crop mixtures remain an obstacle in accommodating both trees and crops on farms of the agroforestry hence need for this research. The results from this study provide information about the nutrient cycling in the Eucalyptus plantations and the aspects of soil fertility that need amendments to enable successful and sustainable cropping under the Eucalyptus trees. In addition, allelopathy and soil water repellency were assessed and their influence on crop performance evaluated.

Moreover, different types of crops were screened for their specific responses to the amount of PAR intercepted to help understand on how to manipulate the tree canopy for easy management practices to cope with soil fertility and water dynamics together with allelopathic effects.

1.3: Justification

Scarce arable land resources due to population increase has intensified competition between food crops and human settlement leaving very little space for trees and therefore; there is need for a balance to accommodate both either in rotation programs or in agroforestry systems. There is need to increase food production to make the population food secure hence the scarce little arable land under trees like the vast Eucalyptus plantations need to be utilized through agroforestry systems or tree-crop rotational programmes. The income generated from tree growing especially Eucalyptus is not only an incentive but also justification for farmers to plant more trees. According to Kenya Forest Service (2009), a hectare of firewood and poles generates a net income of Ksh 540,000 and Ksh 1,000,000 respectively over a period of 8 years.

This is a high return compared with Ksh 88 000 for low to medium production maize, Ksh 96,000 for medium production maize, Kshs 376,000 for high production maize and Ksh 630,000 for tea over the same period (Kenya Forest Service (2009). On-farm Eucalyptus tree farming in Kenya is very essential to humanity as it is a cheap source of energy, high quality fiber for pulp industry, firewood and timber (Oballa *et al.*, 2010) as well as its contribution to carbon sequestration which help mitigate climate change effects. Continuous use of Eucalyptus poles for electricity transmission as an alternative to concrete poles ensures sustainable or more planting of these trees which still contributes to our economy and as a source of green energy.

1.4: Objectives

1.4.1: Overall Objective

Nutrient dynamics, allelopathy levels and crop performance under Eucalyptus tree canopies (plantations)

1.4.2: Specific Objectives

1. To evaluate and monitor nutrient dynamics in *Eucalyptus grandis* plantations before and during intercropping
2. To assess the levels of allelopathy in *Eucalyptus grandis* plantations and its effect on crop germination and soil water repellency
3. To evaluate and model the performance of crops under *Eucalyptus grandis* tree canopies and its potential for agroforestry

1.5: Hypotheses

1.5.1: Research hypothesis

The nutrient dynamics, allelopathy of the soils and light capture influence the crop performance under the Eucalyptus trees

1.5.2: Statistical hypotheses

H_A**:** There are significant changes in the soil and plant tissue nutrients across the different ages of *Eucalyptus grandis* plantations with or without crops growing underneath

H_A: The allelochemicals produced by different ages of *Eucalyptus grandis* tree affect soil water repellency and crop performance

H_A: The different ages of *Eucalyptus grandis* tree canopies have positive interactions on the growth and performance of crops underneath

CHAPTER TWO

LITERATURE REVIEW

2.1: Eucalyptus Tree: Origin, Botany and Propagation

Eucalyptus (gum trees), is a diverse genus of flowering trees and shrubs in the myrtle family (*Myrtaceae)*, order (*Myrtales*), sub order (*Myrtoideae*), tribe (*Eucalypteae*) (Sheppard *et al.*, 2007; Oballa *et al.*, 2010) and is believed to be native to Australia, and adjacent islands of New Guinea and Indonesia. Eucalyptus' is a combination of Greek words *eu* and *kalýpto* meaning 'well covered', in reference to the cap protecting the bud, a name first published in 1788 after French botanist Charles Louis L'Hritier de Brutelle described *Eucalyptus obliqua* (Messmate Stringy bark). In 2004, Currency Creek Arboretum (CCA) in South Australia which specializes in *Angophora*, *Eucalyptus* and *Corymbia* had planted over 900 species and subspecies (over 6000 plants) of *Eucalypts* (Sheppard *et al.*, 2007). Eucalyptus can be classified into four main categories according to tree size; Small (10 m), Medium-sized (10–30 m), Tall (30–60 m) and Very tall (over 60 m) (Sheppard *et al.*, 2007). Most *Eucalyptus* spp are evergreen but some tropical species lose their leaves at the end of the dry season, and their leaves are covered with oil glands an important feature of the genus with mature trees having a patchy characteristic shade because the leaves usually hang downwards (Sheppard, *et al.*, 2007). The tree is propagated from seed and through vegetative (cuttings) while planting material is collected from trees with superior characteristics; tall, good form, little taper and healthy (Oballa *et al.*, 2010). Seeds of Eucalyptus readily germinate without any pre-treatment but because of their small size; they are usually mixed with sand, sawdust or fine soil before sowing in seedbed (Oballa *et al.*, 2010).

2.2: Soil Nutrient and Water Dynamics under Eucalyptus trees

Long-term plantations of Eucalyptus have been reported to improve the soil fertility i.e. within a period of 8 to 10 years (Couto & Betters, 1995). Comparative studies of soils under Eucalyptus trees and adjacent grasslands have shown no significant differences in fertility if the trees take longer than 10 years (Couto & Betters, 1995). It has also been reported that soils under Eucalyptus tree have high level of micronutrients compared to those under old tea bushes (Oballa & Langat, 2002). Moreover, local farmers in Kenya without research findings often associate the dense root network of Eucalyptus with lowered water tables and drying up of springs (Kenya Forest Service, 2009). Such allegations have been proved correct by Lane *et al.*, (2004), whereby Eucalyptus plantations on lands previously under crops and indigenous trees was found to lower water tables due to its deep and dense root network and soil hydrophobicity. According to Alemie (2009), growing of Eucalyptus trees influenced soil available phosphorus, exchangeable calcium, total nitrogen, soil water content, soil hydrophobicity, light intensity and the density of the undergrowth. The effect was distance-dependent from the Eucalyptus stand with studies indicating at 5 m from tree stand; there was greatest reduction of available phosphorus (3.5 mg kg^{-1}), total nitrogen (0.1 %) and soil water content of 8.7 % than at 40 m away (Alemie, 2009). Furthermore, soil water repellency has been reported in the top soils up to more than 2 m distance from Eucalyptus tree with growth attributes of crops such as height, yield, biomass and population count decreasing with distance to Eucalyptus trees (Alemie, 2009). In Sudan (EI-Amin *et al.*, 2001), Eucalyptus tree was associated with crop yield reduction due to nutrient depletion and production of toxic exudates.

Nutrient mining and export out from the Eucalyptus plantation's soil system through harvesting has been reported to deplete soil fertility (Zerfu, 2002). Eucalyptus seedlings are vulnerable to severe water stress unlike the seedlings of indigenous deciduous tree species (Gindaba *et al.,* 2004) therefore need more water to compete with neighboring plants for the available water in the soil which results to their reduced growth performance. Scientific studies also show *Eucalyptus* spp being efficient in water use for biomass accumulation despite the species consuming huge amounts of water compared to other tree species i.e. *Eucalyptus* spp consumes twice amount of water taken up by *Acacia auriculiformis* or *Albizzia lebbek.* For example, *Eucalyptus* spp require 785 litres of water to produce 1 Kg of biomass compared to cotton coffee or bananas which require 3,200 litres, sunflower 2,400 litres, and maize, potato and sorghum 1,000 litres. The water budget for Eucalyptus is a function of many factors; rainfall, soil type, type of species (Senelwa *et al.,* 2009).

2.3: Soil Water Repellency and Water dynamics

Soil hydrophobicity or water repellency is a reduction in the rate of wetting and retention of water in soil caused by the presence of hydrophobic coatings on soil particles (Dekker *et al.,* 1998). Soil water repellency has important consequences for ecological and hydrological properties of soils and usually retards infiltration capacity and induces preferential flow, a scenario occurring on a wide range of soils with varying climatic conditions (Dekker *et al.,* 1998). Water repellency in soil affects the soil water contact angle which then affects the imbibing behavior of soils (Bauters *et al.,* 2000) leading to reduced surface water infiltration.

According to Fishkis (2015), an understanding of the relation between soil water repellency and soil moisture is a prerequisite of water-flow modelling in water-repellent soils. Furthermore, the relation between soil water repellency and soil moisture in different soils with different particle-size distributions has a positive relationship between contact angle and the soil moisture pressure values (Fishkis, 2015). The relationships between contact angle and water content in the soils have showed a significant hysteresis in drying conditions than during wetting Fishkis (2015). Soil water repellency is a function of the interaction of cohesion and adhesion forces and it affects the contact angle and the matrix potential. If the contact angle is below 90°, the matrix potential is negative and therefore water will infiltrate under a negative pressure but if the angle exceeds 90° the matrix potential is positive (Bauters *et al.,* 2000). The relationship between water potential and water content is influenced by soil texture and porosity and according to Kajiura & Tange (2010); water potential is a better indicator for water repellency than the moisture content. In soil water repellency measurements, the question is always about persistence and severity of water repellency. Persistence has been described as the time taken for the water droplet to infiltrate the soil while severity is described as the degree of water repellency during a limited period of time expressed as the angle formed at the first appearance of droplet entry into the soil otherwise known as the initial advancing contact (Roy & MacGill, 2002). Persistence is a kinetic measurement and is affected by vapor pressure and the arrangement of organic molecules while severity is a thermodynamic measurement (Roy & MacGill, 2002). Soil water repellency is caused and influenced by several processes in the soil; the most important being the presence of hydrophobic organic coatings (Doerr *et al.,* 2000).

These hydrophobic compounds are either polar with amphiphilic structures or non-polar aliphatic hydrocarbons. Biological causes of water repellency in the soil are the products of microbial plant decomposition including waxes, aromatic oils or resins. According to Mueller & Deurer (2011), soil water repellency is also influenced by soil physical properties like soil texture, bulk density and even atmospheric conditions (humidity and temperatures) and even chemical properties like carbon and nitrogen contents, pH and the bulk density (Deurer *et al.*, 2011). Fine textured soils such as clay have a bigger specific surface area and are thus less exposed to organic coatings (Woche *et al.*, 2005). Deurer *et al.*, (2011) showed that a decrease in bulk density leads to an increase in soil water repellency a fact explained by the accumulation of hydrophobic organic material in the topsoil. Furthermore, the effects of fire have also been reported to also induce hydrophobicity due high temperatures which volatilizes and condense the hydrocarbons in the soil (Doerr *et al.*, 2000).

The degree of water repellency has been measured with the molarity of ethanol droplet (MED) test and the persistence water repellency with the water droplet penetration time (WDPT) tests. In the WDPT tests, the contact angle is determined by the cohesive energy of the organic film which is adsorbed on the soil and therefore persistence in repellency is determined by the difference in cohesive energies between this adsorbed film and the water (Douglas *et al.*, 2007). Water repellency is a transient property and it varies depending on the soil moisture content with repellency occurring mostly in dry soils but disappears when the water content exceeds critical limit (Ritsema & Dekker, 1994). The variability of the critical water content has been said to be caused by the wetting history of the soil and the distribution of the water in and around the micro aggregates of the soil

(Dekker *et al.,* 2001). A transition zone for water repellency has been proposed by Dekker *et al.,* (2001) where the soil is either hydrophobic or hydrophilic. In this transition zone, the upper threshold of the transition zone indicates the absence of soil water repellency while the lower limit cannot be used to predict repellency as it is not specified value (Doerr *et al.,* 2000). Soil water repellency has been found to have a non-linear relationship with the water content whereby the relationship between water content and soil water repellency has brought about the idea of actual and potential water soil water repellency. Actual soil water repellency is measured on the field moist soil and the potential of water repellency is measured in an oven dried soil (Landl, 2013).

Several approaches have been employed in the management of soil water repellent soils including; application of surfactants in order to increase the soil water infiltration, claying for sandy soils and selection of plant species which cope with low soil moisture availability (Landl 2013). In addition, cultivation and liming have been suggested to reduce hydrophobicity in the soil. Lastly, inoculation of soil with wax-degrading bacteria as a biological way to reduce hydrophobicity has been suggested by Roper (2006).

Numerous techniques have been developed to determine the water repellency of soil and the most common method is the water droplet penetration time (WDPT) test, which is based on the time taken for a drop of water to infiltrate into the soil (Dekker *et al.,* 1998; 2009). This test can be set up easily and conducted in the field therefore very useful in demonstrating the occurrence of water repellency under field conditions. In addition, another method which employs the molarity of ethanol droplet (MED) test, which is an extension of the WDPT test (DeBano, 1981; 2000), uses different concentrations of ethanol to alter the surface tension of the liquid (Moody, and Schlossberg 2010).

Hydrophobicity index has been defined as the ratio of the sorptivities of water and ethanol which is an indicator of the degree of soil hydrophobicity whereby water infiltration is impeded by soil hydrophobicity, while ethanol infiltration is not, (Moody & Schlossberg, 2010). In a soil that is not hydrophobic, water and ethanol will infiltrate at a similar rate; however, in hydrophobic soils, infiltration of water will be slowed and ethanol will be unaffected by the hydrophobicity. According to Dekker *et al*.,(2009; 1998), there are seven classes of repellency on the basis of the time needed for the water drops to penetrate into the soil: class 0, wettable, non-water repellent (infiltration within 5 s); class 1, slightly water repellent (5–60 s); class 2, strongly water repellent (60–600 s); class 3, severely water repellent (600–3600 s); and extremely water repellent (>1 h), further subdivided into class 4 (1–3 h); class 5 (3–6 h); and class 6 (>6 h). In this study, the objective was to measure the persistence of water repellency by the soil which was based on water content using water droplet penetration time (WDPT) test.

2.4: Allelopathy in Eucalyptus Trees

In 1937, Austrian plant physiologist, Hans Molisch coined the name ‘allelopathy’ for the plant–plant interference and as a consequence, he has been labeled as the father of allelopathy (Li *et al.*, 2010). Eucalyptus trees contain allelochemicals which have harmful effects on other plants under its canopy in the ecosystem which hampers germination, death of seedling and significant reduction in growth and yield (Waller, 1987). Allelochemicals produced by invasive species in forests can inhibit the growth of competing vegetation direct or indirectly, thereby providing the invader with a competitive advantage (Ridenour and Callaway, 2001).

In the ecosystem, phenolic compounds are said to be the most important and common plant type of allelochemicals, (Wang *et al.*, 2006). Phenols are chemical compounds consisting of a hydroxyl group (-OH) bonded directly to an aromatic hydrocarbon group and according to Zeng *et al.*, (2008), they include structures such as simple aromatic phenols, hydroxy substituted benzoic acids and benzyl aldehydes, hydroxy substituted cinnamic acids, coumarins, tannins, and flavonoids.

In terms of structure and properties, allelochemicals have been classified into the following categories: (1) water-soluble organic acids, straight-chain alcohols, aliphatic aldehydes, and ketones; (2) simple unsaturated lactones; (3) long-chain fatty acids and polyacetylenes; (4) quinines (benzoquinone, anthraquinone and complex quinines); (5) phenolics; (6) cinnamic acid and its derivatives; (7) coumarins; (8) flavonoids; (9) tannins; (10) steroids and terpenoids (sesquiterpene lactones, diterpenes, and triterpenoids) (Wang *et al.*, 2006). Some of the phenolic allelochemicals that have been isolated from the leachates of bark, fresh leaves and leaf litter of *Eucalyptus tereticornis, E. camaldulensis, E. polycarpa and E. microtheca* include; p-coumaric, gallic, gentisic, p-hydroxybenzoic, syringic and vanillic acids and catechol (Li *et al.*, 2010) (Figure 1).

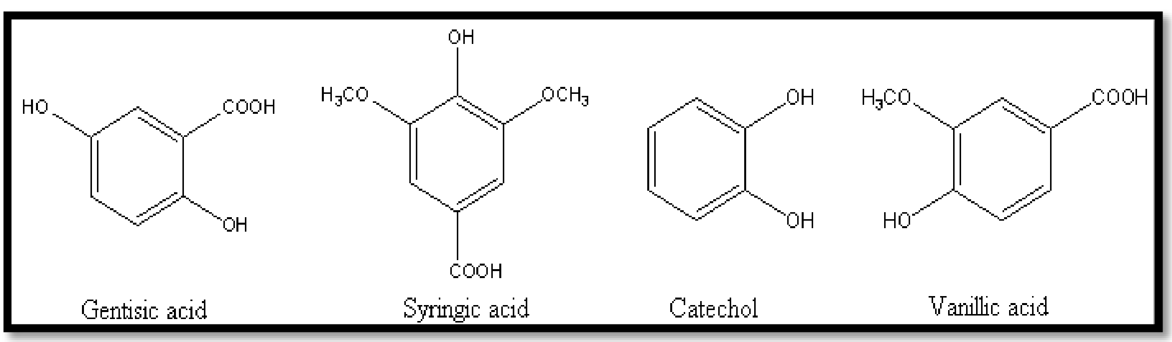


Figure 1: Phenolic allelochemicals isolated from Eucalyptus trees
(Source: Li *et al.*, 2010)

The phenolic compounds are distributed in plants and very common in plant decomposition products, and they are important precursors of humic substances in soils (Li *et al.,* 2010). Moreover, phenolics in soils can occur in the three forms: free, reversibly bound, and bound forms whereby the ortho-substituted phenolic compounds, such as salicylic and o-coumaric acids, and dihydro-substituted phenolics, such as protocatechuic and caffeic acids, are adsorbed by clay minerals by forming chelate complexes with metals (Li *et al.,* 2010). Free phenolic compounds may accumulate in rhizosphere soils, especially in soils flooded with vegetable waste waters, (Li *et al.*, 2010). Studies of extracts of leaf litter and root exudates of *Eucalyptus urophylla*, *E. citriodora* and *E. camaldulensis* have indicated inhibition on the germination speed and seedling growth of Chinese cabbage and radish plant (Zhang and Fu, 2010). In addition, both extracts of leaf litter and root exudates of *Eucalyptus* spp stimulated the seed germination of cucumber while their leaf litter was inhibitory to seedling growth meaning that crop can be grown well under *Eucalyptus* spp, if their leaf litter were removed in tree-crop agroforestry systems (Zhang and Fu, 2010).

From previous studies, it is clear that effects of leaf litter are stronger than root exudates and litter-fall removal seems to be an option for management strategy to reduce the allelopathic effects of *Eucalyptus* spp on understory crops but the issue of different ages and the quantity of allelochemicals was addressed in this study.

2.5: Productivity of Tree-Crop Mixtures: Light Interception and Management

Light interception by different components of a multi-layered agroforestry systems like the Eucalyptus-crop mixtures and the distribution of the photosynthetically active radiation (PAR) within the canopy units, are the key factors influencing the productivity of tree-crop mixtures (Nair, 1979; 1983; Loomis and Connor, 2002). To modify existing or create new agroforestry systems, information on newly created patterns for light capture is required (Johar *et al.,* 2017; Whiting, 2011).Therefore it is important to estimate the PAR intercepted by each component of the systems at any given time, and to integrate it to reflect the time they occupy in space (Nair, 1993). In addition, the productivity of plants intercropped under a tree stand will be negligible if the tree canopy is able to intercept most of the light, but tree crops are inefficient in the interception of radiant energy as they take many years to produce a full canopy (Nair, 1993).

The productivity of crop canopies has been quantified using concepts of Leaf Area Index (LAI) and the Crop Growth Rate (CGR) as estimators of the crop's ability to capture light energy available for plant growth (Gardner *et al.,* 1985; Campillo *et al.,* 2012) therefore, necessary tools used to assess productivity in this study. The amount of growth attained by a plant within a given period of time is a function of the net rate of photosynthesis, which is the difference between gross photosynthesis and respiration (Nair, 1993). Photosynthesis rates are primarily determined by solar radiation interception, $C0_2$ concentration in the atmosphere, temperature and the availability of moisture and nutrients (Gardner *et al.,* 1985). The major management options for manipulating photosynthesis of plant communities in agroforestry systems is based on the manipulation of the light (radiation) (Nair, 1983).

The amount of solar radiation intercepted by a canopy is dictated by many factors including; the leaf angle, size, shape and even the thickness, together with its chlorophyll concentration are key determinants (Campillo *et al.,* 2012) and it is believed that only 50% of the incident radiation intercepted by plant canopy is utilized for photosynthesis (Varlet-Gancher *et al.,* 1993; Loomis and Connor, 2002). Maximum productivity in crop canopies depends on the capture of incident solar radiation which is influenced by optimal levels of water and nutrients (Loomis and Connor, 2002) in this case from soils under the Eucalyptus tree canopy. Agroforestry combinations can cause considerable modifications in the availability of these growth factors which may not be marked enough to cause significant effects on photosynthetic rates; however, various plants react differently in their response to the interacting effects of shade, nutrients, and even temperature (Nair, 1993).

2.6: Tree-Crop Mixtures: Selection of Plants/Crops

Recent studies by Chaturvedi *et al.,* (2017) and Mugunga (2016), suggest integration of Eucalyptus trees and crops is possible especially in spatially zoned agroforestry systems or as mixtures although the edge effect interactions between trees and crops seemed to affect crop yields. Therefore, selection of species to be used in these agroforestry systems should be based on cultural, economic as well as environmental factors (Nair, 1993) although the photosynthetic pathways of different species is an important physiological consideration in the search for "new" species. Under good agronomic management in the tropics and subtropics, C_4 monoculture systems should be more productive than C_3 (Monteith, 1978). The C_3 species include grasses such as wheat, oats, barley, rice, rye, and dicot species (legumes, cotton, tobacco, and potatoes) and almost all trees (Nair, 1993). This selection of C_3 may be significant in agroforestry systems where annual or seasonal canopy types can be found as well as the permanent overstory type, (Tieszen, 1983). In the annual or seasonal type of agroforestry, it is deemed important to build up leaf area as quickly as possible hence C_4 plants are said to be the best suited for this function. In conditions with a permanent woody over-story with the trees possessing the C_3 pathway; the under-story proposed to be C_3 crops (Tieszen, 1983). Finally, if shading is significant, the understory plants preferred should be C_3 as they have a greater efficiency of CO_2 uptake at lower irradiance levels than C_4 plants (Tieszen, 1983). The outputs from the interactions between trees and crops are influenced by many factors including environmental conditions and plant species (Sheley and James, 2014). Therefore, there is need to screen more crop species for their specific responses as they grow under Eucalyptus trees for easy management practices to cope with the dynamics of water and soil fertility coupled with allelopathy.

CHAPTER THREE

MATERIALS AND METHODS

3.1: Materials

3.1.1: Study Sites/Area

The experiments were established at the KEFRI Muguga Forest Eucalyptus Plantations situated in Muguga, Kiambu County. The site is located about 25 km north-west of Nairobi city Centre, off Nairobi-Nakuru road with latitude 1^0 15’ 0"S and longitude 36^0 40’ 0"E; at an elevation of 2040 m above sea level. Its agro-ecological zone is Lower Highlands (LH_3) (Jaetzold *et al.,* 2009) with average rainfall of 900 – 1200 mm p.a. The area experiences both long and short rains. The area is characterized by heavy well drained, extremely deep, dusky red to dark reddish brown, friable clays of volcanic origin developed on tertiary basic igneous rocks, (Jaetzold *et al.,* 2009). The soils have moderate to high fertility with a pH of 5.8 and are classified as Ferralic Lixic Nitisols (Eutric) (IUSS Working Group WRB, 2006). The experiments were conducted inside the *Eucalyptus grandis* plantations during the wet (April-September) and dry (Nov-March) periods of the years 2015 and 2016.

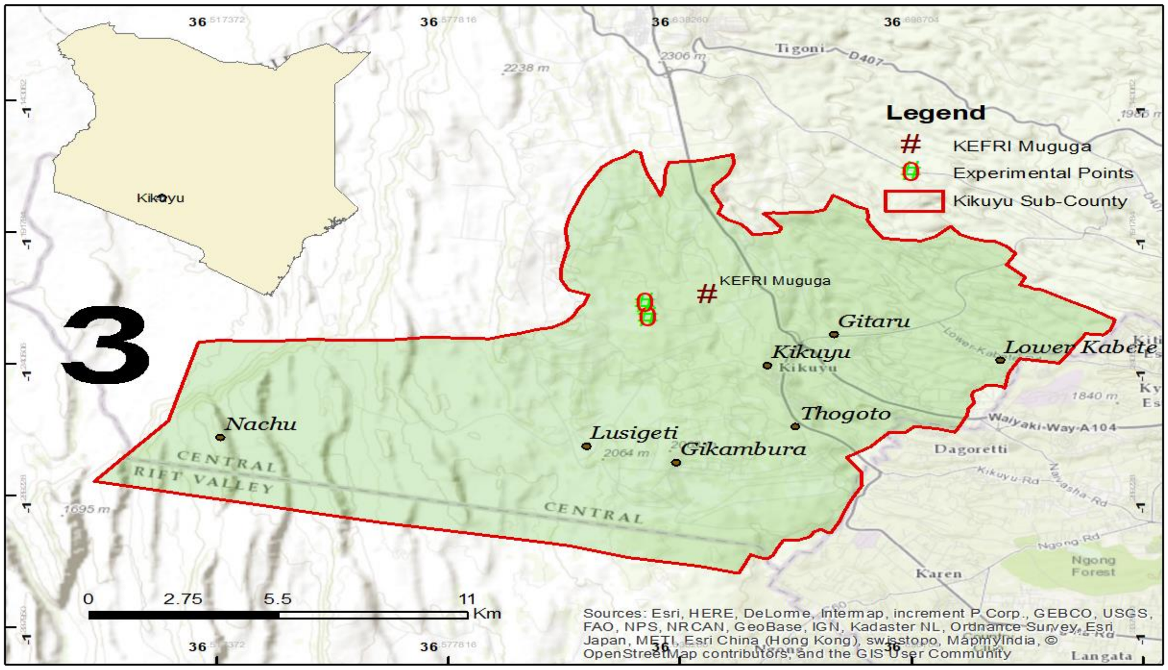


Figure 2: Location (Map) of the Study area

3.1.2: *Eucalyptus grandis* Maiden. (Rose gum)

The above named species was chosen because it is the most dominant in Kenya and in the study area with fast growth rate. *Eucalyptus grandis* is a straight fast-growing tree which can grow to a height of up to 50 m and diameter at breast height (dbh) of 2 m. In Kenya, the species has high growth rate in the highlands, where altitude ranges from 1400 to 2200 metres above sea level (m.a.s.l.) and mean annual rainfall of above 900 mm, (Oballa *et al.*, 2010). The species grows in well-drained range of soil types (Food and Agriculture Organization, FAO, 1979) including the Nitisols, Ferralsols, Acrisols and Andosols. Kenya Forestry Research Institute (KEFRI) through selection and breeding, developed fast-growing straight trees that attain mean annual volume growth of above 45 $m^3ha^{-1}yr^{-1}$ and height growth of 5 m yr^{-1} at age 3 to 5 years (Oballa and Giathi, 1996).

Eucalyptus grandis is mainly grown for power transmission poles, domestic and industrial wood fuel, and timber.

3.1.3: Description of *Eucalyptus grandis* plantations

The *Eucalyptus grandis* used were plantations of pure stands. The plantations aged 1.5, 3, 6, 12, and 20 years, the spacing was 4 m by 3 m but for the 40 years of age, the plantation was scattered as some of the trees had died or fallen by strong winds over time with grown undergrowth consisting of grass and twigs. For plantation ages of 1.5, 3, 6, 12, 20 years, there was little undergrowth consisting mainly grasses. The plantations had always been established on lands previously cropped with beans, maize and potatoes after they had been left fallow for at least a year. The plantations were established in blocks of more than 0.5 ha in pure stands on flat to gently rolling lands. The trees were not fertilized.

Figure 3: Eucalyptus tree plantations of different ages at the study site
(Source : Author, 2016)

3.1.4: Farm Crops

For this study, the following farm crops were selected because of their popularity as the main crops grown in the study area: Irish potatoes (*Solanum tuberosum* L.), Common bean (*Phaseolus vulgaris*), a grain legume and the Black Night shade (*Solanum villosum*) commonly known as Mnavu (Swahili), Managu (Kikuyu). Kenya Mpya which is a common variety of Irish potato developed by Kenya Agricultural and Livestock Research Organization (KALRO) was used in this study and it is oval in shape; white skinned in color with pink eyes with average yields of 35-45 tons per hectare and is good for chips and mashing. The variety has very high tolerance to late blight and it matures early (3 months) (Kenya Agricultural Research Institute (KARI, 2008). For common beans, a local variety known as Rose Coco (GLP 2) also developed by KALRO was used in this study. The variety is for altitudes of 1500-2000 m, maturity of 3 months period, with yield range of 1.8-2.0 t/ha and its widely adaptable for medium and high rainfall areas, besides being resistant to anthracnose. For Nightshade vegetable, *Solanum villosum* was adopted in this study. The species had been improved on by KALRO (previously KARI) resulting to better yields (AVRDC, 2003). The seeds for common beans and black night shade were sourced from the local agro-vets (agro dealer shops) while for the potatoes was sourced from KALRO Tigoni Gene bank Centre. The crops were planted inside *Eucalyptus grandis* plantations of ages 3 and 6 years with another experiment similar being set up in the open field in the same area for comparison purposes. The experiment in the open field was set up on land left fallow for one year previously cropped with maize and beans after harvesting of mature *Eucalyptus grandis* trees 3 years earlier. For experimental design and layout see Objective 3 (section 3.5.2, Figure 7).

3.2: Methods

3.3: Soil and Plant nutrients dynamics in *Eucalyptus grandis* plantations before and during intercropping

3.3.1 Activities

This objective had two main activities: 1). characterizing the soil and plant tissue nutrient levels under different ages of Eucalyptus trees with the aim of establishing crops under the trees and 2), to monitor the soil nutrient changes under the tree canopies after crops have been introduced. The soils under *E. grandis* of ages 1.5, 3, 6, 12, 20 and above 40 years were sampled and analyzed.

3.3.2: Design and Methodology for Soil Sampling

Soil profile pits and auger samples under tree canopies were used for this study. The experiment adopted RCBD design with age of plantation being the treatment. Blocks were generated depending on the homogeneity of the land (topography and soil physical attributes). Radial cluster method was used for sampling of soils i.e. one profile pit was surrounded by three soil auger samples (Figure 4). Three (3) soil profile pits were used for each age of *E. grandis* hence 18 auger points per age of plantation (6 age treatments). Soil sampling down the profile was at the following depths; 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm after which samples were pretreated and analyzed in the laboratory.

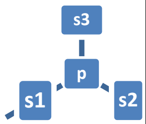
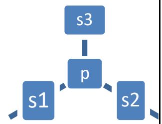
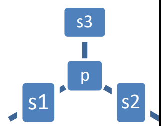
Age of Eucalyptus Plantation										
1.5yrs		3yrs		6yrs		12yrs		20yrs		>40yrs
	**B1**				**B1**					
	B2				**B2**					
	B3				**B3**					

Figure 4: Radial cluster method for soil sampling in the Eucalyptus plantation

Key: S1, **S**2 and **S**3 are auger points while **P** is soil profile point arranged in a radial cluster design. **B1**, **B2** and **B3** are blocks. Adapted from, FAO (2008).

Figure 5: Litter fall on the canopy floor inside the Eucalyptus plantations
(Source : Author, 2016)

3.3.3 Frequency of Soil Sampling

Soil sampling was twofold: 1) sampling was carried out under different ages of Eucalyptus plantation for characterizing soil nutrient status as mentioned in the activities section 3.3.1 above. 2), sampling was carried out in the crop plots before planting and after harvesting of the crops for every growing season to monitor nutrient changes.

3.3.4: Weather conditions during the soil sampling period

First/initial soil sampling under the canopies was carried out between August and October 2015 before crops were planted inside the canopy from November 2015 short rains with soil moisture content ranging between 35-40%.

3.3.5: Soil Physical parameters

The analyses included; bulk density (core ring method), water content (gravimetric, potentiometric), texture (Hydrometer method). Detailed information is found in documented standard protocols including Okalebo *et al.,* (2002).

3.3.6: Soil Chemical parameters

The parameters included; organic matter (OM) using loss of ignition method, organic carbon (OC), (Walkley & Black method), total nitrogen, (Kjeldahl method), total phosphorus (Kjeldahl digestion and colorimetric determination, available phosphorus (Olsen method); exchangeable bases i.e. potassium (K), calcium (Ca), magnesium (Mg); pH (Glass electrode method), electrical conductivity (EC) (Potentiometric method). In addition, extractable micronutrients; iron (Fe) and manganese (Mn) were analyzed. Detailed information is found in documented standard protocols.

3.3.7: Protocols/Procedures for Laboratory Analysis of Soils

Soil analyses were done at the Kenya Forestry Research Institute (KEFRI) Soil Science Laboratories at Muguga. The content of total nitrogen and phosphorus were measured in a digest obtained by treating soil sample with hydrogen peroxide, sulphuric acid, selenium powder and salicylic acid. Hydrogen peroxide oxidises the organic matter while the selenium compound acts as catalyst for the process and the sulphuric acid completes the digestion at elevated temperatures. Salicylic acid prevents the loss of nitrates. After this acid digestion of the soil sample, colorimetric determination of the nutrients was done using the UV-VIS spectrophotometer. For soil available (Olsen) phosphorus, the soil was extracted with 0.5 M solution of sodium bicarbonate at pH 8.5 followed by colorimetric determination using the UV-VIS spectrophotometer.

To determine exchangeable bases (potassium, calcium and magnesium) in the soils; a soil sample was extracted with an excess of 1 M NH_4OAc (ammonium acetate) solution such that the maximum exchange occurs between the NH_4 and the cations originally occupying exchange sites on the soil surface. Then amounts of each exchangeable metal cations in the soil extract were then determined by atomic absorption spectrophotometry at specific metal wavelengths. For determination of extractable micronutrients (manganese and iron); the soils were extracted in 1% EDTA, and then the filtrate was aspirated into an air-acetylene flame of an atomic absorption spectrophotometer and absorbance read at specific metal wavelengths.

The organic carbon in the soil was determined by subjecting the soil to complete oxidation (sulphuric acid and aqueous potassium dichromate mixture) followed by titration using ferrous ammonium sulphate on the unused potassium dichromate (Nelson and Sommers, 1975). The difference between added and residual potassium dichromate gives a measure of organic carbon content of soil.

Organic matter in the soil was determined through the loss of ignition method whereby the sample was ignited slowly in a muffle furnace to a final temperature of 550°C. The loss in weight represents the moisture and organic matter content of the sample, while the residue represents the ash. Soil pH was measured on 2.5:1 soil water suspension while electro conductivity measured in a saturated soil paste extract.

3.3.8: Sampling of Litter and fresh leaves of Eucalyptus trees

In this study, litter referred to dead un-decomposed leaves and branches collected on the ground below the Eucalyptus tree canopy. The leaf samples referred to the fresh leaves plucked from the Eucalyptus trees specifically at the base and at the middle of the tree canopy. Radial cluster sampling was used as elaborated in (section 3.3.2). The trees near the auger hole points were sampled from which the surface litter in quadrats was collected for laboratory analysis. The litter from quadrats measuring 1 m by 1 m was heaped together and about 200 g of the material sampled and air dried for 7 days prior to laboratory analysis. The fresh leaves were collected from tree branches cut from the base and at the middle of the canopy from trees near soil auger hole points in each of the blocks as outlined in section 3.3.2 above. About 200 g of fresh leaves were collected, air dried for more than 7 days before laboratory analysis was done.

3.3.9: Protocols for analysis of Eucalyptus Litter and fresh Leaves

The analyses included; organic matter (OM) (loss of ignition method), total nitrogen (Kjeldahl method), total phosphorus, potassium (K), calcium (Ca), magnesium (Mg). In addition, total micronutrients; iron (Fe), manganese (Mn) and copper (Cu) were analyzed. The content of total nitrogen and phosphorus were measured in a digest as explained in Section 3.3.7.

The total cation concentration of potassium, calcium and magnesium in plant tissues plus micronutrients (manganese and iron) were determined by first digesting samples as mentioned above (in a mixture of sulphuric acid, salicylic acid, hydrogen peroxide and selenium powder) and detected through atomic absorption spectrophotometer at specific wavelengths. Organic matter in plant sample was determined through the loss of ignition method as explained in Section 3.3.7.

3.3.10: Data Analysis

Data analysis involved Multivariate analysis of variance (MANOVA) to ascertain the effects of tree age and soil depth on the nutrient concentrations in the soils under Eucalyptus trees. Correlations of soil nutrients were done using Pearson's method with two tailed T-test. In addition, the effect of cropping under the tree on the soil nutrient concentrations was evaluated. Multiple comparisons and Mean separation were done using Fisher's protected Least Significance Difference (LSD) and Tukey's HSD tests due to the assumed parametric variance from the treatment units. The Tukey method was preferred due to its ability to test all pairwise differences with reduced probability of making a Type I error in drawing conclusions. The statistical software packages used were GenStat Edition 16 (VSN International, 2013) and IBM SPSS Statistics Version 23 formerly SPSS (IBM Corp, 2016).

3.4: Levels of Allelopathy in *Eucalyptus grandis* trees and its effect on crop germination and soil water repellency

3.4.1: Activities

1. Analysis of total soluble polyphenols as allelochemicals present in litter, leaf and soil under Eucalyptus tree canopies and test its effect on crop seed germination
2. Determination of soil water repellency/hydrophobicity under Eucalyptus canopies

3.4.2: Determination of water soluble polyphenols in soil under Eucalyptus trees and plant tissues (litter and leaves)

3.4.3: Sampling of soil and plant tissue materials (litter and fresh leaves)

In this study, litter referred to dead un-decomposed leaves and branches collected on the ground below the Eucalyptus tree canopy. The fresh leaf samples were plucked from the Eucalyptus trees specifically at the base and at the middle of the tree canopy. Radial cluster sampling was used as elaborated in (section 3.3.2). The trees near the auger hole points were sampled from which the surface litter in quadrats was collected for laboratory analysis. The litter from quadrats measuring 1 m by 1 m was heaped together and about 200 g of the material sampled and air dried for 7 days prior to laboratory analysis. The fresh leaves were collected from tree branches cut from the base and at the middle of the canopy from trees near soil auger hole points in each of the blocks as outlined in section 3.3.2 above. About 200 g of fresh leaves were collected, air dried for more than 7 days before laboratory analysis. Soil sampling was carried out at 0-10 cm and 10-20 cm, after which samples were pretreated (air dried and sieved) and analyzed in the laboratory.

3.4.4: Laboratory protocols for analyzing total water soluble polyphenols

The water soluble polyphenol compounds in plant tissues and soil were extracted with methanol and analyzed by the Folin-Denis reagent (Waterman and Mole, 1994). The samples were dried at 35-40^{o}C, crushed and passed through 1mm sieve mesh. Extraction was done using aqueous methanol at 80^{o}C for 1 hour. The filtrate was then reacted with Folin-Ciocalteu/Folin-Denis reagent and absorbance read at 760 nm with the UV Spectrophotometer.

3.4.5: Testing Eucalyptus allelopathy on germination of test crops

For the laboratory germination tests, 10 certified seeds of common beans were sown on cotton wool fully soaked in water soluble polyphenols solutions of different concentrations in petri dishes at temperatures 20-25^{o}C. The seeds were partially submerged in the solution in petri dishes with control (distilled water). Daily germination (%) was calculated from the germination count recorded daily from 2-days after sowing till 14 days. The original polyphenols concentrations of litter and fresh leave samples were diluted by a factor of 10, 20, 30, 40, and 50 until germination attained. Dilution was done using distilled water. For the soil, dilution was not done as the germination occurred at original natural polyphenol concentration.

3.4.6: Determination of soil water repellency in soils under *Eucalyptus grandis* trees

3.4.7: Experimental Design and Methodology

This study was carried out in the field (*in situ* experiment) to characterize soil water repellency as a result of allelochemical accumulation in soils growing under Eucalyptus trees of different ages. Soil profile pits up to 100 cm depth were dug inside the plantations as described before (Section 3.3.2 above).

The experiment was a factorial arrangement in Randomized complete block design (RCBD) with age of plantation, soil depth and season (dry or wet) as treatments. Soil sampling was at the following depths; 1 cm (surface), 10 cm, 20 cm, 40 cm, 60 cm, 80 cm and 100 cm. Soil moisture was measured in the field using a moisture probe and in the laboratory by gravimetric method.

3.4.8: Procedure/Protocols for measuring soil water repellency

The procedures or protocols followed were those of Dekker *et al.,* (1998, 2009). The method used was the Water Drop Penetration Time (WDPT) test, which is based on the time taken for a drop of water to infiltrate into the soil. Three (3) drops of distilled water were placed on the smoothened surface of a soil surface for each horizon using a standard medicine dropper. Then, by use of a stop watch, the time that elapsed before the droplets were absorbed or infiltrated into the soil was recorded. The same procedure was repeated using ethanol 99 ethanol v/v with the time being recorded. Soil water repellency (persistence) was measured basing on water content.

3.4.9: Data Analysis

Data analysis involved analysis of variance to ascertain the effects of tree age, soil moisture and depth on the hydrophobicity of the soils. Mean separation were done using

Fisher's protected Least Significance Difference (LSD) and Tukey's HSD tests due to the assumed parametric variance from the treatment units. The Tukey method was preferred as it has reduced probability of making a Type I error. GenStat Edition 16 (VSN International, 2013) statistical software was used. In addition, stepwise multiple regressions on the factors influencing soil water repellency was done using IBM SPSS Statistics Version 23 formerly SPSS (IBM Corp, 2016).

3.5: Evaluate and model the performance of crops under *Eucalyptus grandis* tree canopies and its potential for agroforestry

3.5.1: Activities

The first activity was to establish and assess the performance of farm crops under Eucalyptus tree canopy so as to evaluate the potential of the trees for agroforestry. Assessment of the performance of the crops was mainly on; germination, growth rates and possible yield potentials. The second activity was to analyze canopy in terms of light resource capture by crops. This was evaluated by measurement of crop leaf area index (LAI) and the amount of photosynthetically active radiations (PAR) reaching the crops.

3.5.2: Experimental Design for establishing crops under Eucalyptus trees

Farm crops i.e. common beans, Irish potatoes and the black nightshade vegetable were planted inside *Eucalyptus grandis* plantations of ages 3 and 6 years. The crops were planted along the rows of Eucalyptus in plot sizes of 4 m by 2 m. Since tree spacing was 4 m by 3 m then minimum tree-crop distance was 0.5 m while 1.5 m the maximum. The experimental design was a factorial arrangement in Randomized complete block design (RCBD) with type of crop (3) and plantation age (2) being treatments replicated thrice. Equal numbers (100) of certified seeds were sown per plot. The recommended spacing for potatoes was 45 cm by 30 cm; common beans 30 cm by 15 cm and 40 cm by 15 cm for night shade vegetable were used. An open field, adjacent to the experiment was used to set up a similar layout for farmer practice comparisons. The open field had Eucalyptus tree which were harvested 3 years prior to the experiment, cropped for two years under maize and beans and finally left fallow for one year. For the experiment in the open field, inorganic fertilizer NPK (17:17:0) was applied during planting with control having none. For the experiment under trees, no fertilizer was added as the study sought to find out the sustainability of the Eucalyptus ecosystem in supporting crops on its own.

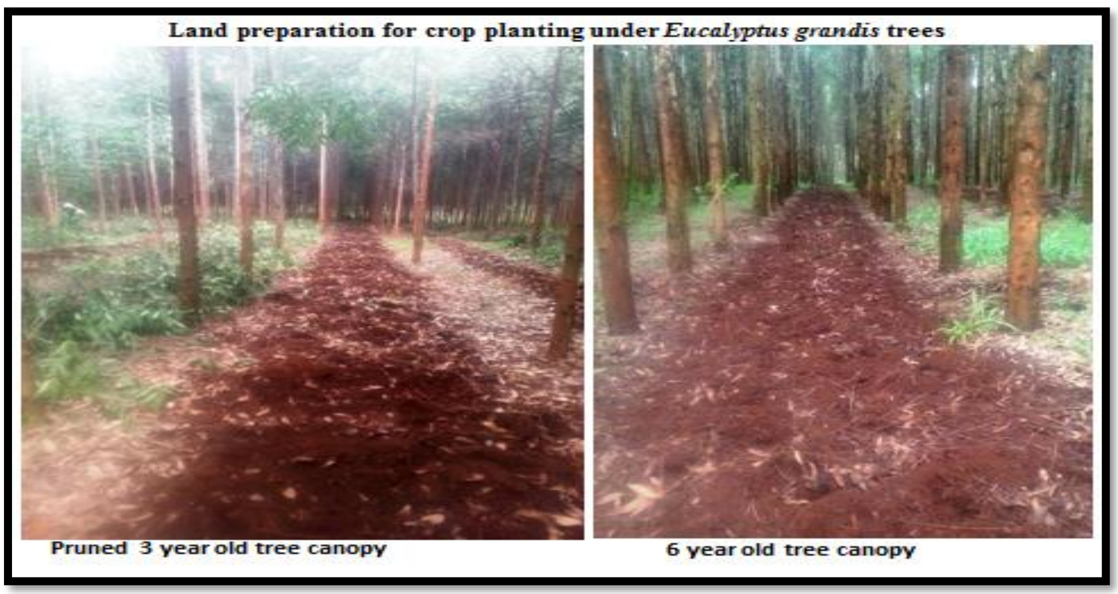


Figure 6: Land preparation in the experimental plots inside the Eucalyptus plantations (Source: Author, 2016)

3.5.3: Experimental Model for cropping inside Eucalyptus plantations

General Linear Model for the Randomized Complete Block Design (RCBD)

$Yijk = \mu + Bi + Aj + Ck + ACjk + \alpha ijk$. Where –

Yijk- Parameter

µ- Overall mean

Bi – Block Effect

Aj – Age of plantation (2)

Ck – Crop type (3)

ACjk – Age of plantation * Crop type (Interaction)

αijk – Residual Error

3.5.4: Experimental Field Layout inside Eucalyptus plantations

The field layout is a shown below in figure 7

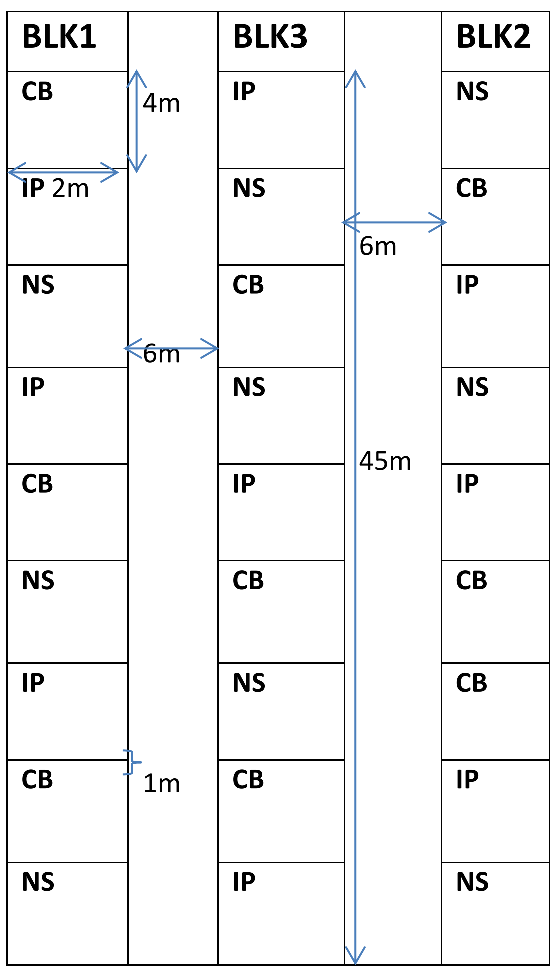


Figure 7: Layout of crops inside the Eucalyptus plantations

Where; CB, NS and IP refer to common bean, nightshade and Irish potatoes respectively. Blocks generated depending on the homogeneity of the land inside the plantations.

3.5.5: Data Collection

Germination (cumulative and percentage) and yields were collected from the experiment. In addition, Leaf area index of crops, photosynthetically active radiation and both soil and air temperatures were collected in crop plots.

3.5.6: Germination Percentage

Daily germination percentage was calculated as follows:

GT = (NT X 100)/N …………………………Equation 1. Where;

GT = germination percentage, NT= number of seeds that actually germinated and N= no. of seeds planted per plot. Germination count was recorded on a two day interval and commencing two days after planting for a period of 3 weeks

3.5.7: Measurement of Photosynthetically Active Radiation (PAR)

Photosynthetically active radiation is the range of visible light that plants can use for photosynthesis usually in the range of the 400 to 700 nm waveband (Biggs, 1984). In this study a portable Light meter (LI-COR Model LI-189) attached to a radiation Quantum sensor (LI-COR Multiplier ((-186.22), tcoff: 0.0036 mols^{-1} m^{-2}) was used to measure PAR (LI-COR, 1995). The sensor is a silicon photodiode with an enhanced response in the visible wavelengths which can make instantaneous measurements of Photosynthetically Active Radiation (PAR) in air or water in micromoles per second per square meter (µmols^{-1} m^{-2}). The LI-189 measures the current output of the sensor, and converts the measured current to units of radiation. The sensor was exposed to the sky at a distance of 0.5 m over the crop canopy and measurements of PAR taken. Measurements per plot consisted of 3 recordings done systematically (middle and at the edges) taken inside the crop plots. PAR measurements were carried out on a weekly basis starting after full germination of the crops. Measurements were done at mid-day when the sun was directly overhead.

3.5.8: Measurement of Leaf Area Index

Leaf area index (LAI) is a dimensionless quantity that characterizes plant canopies computed as the one-sided green leaf area per unit ground surface area in broadleaf canopies. LAI is used to predict photosynthetic primary production, evapotranspiration and as a reference tool for crop growth. In this study, a Plant canopy analyzer equipment (LI-COR Model: LAI-2000) was used to measure and compute the amount of foliage in a crop canopy (LAI). The measurements are made above and below the canopy which are then used to compute canopy light interception at five zenith angles, from which LAI is computed using a model of radiative transfer. The sensor measures how quickly radiation is attenuated as it passes through the canopy (LI-COR, 1992), www.licor.com/LAI-2000. The LAI-2000 employs gap fraction analysis technique to estimate LAI (Welles and Norman, 1991). Since the crops were planted in rows then the readings were made along diagonal transects between the rows but at even intervals across the row so as to improve the spatial average. In this study, two (2) above canopy readings were made with each having four (4) below canopy readings (one above canopy reading was followed by four (4) below canopy readings, the process which was repeated once for one complete set of measurement per plot). For the four (4) below canopy readings the samples were taken across the plot; the first location was at the beginning/edge of the first row, the second taken ¼ point of second row way across in the plot, the third point was at mid-point of the third row and the fourth point was taken at the ¾ point of fourth row way across the plot. Leaf area index was measured at the same geo-referenced points in crop plots on a fortnight (14 days) basis starting 1 month after emergence of the crops up to harvest maturity (after foliage had fully developed). Measurements were carried out in diffuse light conditions (No direct sunlight).

3.5.9: Measurement of soil and Air temperatures

The soil temperatures in the crop canopies were measured by use of a soil thermometer inserted in the soil at the middle of the crop plots (1.5 m from the tree) in the rows to a depth of 50 cm. Air temperatures were measured by the field thermometer held above the crop canopy. Both measurements were carried out on a weekly basis.

3.5.10: Harvesting and measurements of crop yields

Measurement of the crop yield was done at harvest maturity from the experimental plots (4 m by 2 m). For common beans, dry kernel weights were measured; harvesting was done when grain had a moisture content of 19% and dried further to 13% when final yield measurements were done. Fresh weight and dry weight of the leaves was measured for nightshade while fresh tuber weight was measured for Irish potatoes.

3.5.11: Data Analysis

Data analysis involved analysis of variance to ascertain the effects of canopy and its age on crop growth performance, canopy attributes (LAI and PAR). Multiple comparisons and Mean separation were done using Fisher's protected Least Significance Difference (LSD) and Tukey's HSD tests due to the assumed parametric variance from the treatment units. GenStat Edition 16 (VSN International, 2013) was used. Correlations of canopy analysis (LAI and PAR) and yield were done using Pearson's method with two tailed T-test. In addition, modeling the relationships (stepwise multiple regression) between canopy attributes and yield was done using IBM SPSS Statistics Version 23 formerly SPSS (IBM Corp, 2016).

CHAPTER FOUR

RESULTS

4.1: Soil and Plant nutrients dynamics in *Eucalyptus grandis* plantations before and during intercropping

4.1.1: Effect of tree age and soil depth on the nutrient concentration in soils under *Eucalyptus grandis*, its litter and fresh leaves

Total nitrogen (TN %)

The effect of Eucalyptus tree age on the concentrations of total nitrogen in the litter was statistically significant ($p \leq .01$) but not for the soil and fresh leaves contents (Figure 8). The TN % in the soil reduced down the soil profile with top horizons of 0-20 cm having higher content (0.41 TN %) compared to 80-100 cm depth having 0.23 TN % **(**Table1). The content of total nitrogen in the soil increased with age of the Eucalyptus plantation (Figure 8).

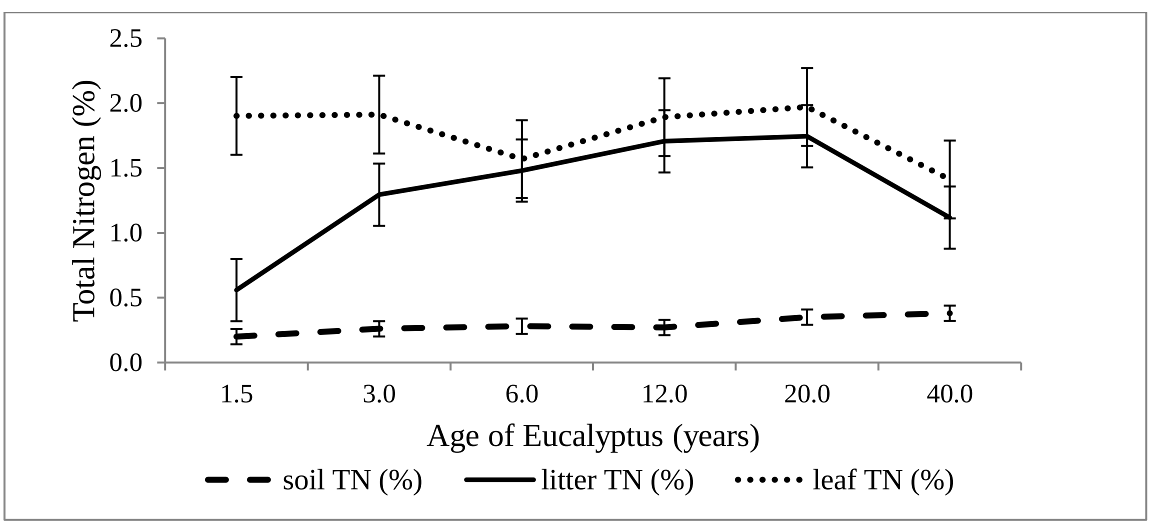


Figure 8: Total Nitrogen in the soil, litter and fresh leaf of *Eucalyptus grandis* trees.

The trends of total nitrogen (TN %) in both leaf and litter were nearly similar across the different Eucalyptus trees of different ages with the maximum being 20 year old tree plantations i.e.1.9 TN% and 1.7 TN% respectively . Nitrogen content in the leaf was more compared to the one for litter.

Table 1: Soil Total nitrogen (%) **content in the soil profile under *Eucalyptus grandis* trees of different ages**

Depth/Age	1.5 years	3 years	6 years	12 years	20 years	40 years	mean
0-20 cm	0.32	0.39	0.34	0.25	0.46	0.63	0.41
20-40 cm	0.24	0.43	0.42	0.37	0.37	0.36	0.37
40-60 cm	0.20	0.33	0.25	0.18	0.28	0.31	0.26
60-80 cm	0.11	0.21	0.25	0.26	0.34	0.28	0.24
80-100 cm	0.12	0.15	0.14	0.30	0.32	0.33	0.23
mean	0.20	0.29	0.28	0.27	0.35	0.38	0.29
	$LSD_{(p=.05)}$	CV (%)					
Age	0.14	34.00					
Depth	0.14						
Age*Depth	0.07						

Soil Organic Carbon (SOC %) and Organic Matter (OM %)

Soil organic carbon reduced significantly with soil depth ($p \leq .001$), with top horizons of 0-20 cm having higher content of 4.21 SOC % compared to 80-100 cm depth having 1.1 SOC %, **(**Table 2). The levels of SOC % concentration in the soil increased with the age of the Eucalyptus tree with 40 year old plantation having the highest (3.08 SOC %).

The age of Eucalyptus tree did not have a significant influence on the amount of organic matter (OM) concentration in the soils under the canopy. Furthermore, there was no significant difference in the quantity of OM (%) present in the leaf and litter of Eucalyptus across the different ages of the tree studied, Figure 9.

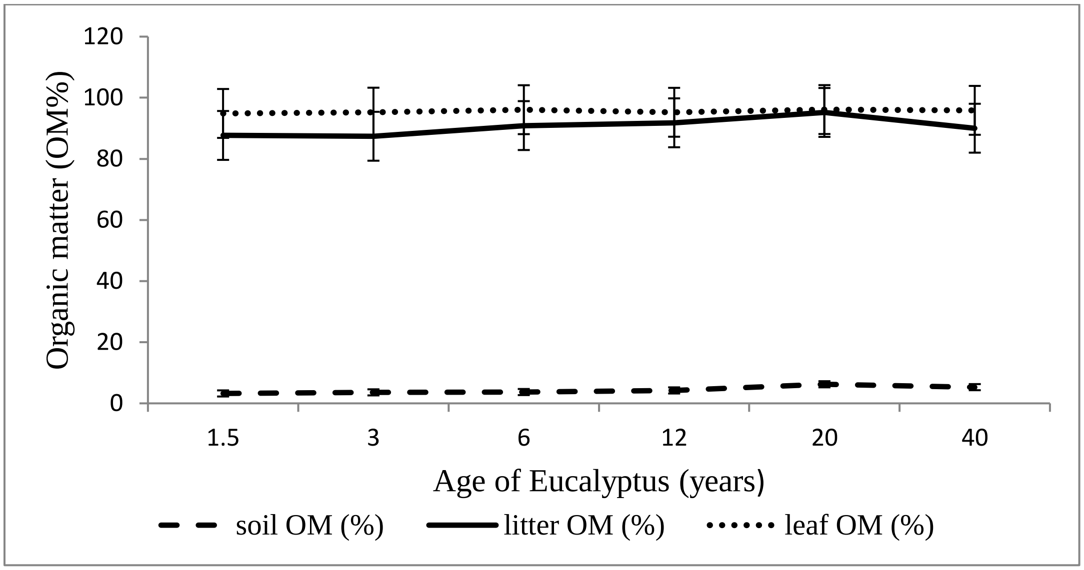


Figure 9: Organic Matter in the soil, litter and fresh leaves of *Eucalyptus grandis* trees of different ages.

Table 2: Soil Organic carbon (%) **content in the soil profile under *Eucalyptus grandis* trees of different ages**

Depth/Age	1.5 years	3 years	6 years	12 years	20 years	40 years	mean
0-20 cm	3.50	3.62	4.31	3.30	4.20	6.30	4.21
20-40 cm	2.44	2.75	1.94	1.80	2.70	4.20	2.64
40-60 cm	1.12	1.25	0.87	1.40	1.90	1.90	1.41
60-80 cm	1.06	1.69	0.94	1.00	0.90	1.30	1.15
80-100 cm	1.00	1.12	0.75	1.30	0.70	1.70	1.10
mean	1.82	2.09	1.76	1.76	2.08	3.08	2.10

	$LSD_{(p=.05)}$	CV (%)
Age	0.41	32.70
Depth	0.78	
Age*Depth	0.79	

Phosphorus: Total and available phosphorus (Olsen)

The age of the Eucalyptus tree had a statistically significant effect on soil total phosphorus

($p \leq .001$) but not available phosphorus with both increasing in the soil as Eucalyptus tree aged (Figure 10). Soil depth had no significant effect on available soil phosphorus (AP) as the amounts were constant or nearly equal for all the depths with top horizon 0-20 cm having marginally higher content (4.28 mg/ kg), Table 3. In addition, Eucalyptus age significantly affected total phosphorus in both leaf and litter ($p \leq .01$). The leaf total P and litter total P were negatively correlated whereby the high levels of total P in the leaf was contrasted by low levels in the litter of the same tree canopy age with both being equal in the 6 year old canopy (156 mg/ kg). The maximum total P content occurred at age 12 (474 mg/ kg) and 20 (438 mg/ kg) for litter and leaf respectively (Figure 10).

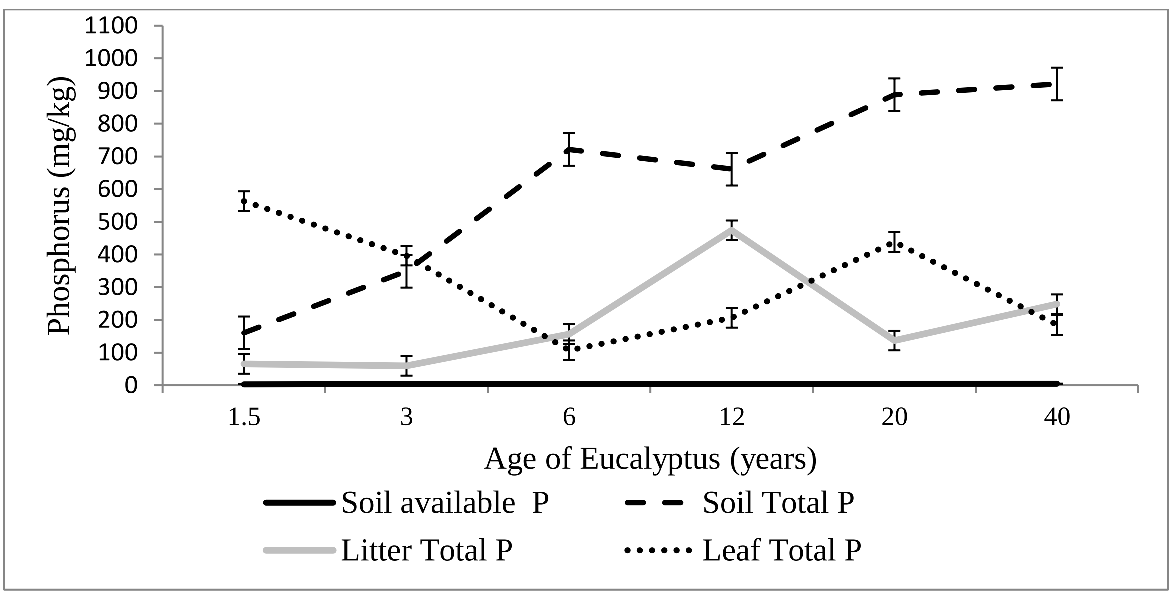


Figure 10: Phosphorus in the soil, litter and fresh leaf of *Eucalyptus grandis* trees of different ages.

Table 3: Available (Olsen) phosphorus (mg/kg) content in the soil profile under *Eucalyptus grandis* trees of different ages.

Depth/Age	1.5 years	3 years	6 years	12 years	20 years	40 years	mean
0-20 cm	2.74	4.64	4.52	4.38	5.12	4.28	4.28
20-40 cm	2.98	2.98	3.69	3.93	4.05	4.98	3.76
40-60 cm	2.74	3.21	3.21	4.40	3.33	4.62	3.59
60-80 cm	2.50	3.33	4.28	4.17	4.28	4.98	3.92
80-100 cm	2.98	2.74	3.45	4.52	4.88	4.93	3.92
mean	2.78	3.38	3.83	4.28	4.33	4.76	3.89
	$LSD_{(p=.05)}$	CV (%)					
Age	0.61	21.50					
Depth	0.81						
Age*Depth	1.18						

Calcium content in the Soil and Eucalyptus litter and fresh leaves

Soil depth significantly affected the content of calcium ($p \leq .05$) in the soil whereby, calcium reduced down the soil profile 0-20 cm (2363 mg/ kg), 80-100 cm (1150 mg/ kg). The soil under Eucalyptus tree aged 12 years (2368 mg/kg) contained more calcium for all the soil depths compared to other tree ages (Table 4). The age of the Eucalyptus tree had a statistically significant effect on soil exchangeable calcium ($p \leq .05$). The maximum soil calcium content occurred at 12 year old trees (2368 mg/kg) with no significant differences between 20 and 40 year old trees (Table 4). In addition, the age of the tree significantly influenced the content of total calcium in both litter and leaf ($p \leq .01$) (Figure 11). The content of calcium in leaf and litter had opposite trends, whereby, increase in the leaf led to reduction in the litter for the same tree age with the maximum for litter occurring at 3 year old (6800 mg/kg) and 40 year old (7900 mg/kg) canopies while lowest in 6 year old.

For fresh leaf, calcium content was lowest in the 3 year old canopy (3043 mg/kg) which surprisingly coincided with the highest litter content. The trend for leaf calcium content was similar to the soil calcium content (Figure 11).

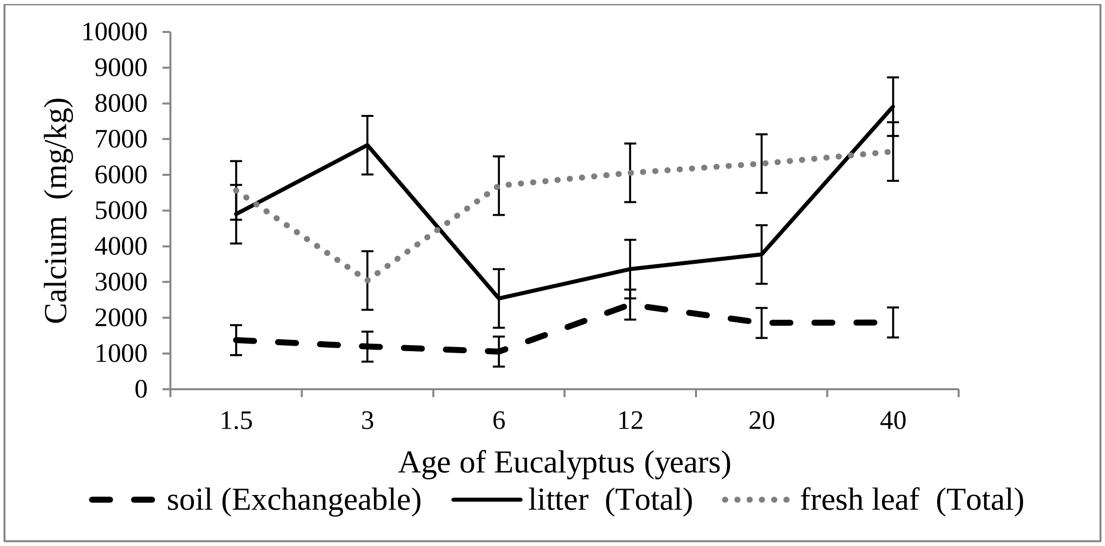


Figure 11: Calcium in the soil, litter and fresh leaf of *Eucalyptus grandis* trees of different ages

Table 4: Exchangeable calcium (mg/kg) content in the soil profile under *Eucalyptus grandis* trees of different ages

Depth/Age	1.5 years	3 years	6 years	12 years	20 years	40 years	mean
0-20 cm	1734.53	2730.49	1823.31	2909.52	2670.38	2311.21	2363.24
20-40 cm	1399.41	1855.61	1891.44	2807.68	2521.71	2048.65	2087.42
40-60 cm	1028.97	597.91	970.88	2291.20	1641.51	1759.49	1381.66
60-80 cm	1078.43	405.63	316.80	2058.65	1278.02	1522.16	1109.95
80-100 cm	1628.50	370.80	264.81	1777.22	1162.26	1702.21	1150.97
mean	1373.97	1192.09	1053.45	2368.86	1854.78	1868.74	1618.65
	$LSD_{(p=.05)}$	CV (%)					
Age	311.50	37.00					
Depth	690.40						
Age*Depth	520.10						

Potassium content in the Soil and Eucalyptus litter and fresh leaves

The age of the Eucalyptus tree had a statistically significant effect on soil exchangeable potassium ($p < .01$), whereby, the content in the soil reduced from ages 1.5 years to 6 years then increased as the tree matured, with 20 year old canopy having the highest (705 mg/ kg) and 6 year old canopy the lowest (387 mg/ kg) (Figure 12). Soil depth had no significant effect on the content of potassium in the soil. Potassium content reduced in 20-40 cm depth before increasing down the profile across all the ages of Eucalyptus plantations (Table 5).

The effect of tree age also significantly affected the content of total potassium for both leaf and litter ($p < .01$). The trends were similar for total K in the leaf and litter with both being equal at the age of 12 years (8488 mg/kg) which was a maximum for litter content.

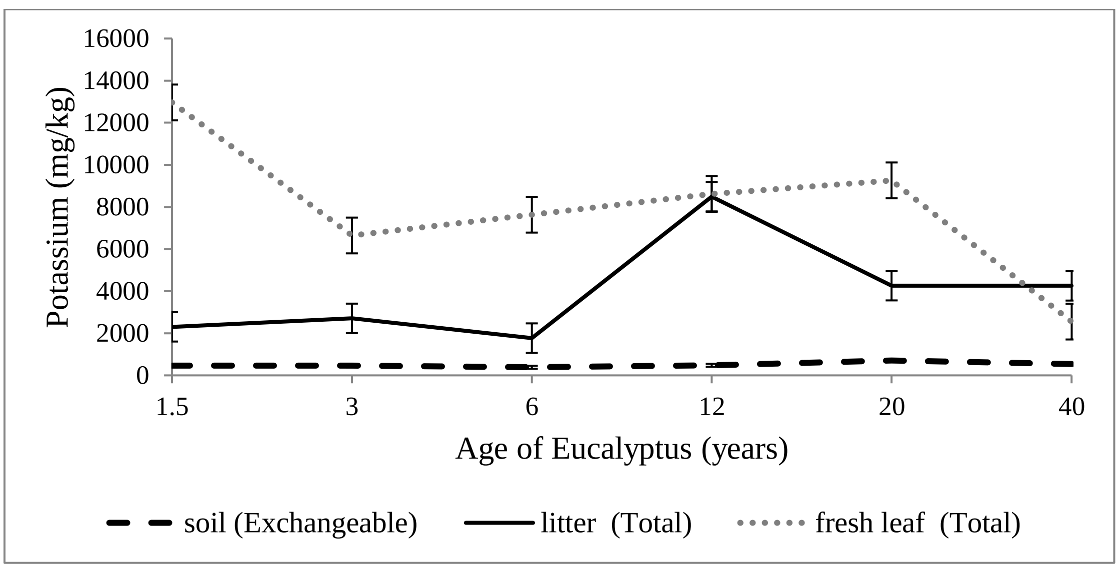


Figure 12: Potassium in the soil, litter and fresh leaf of *Eucalyptus grandis* trees of different ages.

Table 5: Exchangeable potassium (mg/kg) in the soil profile under *Eucalyptus grandis* trees of different ages.

Depth/Age	1.5 years	3 years	6 years	12 years	20 years	40 years	mean
0-20 cm	482.81	467.623	325.11	397.20	581.40	817.78	511.99
20-40 cm	354.63	417.3582	263.17	339.63	551.14	533.85	409.96
40-60 cm	408.89	493.4952	306.72	529.90	763.52	439.35	490.31
60-80 cm	523.25	490.3948	493.73	578.74	862.11	450.06	566.38
80-100 cm	520.29	415.0571	547.07	561.40	769.86	433.99	541.28
mean	457.98	456.7857	387.16	481.38	705.60	535.01	503.98
	$LSD_{(p=.05)}$	CV (%)					
Age	60.40	28.80					
Depth	166.00						
Age*Depth	115.60						

Manganese and iron content in the Soil and Eucalyptus litter and fresh leaves

The age of the Eucalyptus tree had a statistically significant effect on soil extractable iron ($p \leq .001$) but not manganese. From plantations aged 1.5 to 6 years, manganese content in the soil reduced then increased as the tree matured with peak values occurring at 20 years of age (1237 mg/ kg). The soil manganese correlated negatively to both litter and leaf contents whereby an increase in the soil content corresponded with a decrease in both leaf and litter with a maximum occurring in the canopy aged 20 years (1237 mg/ kg) which corresponded to lowest leaf and litter contents (Figure 13). Soil depth had no significant effect on the content of iron and manganese. Both iron and manganese had similar trends; reducing down the soil profile with iron 0-20 cm (745 mg/ kg), 80-100 cm (710 mg/ kg) Table 7,while manganese 0-20 cm (1212 mg/ kg) and 80-100 cm (1009 mg/ kg), (Table 6).

For the leaf and litter concentrations, the effect of tree age was statistically significant for both total manganese and iron ($p \leq .01$). For manganese in the tree tissues, both litter and leaf content had similar trends with peak values at canopy aged 3 years (1458 mg/ kg) and (904 mg/ kg) with lowest contents at canopy aged 20 years (835 mg/ kg) and (633 mg/ kg) respectively. The content of iron in the soil was higher than in the leaf and reached maximum at tree ages 6 and 20 years. The iron leaf content had a perfect but opposite trends with the soil content whereby both reduced from canopy age 1.5 up to 3 years then, took opposite directions with an increase in the soil leading to a reduction in the leaf with a maximum of soil coming in 6 year old canopy (847 mg/ kg) corresponding to lowest content in leaf (260 mg/ kg). For iron content in the litter, the trend was different from both leaf and soil, being maximum at canopy age of 3 (2550 mg/ kg) and reducing up to 40 years (407 mg/ kg) as the tree matured (Figure 14).

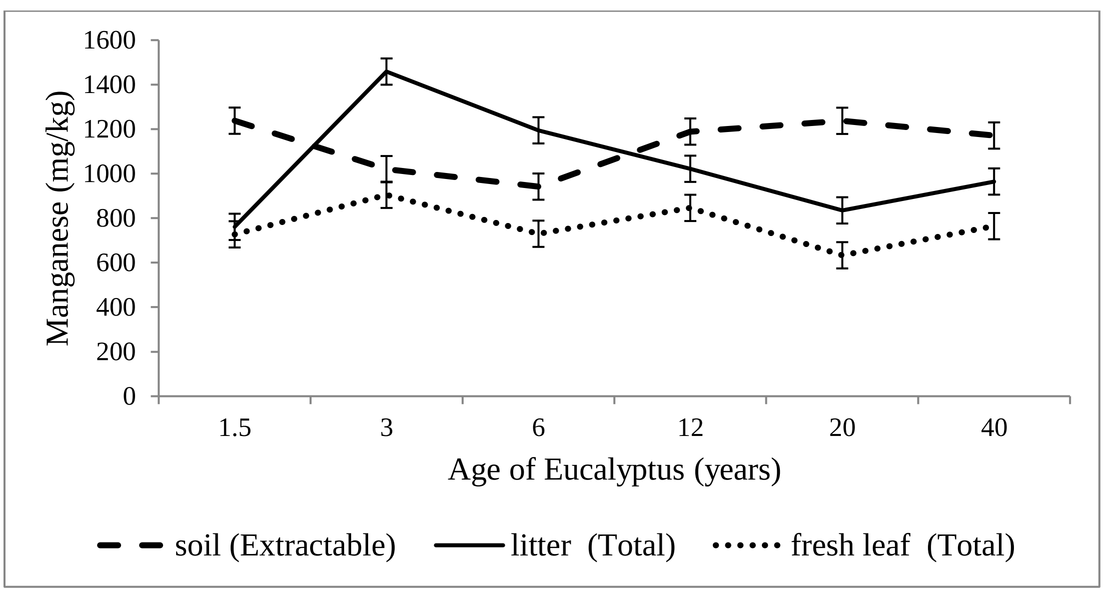


Figure 13: Manganese in the soil, litter and fresh leaf of Eucalyptus grandis *trees* of different ages.

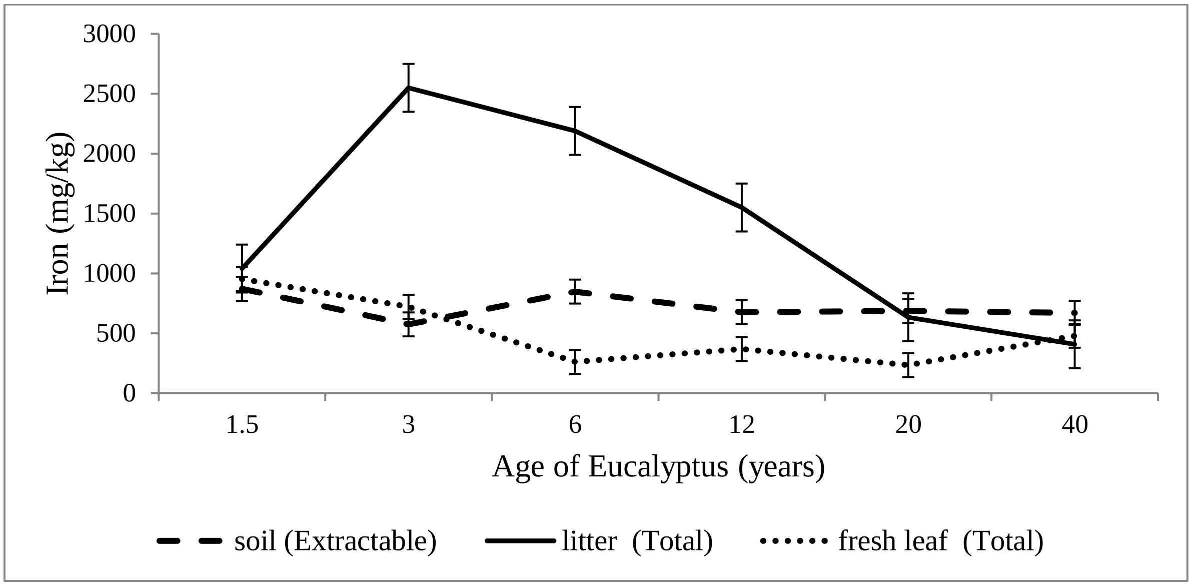


Figure 14: Iron content in the soil, litter and fresh leaf of *Eucalyptus grandis* trees of different ages

Table 6: Extractable manganese (mg/kg) content in the soil profile under *Eucalyptus grandis* trees of different ages.

Depth/Age	1.5 years	3 years	6 years	12 years	20 years	40 years	mean
0-20 cm	1221.58	1088.85	1208.82	1260.45	1242.56	1252.58	1212.47
20-40 cm	1258.19	1210.51	1242.46	1250.12	1236.98	1215.26	1235.58
40-60 cm	1247.47	1165.86	1230.61	1172.10	1237.26	1166.27	1203.26
60-80 cm	1237.94	666.30	661.51	1167.11	1234.59	1058.52	1004.33
80-100 cm	1225.04	970.00	366.20	1096.05	1235.78	1164.58	1009.61
mean	1238.04	1020.31	941.92	1189.17	1237.43	1171.44	1133.05

	$LSD_{(p=.05)}$	CV (%)
Age	155.00	17.00
Depth	220.40	
Age*Depth	303.60	

Table 7: Extractable iron (mg/kg) content in the soil profile under *Eucalyptus grandis* trees of different ages.

Depth/Age	1.5 years	3 years	6 years	12 years	20 years	40 years	mean
0-20 cm	841.62	502.62	873.22	879.07	643.23	730.47	745.04
20-40 cm	833.04	547.61	735.84	901.17	673.03	715.20	734.32
40-60 cm	859.98	552.87	903.46	572.85	679.43	644.68	702.21
60-80 cm	901.35	588.20	868.19	570.96	696.59	657.26	713.76
80-100 cm	919.26	678.54	859.10	459.44	739.34	606.30	710.33
mean	871.05	573.97	847.96	676.70	686.32	670.78	721.13
	LSD$_{(p=.05)}$	CV (%)					
Age	144.40	20.30					
Depth	168.20						
Age*Depth	274.20						

Soil PH and electrical conductivity (EC)

The age of the plantation had a statistically significant effect on soil pH ($p \leq .001$), but not electrical conductivity. Both parameters had a similar trend peaking in the 12 year old plantation (7.07, 0.05) respectively (Figure 15). The soil PH remained fairly constant and acidic (5.9 - 5.7) for tree ages of 1.5, 3 and 6 years before it rose to reach neutral levels (7.07) at age 12 years and slightly reduced but remained above (6.0). The trend was the same for electrical conductivity which was also high at 12 years of age.

Soil depth had no significant effect on Soil pH and electrical conductivity (Table 8). The 20-40 cm soil depth was significantly less acidic (increased pH) compared to top or underlying horizons across all the ages of Eucalyptus tree plantations studied. The soil electrical conductivity was highest at 20-40 cm depth (0.064) coinciding with the highest soil pH (6.57) and then reduced down the soil profile across all the ages of Eucalyptus tree studied (Table 9). Both soil pH and EC had similar trends, (Table 8 & 9).

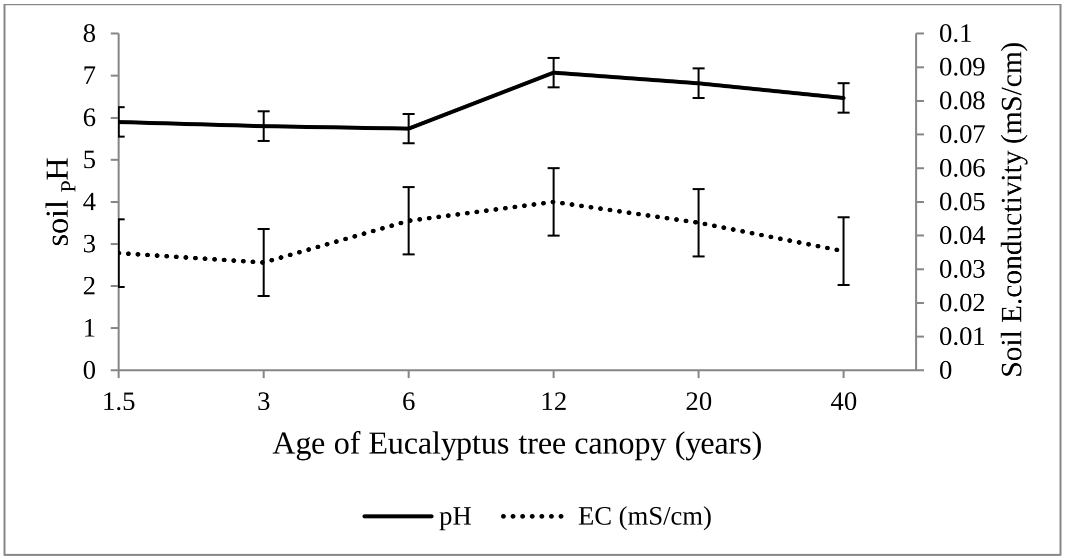


Figure 15: Soil pH and E. conductivity of the soils under *Eucalyptus grandis* trees

Table 8: Soil pH under *Eucalyptus grandis* trees of different ages.

Depth/Age	1.5 years	3 years	6 years	12 years	20 years	40 years	mean
0-20 cm	5.84	5.90	5.23	6.57	6.51	6.68	6.12
20-40 cm	6.14	6.19	6.23	6.60	6.95	7.01	6.57
40-60 cm	5.75	5.85	6.00	7.45	7.13	6.16	6.52
60-80 cm	5.97	5.53	5.73	7.60	6.62	6.06	6.35
80-100 cm	5.61	5.52	5.57	7.12	6.90	6.43	6.35
mean	5.86	5.80	5.74	7.07	6.82	6.47	6.38

	$LSD_{(p=.05)}$	CV (%)
Age	0.11	9.60
Depth	0.71	
Age*Depth	0.17	

Table 9: Soil electrical conductivity (mS/cm) under *Eucalyptus grandis* trees of different ages

Depth/Age	1.5 years	3 years	6 years	12 years	20 years	40 years	mean
0-20 cm	0.034	0.03	0.06	0.13	0.07	0.06	0.061
20-40 cm	0.044	0.04	0.08	0.06	0.07	0.10	0.064
40-60 cm	0.027	0.02	0.04	0.05	0.05	0.05	0.04
60-80 cm	0.037	0.05	0.04	0.06	0.04	0.04	0.04
80-100 cm	0.032	0.03	0.04	0.07	0.03	0.02	0.036
mean	0.034	0.03	0.05	0.07	0.06	0.06	0.05
	$LSD_{(p=.05)}$	CV (%)					
Age	0.03	42.00					
Depth	0.02						
Age*Depth	0.01						

4.1.2: Correlation coefficients of soil nutrients under the Eucalyptus tree canopies

Exchangeable calcium was positively correlated with pH $r = .50$ $p \leq .01$, electrical conductivity $r = .487$ $p \leq .01$, organic carbon $r = .592$ $p \leq .01$ total nitrogen $r = .446$ $p \leq .05$, available phosphorus $r = .469$ $p \leq .01$ and extractable manganese $r = .607$ $p \leq .01$. However calcium had a negative correlation with exchangeable potassium and iron although the relationship was not significant statistically. Total nitrogen was positively and significantly correlated with organic carbon $r = .645$ $p \leq .01$, available phosphorus $r = .396$ $p \leq .05$, exchangeable calcium $r = .446$ $p \leq .01$, and extractable manganese $r = .384$ $p \leq .05$. Exchangeable potassium was significantly and positively correlated with pH $r = .446$ $p \leq .05$ and exchangeable magnesium $r = .425$ $p \leq .05$ while negatively correlated with exchangeable calcium and iron but not significant.

Exchangeable magnesium was significantly and positively correlated with available phosphorus $r = .418$ $p \leq .05$ and exchangeable potassium $r = .425$ $p \leq .05$ but negatively and not significant to extractable manganese, extractable iron and electrical conductivity.

Extractable manganese had a positive and statistically significant correlation with exchangeable calcium $r = .607$ $p \leq .01$, total nitrogen $r = .384$ $p \leq .05$ and pH $r = .388$ $p \leq .05$. Extractable iron had a negative but not significant correlation with most of other soil nutrients i.e. organic carbon, total nitrogen, available phosphorus, exchangeable potassium, exchangeable calcium, exchangeable magnesium and pH (Table 10).

Table 10: Pearson coefficients: Soil nutrients under *Eucalyptus grandis* trees

	pH (1:2.5)	E.C (mS/cm)	OC (%)	N (%)	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Mn (ppm)	Fe (ppm)
pH (1:2.5)	1	.19	-0.02	0.14	0.22	.44*	.50**	.20	.51**	-.21
E.C (mS/cm)		1	.34	.13	.25	-.05	.48**	-.18	.11	.16
OC (%)			1	.64**	.29	.06	.59**	.02	.30	-.03
N (%)				1	.39*	.22	.44*	.17	.38*	-.20
P (ppm)					1	.23	.46**	.41*	.05	-.35
K (ppm)						1	-.01	.42*	.01	-.23
Ca (ppm)							1	.02	.60**	-.15
Mg (ppm)								1	-.17	-.30
Mn (ppm)									1	.01
Fe (ppm)										1

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

4.1:3: Effect of crop cultivation on soil nutrients under *Eucalyptus grandis* trees

Crop cultivation under Eucalyptus trees reduced total nitrogen ($p \leq .001$), Figure 18; potassium ($p \leq .05$), Figure 21 in the soil while available phosphorus ($p \leq .001$), Figure

17; pH ($p \leq .001$), Figure 16; magnesium ($p \leq .001$) Figure 22 and manganese ($p \leq .036$) Figure 23, increased in the soil (0-20 cm, 20-40 cm depths). Soil organic carbon ($p = .06$) Figure 19; exchangeable calcium ($p = .65$) Figure 20; extractable iron ($p = .90$), Figure 24; were unchanged during cultivation and cropping. The interaction of season and depth was statistically significant for available (Olsen) phosphorus ($p =.036$), total nitrogen ($p < .001$), exchangeable magnesium ($p = .003$) and % OC ($p =.011$).

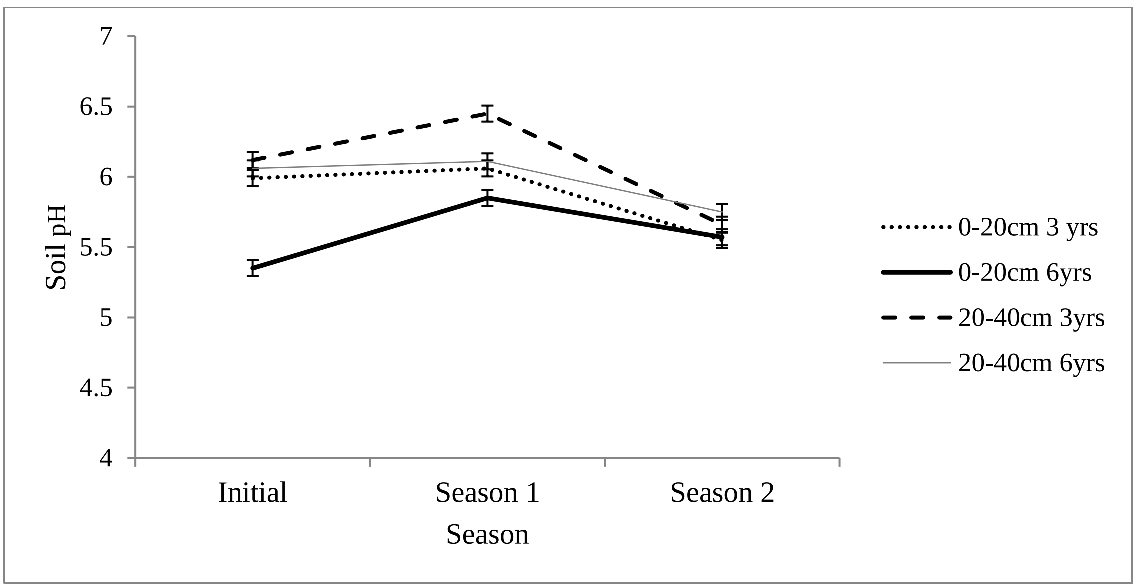


Figure 16: Changes in soil pH during cropping period under *Eucalyptus grandis* trees.

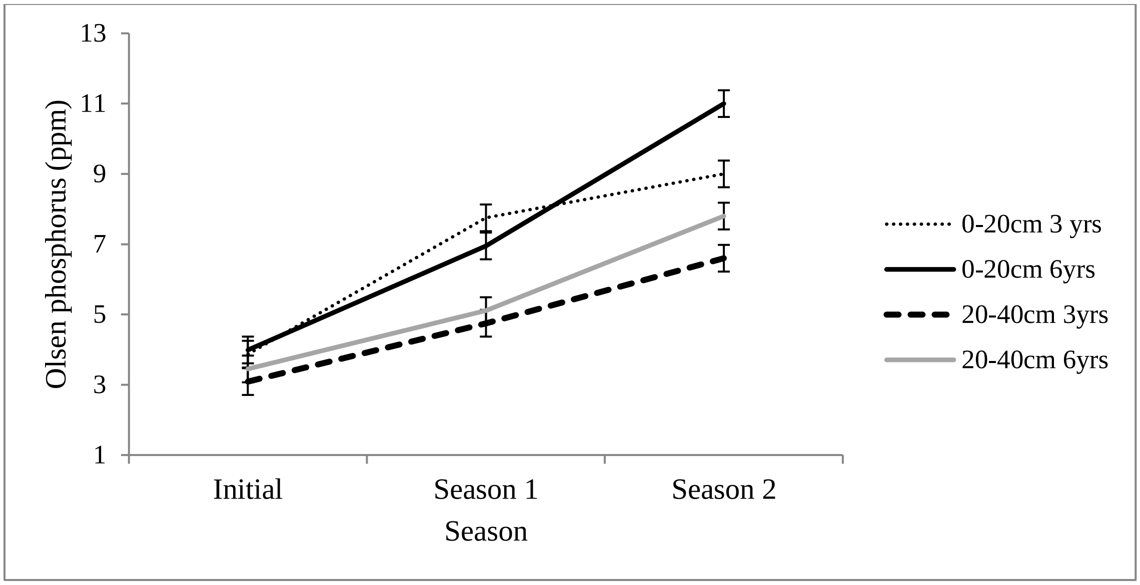


Figure 17: Changes in soil available phosphorus during cropping period under *Eucalyptus grandis* trees.

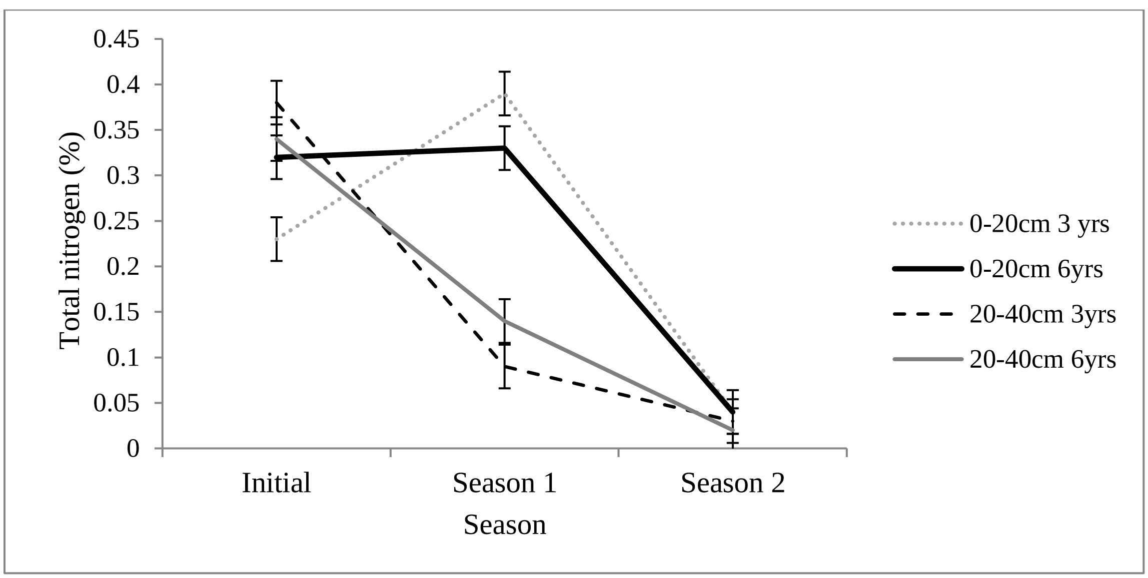


Figure 18: Changes in total nitrogen during cropping period under *Eucalyptus grandis* trees.

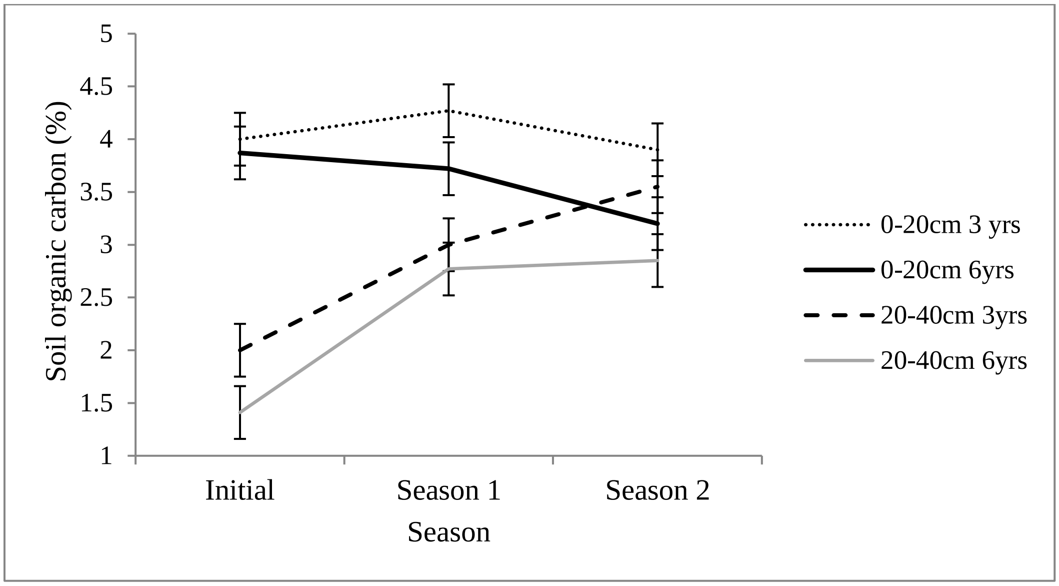


Figure 19: Changes in soil organic carbon (SOC) during cropping period under *Eucalyptus grandis* trees.

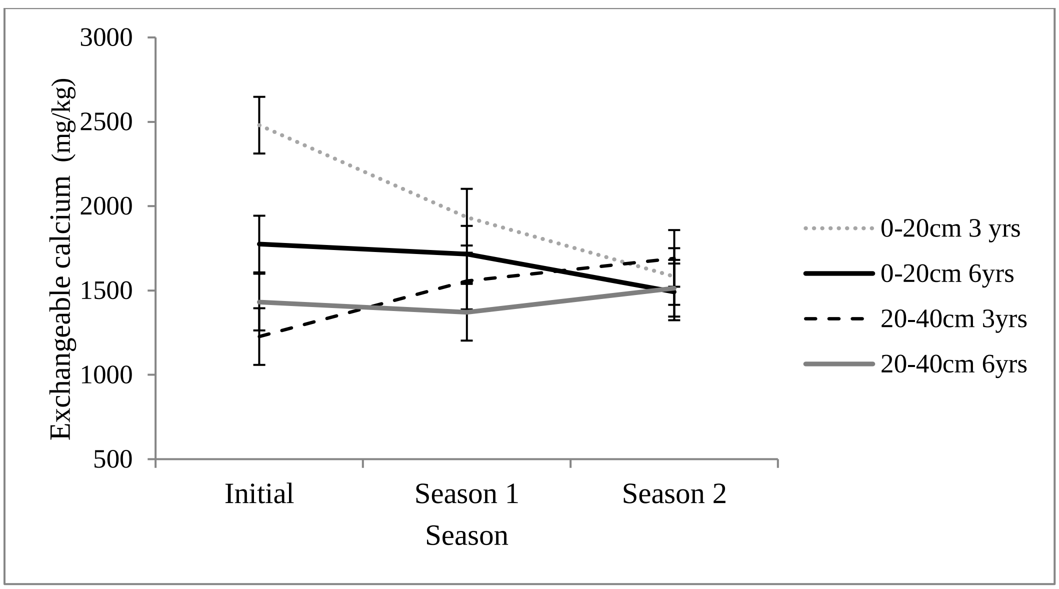


Figure 20: Changes in soil exchangeable calcium during cropping period under *Eucalyptus grandis* trees.

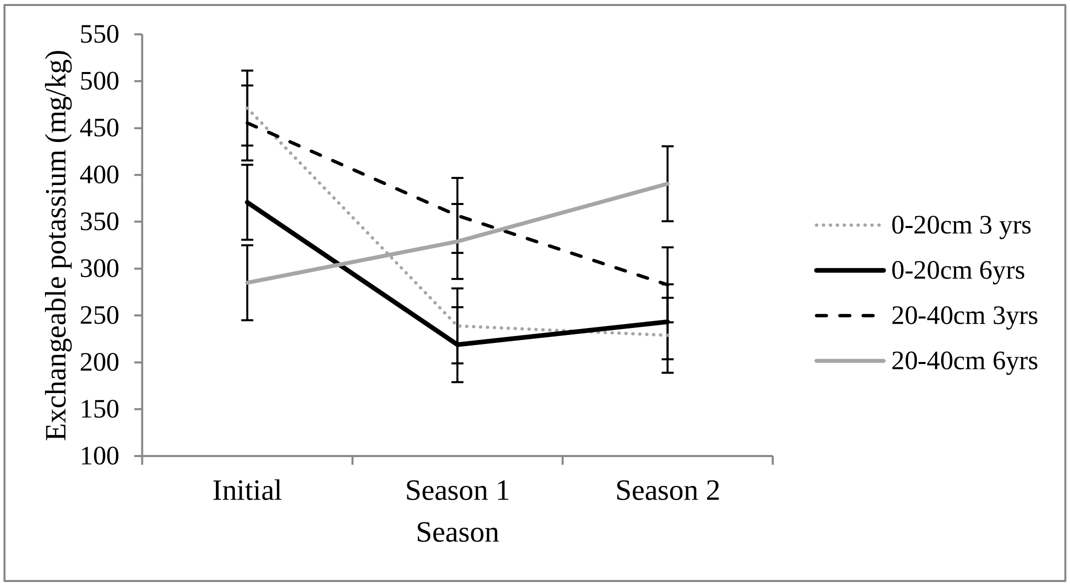


Figure 21: Changes in soil exchangeable potassium during cropping period under *Eucalyptus grandis* trees.

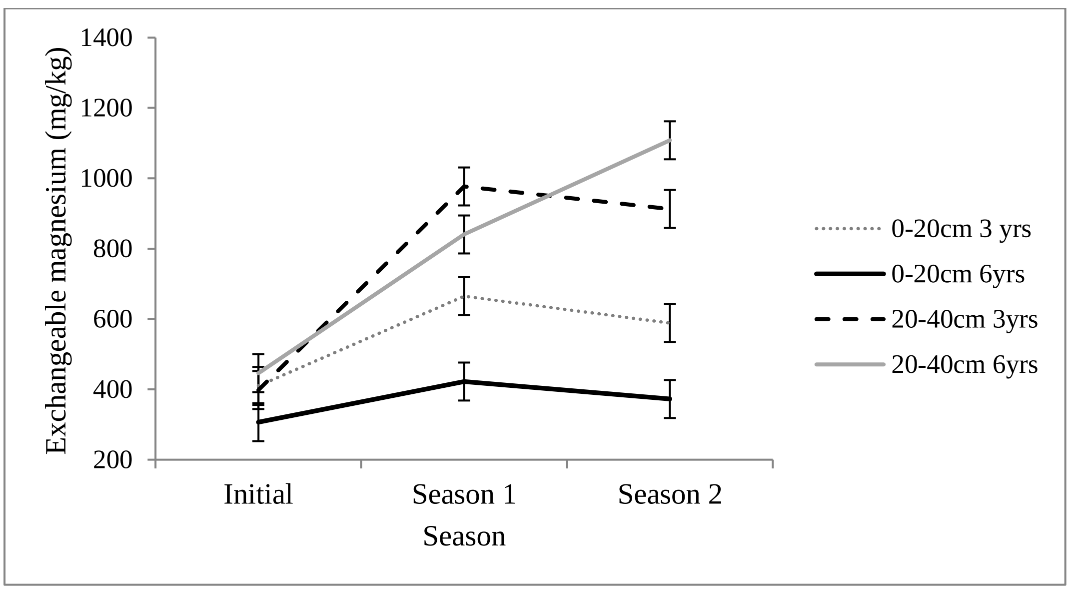


Figure 22: Changes in soil exchangeable magnesium during cropping period under *Eucalyptus grandis* trees.

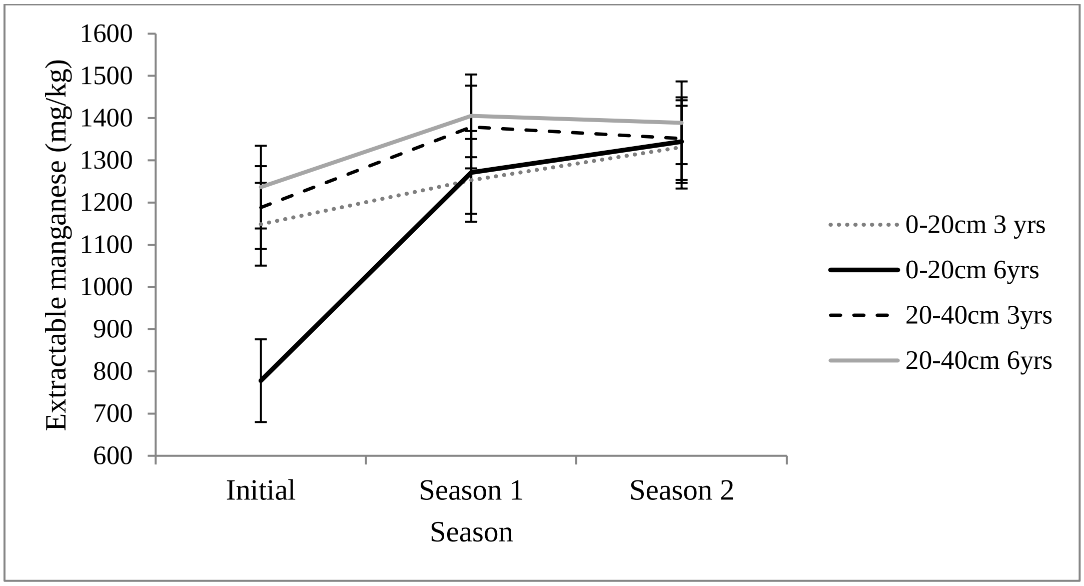


Figure 23: Changes in soil extractable manganese during cropping period under *Eucalyptus grandis* trees.

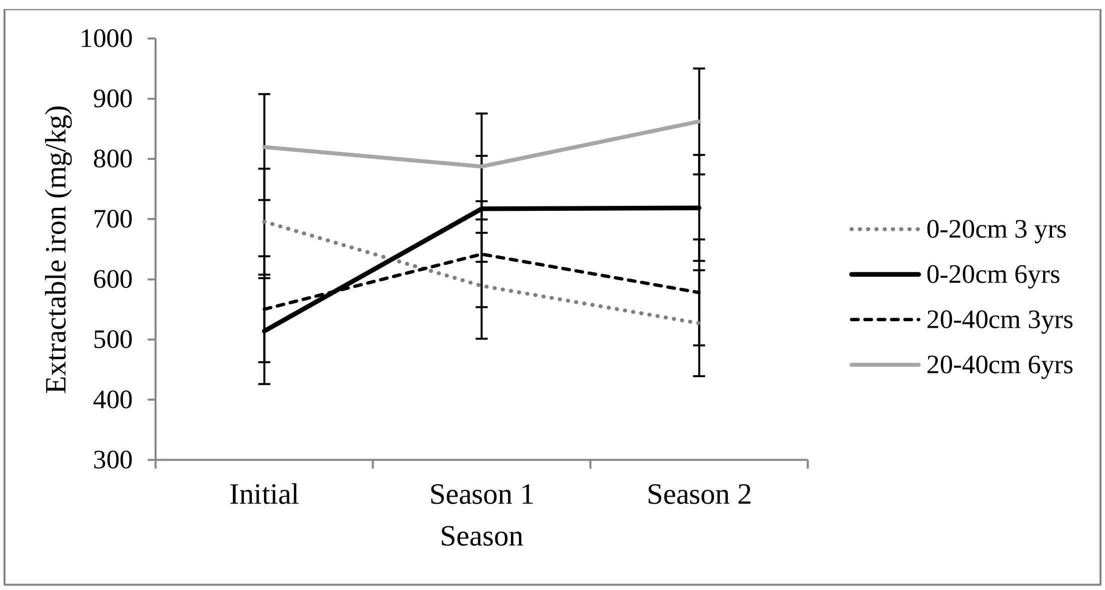


Figure 24: Changes in soil extractable Iron during cropping period under *Eucalyptus grandis* trees.

4.2: Levels of Allelopathy in *Eucalyptus grandis* trees and its effect on crop germination and soil water repellency

4.2.1: Effect of tree age on the content of soluble polyphenols in the soil, litter and leaves of *Eucalyptus grandis*

The effect of age of Eucalyptus tree on the concentration of soluble polyphenols in leaves, litter and soil was significant statistically ($p \leq .01$). The amount of soluble polyphenols in litter and fresh leaves were statistically different from each other ($p \leq .05$) with the fresh leaves containing nearly double amounts than of that of litter i.e. 66 mg/g and 43 mg/g respectively (Table 11). The trees aged 6 and 12 years had the lowest amount of soluble polyphenols in their leaves (55.85 mg/g, 62.05 mg/g) and litter (25.51 mg/g, 23.10 mg/g) (Table 11; Figure 25). The content of water soluble polyphenols in the soil reduced with age up to 12 years of age then increased rapidly as the tree matured with trees over 40 years producing the highest content (Table 11).

Table 11: Soluble Polyphenols content in soils under *Eucalyptus grandis*, its litter and fresh leaves

Age of Eucalyptus tree	Litter (mg/g)	Fresh leaves (mg/g)	Soil 0-10cm (mg/g)
1.5 years	45.85a	62.74a	0.28a
3 years	34.13b	65.15a	0.012b
6 years	25.51c	55.85b	0.052c
12 years	23.10c	62.05ab	0.22abd
20 years	55.50d	73.43c	0.28abd
40 years	75.03e	82.36d	1.12e
Mean	43.19	66.93	0.33
$LSD_{(p=.05)}$	8.10	3.90	0.17
CV (%)	22.00	24.00	29.00

A mean value followed by the same letter in the same column, do not differ significantly from each other at 5% level of significance according to Tukey's HSD Test.

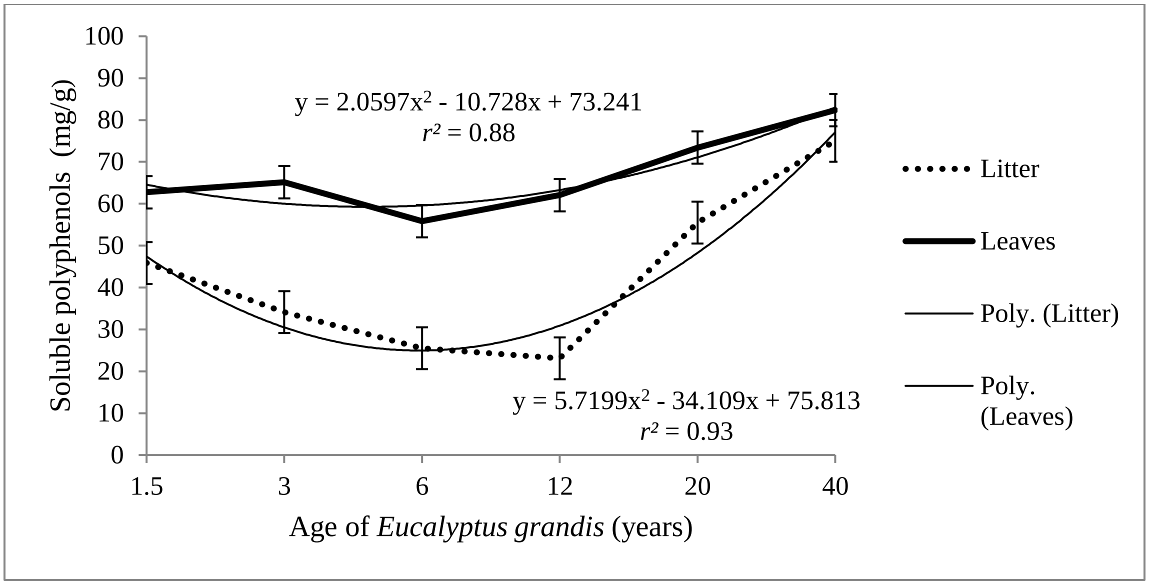


Figure 25: Soluble polyphenols in *Eucalyptus grandis* litter and leaf of different ages

The amount of soil soluble polyphenols increased with the age of the Eucalyptus tree especially from 12 years (0.22 mg/g) of age to 40 years (1.12mg/g) (Table 11). When compared to plant tissue (leaves and litter), the amount of soluble polyphenols in the soil was 50 to 100 times less than that present in the tissues (Table 11). The effect of soil depth on the amount of soluble phenols present in the soils under the Eucalyptus tree was statistically significant ($p \leq .01$). The amount of soluble phenols present in the soil under Eucalyptus canopy was high in top soil and less or none for increasing soil depths. For 10-20 cm soil depths, the amount of soluble polyphenols could not be detected for ages 1.5, 3, 6 and 12 years (Figure 26). The Eucalyptus trees aged 3 (0.012 mg/g) and 6 (0.052 mg/g) years had the lowest amount of soluble polyphenols in soils but generally there were no significant differences for ages 1.5, 3, 6 and 12 years for 0-10 cm depth (Table 11; Figure 26).

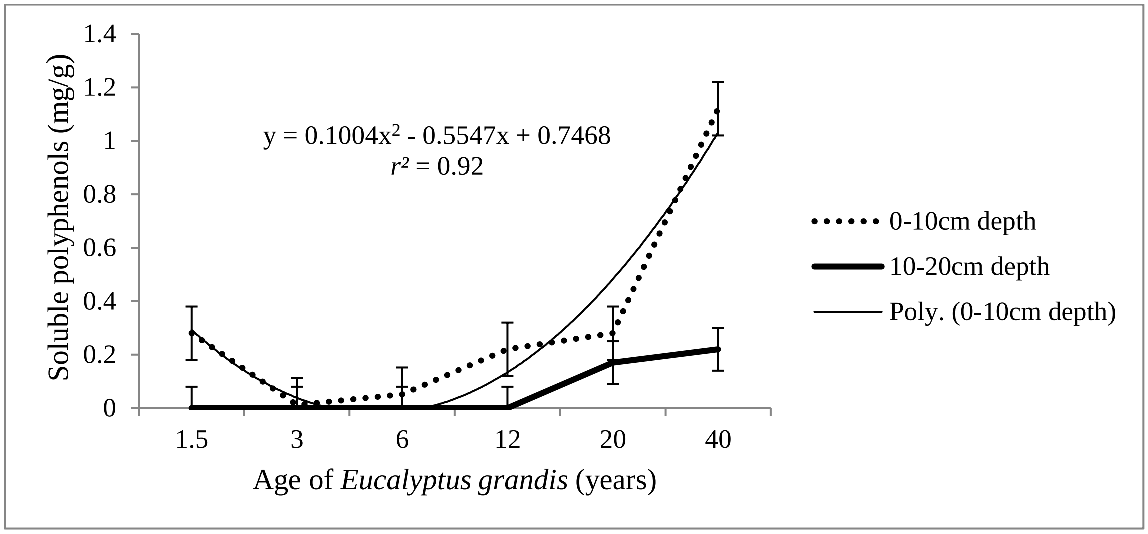


Figure 26: Soluble polyphenols in soils under *Eucalyptus grandis* trees of different ages

4.2.2: Effect of the water soluble polyphenols (soil, litter and leaves of *Eucalyptus grandis)* on germination of crops

The aqueous soluble polyphenol extract from litter and fresh leaves completely inhibited the seeds germination of common bean (Figure 27, 28 and 29). However, in diluted extracts (50 times of their original concentrations), the germination was 80 % and 50 % in litter and fresh leaves, respectively. The final litter polyphenol concentrations after dilution gave the following germination (%) for different ages of trees; 1.5 years (0.92 mg/g, 40 %), 3 years (0.68 mg/g, 60 %), 6 years (0.51 mg/g, 80 %), 12 years (0.46 mg/g, 70%), 20 years (1.11 mg/g, 40 %) and 40 years (1.31 mg/g, 40 %) (Figure 27). For fresh leaves dilution gave the following germination percentages for different ages of trees; 1.5

years (1.28 mg/g, 40 %), 3 years (1.30 mg/g, 40 %), 6 years (1.11 mg/g, 50 %), 12 years (1.24 mg/g, 40 %), 20 years (1.47 mg/g, 50 %) and 40 years (1.65 mg/g, 40 %) (Figure 28). Germination for litter polyphenols content started at 2.77 mg/g (10 % germination) in the 20 year old trees, while for the fresh leaves, germination started at 2.17 mg/g (20 % germination) in the 3 year old trees. The concentration of soluble polyphenols in litter and fresh leaves which permitted the germination after dilution was similar (< 3.0 mg/g) to that in soil and that is why germination of crops under the trees canopy in the field was high, despite high litter content in the soil. The lowest germination for the soil polyphenol content occurred at 1.12 mg/g concentration (50 % germination) in the 40 year old trees (Figure 29). The germination of common beans in undiluted soil aqueous polyphenol was 80 % (0.012 mg/g) for soils under 3 years of age compared to 95 % in control (distilled water) (Figure 29). Soil soluble polyphenol extract without dilution did not inhibit germination of beans.

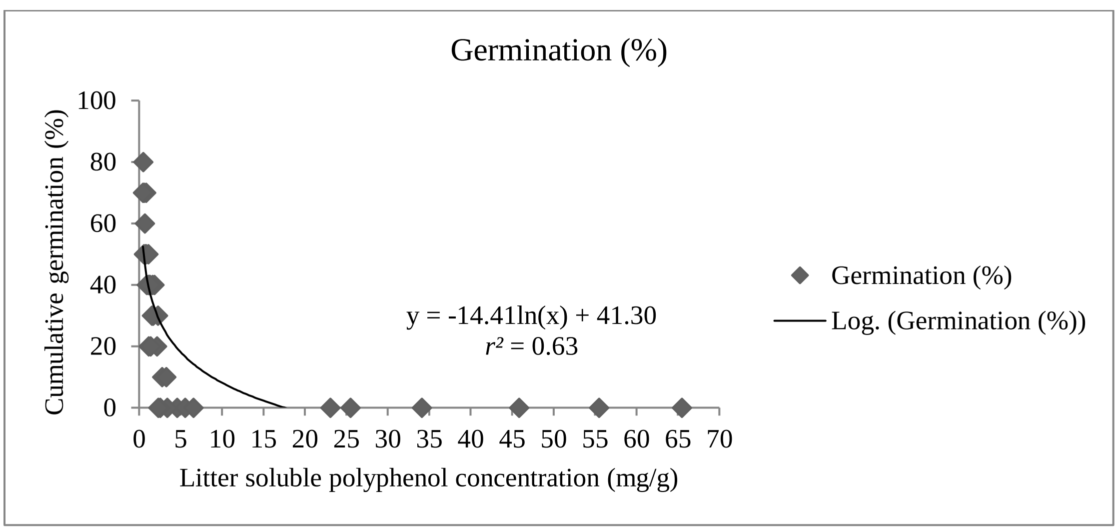


Figure 27: Effect of *Eucalyptus* litter soluble polyphenols on cumulative germination of beans

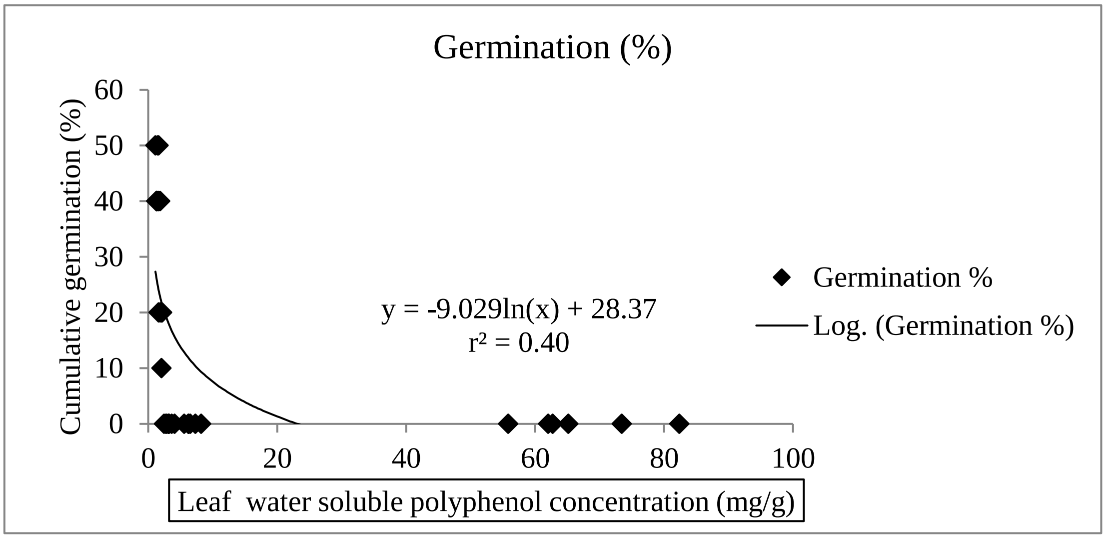


Figure 28: Effects of Eucalyptus fresh leaf soluble polyphenols on cumulative germination of beans

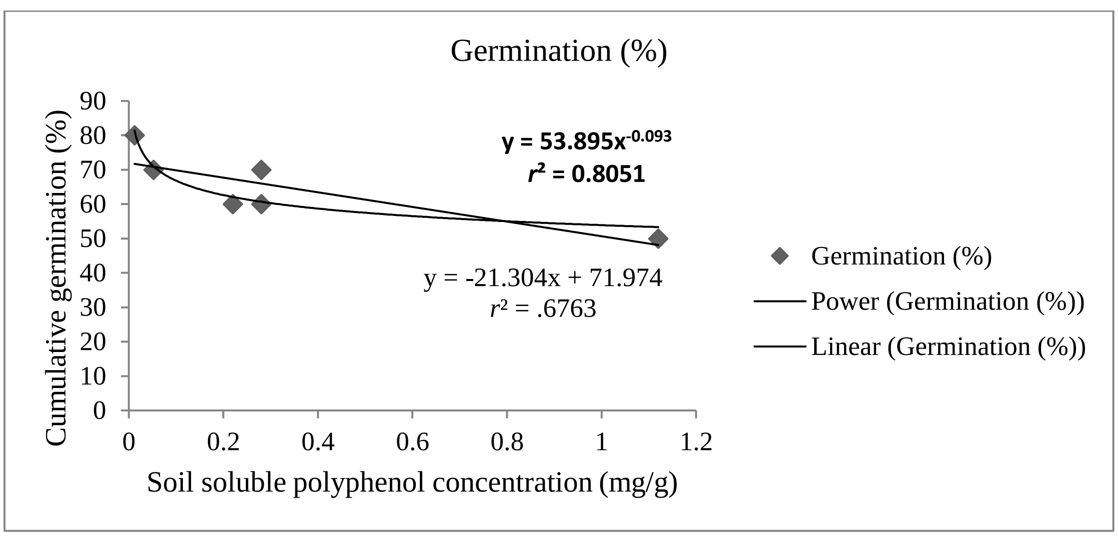


Figure 29: Effect of soil soluble polyphenols on cumulative germination of beans

The relationships between age of Eucalyptus and soil soluble polyphenols followed best that of polynomial regression form of linear regression producing highest r^2 =.65 although the simple linear r^2 =.64 was more realistic for prediction because the former would give negative values. This relationship was also seen between cumulative germination and the soil soluble polyphenols under Eucalyptus. Although most research in bioscience explore the hyperbolic functions e.g. rectangular hyperbola models of the form y = (m*x) / (k+x) and others then it would be it suitable if modified non rectangular hyperbolic functions are employed to fully model these relationships. For instance, the hyperbolic function y = (m*x) / (k+x) of germination and the soil polyphenol content across the different ages of Eucalyptus (Figure 29) was found to be;

$$y = \frac{(59.45 * x)}{(-.003 + x)}$$

Where *m* and *k* refer to slope and the intercept respectively, m =59.45, k = -0.003.

4.2.3: Effect of tree age and soil depth on the levels of soil water repellency in *Eucalyptus grandis* plantations

The age differences in Eucalyptus trees significantly affected soil water repellency (hydrophobicity) in different soil depths down the profile ($p \leq .001$). Furthermore, the effect of soil depth, season (wet and dry spells), and the interaction of age and soil depth significantly affected soil water repellency ($p \leq .001$). Water repellency in the soil was very high or strong during dry spells when the soil had less moisture but during the wet season the soils were less hydrophobic (Figures 30, 31 and 32).

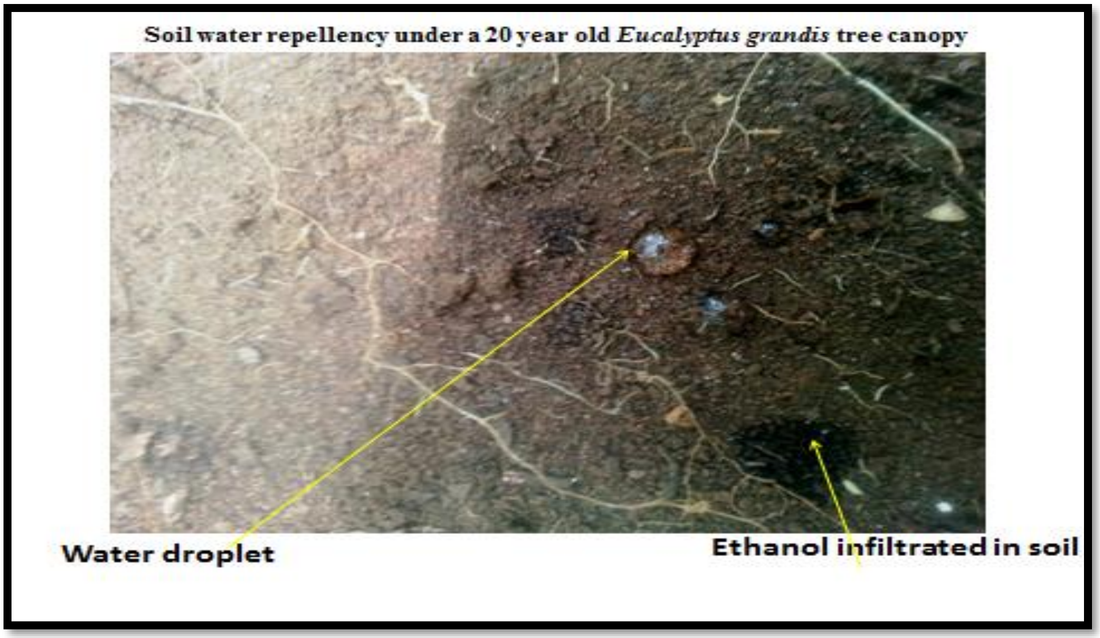


Figure 30: Soil water repellency in a 20 year old canopy (Source: Author)
(Source: Author, 2016)

Soil water repellency increased with age of the Eucalyptus tree with trees over 40 years having soils 45 times more repellent than those of 1.5 years old. Soil hydrophobicity reduced down the soil profile with surface 1 cm up to 10 cm depth being extremely water repellent while at the 100 cm depth being not repellent (Figure 32).

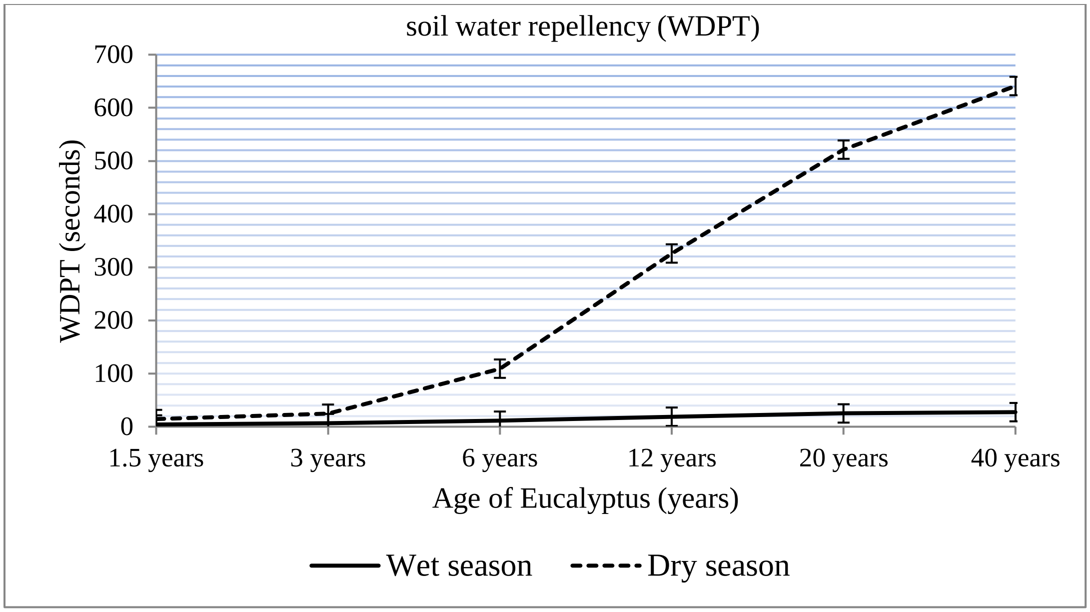


Figure 31: Soil water repellency under *Eucalyptus grandis* during wet and dry season

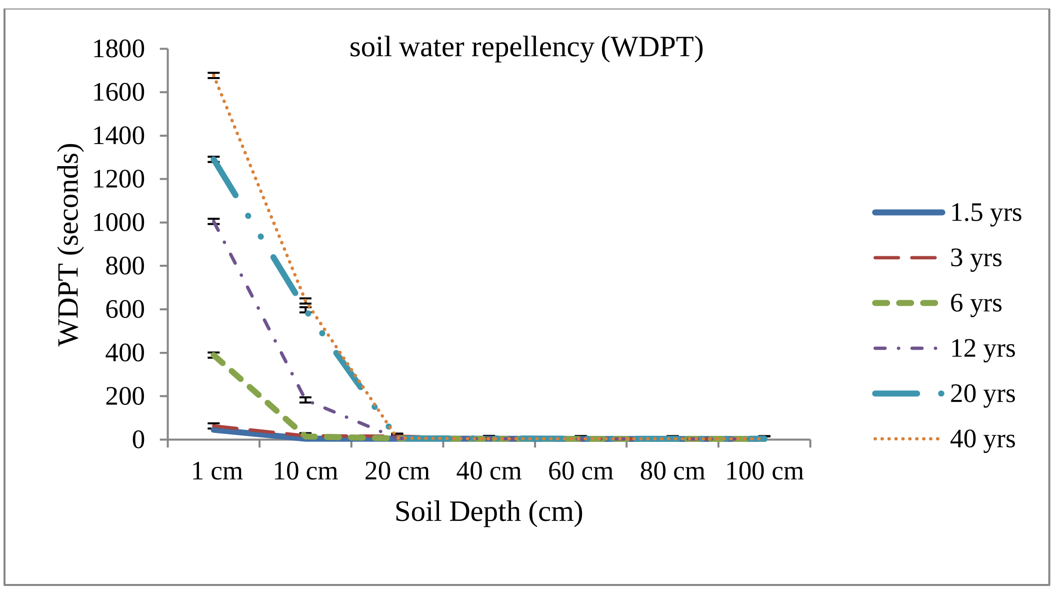


Figure 32: Soil water repellency in differently aged *Eucalyptus grandis* plantations.

4.2.4: Soil Water repellency severity classes under *Eucalyptus grandis*

Generally, the soils were found not to be water repellent below 40 cm depth across all the ages of Eucalyptus tree canopies irrespective of wet or dry conditions (Table 12).

Table 12: Soil water repellency (seconds) classes at different soil profile depths

	Soil Depth/ Age	Surface 1cm	10cm	20cm	40cm	60cm	80cm	100cm	mean
DRY season	1.5 years	79.3 c2	4.3 c0	4 c0	4 c0	3.3 c0	3 c0	2.7 c0	14.3
	3 years	99.3 c2	30.3 c1	8.3 c0	4 c0	3 c0	3 c0	2.7 c0	24.3
	6 years	720 c3	24.7 c1	7.7 c1	3 c0	3 c0	3 c0	3 c0	109.2
	12 years	1900 c3	360 c2	8 c1	4 c0	3 c0	3 c0	3 c0	325.8
	20 years	2440 c3	1180c3	9 c1	6.7 c1	4.7 c0	4.3 c0	4.3 c0	521.2
	40 years	3200 c3	1260c3	10 c1	5 c1	4.3 c0	4 c0	4 c0	641
WET season	1.5 years	11.7 c1	3.3 c0	3 c0	3 c0	3 c0	3 c0	2.7 c0	4.2
	3 years	26.7 c1	5 c1	3.3 c0	3 c0	3 c0	3 c0	3 c0	6.7
	6 years	58.3 c1	5.3 c1	3.3 c0	3 c0	3 c0	3 c0	3 c0	11.2
	12 years	110 c2	5.3 c1	4.3 c0	3 c0	3 c0	3 c0	3 c0	18.8
	20 years	141.7 c2	15.7 c1	3.7 c0	4 c0	3.7 c0	3 c0	3.3 c0	25
	40 years	154.7 c2	17 c1	5.7 c1	4.7 c0	3.3 c0	3.3 c0	3.3 c0	27.4
	mean	745.1	242.5	7.5	3.9	3.3	3.2	3.1	144.1

Key: class 0 (c0), wettable, non-water repellent (infiltration within 5 s); class 1 (c1), slightly water repellent (5–60 s); class 2 (c2), strongly water repellent (60–600 s); class 3 (c3), severely water repellent (600–3600 s); and extremely water repellent (>1 h), further subdivided into class 4 (1–3 h); class 5 (3–6 h); and class 6 (>6 h), (Dekker et al., 1998; Dekker et al., 2009).

4.2.5: Modeling the effects of soil depth, soil polyphenol content, moisture and age of *Eucalyptus grandis* on soil water repellency

Correlation Analysis

Soil water repellency (WDPT) correlated negatively with soil depth for both dry (r = -.537, $p \leq .001$), and wet (r = -.54, $p \leq .001$) spells. Soil moisture and soil depth had a negative correlation (r = -.36, $p \leq .001$) during wet spell, but a positive correlation for dry spell (r = .564, $p \leq .001$). Soil water repellency was positively correlated with polyphenol content in soil (r = .799 $p \leq .001$), litter (r =.336 $p \leq .001$) and leaf (r =.40 $p \leq .001$). Soil soluble polyphenols was positively correlated to both litter and leaf polyphenols (r = .58, $p \leq .001$), (r = .59, $p \leq .001$) respectively (Table 13).

Soil water repellency and soil moisture content

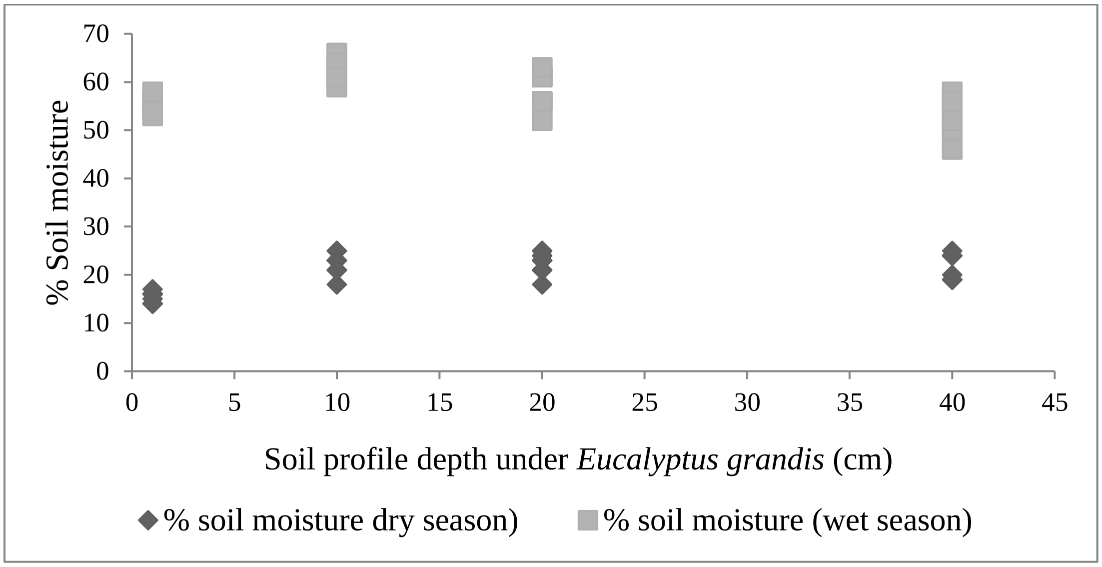
Soil water repellency (WDPT) correlated negatively with soil depth for both dry (r = -.537, $p < .001$), and wet (r = -.54, $p < .001$) spells (Figure 33) (Table 12). Soil moisture and soil depth had a negative correlation (r = -.36, $p < .001$) during wet spell but positive during dry spell (r = .564, $p < .001$) (Table 12; Figure 33). The correlations between plantation age to both soil moisture and soil depth were not significant.

Table 13: Correlation for WDPT, polyphenol content, soil moisture, soil depth and age of tree (Pearson coefficients)

	Age	Soil depth (cm)	WDPT (s)	Soil moisture (%)	Soil polyphenol (mg/g)	Litter polyphenol (mg/g)	Leaf polyphenol (mg/g)
Age	1	0	.45**	0.03	.64**	.79**	.89**
Soil depth (cm)		1	-.53**	.56**	-.47**	-0.003	0.01
WDPT (s)			1	-.53**	.79**	.33**	.40**
Soil moisture (%)				1	-.28*	0.08	0.06
Soil polyphenol (mg/g)					1	.58**	.59**
Litter polyphenol (mg/g)						1	.92**
Leaf polyphenol (mg/g)							1

Soil water repellency and soluble polyphenols content in the soil

Soil water repellency significantly had a positive correlation with soluble polyphenol content of soil (r = .799 $p \leq .001$), litter (r = .336 $p \leq .001$) and leaf (r = .40 $p \leq .001$), (Table 12). The best fit relationship between soil water repellency and soil polyphenol was a polynomial form of linear regression producing highest r^2 =.65 although the simple linear r^2 =.64 was more realistic for prediction because the former would give negative values (Figure 34, 35 & 36).



33: Soil moisture content at different soil depths under *Eucalyptus grandis* trees.

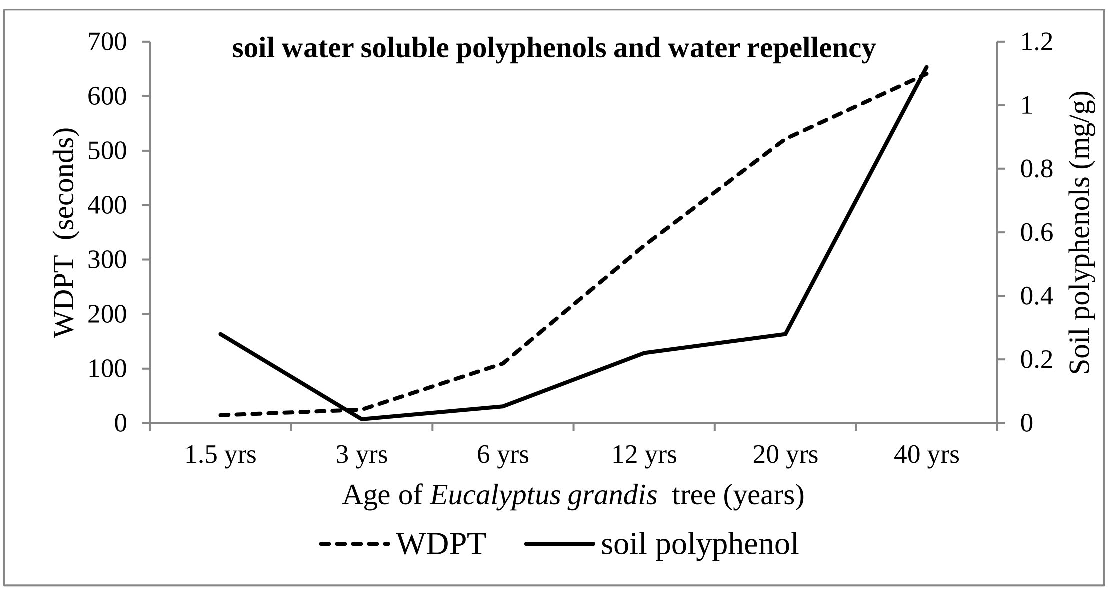


Figure 34: Water repellency and soluble polyphenol in soils under *Eucalyptus grandis*.

Soil soluble polyphenols was positively and significantly correlated to both litter and leaf polyphenols (r = .58, $p \leq .001$), (r = .59, $p \leq .001$) respectively, (Table 13). The relationship between soluble litter polyphenols and leaf soluble polyphenols was so strong (r = .925 $p \leq .001$) followed best that of Polynomial regression form of linear regression producing highest r^2 =.87 and the simple linear r^2 = .85. Simple linear regression would predict negative values (Figure 36). In figure 35, the relationship between soil water repellency and soluble polyphenol content showed a two stage cluster in the trend and therefore hyperbolic function models e.g. rectangular hyperbola models of the form y = (m*x) / (k+x) and others would also fit this relationship.

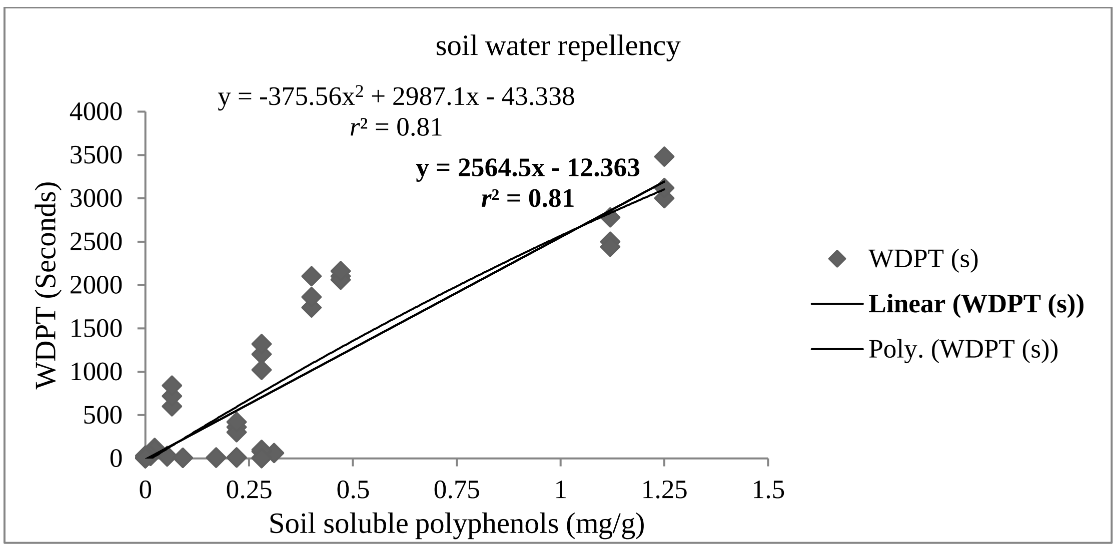


Figure 35: Regression: soil soluble polyphenols and soil water repellency under *Eucalyptus grandis* trees

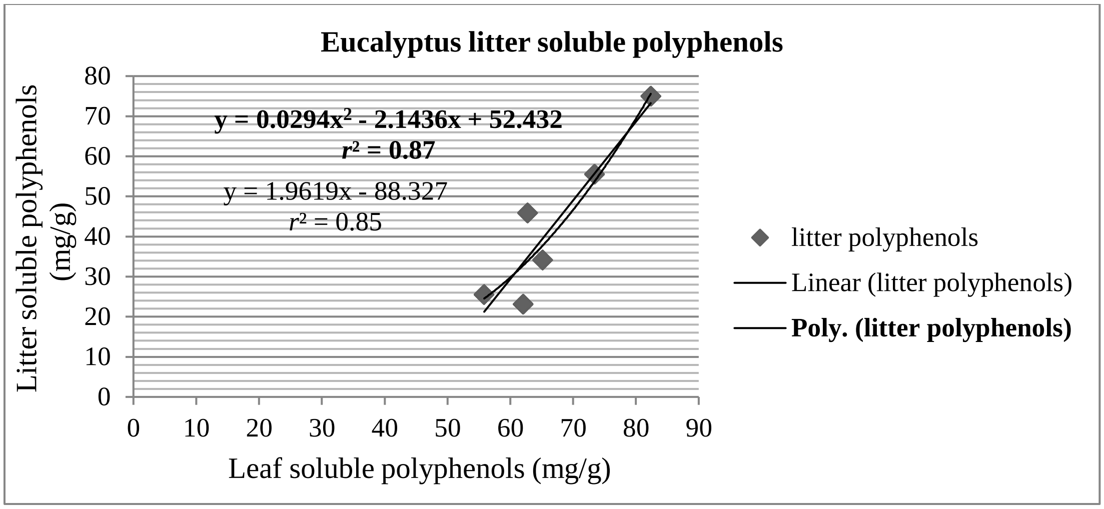


Figure 36: Regression: litter and leaf soluble polyphenols of *Eucalyptus grandis* trees

Stepwise Regression Analysis

From the field measurements, it was found that soils beyond 40 cm depth were not water repellent across the different ages of Eucalyptus trees studied. Therefore, Stepwise regression analysis was done limiting the soil depth to top 40 cm which exhibited water repellency (surface 1 cm, 10 cm, 20 cm and 40 cm). From the analysis, the model validity was significant and strong with $r^2 = .741$). Excluding soil depth from the model did not change the model with r^2 changing from .741 to .74 (Table 14). From the results: soil water soluble polyphenol and soil moisture contents significantly contributed to the overall model but not the age of Eucalyptus and soil depth. These results meant that soil soluble polyphenol content and the soil moisture content were the most important and consistent factors influencing water repellency in soils under *Eucalyptus grandis* trees.

Table 14: Regression coefficients: Soil depth, soil polyphenols, soil moisture and Age of tree

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	1783.3	362.4		4.92	.001	1059.8	2506.7
	Age	3.4	5.9	.053	.58	**.561**	-8.4	15.4
	% soil moisture	-81.1	18.8	-.32	-4.29	.001	-118.8	-43.4
	soil phenol	1733.7	276.3	.65	6.27	.001	1182.1	2285.3
	soil Depth (cm)	-2.6	5.2	-.044	-.49	**.619**	-13.2	7.9
Predictors: (Constant), soil Depth (cm), Age, % soil moisture, soil polyphenol. Dependent Variable: WDPT (s) r^2=0.741)								

WDPT (s) =1783.31+1733.71 [soil phenol] - 81.13 [soil moisture] – 2.64 [soil depth] + 3.49 [age], r^2 = .74) $p \leq .001$

WDPT (s) = 1821.34+1805.45[soil phenol] - 85.25 [soil moisture] +2.39 [age], r^2= .74) $p \leq .001$

WDPT (s) = 876.89 – 16.48[soil depth] -13.99 [soil moisture] +15.65 [age], r^2 = .39) $p \leq .001$

WDPT (s) = 795.04-14.04 [soil moisture], r^2 = .161) $p \leq .001$

WDPT (s) = 1827.45+18.01 [soil phenol], r^2 = .65) $p \leq .001$

WDPT (s) = 35.32 + 15.59 [age] $p \leq .001$ constant not significant

4.2.6: Effect of crop cultivation on soil water repellency under *Eucalyptus grandis* trees

Cultivation of crops under Eucalyptus trees reduced soil water repellency whereby by the end of the second season of cultivation, soil water repellency had reduced by nearly 100 times for 1 cm soil depth, 6 times for 10 cm soil depth and 2 times for 20 cm soil depth**,** Figure 37.

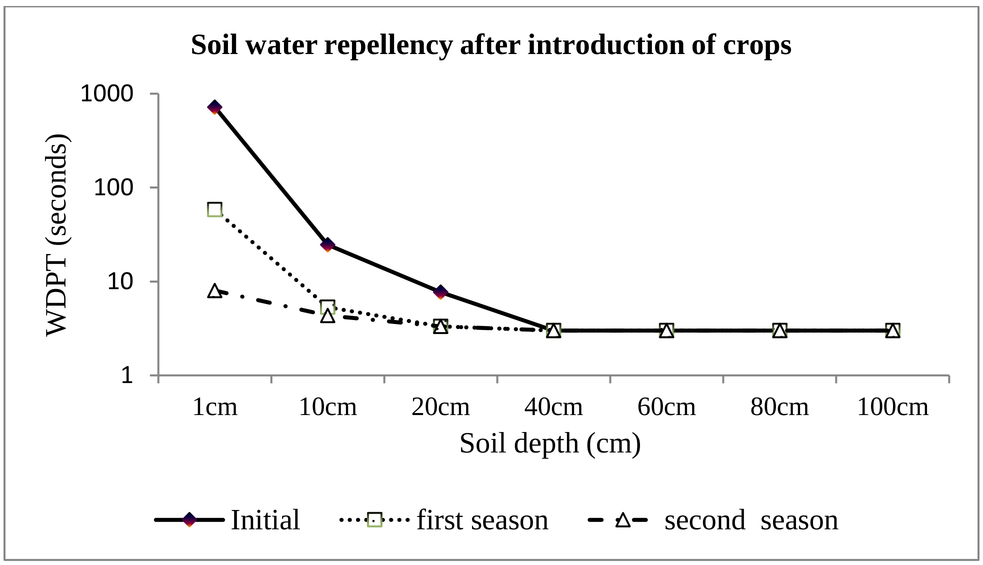


Figure 37: Changes in soil water repellency during cultivation under *Eucalyptus grandis* trees.

4.3: Evaluation and modeling the performance of crops under *Eucalyptus grandis* tree canopies and its potential for agroforestry

4.3.1: Weather Conditions during the Cropping period

Season 1 received more rainfall than season 2 which was characterized by low temperatures and dense cloud cover for most of the cropping period. The temperatures in the open field were slightly higher than under the tree canopy (Table 15).

Table 15: Mean monthly soil, air temperatures and rainfall during the cropping period

	Under trees		**Open field**		
	Air temp (°C)	Soil temp (°C)	Air temp (°C)	Soil temp (°C)	Rainfall (mm)
Season 1:					
2015	Mean	mean	mean	mean	mean
NOV	18	12	22	16	100
DEC	21	15	24	17	81
2016					
JAN	22	15	24	16	40
FEB	24	17	27	20	20
Season 2:					
2016					
MAY	19	14	21	15	90
JUNE	18	14	18	14	40
JULY	16	15	18	15	20
AUG	21	19	24	22	0

4.3.2: Soil fertility status before establishment of crops under 3 and 6 year old *Eucalyptus grandis* canopies (Experimental plots)

The soil status (chemical and physical) under the Eucalyptus tree canopies and the open field differed greatly. The content of available phosphorus (Olsen) was lower under canopies (3.3 and 3.89 mg/ kg) than the open field (9 mg/ kg). However, total phosphorus under the canopies (396 and 721 mg/ kg) was many times higher than in the open field (141 mg/ kg). The exchangeable bases (cations) were very high under the canopies than in the open field. Soils in the open field had a higher bulk density but lower field capacity moisture levels. Both soils under the canopies and the open field had clay-loam texture grades (Table 16).

Table 16: Soil characteristics under 3 and 6 year old Eucalyptus tree canopies

Parameter (0-20 cm depth)	3 year old canopy	6 year old canopy	open field (fallow)
Chemical parameters			
pH (1:2.5)	5.7	5.8	5.9
Available phosphorus (Olsen) (mg/ kg)	3.3	3.8	9
Total phosphorus (mg/ kg)	396	721	141
Total Nitrogen (TN %)	0.26	0.28	0.13
Organic Matter (OM %)	3.5	3.6	3.1
Calcium (mg/ kg)	1192	1053	712
Magnesium (mg/ kg)	457	470	268
Potassium (mg/ kg)	456	387	211
Manganese (mg/ kg)	1020	941	792
Iron (mg/ kg)	537	847	741
Physical parameters			
Bulk density (g/cm^3)	0.94	0.92	1.2
Moisture content (%)	29-35	30-35	32
Field capacity v/v	55	57	51
Texture grade	clay loam	clay loam	clay loam

4.3.3: Crop performance under *Eucalyptus grandis* tree canopies

Germination of crops

Germination for crops under the canopy was higher (beans 96 %, potatoes 92 %) than field (beans 84 %, potatoes 90 %), (Figures 38 & 39) and was not significantly different statistically. Survival rate for nightshade 14 days after planting was 100 % under the canopy while 95 % in the open field with no statistically significant differences between canopy and open field (p = .06), Figure 40. The number of days elapsed before onset of germination after sowing was highly affected by the type of canopy and age (p < .001) i.e. more than twice for germination in the open field with potatoes taking 4-8 days to germinate under open field while more than 8 days under the canopy (Figure 38). Beans took 2 days under open field and more than 4 days under the canopy (Figure 39). The effect of canopy and season on the germination of beans and Irish potatoes was statistically significant (p ≤ .001), with both crops recording higher germination percentages in the second season.

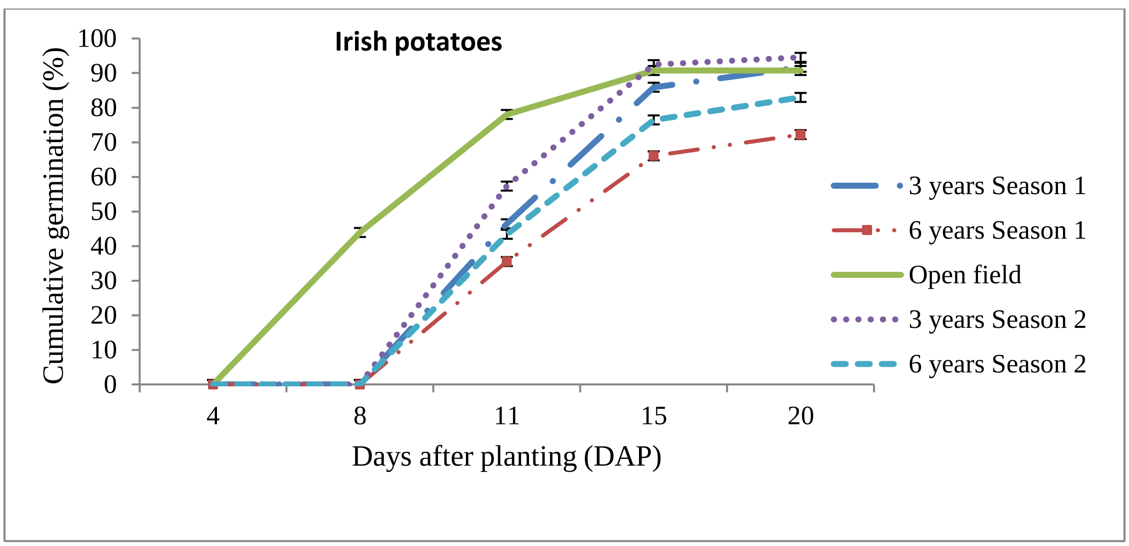


Figure 38: Cumulative germination (%) in Irish potatoes under *Eucalyptus grandis* trees

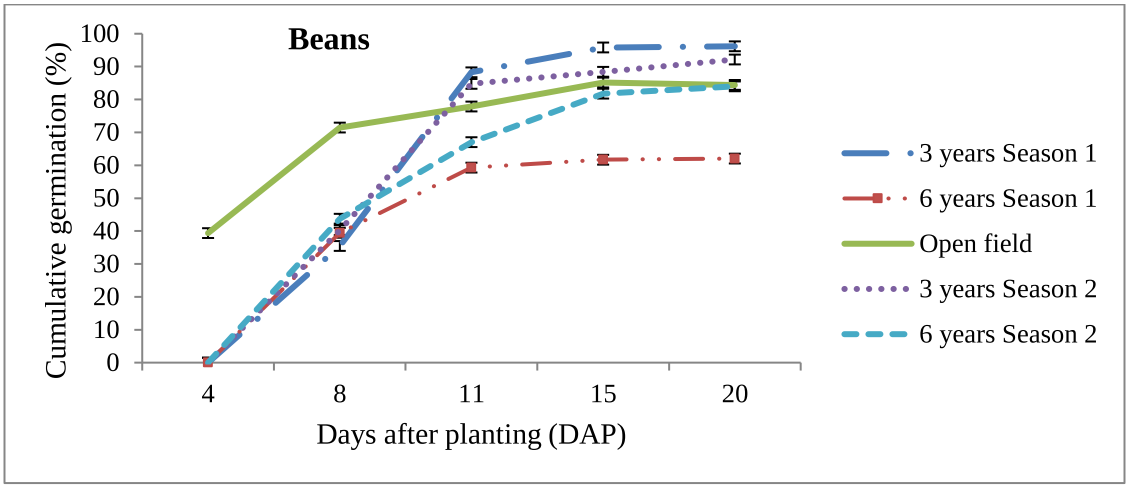


Figure 39: Cumulative germination (%) in common beans under *Eucalyptus grandis* trees of different ages.

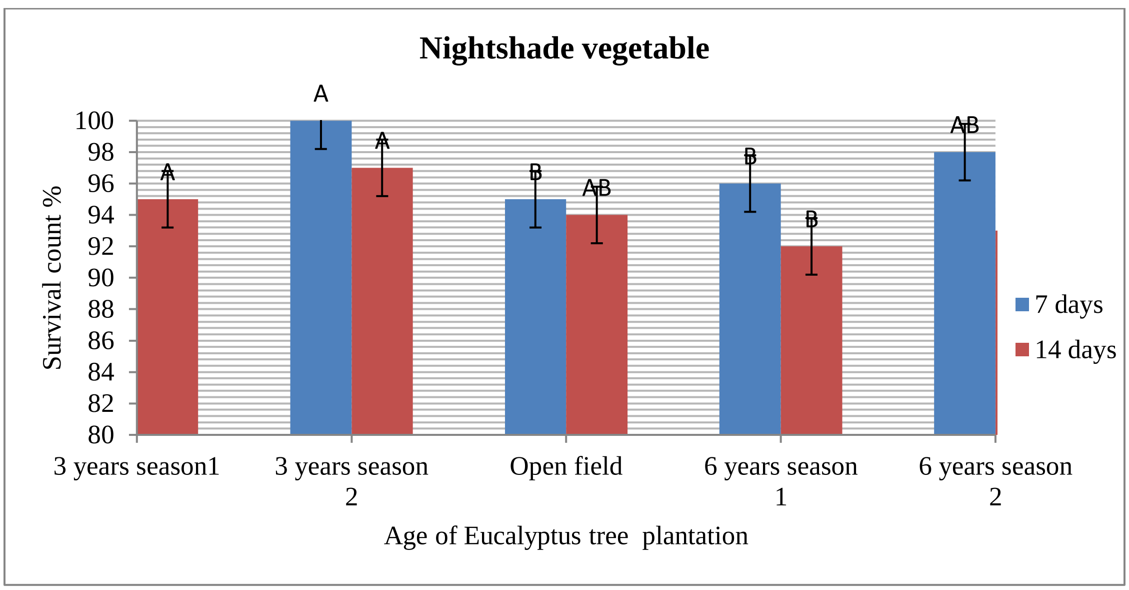


Figure 40: Survival count (%) of nightshade vegetable under *Eucalyptus grandis* trees.

Photosynthetically Active Radiation (PAR) under *Eucalyptus grand*is tree canopies of different ages

The amount of PAR reaching the crops under the tree canopy was many (10) times less and significantly different from that recorded in the open field ($p \leq .001$). On average**,** The PAR recorded in the open field was as expected many times compared to that recorded under canopy with potatoes (849.1 µmols^{-1} m^{-2}) beans (848.6 µmols^{-1} m^{-2}) nightshade (769.5 µmols^{-1} m^{-2}), Table 17. The maximum PAR recorded in the open field was 1881 µmols^{-1} m^{-2} (February) and minimum 67.3 µmols^{-1} m^{-2} (June) 2016. The age difference in the canopies had no significant difference on the PAR reaching the crops. Pruning of the canopy increased the amount of PAR and it was statistically significant ($p \leq .001$). Seasonal variations significantly affected the amount of PAR reaching the crops (Table 17).

Table 17: PAR under Eucalyptus canopies of different ages (µmols^{-1} m^{-2})

Plantation age	Potatoes	Beans	Nightshade
Plantation of 3 years: season 1	30.65a	31.64a	31.45a
Pruned plantation of 3 years: Season 1	142.43b	70.01b	81.09b
Plantation of 6 years: season 1	37.23ab	36.41ab	38.08ab
Plantation of 6 years: season 2	88.20b	64.57b	82.32b
Control/Open field	849.10c	848.60c	769.50c
CV (%)	10.92	15.30	23.10
LSD$_{(p=.05)}$	39.45	17.00	25.50

A mean value followed by the same letter in the same column, do not differ significantly from each other at 5% level of significance according to Tukey's HSD Test.

Leaf Area Index (LAI) of crops grown under the Eucalyptus trees

The age differences in the tree canopies significantly affected the LAI of the understory crops ($p \leq .001$). In addition, LAI values of potatoes and beans in the open field were higher and significantly different from those under the tree canopy; however the situation was different for nightshade where the difference was not significant. The age difference in the canopies had a significant difference on the LAI of potatoes and beans with 6 year old canopy (1.39, 1.54) having a bigger effect on LAI compared to 3 year old (1.09, 0.93) respectively. The story was opposite for nightshade with 6 year old tree canopy recording less (0.61) compared to 3 year old (0.89), Table 18**;** Figure 43. Pruning of the canopy significantly increased the LAI for beans and potatoes with no effect on nightshade's LAI, Table 18. Seasonal variations affected the LAI of nightshade significantly but not for beans and potatoes. Generally, the LAI was higher in potatoes and beans compared to nightshade, Table 18; (Figures 41, 42, 43, 44& 45).

Table 18: Leaf Area Index (LAI) of crops under Eucalyptus canopies of different ages

Plantation age	Potatoes	Beans	Nightshade
Control/Un-Fertilized open field	1.12a	1.04a	0.70a
Plantation of 3 years: season 1	1.09a	0.93a	0.90b
Pruned plantation of 3 years	1.67b	1.20b	0.74a
Plantation of 6 years: season 1: Season 1	1.36c	1.39bc	0.89b
Plantation of 6 years: season 2	1.39c	1.54c	0.61c
Open field	2.65d	2.36d	1.16d
CV (%)	24.10	28.70	23.10
$LSD_{(p=.05)}$	0.21	0.24	0.30

A mean value followed by the same letter in the same column, do not differ significantly from each other at 5% level of significance according to Tukey's HSD Test.

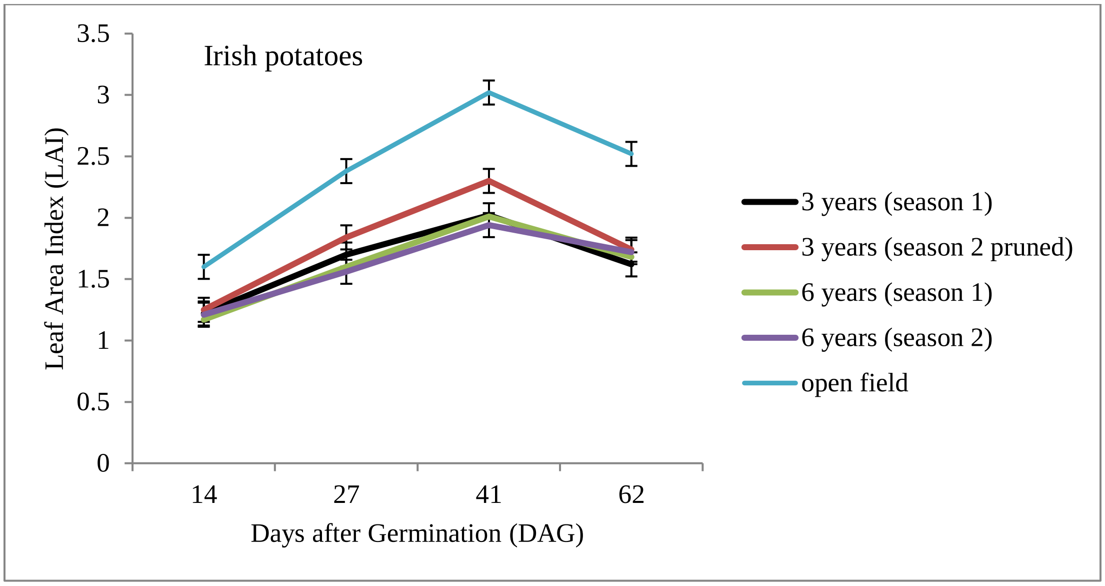


Figure 41: LAI measurements in Potato crop during the growing period under Eucalyptus canopies.

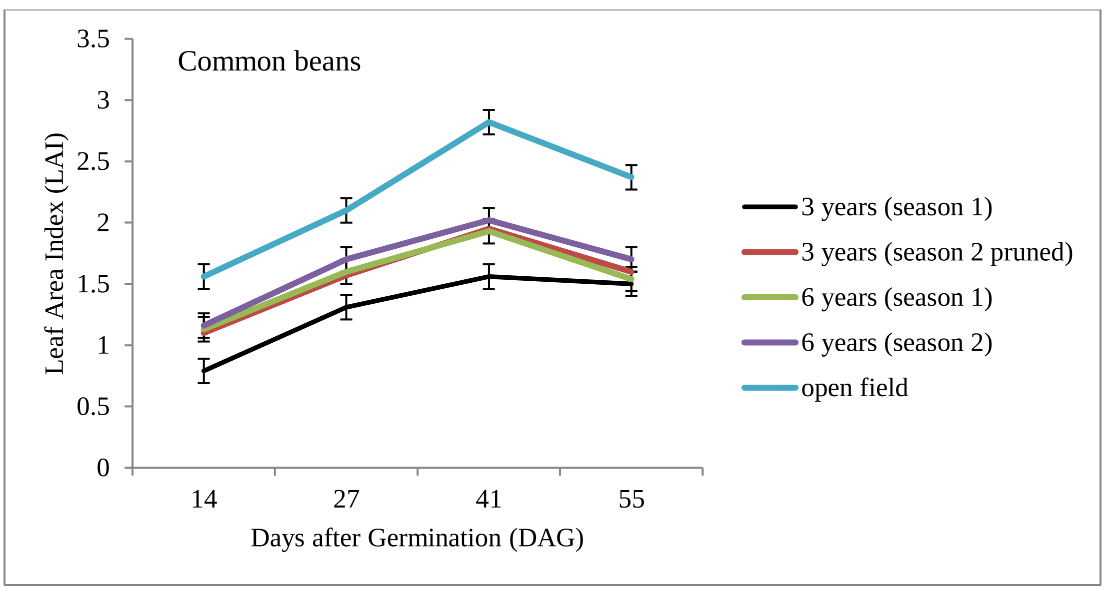


Figure 42: LAI measurements in Bean crop during the growing period under Eucalyptus canopies.

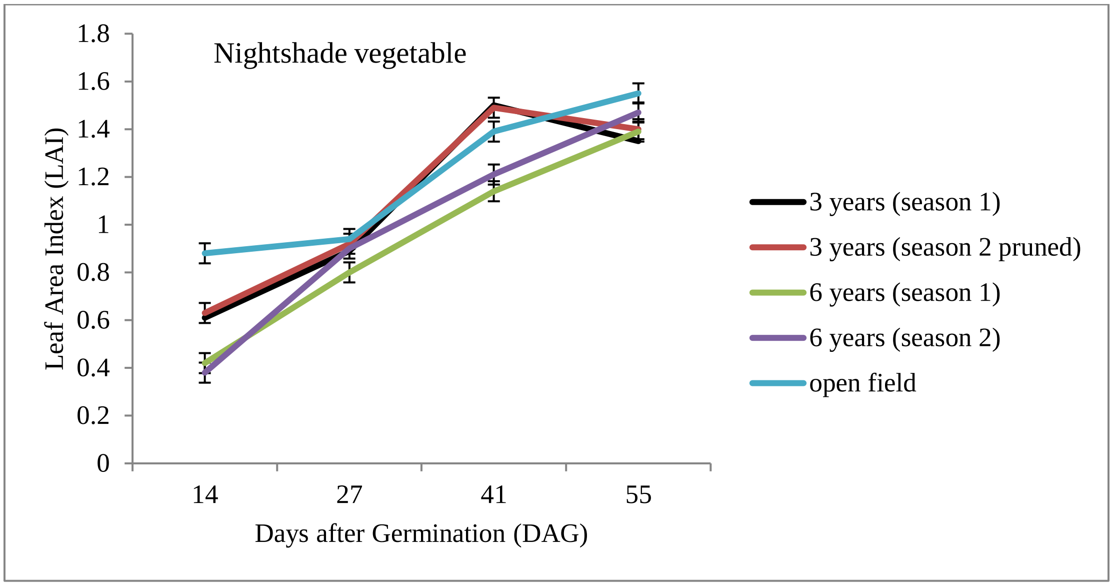


Figure 43: LAI measurements in Nightshade vegetable during the growing period under Eucalyptus canopies.

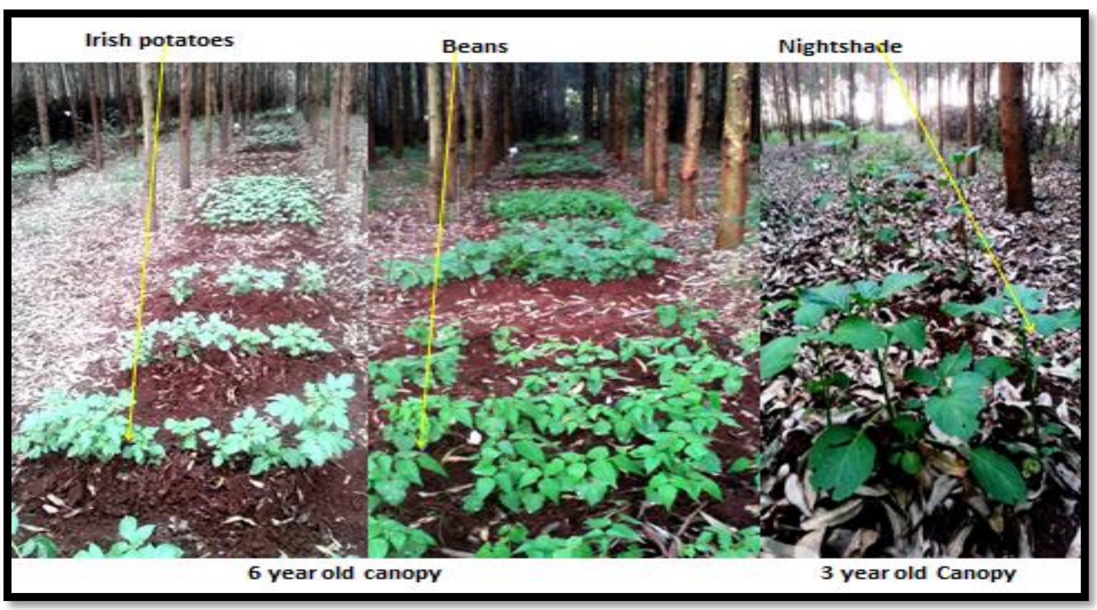


Figure 44: Performance of crops under 3 and 6 year old Eucalyptus trees, season 1. (Source: Author, 2016)

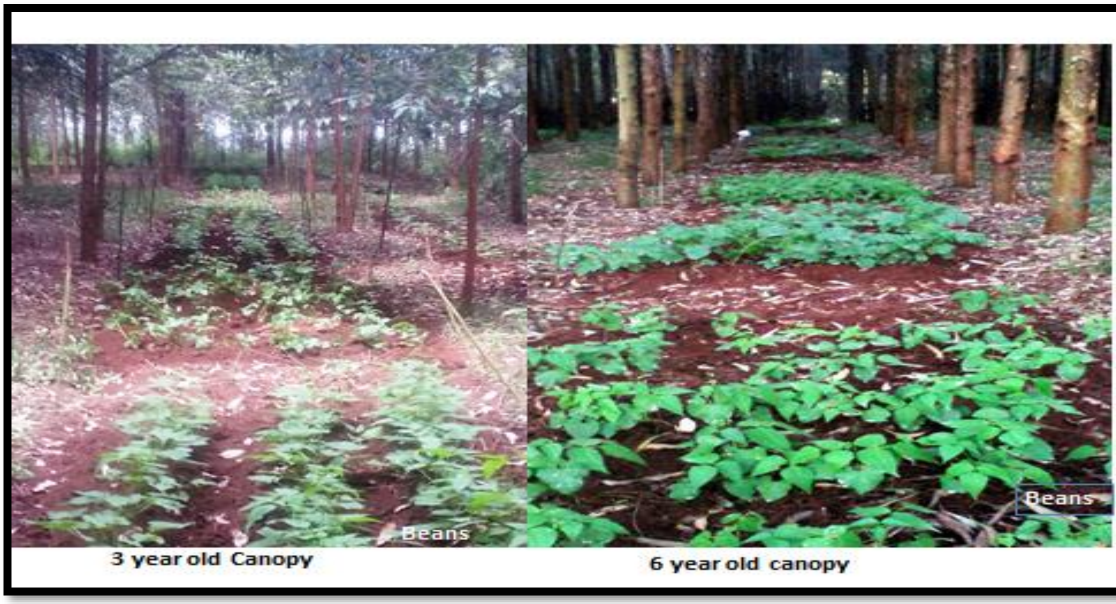


Figure 45: Performance of crops under 3 and 6 year old Eucalyptus trees, season 2. (Source: Author, 2016)

Yields of crops under *Eucalyptus grandis* trees

The differences in yield between the canopy and the open field were statistically significant for beans, potatoes and nightshade ($p \leq .001$). The control (non-fertilized open fields) performed significantly poorer (4.63, 0.23, 0.17 t/ha) compared to crops under canopy which had no fertilizer added (5.77, 0.27, 0.32 t/ha) for all the tested crops (Table 19). For beans and potatoes, canopy differences in terms of age and even pruning had no significant effect on yield (Table 19). For nightshade, yield under fertilized open field was not significantly different from those under the canopies. Pruning of the Eucalyptus tree canopies had no significant change on yields of the nightshade with yields higher than open fertilized fields. Seasonal variations did not have a significant change on the yields of the tested crops. Age of the tree canopy had a significant effect on the yields of nightshade but not for potatoes and beans with a 3 year old canopy (0.32 t/ha) giving a higher yield compared to a 6 year old (0.21 t/ha) for two consecutive seasons.

Table 19: Yield of crops under *Eucalyptus grandis* tree canopies of different ages

Canopy	Potatoes (t/ha)	Beans (t/ha)	Nightshade (t/ha)
Control/Un-Fertilized open field	4.63a	0.23a	0.17a
Plantation of 3 years: season 1	5.31ab	0.22a	0.29b
Pruned plantation of 3 years:			
Season 1	5.77b	0.27a	0.32b
Plantation of 6 years: season 1	5.14ab	0.22a	0.22c
Plantation of 6 years: season 2	5.12ab	0.25a	0.21ac
Open field (Fertilized)	9.61c	0.49a	0.29b
CV (%)	10.30	31.40	13.50
$LSD_{(p=.05)}$	1.21	0.44	0.08

A mean value followed by the same letter in the same column, do not differ significantly from each other at 5% level of significance according to Tukey's HSD Test

4.3.4: Modeling PAR, LAI and Yield of crops under Eucalyptus trees

Correlation Analysis: PAR, LAI, and Yield

The yields of tested crops were positively and significantly correlated to LAI and PAR. The strength of the linear relationship between yield and LAI was stronger in potatoes and weaker in nightshade; $r = .74$ followed by beans $r = .64$ and then nightshade $r = .23$ (Table 20), and statistically significant in all the 3 tested crops ($p < .01$). Correlation between Yield and PAR was positive and statistically significant ($p < .01$) in all of the crops tested with still potatoes having a stronger relationship $r = .67$ followed by beans $r = .55$ and then nightshade $r = .20$, (Table 22). Correlation between LAI and PAR was positive and statistically significant (p < .01) in all of the tested crops (potatoes r = .57, beans r = .51, and nightshade r = .41 (Tables 20, 21 & 22).

Table 20: Pearson Correlation coefficients: Beans

	Yield	LAI	PAR
Yield	1	.64**	.55**
LAI		1	.51**
PAR			1

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Table 21: Pearson Correlation coefficients: Potatoes

	Yield	LAI	PAR
Yield	1	.74**	.67**
LAI		1	.57**
PAR			1

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Table 22: Pearson Correlation coefficients: Nightshade

	Yield	LAI	PAR
Yield	1	.23**	.20**
LAI		1	.41**
PAR			1

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Regression Analysis: PAR, LAI, and Yield

Regression analysis was performed using Yield as the dependent variable while PAR and LAI as the independent or predictor variables in the model. Linear regression relationships seemed to be the best models having higher r^2 values. From the results, all the predictors were significant.

Beans

For beans the coefficients for PAR and LAI were positive PAR (b = 7.2E-5) significant ($p < .001$), meaning that increase in PAR under the tree increased the yield significantly. For Leaf area index, LAI (b = .088) significant ($p \leq .001$), indicating that increase in LAI increased the yield significantly. The model was significant with F-test (df 188, ($p \leq .001$) and t-test for both PAR and LAI (5.03, 7.97). The $r^2 = .48$ meant approximately 48% of the variance in yield was accounted for by the model, in this case, the two predictors (LAI and PAR). Linear equations for each variables/ predictors were developed;

Yield (kg) = .088 + 7.281E^{-5} [PAR] + .088 [LAI], r^2 = .484 $p \leq$.001

Yield (kg) = 0.212 + 0.00 [PAR], r^2 =.311 $p \leq$ .001

Yield (kg) = 0.064 + 0.116 [LAI], r^2 = .415 $p \leq$. 001

Potatoes

For potatoes the coefficients for PAR and LAI were positive PAR (b = .001)) significant (p < .001), meaning that increase in PAR under the tree increased yield significantly. For Leaf area index, LAI (b = 1.216) significant ($p \leq$ .001), indicating that increase in LAI increased the yield significantly. The model was significant with F-test (df 230, ($p \leq$ .001) and t-tests for both PAR and LAI (7.70, 11.05).

The r^2 = .64 meant approximately 64% of the variance in yield was accounted for by the model, in this case, the two predictors (LAI and PAR). Linear equations for each variables/ predictors were developed;

Yield (kg) = 2.71 + .001 [PAR] + 1.21 [LAI], r^2= .64) $p \leq$ .001)

Yield (kg) = 4.49 + 0.002 [PAR], r^2 =.45) $p \leq$ .001)

Yield (kg) = 2.22 + 1.70 [LAI], r^2 =.55) $p \leq$ .001)

Nightshade

For nightshade the coefficients for PAR and LAI were positive PAR (b = .005) but not significant (p = .09), meaning that increase in PAR under the tree canopy did not necessarily increase yield. For Leaf area index, LAI (b = 9.30) significant (p = .024), indicating that increase in LAI increased the yield significantly. The model was significant with F-test (df 194, ($p \leq$ .001) and t-tests for both PAR and LAI (1.70, 2.28), statistically significant for LAI alone

($p < .05$). The r^2 =.065 meant approximately 1% of the variance in yield was accounted for by the model, in this case, the LAI. Linear equations for each variables/ predictors were developed;

Yield (kg) = 0.19+.005 [PAR] +9.30 [LAI], $r^2 = .065$, $p \leq .001$

Yield (kg) = 0.21+ 0.007[PAR], $r^2 =.04$ $p \leq .05$

Yield (kg) = 0.81+ 12.55 [LAI], $r^2 =.05$ $p \leq .001$

CHAPTER FIVE

DISCUSSION

5.1: Soil and Plant nutrients dynamics in *Eucalyptus grandis* plantations before and during intercropping

5.1.1: Effect of tree age and soil depth on the nutrient concentration in soils under *Eucalyptus grandis*, its litter and leaves

The age of the Eucalyptus tree plantation and the soil depth positively and negatively influenced the nutrient concentrations in the Eucalyptus plantations of different ages. The organic carbon (OC) content, total nitrogen (TN) and calcium significantly reduced with increasing soil depth under Eucalyptus trees. These changes in the nutrients could perhaps be attributed to the different rates of litter fall under different ages of Eucalyptus canopy which influenced the mineralization rates. By soil standards for crops (Agricultural Bureaus of SA, 2010; Hughes *et al.*, 1996), (Appendix 20), the amount of available phosphorus was very low (deficient to critically deficient) and it was constant or nearly equal for all the depths with top horizon 0-20 cm having higher content (4.28 mg/ kg). The leaf total P and litter total P were negatively correlated whereby the high levels of total P in the leaf was contrasted by low levels in the litter of the same canopy with both being equal in the 6 year old canopy. The maximum total P content occurred at age 12 (474 mg/ kg) and 20 (438 mg/ kg) for litter and leaf respectively. The low availability of phosphorus in the soil could be attributed to high concentrations of manganese which lead to increased fixation. From literature, the forms of soil P variability and availability in the soil have been linked with the amount of extractable manganese in the soil (Singh *et al.*, 2015). In this study, manganese (1133 mg/ kg), magnesium (1108 mg/ kg), and potassium (503 mg/ kg) levels in the soil were very high and even in the Eucalyptus tissues.

These could affect even the growth of very sensitive crops under the canopy especially from manganese toxicity. The findings in this study are also in agreement with those of Alemie (2009) who studied on the effect of distance gradients from the Eucalyptus stand on soil fertility where a significant effect was reported on soil available phosphorus, exchangeable calcium, total nitrogen (TN) with no change in potassium (K) concentration.

Soil depth significantly affected the content of total nitrogen and organic carbon. Both total nitrogen and % OC reduced down the soil profile with top horizons of 0-20 cm having marginally higher content compared to lower soil depths. The high content of both nutrients was high in top horizons probably due to high litter fall on the soil surface which mineralizes to form % OC and then contributes to total nitrogen pools. The trends of total nitrogen in both leaf and litter were similar across the different ages of Eucalyptus with the maximum being 20 year old canopy. The content of total nitrogen in litter was significantly different across different ages of Eucalyptus canopies but not the leaf content. Total nitrogen content in litter and leaves have been reported not to change with time or age in soils under Eucalyptus by Leite *et al.*, (2011), a fact attributed to sustainable N cycling rates. If considering crop production then two parameters were adequate and considered high in the soil (Agricultural Bureaus of SA, 2010; Hughes *et al.*, 1996), (Appendix 20). There was no significant difference in the quantity of OM % present in the leaf and litter of Eucalyptus tree of different ages. Lack of significant changes in soil organic carbon levels under different ages of Eucalyptus tree canopies could also be attributed to presence of complex phenolic compounds which are responsible for low decomposition rates of soil organic matter a fact reported by Northup *et al.,* (1998); Bernhard-Reversat (1998) and Min *et al.,* (2015).

Soil depth also significantly affected the content of calcium and magnesium in the soil but not potassium. Calcium reduced down the soil profile 0-20 cm (2363 mg/ kg) 80-100 cm (1150 mg/ kg) while potassium and magnesium increased a fact attributed to leaching and mobility of the elements compared to calcium which in most cases is bound to anions like phosphates hence less mobile in the soil. Both potassium and magnesium reduced in 20-40 cm depth before increasing down the profile. Potassium (exchangeable) content in the soil was very high going with soil standards (Appendix 20) with 20 year old tree canopy having the highest (705 mg/ kg) and 6 year old tree canopy the lowest (387 mg/ kg). For total potassium (K) in the leaf and litter, the contents for both were equal at the tree age of 12 years (8488 mg/ kg) which was a maximum for litter content. Both leaf and litter total potassium (K) contents were statistically significant across the differently aged plantations with leaf (8,008 mg/ kg) content being more than that of litter (4,782 mg/ kg). The trend for leaf calcium content was similar to the soil calcium content. The content of calcium in both leaf and litter followed the trend of total P whereby, increase in the leaf led to reduction in the litter for the same canopy with the maximum for litter occurring at 3 year old (6800 mg/ kg) and 40 year old (7900 mg/ kg) canopies while lowest in 6 year old. For fresh leaf, calcium content was lowest in the 3 year old canopy which surprisingly coincided with the highest litter content. The 3 year old canopy was thick and closed with more leaves compared to 6 year old which was open with mostly less young leaves therefore the former was actively growing absorbing more calcium to its leaves and therefore its litter would have high content as the element is less mobile hence deficiency is seen in young leaves as supported by results from this study and by the fact that calcium has been found to be retained in the aging plant tissues (Grove *et al.,* 1996).

Leite *et al.,* (2011) reported decrease below adequate levels in the concentration of phosphorus and calcium in *E. grandis* leaf of ages 2.5 to 6.75 years. In the same study (Leite *et al.,* 2011); magnesium, zinc, and boron were below the critical levels with no significant changes with age of Eucalyptus tree.

For manganese, the soil content correlated negatively to both litter and leaf contents whereby an increase in the soil content corresponded with a decrease in both leaf and litter with a maximum occurring in the canopy aged 20 years (1237 mg/ kg) which corresponded to lowest leaf and litter contents. Manganese in both litter and leaf content had similar trends with peak values at canopy age 3 (1458 mg/ kg) and (904 mg/ kg) with lowest at canopy age 20 (835 mg/ kg) and (633 mg/ kg) respectively. Moreover, soil depth had no significant effect on the content of iron and manganese as both had a similar trend reducing down the soil profile with iron 0-20 cm (745 mg/ kg), 80-100 cm (710 mg/ kg) while manganese 0-20 cm (1212 mg/ kg) and 80-100 cm (1009 mg/ kg). Both iron and manganese together with aluminium have been linked to phosphorus fixation (Singh *et al.,* 2015), especially in acidic soils whereby they form insoluble complexes rendering them less mobile a fact supported by high content of soil total P in this study. Since the organic matter was very high in the soils then formation of complex compounds or chelation with humus could be another explanation of their immobility in the soil. It has been documented that soils high in organic matter (> 6.0 %) and pH above 6.5 may exhibit manganese deficiency whereby increase in organic matter in the soil leads to reduction in exchangeable manganese as a result of formation of manganese complexes (Schulte and Kelling, 1999).

For the content of iron in Eucalyptus tissues, the leaf content had a perfect but opposite trends with the soil whereby both reduced between tree age 1.5 and 3 years then took opposite directions with an increase in the soil content leading to a reduction in the leaf with a maximum of soil coming in 6 year old canopy (847 mg/ kg) corresponding to lowest content in leaf (260 mg/ kg).

For iron content in the litter, the trend was different from both leaf and soil producing double maxima at tree ages of 3 and 40 years (2550 mg/ kg) and double minima at ages 1.5 and 20 years (633 mg/ kg). From literature, there is a balance between manganese and iron in the soil and even in the plant tissues especially the leaves whereby manganese toxicity leads to iron deficiency. This may be as a result of manganese ion being similar in size to magnesium and iron ions and can therefore substitute any of these elements in silicate minerals or iron oxides in the soil (Schulte and Kelling, 1999). In this study, going by the soil standards (Agricultural Bureaus of SA, 2010; Hughes *et al.,* 1996) and (Appendix 19), manganese was very high while low in iron content when the soil type was factored in (Nitsols). Furthermore, manganese in the soil occurs as exchangeable manganese either as organic matter bound, or as oxides of manganese. Manganese content in soils varies widely with some soils having up to 3000 ppm (Schulte and Kelling, 1999), 20-10000 mg/kg (Sparks (1995), 15-17 mg/kg in acid soils (Hue & Mai, 2002; Millaleo *et al.,* 2010). In addition, the levels of manganese in both litter and leaf content had similar trends with peak values at tree age of 3 years (1458 mg/ kg) and (904 mg/ kg) with lowest contents at tree canopy age of 20 years (835 mg/ kg) and (633 mg/

kg), respectively. Manganese contents of plant leaves differed greatly between species with levels of 30-500 mg/kg being reported as normal (Clarkson, 1988).

Schulte and Kelling (1999), reported manganese levels of between 300-400 ppm in plant tissues being labeled excessive, especially in crops and therefore, the contents of manganese in *Eucalyptus grandis* was very high. Studies on nutrient relations in *Eucalyptus grandis* (0.25, 2.5, 4.5, and 6.75 years) by Leite *et al.*, (2011) revealed nutrient concentrations in tree was significantly affected by population density. Furthermore, the concentration of phosphorus, potassium, calcium and magnesium in litter and above ground tissues reduced with increase in Eucalyptus age (Leite *et al.*, 2011).

These differences in age have been attributed to the tree physiology as it grows whereby there is a reduction in leaves and branches and an increase in woody component of the stem as explained by Leite *et al.*, (2011).

Nutrient use efficiency in forest canopies has been reported to increase with age due to an increased wood mass which has low nutrient concentration (Miller, 1984; Bouillet *et al.*, 2008). According to Miller, (1984) and Grove *et al.*, (1996), nutrient concentration in the forest canopies depends on the stage of growth or age whereby the nutrient concentrations are high in leaves and branches when the trees are very young where high amounts of nutrients are mined from the soil. This stage is followed by crown closing stage whereby in this study it occurred when trees were between 1.5 and 3 years old characterized by dense canopy. At this stage, leaf biomass is believed to be stable with heartwood forming which in itself has low nutrient concentration with the last stage being described as the one where the produced biomass is being maintained by the tree (Grove *et al.,* 1996).

5.1.2: Effect of crop cultivation on soil nutrient concentrations under Eucalyptus trees

Crop cultivation under Eucalyptus trees reduced total nitrogen and potassium in the soil while available phosphorus, pH, magnesium and manganese increased in the soil (0-20 cm, 20-40 cm depths). Soil organic carbon, exchangeable calcium and extractable iron were unchanged during cultivation and cropping. The soil organic carbon content under the tree was high when crop production is considered (Appendix 20) and did not fluctuate much per cropping season leading to the availability of nitrogen for crop use. However, the level of depletion was very high for nitrogen per season which may not sustain good yields and hence additional fertilization required. Among many factors such as high litter fall rates which maintain organic carbon levels under the tree canopy, the presence of complex phenolic compounds in Eucalyptus soils have been labeled responsible for low decomposition rates of soil organic matter a fact reported by Northup *et al.,* (1998); Bernhard-Reversat (1998) and Min *et al.,* (2015). With continuous cropping the levels of potassium, magnesium and manganese seemed to reduce in the plough layer (0-20 cm) and accumulate in the sub-surface horizons. These results are partly in agreement with studies by Couto and Betters, (1995) which revealed that growing of Eucalyptus with crops in short rotation depleted soil nutrients rapidly but soils which have been under Eucalyptus trees for longer periods without crops were found to have higher levels of micronutrients. The availability of soil phosphorus for plant/crop use was the most pronounced problem in this study which could limit successful plant growth (Appendix 20), especially crop production under the tree averaging critical to very low levels (2 to 5 mg/kg). Total soil P was high and increased as the tree aged averaging (160 to 900 mg/kg) for 1.5 and 40 year trees, respectively.

In addition, soil P availability increased with the cropping seasons moving from critical to very low, then low after two cropping seasons (2 to 11 mg/kg). Such cases have been reported elsewhere; soil phosphorus in the forested Alfisols inhabited by Oak trees by Singh *et al.*, (2015) recorded total P concentrations of 15.6 to 410 mg/kg and available P concentration of 0.29 to 30.6 mg/kg. The forms of soil P variability and availability in the soil have been linked to the amount of extractable manganese in the soil (Singh *et al.*, (2015). Such findings agree with those observed in this study where manganese, magnesium and potassium were very high soil (Appendix 19) and this could affect the growth of very sensitive crops, especially by manganese toxicity. In sub-tropical forests in China (Liu *et al.,* 2014), soils under old monsoon evergreen forests have been reported to contain more available P but less total P when compared to young pine and coniferous forests. In the same study, soil total N correlated significantly to soil available P which agrees with findings in this study whereby, total nitrogen in the soil positively and significantly correlated with organic carbon, phosphorus, calcium and manganese.

The results of this study would form a basis of agroforestry initiatives in Eucalyptus crop mixtures especially when soil amendments is needed because status of fertility are known, whether toxicity or deficiency. In addition, the results would be used in rehabilitating the soils after Eucalyptus trees have been harvested for cropping purposes. These results are specific to a particular soil type or other related soils like Acrisols and

Ferrasols. Finally, the choice of crops to be planted under Eucalyptus trees or plantations should be able to withstand low levels of phosphorus and high levels of potassium, magnesium and the nearly toxic levels of manganese. Crops like beans, lettuce, oat, and soybean have high manganese requirements while forage legumes, mint, and potatoes are susceptible to manganese toxicity (Schulte and Kelling, 1999).

5.2: Levels of Allelopathy in *Eucalyptus grandis* trees and its effect on crop performance and soil water repellency

5.2.1: Levels of soluble polyphenols in soils under *Eucalyptus grandis* and its tissues (litter and leaves) and its effect on crop germination

Information about the composition and amount of phenolic compounds is useful in understanding of soil water repellency as a result of nutrient cycling (Halvorson *et al.*, 2009), especially the soil organic matter formation under the Eucalyptus tree canopies. In this study, the effect of age of Eucalyptus tree on the concentration of water soluble polyphenols in its leaves (66 mg/g), litter (43 mg/g) and soil (0.33 mg/g) underneath was significant. The amount of soil soluble polyphenols was observed to increase with the age of the Eucalyptus trees especially from 12 years of age to 40 years. The trend in the soil content was two-fold whereby; the content reduced with age up to 12 years (0.22 mg/g) then increased rapidly as the tree matured with trees over 40 years (1.12mg/g) producing the highest content. The amount of soluble polyphenols in the canopy litter was significantly different from that of fresh leaves with the latter (leaves) (66 mg/g) containing nearly double amounts of that of litter (43 mg/g). There were no differences in the amounts of soluble polyphenols present in the leaves and litter for trees of ages 1.5, 3, 6 and 12 years. The Eucalyptus tree aged 6 and 12 years had the lowest amount of soluble polyphenols in their leaves (55.85 mg/g, 62.05 mg/g) and litter (25.51 mg/g, 23.10 mg/g). The Soil soluble polyphenols was positively and significantly correlated to both litter and leaf polyphenols. The amount of soluble polyphenols in the soil was 50 to 100 times less than that present in the tissues (leaves and litter) perhaps due to the fact that they are of plant origin and hence its high content in Eucalyptus tissues.

The phenolic compounds are distributed in plants and very common in plant decomposition products, and they are important precursors of humus in soils (Li *et al.*, 2010).

Manganese phyto-toxicity has been linked with increased phenolic compounds production in leaf cells as tolerance mechanism for manganese toxicity (Baldisserotto *et al.*, 2004) and perhaps one of the reasons why Eucalyptus have high contents of polyphenols.

The effect of soil depth on the amount of soluble polyphenols present in the soils under the Eucalyptus trees was significantly different with top soil containing high amounts and less or none with increasing soil depths. The Eucalyptus canopy aged 3 (0.012 mg/g) and 6 (0.052 mg/g) years had the lowest amount of soluble polyphenols in soils but generally there were no significant differences for ages 1.5, 3, 6 and 12 years for 0-10 cm and 10-20 cm depth. For 10-20 cm soil depths, the amount of soluble polyphenols could not be detected for ages 1.5, 3, 6 and 12 years. Since most phenolic compounds are water soluble and are retained in solution between soil particles (Hebatpuria *et al.*, 1999), then perhaps this explains why they could not be detected in the soil layer because of leaching.

Moreover, polyphenols are present in many forms including freely dissolved soluble forms, adsorbed or as complex ones (Min *et al.*, 2015). Low content of soluble polyphenols in the soil could also be attributed to the extracting medium where differences have been reported for example, Cvikrová *et al.*, (2013), hot water extraction in top soil gave low contents compared to the leaves for deciduous and coniferous trees. Another reason why soluble polyphenols in the soil were low is the fact that they undergo transformations once in the soil including influence on several plant-soil interactions especially allelopathy and humification (Muscolo *et al.*, 2001).

The composition of polyphenols in a soil is also known to be influenced by type of soil and vegetation cover (Strobel, 2001). Moreover, determination of total polyphenols in the soil has limitations ranging from the extracting solvent, source of the material interfering with precipitates during colorimetry and the effect of non-phenolic oxidizable compounds, Halvorson *et al.*, (2009). For instance, MSA-MeOH extracted more total polyphenol in the soil than aqueous acetone with no differences in the plant material when both extractants were used (Halvorson *et al.*, 2009). The use of Prussian Blue Assay or Folin Dennis reagent in colorimetric methods have been shown to give different results and the source of the material also plays a major role in the quantities extracted as plant based samples contain more total polyphenols compared to soil for instance total phenolics in forages and their resulting manures were of 1-2 orders of magnitude greater than mineral soil (Halvorson *et al.*, 2009). Lastly, the use of more conventional and advanced techniques to extract polyphenols from soil materials like ultrasonic extraction, Soxhlet extraction, microwave assisted micellar extraction and solid phase extraction techniques like SPME-HPLC have their own advantages and limitations and influence quantity of phenols determined (Santana *et al.*, 2009).

In this study, the aqueous polyphenol extract from litter and fresh leaves completely inhibited the seeds germination of common bean. However in diluted extracts (50 times of their original concentrations), the germination was 80% and 50% in litter and fresh leaves, respectively. Soil soluble polyphenol extract without dilution did not inhibit germination of common beans registering up to 80% compared to control (distilled water) which recorded 95%.

The concentration of soluble polyphenols in litter which permitted germination was in the same orders with that of the soil which was nearly < 3.0 mg/g and these would explain why germination of crops under the canopy in the field was high despite high litter content in the soil. Results in this study partly agree and disagrees with others like those of Waller, (1987) which suggested that Eucalyptus trees contain allelochemicals which have harmful effects on other plants under its canopy hampering germination and reduction in growth and yield. In other studies on Eucalyptus allelopathy; extracts of leaf litter and root exudates of *Eucalyptus urophylla*, *E. citriodora* and *E. camaldulensis* have indicated inhibition on the germination speed and seedling growth of Chinese cabbage and radish plant (Zhang and Fu, 2010). Ahmed *et al.,* (2008) proposes use of *Vigna unguiculata*, and *Cicer arietinum* in agroforestry with Eucalyptus trees as their performance was not inhibited by *E. camaldulensis* litter although the effect depended on concentration of extract from litter and the crop species. Studies by May and Ash, (1990) revealed no growth suppression on *Lolium Lemna* by fresh leaves of Eucalyptus while leaf essential oils, litter and bark leachates suppressed growth and these depended to the concentration of leachates. Moreover, soils containing water-soluble phenols without humus in them were found to inhibit cell growth and seed germination of some herbaceous and leguminous plants (Muscolo, 2013). Suggestions by Zhang and Fu, (2010); Alemie, (2009) for removing canopy surface litter to reduce allelopathy seem valid although as observed in this study, continuous cultivation and mixing of litter with soil is recommended especially for sustainability of fertility under the canopy. In addition, previous studies have also indicated that the effects of leaf litter are much stronger than root exudates a fact supported by results of this study whereby the litter soluble polyphenol content was higher than that contained the soil.

5.2.2: Soil water repellency under *Eucalyptus grandis* tree canopies of different ages

The persistence of soil water repellency/soil hydrophobicity correlated significantly with the amount of soluble phenolic compounds in the Eucalyptus litter and soil hence the soil water repellency index alone could be used to give an insight of the quantity of the polyphenols present in the soil of a particular Eucalyptus plantation of known age. Soil water soluble polyphenol, soil moisture, soil depth and age of Eucalyptus were the key predictors of soil water repellency with soil soluble polyphenol content and the soil moisture content being the most strong or consistent factors influencing water repellency in soils under Eucalyptus tree canopies. Soil water repellency in different soil depths down the soil profile was significantly affected by age difference in Eucalyptus canopies. Furthermore, the effect of soil depth, moisture content (wet and dry spells), and the interaction of age and soil depth significantly affected soil water repellency. Soil water repellency was very high or strong during dry spells (WDPT 272s) when the soil had less moisture but less hydrophobic during the wet season (WDPT 15s). Soil water repellency increased with age of the Eucalyptus plantation with trees over 40 years having soils 45 times repellent than those of 1.5 years old, a fact attributed to the high concentration of soluble polyphenols in the soil. Soil hydrophobicity reduced down the soil profile with surface (up to 10 cm) being extremely water repellent while at the 100 cm depth being not repellent. Generally, the soils were found not to be water repellent below 40 cm across all the ages of Eucalyptus tree canopies studied irrespective of the season being wet or dry. Soil water repellency was greatly affected by soluble polyphenol content in the soil and litter having positive significant relationship. The age of Eucalyptus tree correlated significantly and positively with soil water repellency irrespective of whether the soil was wet although the relationship was stronger in dry spells.

Soil water repellency significantly correlated negatively with soil moisture during dry spells but not significant in wet spells. Moreover, soil water repellency correlated negatively with soil depth for both dry and wet spells while soil moisture and soil depth had a negative relationship during wet spell but a positive one during the dry spell. This meant that under the Eucalyptus canopy, soil moisture increased down the soil profile during dry spells but completely opposite during wet spells perhaps due to capillarity. There were no significant relationships between age of the Eucalyptus canopy to both soil moisture and soil depth.

From the results, it could be concluded that soil polyphenol content and the soil moisture content were the most consistent factors influencing water repellency in soils under Eucalyptus trees. Cropping or continuous cultivation of the canopy soils significantly reduced the soil water repellency and these results are in line with a number of literatures elsewhere including those of Malvar *et al.,* (2015) who also found out that the severity of soil water repellency decreases with increasing soil depth with its patterns influenced by rainfall. Doerr *et al.,* (2006) reported a relationship between soil water repellency and land cultivation. Soil water repellency in pine and Eucalyptus on sandy loam soils was found to be strong during dry period and weak in wet periods and correlating negatively with soil moisture content (Rodríguez-Alleres and Benito, 2011). In *Eucalyptus globulus* plantations, soil surface water repellency has been reported to occur in dry summers and absent in wet winters (Leighton-Boyce, 2017) a problem associated with soil moisture. The transitional moisture levels from which below it the soil is hydrophobic and above it is not, was reported to be 21–50% for pine soils and 17–36% for Eucalyptus soils (Rodríguez-Alleres and Benito, 2011).

Elsewhere, the moisture range defining the presence or absence of repellency in *Pinus Pinaster* plantation under field conditions was reported to be 22–57% (Rueda *et al.,* 2016). Leighton-Boyce, (2017) suggested that soil moisture below 14%, and above 27% is a transition zone in soils under *Eucalyptus globulus.* Rodríguez-Alleres and Benito, (2011) highlights the lower and upper bounds of the transition moisture zone to coincide to soil moisture contents at the permanent wilting point and at field capacity respectively. Finally, the relationships between contact angle and water content in the soils have showed a significant hysteresis in drying conditions than during wetting (Fishkis, 2015).

In this study, under *Eucalyptus grandis,* the transition zone was found to be between 14% and 25% soil moisture contents while above 46% soil moisture, there was no soil repellency at all. Therefore, from this study it can be concluded that; soil water repellency as a result of accumulation of water soluble polyphenol in the soil causes soil moisture stress leading to crop failure for example reduced or no germination. To reduce hydrophobicity in the soil, several approaches have been employed in the management of soil water repellent soils which include; application of surfactants in order to increase the soil water infiltration, claying for sandy soils and selection of plant species which cope with low soil moisture availability (Landl 2013). In addition, cultivation and liming have been suggested to reduce hydrophobicity in the soil. Lastly, inoculation of soil with wax-degrading bacteria as a biological way to reduce hydrophobicity has been suggested by Roper (2006). From this study, continuous cultivation and mixing of litter with the soil is a recommended way to reduce water repellency in the soil under Eucalyptus trees.

5.3: Evaluation and modeling the performance of crops growing under *Eucalyptus grandis* tree canopies and its potential for agroforestry

Light interception by different components of a multi-layered agroforestry systems and the distribution of the photosynthetically active radiation (PAR) within canopy units, are the key factors influencing the productivity of tree-crop mixtures, (Nair, 1983). Therefore it is important to estimate the PAR intercepted by each component of the systems at any given time to be used in assessing and managing the productivity of agroforestry systems, (Nair, 1993).

In this study, the age differences in the Eucalyptus tree canopies had no significant effect on the amount of PAR reaching the understory crops but as expected pruning of the canopy branches significantly increased the amount of PAR reaching the understory. Seasonal variations in weather conditions significantly affected the amount of PAR reaching the understory crops. The effect of the amount of PAR reaching the understory on the LAI and the yields of crops was stronger in potatoes and beans. Correlation between yield and for both PAR and LAI was positively and significantly correlated in the tested crops with potatoes having a stronger relationship. Such results have been revealed elsewhere in Soybean where yield had a positive linear relationship with LAI (Jones, 2002).

The tested crops grown under Eucalyptus trees had significantly higher yields compared to the un-fertilized crops in open field which was explained by the simple fact that the soils under the tree canopy were rich in plant nutrients from litter mineralization. The different ages of the Eucalyptus tree canopies and pruning of the branches had a significant effect on yields of nightshade but not for beans and potatoes.

The differences in yield between the tree canopy and the open field crops were significant for beans and potatoes but not nightshade. The non- fertilized open fields or controls had low yields compared to crops under trees which had no fertilizer added for all the tested crops. For beans and potatoes, the tree canopy differences in terms of age and even pruning had no significant effect on yield. Furthermore, bean production in the open field was twice that under trees; fertilized open field beans produced the highest (0.49 t/ha) followed by under pruned canopy aged 3 years (0.27 t/ha), 6 year old tree canopy (0.25 t/ha) and non- fertilized open field (0.23 t/ha). The yields for common bean were way below of those reported by KALRO (KARI, 2008) of the tested variety when planted in the open field of 1.8-2.0 t/ha and even below the national production of common beans in 2013 which was 0.5 MT/ha (USAID, 2016). The yield production for potatoes had the same trend as beans, whereby the yields from fertilized open field were twice that under tree canopy. The fertilized open field produced (9.6 t/ha), pruned tree canopy aged 3 years (5.7 t/ha), 6 year old canopy (5.1 t/ha) and non-fertilized open field (4.6 t/ha). Just like beans, there was no significant difference in potato yields across the different tree canopies. The potato yields were below those reported by KARI in 2008, when the variety was released whereby, the yields should be in range of 35-45 t/ha when planted in the open field. Furthermore, the yields were below those of national production of 2014 which was 13.4 MT/ha (USAID, 2014). For nightshade, yield under fertilized open field was not significantly different from those under the tree canopies. Pruned tree canopy aged 3 years produced the highest (0.32 t/ha), fertilized open field (0.29 t/ha) followed by 6 year old tree canopy (0.22 t/ha) and un-fertilized open field (0.17 t/ha). Pruning of the Eucalyptus tree canopies had significant effect on yields of the nightshade with yields higher than open fertilized fields.

Seasonal variations did not have a significant effect on the yields of the tested crops. The age of the tree canopy had a significant effect on the yields of nightshade but not for potatoes and beans with a 3 year old canopy giving a higher yield compared to a 6 year old for two consecutive seasons. Compared to national production of 7.5 MT/ha (2014) and 9.9 MT/ha (2013), (USAID, 2014), the nightshade yields were low and this could be due to a number of factors ranging from variety, spacing, fertilization and the mode of establishment.

In conclusion, nightshade vegetable performed better under the tree canopy compared to beans and potatoes, producing yields not significantly different as when grown and fertilized in the open field. This was attributed to the fact that nightshade as one of the C_3 photosynthetic pathway plants perhaps utilized light more efficiently therefore performing better under reduced solar radiation. From literature, it has been suggested by

Nair, (1993) and Tieszen, (1983), that for annual or seasonal type of agroforestry such as cropping under Eucalyptus, then it is suggested that understory plants should be able to build up leaf area as quickly as possible. In conditions with a permanent woody over-story like in this study growing under Eucalyptus trees, where the trees possess the C_3 pathway; then under-story plants should be C_3 crops (Tieszen, 1983) hence the choice of nightshade. In addition, if shading is so significant by the understory then the choice should be C_3 plants as they have a greater efficiency of CO_2 uptake at lower irradiance levels than C_4 plants. However, for the open over-story systems, C_4 crops have been suggested to be understory species (Tieszen, 1983). The amount of solar radiation intercepted by a canopy is dictated by many factors including; the leaf angle, size, shape, thickness and chlorophyll concentration (Campillo *et al.*, 2012).

It is believed that only 50% of the incident radiation intercepted by plant canopy is utilized for photosynthesis (Loomis and Connor, 2002; Varlet-Gancher *et al.,* 1993). Maximum productivity in crop canopies depends on the capture of incident solar radiation which is influenced by optimal levels of water and nutrients (Loomis and Connor, 2002) in this case from soils under the Eucalyptus tree canopy. For instance, the availability of soil nitrogen has been reported to influence the efficiency of radiation interception by a canopy, Scott-Green *et al.*, (2003). Leaf Area index (LAI) has been defined from literature as the area of green leaves per unit area of the ground (Jonckheere *et al.*, 2004) and it is affected by many factors including the species type, stage of growth, management practices etc. In this study, leaf area index (LAI) of the understory crops was significantly affected by shade of Eucalyptus tree canopies of different ages. In addition, LAI of potatoes and beans grown in the open field was higher and significantly different from that grown under trees. However, the difference was minimal for nightshade. Pruning of the Eucalyptus tree canopy branches significantly increased the LAI of beans and potatoes but not of nightshade. Seasonal variations significantly affected the LAI of nightshade but not of beans and potatoes. Generally, the LAI was higher in potatoes and beans compared to nightshade with 6 year old tree canopy having a bigger effect on LAI compared to 3 year old, a fact contributed by more PAR recorded under 6 year old tree canopy and perhaps due to differences in the crop species. In fact, from literature, LAI of Irish potatoes have been known to be influenced by the cultivar planted and even water stress (Gordon *et al.,* 1997) with maximum LAI values of 2-4 recorded for different cultivars. In Soybean, soil type is reported to influence the LAI and yield (Jones, 2002). Similar results have been reported by Deshi *et al.,* (2015) with optimum and minimum LAI values of 3.45 and 2.16, respectively for different varieties of Irish potatoes planted in open field.

In addition, Soybean grown in open fields, have recorded LAI values of 3.5 to 4.0 (Jones, 2002). Most annual crops grown in the open field have recorded maximum LAI values of between 2 and 4 while for trees, maximum values of 8 have been observed for deciduous forests (Beadle, 1993) and these agrees with the findings in this study where the age difference in the tree had a huge significant difference on the LAI of potatoes and beans with 6 year old tree canopy (1.39, 1.54) having a bigger effect on LAI compared to 3 year old (1.09, 0.93) respectively and up to (3.0) in the open field. However, the story was opposite for nightshade with 6 year old tree canopy recording less (0.61) compared 3 year old (0.89). High values of LAI in plants have been linked to better performance of the plant canopy (Boken and Chandra, 2012) with the concept of leaf area index (LAI) being proposed to be used as an estimator of the crop's ability to capture the light energy available for plant growth, (Campillo *et al.*, 2012). Plant canopy photosynthetic rates have been shown to increase as leaf area increases (Westgate, 1999). A number of researchers have concluded that the maximum rate of canopy photosynthesis occurs when between 90 and 95% of available solar radiation is intercepted by the canopy (Christy and Williamson, 1985; Westgate, 1999). For example, in late-planted soybean, increasing leaf area to maximize light interception (LI) has been deemed important for increased biomass often associated with higher yields (Wells, 1991). Selection of species to be used in agroforestry should be based on cultural, economic as well as environmental factors (Nair, 1993), although the photosynthetic pathways of different species are an important physiological consideration.

For increased crop production under the Eucalyptus trees, management strategies should be geared towards increasing or maximizing the penetration of solar radiation to reach the understory crops.

In addition, the crop species that thrive better under low levels of PAR like in this scenario the nightshade should be selected. Such strategies include tree management practices like spacing and pruning of branches. Other important factors to consider are soil water availability to crops and providing deficient soil nutrients in this case the phosphorus availability to crops. Finally, the choice of crops to be planted under Eucalyptus trees should be able to withstand low levels of phosphorus and high levels of cations in this case potassium, magnesium and the nearly toxic levels of manganese.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1: Monitor and evaluate dynamics in soil and plant tissue nutrients concentrations in *Eucalyptus grandis* plantations before and during intercropping

i. The age of the Eucalyptus tree plantation and the soil depth positively and negatively influenced the nutrient concentrations in the Eucalyptus plantations of different ages. The contents of organic carbon, total nitrogen and calcium significantly reduced with increasing soil depth under Eucalyptus trees. Nitrogen, phosphorus, calcium, potassium, manganese and iron contents in litter and leaves of Eucalyptus changed as the tree aged.

ii. Crop cultivation under Eucalyptus trees reduced total nitrogen and potassium in the soil while available phosphorus, pH, magnesium and manganese increased in the soil. Soil organic carbon, exchangeable calcium and extractable iron were unchanged during cultivation and cropping. The effect was pronounced in the 0-20cm and 20-40cm cm soil depths at the end of each of the cropping season.

iii. The availability of soil phosphorus for crop use was the most limiting nutrient for successful crop production averaging critical to very low levels but its availability to crops increased with the cropping seasons moving from critical to very low then low after two cropping seasons. In addition, potassium, magnesium and manganese levels were very high in the soil and even in the Eucalyptus tissue system and these could affect the growth of very sensitive crops especially from manganese toxicity.

6.1.2: Assess levels of Allelopathy in *Eucalyptus grandis* trees and its effect on crop germination and soil water repellency

i. The soil aqueous polyphenol content increased with age of Eucalyptus tree and reduced down the soil profile. The polyphenol content in the soil was 50 to 100 times less than those present in the litter and leaves of Eucalyptus.

ii. The polyphenol extract from litter and fresh leaves completely inhibited the seeds germination of common bean but not the soil extract (80% germination).

iii. Soil water repellency under Eucalyptus trees was mainly influenced by the contents of water soluble polyphenols and moisture available in soil. The persistence and severity of soil water repellency was very strong during dry spells when the soil had less moisture and vice versa during the wet periods.

iv. Soil water repellency increased with age of the Eucalyptus trees and reduced down the soil profile. Crop cultivation and mixing of the soils with litter under Eucalyptus trees reduced the soil water repellency.

6.1.3: Evaluate and model the performance of crops growing under *Eucalyptus grandis* tree canopies and its potential for agroforestry

i. Germination of crops under Eucalyptus trees of different ages was high (beans 90%, potatoes 80%, nightshade 100%) with no difference when planted in the open field.

ii. The leaf area index (LAI) and yield of potatoes and beans reduced under Eucalyptus trees. However, the difference was minimal for nightshade grown under tree shade or in the open field

iii. The age differences in the Eucalyptus trees had no significant effect on the amount of PAR penetrating the canopies to reach the understory crops.

6.2 Recommendations

- From the study, successful intercropping with Eucalyptus trees can be carried out during the initial stages of a Eucalyptus plantation and even at later stages as long as the tree spacing allow enough light to reach the understory crops. Soil fertility under the trees supports successful cropping.
- It is recommended to continuously cultivate the soils under Eucalyptus trees during intercropping to reduce soil water repellency. In addition, litter mixing with soil during cultivation under Eucalyptus trees would reduce soil water repellency. Cultivation helps to reduce allelopathic effects.
- Nightshade vegetable can be grown under Eucalyptus canopy/shade without reduction in yield. Irish potato and common bean are potential crops for agroforestry with Eucalyptus trees but require special canopy management as their yields were low and had selected disease incidences.

6.3 Way forward

- More research on how to improve phosphorus availability to crops growing under Eucalyptus trees and how to reduce the possibility of manganese toxicity.
- Research to find out the optimum spacing of Eucalyptus trees which permit enough light to reach understory crops to produce optimum crop yields in this case Irish potatoes and common beans. In addition, screening of more crop species to be intercropped with Eucalyptus tree especially those which can thrive well under shade and which can withstand low phosphorus availability to be enhanced.

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APPENDICES

Appendix I: Age effect of *Eucalyptus grandis* tree on soil nutrients (Univariate Tests)

Dependent Variable		Sum of Squares	Df	Mean Square	F	Sig.
PH	Contrast	7.144	5	1.429	12.140	.000
	Error	2.825	24	.118		
E.C mS/cm	Contrast	.005	5	.001	3.677	.013
	Error	.006	24	.000		
%C	Contrast	6.330	5	1.266	.631	.678
	Error	48.138	24	2.006		
N %	Contrast	.111	5	.022	2.164	.092
	Error	.246	24	.010		
P (ppm)	Contrast	12.909	5	2.582	10.037	.000
	Error	6.174	24	.257		
K (ppm)	Contrast	300584.363	5	60116.873	4.601	.004
	Error	313578.393	24	13065.766		
Ca (ppm)	Contrast	6211951.546	5	1242390.309	2.809	.039
	Error	1.061E7	24	442249.434		
Mg (ppm)	Contrast	241971.899	5	48394.380	5.395	.002
	Error	215292.481	24	8970.520		
Cu (ppm)	Contrast	2.597	5	.519	3.905	.010
	Error	3.193	24	.133		
Mn (ppm)	Contrast	378920.887	5	75784.177	2.054	.107
	Error	885435.922	24	36893.163		
Fe (ppm)	Contrast	329697.103	5	65939.421	7.329	.000
	Error	215929.798	24	8997.075		

Appendix II: Age effect of *Eucalyptus grandis* on soil nutrients (Multivariate Tests)

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	1.000	3809.535[a]	11.000	14.000	.000
	Wilks' Lambda	.000	3809.535[a]	11.000	14.000	.000
	Hotelling's Trace	2993.206	3809.535[a]	11.000	14.000	.000
	Roy's Largest Root	2993.206	3809.535[a]	11.000	14.000	.000
Age	Pillai's Trace	3.573	4.097	55.000	90.000	.000
	Wilks' Lambda	.000	5.251	55.000	68.390	.000
	Hotelling's Trace	26.356	5.942	55.000	62.000	.000
	Roy's Largest Root	14.723	24.092[b]	11.000	18.000	.000
a. Exact statistic b. The statistic is an upper bound on F that yields a lower bound on the significance level						
c. Design: Intercept + Age						

Appendix III: Effects of soil depth on soil nutrients under *Eucalyptus grandis* trees of different ages (Univariate Tests)

Dependent Variable		Sum of Squares	df	Mean Square	F	Sig.
PH	Contrast	.611	4	.153	.408	.801
	Error	9.358	25	.374		
E.C mS/cm	Contrast	.003	4	.001	1.923	.138
	Error	.009	25	.000		
%C	Contrast	42.710	4	10.678	22.703	.000
	Error	11.758	25	.470		
N %	Contrast	.112	4	.028	2.834	.046
	Error	.246	25	.010		
P (ppm)	Contrast	1.571	4	.393	.561	.693
	Error	17.512	25	.700		
K (ppm)	Contrast	86251.292	4	21562.823	1.021	.416
	Error	527911.464	25	21116.459		
Ca (ppm)	Contrast	7846963.812	4	1961740.953	5.462	.003
	Error	8978974.148	25	359158.966		
Mg (ppm)	Contrast	80034.356	4	20008.589	1.326	.288
	Error	377230.023	25	15089.201		
Cu (ppm)	Contrast	1.823	4	.456	2.873	.044
	Error	3.967	25	.159		
Mn (ppm)	Contrast	321346.091	4	80336.523	2.130	.107
	Error	943010.718	25	37720.429		
Fe (ppm)	Contrast	7645.069	4	1911.267	.089	.985
	Error	537981.832	25	21519.273		
The F tests the effect of Soil Depth. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.						

Appendix IV: Effects of soil depth on soil nutrients under *Eucalyptus grandis* trees of different ages (Multivariate Tests)

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	.998	811.653[a]	11.000	15.000	.000
	Wilks' Lambda	.002	811.653[a]	11.000	15.000	.000
	Hotelling's Trace	595.212	811.653[a]	11.000	15.000	.000
	Roy's Largest Root	595.212	811.653[a]	11.000	15.000	.000
Soil Depth	Pillai's Trace	1.832	1.383	44.000	72.000	.110
	Wilks' Lambda	.013	2.864	44.000	59.341	.000
	Hotelling's Trace	24.173	7.417	44.000	54.000	.000
	Roy's Largest Root	22.390	36.639[b]	11.000	18.000	.000

a. Exact statistic

b. The statistic is an upper bound on F that yields a lower bound on the significance level.

Appendix V: Seasonal variations in soil nutrients during cropping under *Eucalyptus grandis* (Univariate Tests)

Dependent Variable		Sum of Squares	df	Mean Square	F	Sig.
pH	Contrast	.936	2	.468	35.526	.000
	Error	.158	12	.013		
E.C mS/cm	Contrast	.000	2	.000	1.622	.238
	Error	.001	12	9.696E-5		
%C	Contrast	1.865	2	.933	3.524	.063
	Error	3.176	12	.265		
N %	Contrast	.340	2	.170	73.097	.000
	Error	.028	12	.002		
P (ppm)	Contrast	100.013	2	50.006	84.764	.000
	Error	7.079	12	.590		
K (ppm)	Contrast	63950.247	2	31975.124	4.824	.029
	Error	79534.385	12	6627.865		
Ca (ppm)	Contrast	101003.800	2	50501.900	.442	.653
	Error	1370490.857	12	114207.571		
Mg (ppm)	Contrast	639012.235	2	319506.117	27.012	.000
	Error	141941.025	12	11828.419		
Cu (ppm)	Contrast	.261	2	.130	11.583	.002
	Error	.135	12	.011		
Mn (ppm)	Contrast	343535.660	2	171767.830	4.421	.036
	Error	466236.618	12	38853.051		
Fe (ppm)	Contrast	6348.668	2	3174.334	.100	.905
	Error	380146.921	12	31678.910		
The F tests the effect of Season. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.						

Appendix VI: Seasonal variations in soil nutrients during cropping under *Eucalyptus grandis* (Multivariate Tests)

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	1.000	7957.739[a]	11.000	2.000	.000
	Wilks' Lambda	.000	7957.739[a]	11.000	2.000	.000
	Hotelling's Trace	43767.562	7957.739[a]	11.000	2.000	.000
	Roy's Largest Root	43767.562	7957.739[a]	11.000	2.000	.000
Season	Pillai's Trace	1.977	23.346	22.000	6.000	.000
	Wilks' Lambda	.000	21.842[a]	22.000	4.000	.004
	Hotelling's Trace	336.837	15.311	22.000	2.000	.063
	Roy's Largest Root	286.868	78.237[b]	11.000	3.000	.002
Age	Pillai's Trace	.991	20.043[a]	11.000	2.000	.048
	Wilks' Lambda	.009	20.043[a]	11.000	2.000	.048
	Hotelling's Trace	110.235	20.043[a]	11.000	2.000	.048
	Roy's Largest Root	110.235	20.043[a]	11.000	2.000	.048
Depth	Pillai's Trace	.998	78.342[a]	11.000	2.000	.013
	Wilks' Lambda	.002	78.342[a]	11.000	2.000	.013
	Hotelling's Trace	430.881	78.342[a]	11.000	2.000	.013
	Roy's Largest Root	430.881	78.342[a]	11.000	2.000	.013
Season * Age	Pillai's Trace	1.901	5.263	22.000	6.000	.024
	Wilks' Lambda	.002	3.652[a]	22.000	4.000	.108
	Hotelling's Trace	41.797	1.900	22.000	2.000	.402
	Roy's Largest Root	26.816	7.313[b]	11.000	3.000	.064
Season * Depth	Pillai's Trace	1.971	18.497	22.000	6.000	.001
	Wilks' Lambda	.000	12.559[a]	22.000	4.000	.012
	Hotelling's Trace	140.695	6.395	22.000	2.000	.144
	Roy's Largest Root	83.766	22.845[b]	11.000	3.000	.013
Age * Depth	Pillai's Trace	.954	3.779[a]	11.000	2.000	.228
	Wilks' Lambda	.046	3.779[a]	11.000	2.000	.228
	Hotelling's Trace	20.785	3.779[a]	11.000	2.000	.228
	Roy's Largest Root	20.785	3.779[a]	11.000	2.000	.228
Season * Age * Depth	Pillai's Trace	1.888	4.592	22.000	6.000	.033
	Wilks' Lambda	.002	3.750[a]	22.000	4.000	.104
	Hotelling's Trace	50.425	2.292	22.000	2.000	.348
	Roy's Largest Root	40.030	10.917[b]	11.000	3.000	.037

a. Exact statistic b. The statistic is an upper bound on F that yields a lower bound on the significance level

c. Design: Intercept + Season + Age + Depth + Season * Age + Season * Depth + Age * Depth + Season * Age * Depth

Appendix VII: Germination (%) for Irish potatoes (Tests of Between-Subjects Effects)

Dependent Variable: Germination % for potatoes					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	385897.430[a]	29	13306.808	258.964	.000
Intercept	632334.642	1	632334.642	12305.876	.000
Season	729.356	1	729.356	14.194	.000
Canopy	24185.055	2	12092.528	235.333	.000
Days after sowing	340013.922	4	85003.481	1654.254	.000
Season * Canopy	398.959	2	199.479	3.882	.022
Season * Days after sowing	506.763	4	126.691	2.466	.046
Canopy * Days after sowing	19650.872	8	2456.359	47.803	.000
Season * Canopy * Days after sowing	412.502	8	51.563	1.003	.434
Error	12332.346	240	51.385		
Total	1030564.418	270			
Corrected Total	398229.775	269			
a. R Squared = .969 (Adjusted R Squared = .965)					

Appendix VIII: Germination (%) for common beans (Tests of Between-Subjects Effects)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	244773.132[a]	29	8440.453	140.746	.000
Intercept	1012363.376	1	1012363.376	16881.321	.000
Season	578.866	1	578.866	9.653	.002
Canopy	21410.930	2	10705.465	178.515	.000
Days after sowing	196226.004	4	49056.501	818.025	.000
Season * Canopy	2145.265	2	1072.633	17.886	.000
Season * Days after sowing	295.567	4	73.892	1.232	.298
Canopy * Days after sowing	22319.504	8	2789.938	46.523	.000
Season * Canopy * Days after sowing	1796.996	8	224.624	3.746	.000
Error	14392.665	240	59.969		
Total	1271529.174	270			
Corrected Total	259165.798	269			
a. R Squared = .944 (Adjusted R Squared = .938)					

Appendix IX: Photo-synthetically Active Radiation (PAR) under *Eucalyptus grandis* canopies (Tests of Between-Subjects Effects)

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	Beans PAR	4.328E7	17	2546167.298	1135.273	.000
	Potatoes PAR	4.234E7	17	2490363.523	381.676	.000
	Nightshade PAR	3.098E7	17	1822147.505	1325.952	.000
Intercept	Beans PAR	1.901E7	1	1.901E7	8476.866	.000
	Potatoes PAR	2.097E7	1	2.097E7	3214.515	.000
	Nightshade PAR	1.635E7	1	1.635E7	11896.057	.000
Age	Beans PAR	2.041E7	2	1.021E7	4550.913	.000
	Potatoes PAR	1.911E7	2	9557354.619	1464.772	.000
	Nightshade PAR	1.626E7	2	8130205.389	5916.241	.000
Days after planting	Beans PAR	7727568.748	5	1545513.750	689.106	.000
	Potatoes PAR	6165093.144	5	1233018.629	188.974	.000
	Nightshade PAR	5548171.538	5	1109634.308	807.466	.000
Age * Days after planting	Beans PAR	1.514E7	10	1514221.822	675.154	.000
	Potatoes PAR	1.708E7	10	1708247.077	261.808	.000
	Nightshade PAR	9230047.551	10	923004.755	671.658	.000
Error	Beans PAR	318474.659	142	2242.779		
	Potatoes PAR	926522.419	142	6524.806		
	Nightshade PAR	195138.968	142	1374.218		
Total	Beans PAR	6.301E7	160			
	Potatoes PAR	6.468E7	160			
	Nightshade PAR	4.793E7	160			
Corrected Total	Beans PAR	4.360E7	159			
	Potatoes PAR	4.326E7	159			
	Nightshade PAR	3.117E7	159			
a. R Squared = .993 (Adjusted R Squared = .992) b. R Squared = .979 (Adjusted R Squared = .976)						
c. R Squared = .994 (Adjusted R Squared = .993)						

Appendix X: Leaf Area Index (LAI) for crops under *Eucalyptus grandis* canopies (Tests of Between-Subjects Effects)

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	Beans LAI	30.201[a]	11	2.746	19.958	.000
	Potatoes LAI	27.182[b]	11	2.471	19.237	.000
	Nightshade LAI	13.406[c]	11	1.219	51.309	.000
Intercept	Beans LAI	306.299	1	306.299	2226.485	.000
	Potatoes LAI	388.009	1	388.009	3020.478	.000
	Nightshade LAI	123.842	1	123.842	5213.645	.000
Age	Beans LAI	16.380	2	8.190	59.533	.000
	Potatoes LAI	12.829	2	6.415	49.934	.000
	Nightshade LAI	1.143	2	.572	24.061	.000
Days after planting	Beans LAI	12.671	3	4.224	30.701	.000
	Potatoes LAI	12.414	3	4.138	32.212	.000
	Nightshade LAI	11.561	3	3.854	162.230	.000
Age * Days after planting	Beans LAI	1.151	6	.192	1.394	.225
	Potatoes LAI	1.939	6	.323	2.516	.026
	Nightshade LAI	.703	6	.117	4.930	.000
Error	Beans LAI	13.207	96	.138		
	Potatoes LAI	12.332	96	.128		
	Nightshade LAI	2.280	96	.024		
Total	Beans LAI	349.708	108			
	Potatoes LAI	427.523	108			
	Nightshade LAI	139.529	108			
Corrected Total	Beans LAI	43.408	107			
	Potatoes LAI	39.515	107			
	Nightshade LAI	15.687	107			
a. R Squared = .696 (Adjusted R Squared = .661) b. R Squared = .688 (Adjusted R Squared = .652)						
c. R Squared = .855 (Adjusted R Squared = .838)						

Appendix XI: Regression analysis for PAR, LAI and YIELD in Beans (Model Summary)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.696[a]	.484	.479	.0855243	.484	88.295	2	188	.000
a. Predictors: (Constant), PAR , LAI, b. Dependent Variable: Yield									

Appendix XII: Regression analysis for PAR, LAI and YIELD in Irish potatoe crop (Model Summary)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.802[a]	.643	.639	.9173989	.643	206.768	2	230	.000
a. Predictors: (Constant), PAR , LAI b. Dependent Variable: Yield									

Appendix XIII: Regression analysis for PAR, LAI and YIELD in Nightshade vegetable (Model Summary)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.256[a]	.065	.056	14.7478064	.065	6.789	2	194	.001
a. Predictors: (Constant), PAR , LAI b. Dependent Variable: Yield									

Appendix XIV: Water Droplet Penetration Time (WDPT) for soil water repellency (Tests of Between-Subjects Effects)

Corrected Model	6.530E7	83	786758.860	242.657	.000
Intercept	5235268.587	1	5235268.587	1614.690	.000
Season	4164685.778	1	4164685.778	1284.495	.000
Age	4003804.317	5	800760.863	246.975	.000
Depth	1.688E7	6	2812550.661	867.462	.000
Season * Age	3469931.603	5	693986.321	214.043	.000
Season * Depth	1.355E7	6	2258375.352	696.541	.000
Age * Depth	1.257E7	30	418909.193	129.202	.000
Season * Age * Depth	1.067E7	30	355657.728	109.694	.000
Error	544702.000	168	3242.274		
Total	7.108E7	252			
Corrected Total	6.585E7	251			
a. R Squared = .992 (Adjusted R Squared = .988)					

Appendix XV: Changes in soil fertility under Eucalyptus trees during cropping (Pairwise mean comparisons for tree Age)

Pairwise Comparisons							
Dependent Variable	(I) Age	(J) Age	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
						Lower Bound	Upper Bound
PH	3 years	6 years	.186*	.047	.002	.084	.288
	6 years	3 years	-.186*	.047	.002	-.288	-.084
E.C mS/cm	3 years	6 years	-.015*	.004	.003	-.024	-.006
	6 years	3 years	.015*	.004	.003	.006	.024
%C	3 years	6 years	.481*	.210	.041	.024	.939
	6 years	3 years	-.481*	.210	.041	-.939	-.024
N %	3 years	6 years	-.002	.020	.904	-.045	.040
	6 years	3 years	.002	.020	.904	-.040	.045
P (ppm)	3 years	6 years	-.540	.314	.111	-1.223	.143
	6 years	3 years	.540	.314	.111	-.143	1.223
K (ppm)	3 years	6 years	32.763	33.236	.344	-39.652	105.179
	6 years	3 years	-32.763	33.236	.344	-105.179	39.652
Ca (ppm)	3 years	6 years	195.518	137.966	.182	-105.084	496.120
	6 years	3 years	-195.518	137.966	.182	-496.120	105.084
Mg (ppm)	3 years	6 years	75.892	44.400	.113	-20.848	172.632
	6 years	3 years	-75.892	44.400	.113	-172.632	20.848
Cu (ppm)	3 years	6 years	-.159*	.043	.003	-.254	-.065
	6 years	3 years	.159*	.043	.003	.065	.254
Mn (ppm)	3 years	6 years	37.720	80.471	.648	-137.610	213.050
	6 years	3 years	-37.720	80.471	.648	-213.050	137.610
Fe (ppm)	3 years	6 years	-139.438	72.662	.079	-297.756	18.879
	6 years	3 years	139.438	72.662	.079	-18.879	297.756
Based on estimated marginal means							
*. The mean difference is significant at the .05 level.							
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).							

Appendix XVI: Changes in soil fertility under Eucalyptus trees during cropping (Pairwise mean comparisons for soil depth)

Pairwise Comparisons

Dependent Variable	(I) Depth	(J) Depth	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
						Lower Bound	Upper Bound
PH	0-20cm	20-40cm	-.298*	.047	.000	-.400	-.196
	20-40cm	0-20cm	.298*	.047	.000	.196	.400
E.C mS/cm	0-20cm	20-40cm	.005	.004	.245	-.004	.014
	20-40cm	0-20cm	-.005	.004	.245	-.014	.004
%C	0-20cm	20-40cm	1.231*	.210	.000	.774	1.689
	20-40cm	0-20cm	-1.231*	.210	.000	-1.689	-.774
N %	0-20cm	20-40cm	.057*	.020	.014	.014	.099
	20-40cm	0-20cm	-.057*	.020	.014	-.099	-.014
P (ppm)	0-20cm	20-40cm	1.957*	.314	.000	1.274	2.641
	20-40cm	0-20cm	-1.957*	.314	.000	-2.641	-1.274
K (ppm)	0-20cm	20-40cm	-54.585	33.236	.126	-127.000	17.831
	20-40cm	0-20cm	54.585	33.236	.126	-17.831	127.000
Ca (ppm)	0-20cm	20-40cm	365.151*	137.966	.021	64.549	665.753
	20-40cm	0-20cm	-365.151*	137.966	.021	-665.753	-64.549
Mg (ppm)	0-20cm	20-40cm	-319.575*	44.400	.000	-416.315	-222.835
	20-40cm	0-20cm	319.575*	44.400	.000	222.835	416.315
Cu (ppm)	0-20cm	20-40cm	.039	.043	.381	-.055	.134
	20-40cm	0-20cm	-.039	.043	.381	-.134	.055
Mn (ppm)	0-20cm	20-40cm	-137.189	80.471	.114	-312.520	38.141
	20-40cm	0-20cm	137.189	80.471	.114	-38.141	312.520
Fe (ppm)	0-20cm	20-40cm	-79.618	72.662	.295	-237.936	78.699
	20-40cm	0-20cm	79.618	72.662	.295	-78.699	237.936

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Appendix XVII: Soil depth and soil fertility during cropping under *Eucalyptus grandis* trees

Dependent Variable	Soil Depth	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
PH	0-20	6.170	.250	5.656	6.684
	20-40	6.570	.250	6.056	7.085
	40-60	6.524	.250	6.010	7.039
	60-80	6.352	.250	5.838	6.867
	80-100	6.351	.250	5.837	6.866
E.C mS/cm	0-20	.061	.008	.046	.077
	20-40	.043	.008	.028	.059
	40-60	.035	.008	.020	.051
	60-80	.040	.008	.024	.056
	80-100	.037	.008	.021	.052
%C	0-20	4.206	.280	3.630	4.783
	20-40	2.637	.280	2.061	3.214
	40-60	1.408	.280	.832	1.985
	60-80	1.148	.280	.571	1.725
	80-100	1.096	.280	.519	1.672
N %	0-20	.365	.040	.282	.448
	20-40	.365	.040	.282	.448
	40-60	.258	.040	.175	.342
	60-80	.242	.040	.158	.325
	80-100	.227	.040	.143	.310
P (ppm)	0-20	4.280	.342	3.576	4.984
	20-40	3.765	.342	3.061	4.468
	40-60	3.586	.342	2.882	4.290
	60-80	3.923	.342	3.220	4.627
	80-100	3.915	.342	3.212	4.619
K (ppm)	0-20	511.987	59.325	389.806	634.169
	20-40	409.963	59.325	287.782	532.145
	40-60	490.312	59.325	368.131	612.494
	60-80	566.381	59.325	444.200	688.562
	80-100	541.280	59.325	419.098	663.461
Ca (ppm)	0-20	2363.241	244.663	1859.348	2867.133
	20-40	2087.417	244.663	1583.525	2591.309
	40-60	1381.660	244.663	877.768	1885.553
	60-80	1109.948	244.663	606.056	1613.840
	80-100	1150.966	244.663	647.074	1654.858
Mg (ppm)	0-20	482.203	50.148	378.920	585.485
	20-40	435.214	50.148	331.932	538.497
	40-60	534.689	50.148	431.406	637.972
	60-80	514.594	50.148	411.311	617.877
	80-100	589.693	50.148	486.410	692.976
Cu (ppm)	0-20	1.084	.163	.749	1.419
	20-40	.775	.163	.440	1.110
	40-60	.557	.163	.222	.892
	60-80	.469	.163	.134	.804
	80-100	.407	.163	.072	.742
Mn (ppm)	0-20	1212.472	79.289	1049.174	1375.771
	20-40	1235.584	79.289	1072.285	1398.883
	40-60	1203.260	79.289	1039.962	1366.559
	60-80	1004.328	79.289	841.030	1167.627
	80-100	1009.609	79.289	846.310	1172.907
Fe (ppm)	0-20	745.037	59.888	621.696	868.378
	20-40	734.315	59.888	610.974	857.656
	40-60	702.213	59.888	578.872	825.554
	60-80	713.760	59.888	590.419	837.101
	80-100	710.330	59.888	586.989	833.671

Appendix XVIII: Mean comparisons for soil water repellency in different soil depths

Comparison	Difference	Lower 95%	Upper 95%	Significant
80-100cm vs 60-80cm	-0.1	-40.1	40	no
80-100cm vs 40-60cm	-0.2	-40.2	39.9	no
80-100cm vs 20-40cm	-0.8	-40.8	39.3	no
80-100cm vs 10-20cm	-4.4	-44.4	35.7	no
80-100cm vs 0-10cm	-239.4	-279.5	-199.4	yes
80-100cm vs 1cm	-742	-782	-701.9	yes
60-80cm vs 40-60cm	-0.1	-40.2	39.9	no
60-80cm vs 20-40cm	-0.7	-40.8	39.3	no
60-80cm vs 10-20cm	-4.3	-44.4	35.7	no
60-80cm vs 0-10cm	-239.4	-279.4	-199.3	yes
60-80cm vs 1cm	-741.9	-782	-701.9	yes
40-60cm vs 20-40cm	-0.6	-40.6	39.5	no
40-60cm vs 10-20cm	-4.2	-44.2	35.9	no
40-60cm vs 0-10cm	-239.2	-279.3	-199.2	yes
40-60cm vs 1cm	-741.8	-781.8	-701.7	yes
20-40cm vs 10-20cm	-3.6	-43.6	36.5	no
20-40cm vs 0-10cm	-238.6	-278.7	-198.6	yes
20-40cm vs 1cm	-741.2	-781.2	-701.1	yes
10-20cm vs 0-10cm	-235.1	-275.1	-195	yes
10-20cm vs 1cm	-737.6	-777.7	-697.6	yes
0-10cm vs 1cm	-502.6	-542.6	-462.5	yes

Appendix XIX: Exchangeable cation levels in soils (mg/ kg) (Okalebo *et al.*, 2002)

Rating	Potassium (K)	Magnesium (Mg)	Calcium (Ca)
Very high	> 300	> 180	> 2400
High	175-300	80-180	1600-2400
Medium	50-175	40-80	1000-1600
Low	50-100	20-40	500-1000
Very low	< 50	< 20	< 500

Appendix XX: Interpretation of soil N and C test results (Okalebo *et al.*, 2002)

Nutrient	Measured value	Rating
Organic C (%)	> 3.0	High
	1.5-3.0	Moderate
	0.5-1.5	Low
	< 0.5	Very low
Total N (%)	> 0.25	High
	0.12-0.25	Moderate
	0.05-0.12	Low
	< 0.05	Very low
Phosphorus (mg/ kg)	> 50	High
	20-30	Moderate
	10-20	Low
	< 10	Very low