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Eucalyptus in Kenya; Impacts on Environment and Society

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Eucalyptus in Kenya; Impacts on Environment and Society

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Doctor of Philosophy in Environmental Dynamics

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Abstract

Eucalyptus trees were introduced to Kenya a little over a century ago. European colonization along with the development of a railway system increased the demand for a fast growing wood source. The expansion of the tree across the fertile lands in Kenya raises concerns about the environmental impact on ecosystems where it has been introduced. These concerns include degraded soils, loss of water resources, co-introduction of ectomycorrhizal species, and allelopathy. Economic benefits to local landowners were also explored as well as the potential for large *Eucalyptus* woodlots to maximize the sequestration of CO_2 from the atmosphere. This was examined through farmer interviews and the collection of data from both *Eucalyptus* and indigenous forests. The results indicate that the density of *Eucalyptus* varied by age and species and managed harvest rates could be utilized to maximize carbon content in *Eucalyptus* to increase carbon sequestration potential of woodlots. In the greenhouse study of allelopathy, *Eucalyptus* did inhibit the growth and germination of the test plants. The indigenous plants were the most strongly affected. The soil analyses indicate that overall, *Eucalyptus* may not have a strong effect on the soils but do have a significant effect on soil moisture and diversity found within the woodlots. Ectomycorrhizal fungi were molecularly identified as some of the same species associating with *Eucalyptus* in Australia, indicating co-introduction. Farmers indicated that they were aware of the environmental concerns associated with cultivating *Eucalyptus* but the economic benefits were greater than the environmental issues.

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Dedication

I dedicate this Doctoral Dissertation to Garrett Kluthe, Luke Kluthe and Kira Kluthe. You can accomplish great things in this world if you work hard and do not let fear stand in the way. Stay awesome.

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Chapter 1. Introduction

Kenya is located on the eastern edge of the continent of Africa and is transected by the equator (Figure 1.1). This sub-Saharan country became a British Protectorate in 1895 and a formal British Colony in 1920. Although Kenya gained independence from England in December 1963, British influence remained in the country, especially in farming practices. Colonized originally to gain important trade routes from the Indian Ocean to the Nile River, early setters also found a suitable environment to establish farms. Through this colonization, new species and new cultivating practices were introduced which would have a profound impact on the ecology of the country (Figure 1.2).

During the early part of colonial rule in Kenya, considerable commercial and industrial development took place. Wood was needed for the construction of the railroads, buildings and for fuelwood used by the train system (Figure 1.3). Importing wood from Europe was both time consuming and costly. The increased demand for lumber created a strain on native forests (Ofcansky 1984). This strain led to the development of a managed indigenous forest harvest rate as well as the establishment of commercial tree plantations (Brown 2003).

The forest management practices were influenced by European forestry standards, where the negative environmental impacts associated with clearing the land of forests were well understood. The fact that forestry practices were followed in Kenya had important ecological and economic consequences (Brown 2003). The prevailing motive for planting *Eucalyptus* was that it was inexpensive and grew rapidly, making it ideal for commercial and industrial purposes (Bennett 2010).

Figure 1.1 Map of Africa with Kenya highlighted. (Map edited from zeemaps.com)

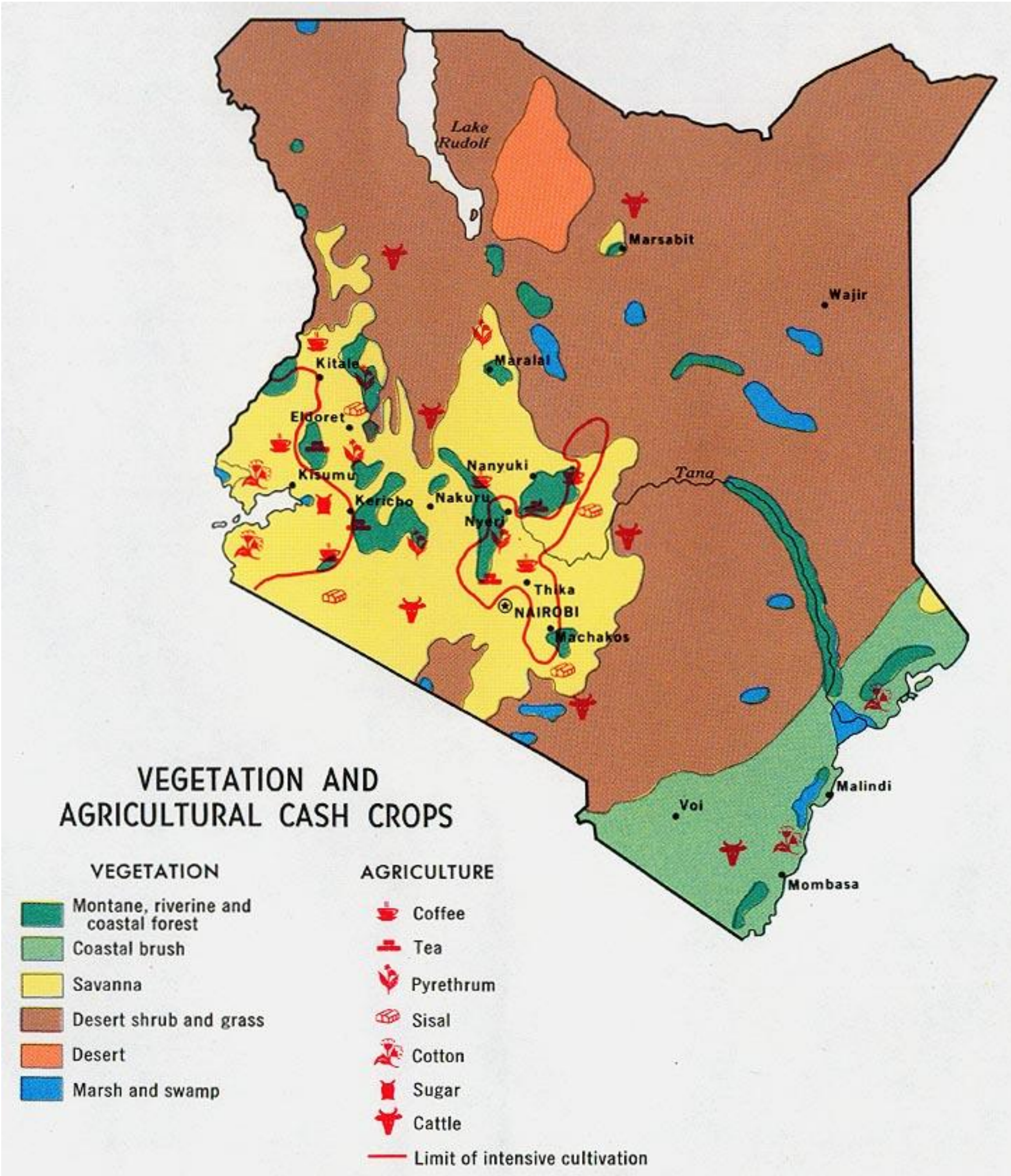


Figure 1.2. Important agricultural crops in Kenya by location (image from http://www.lib.utexas.edu/maps/africa/kenya_veg_1974.jpg).

Today, various species of *Eucalyptus* are planted throughout Kenya due to their rapid growth and ability to survive in marginal environments where soils may be depleted or water is scarce (Dessie 2011). Several species of *Eucalyptus* have been planted, with the predominate species in the western highlands being *Eucalyptus saligna* Sm., commonly called blue gum. The optimal elevation for this species ranges from 1600 to 2500 m in regions with an annual rainfall ≥ 1,000 mm (Dessie 2011). *Eucalyptus saligna* has a moderate to deep root system and prefers well drained soils, although it can be grown in a wide variety of soils (Florabank 2013). This species grows better above 2200 m above sea level. In the 1600 to 2200 m elevation range *Eucalyptus grandis* Hill ex Maiden becomes a dominate species in the highlands area.

Eucalyptus trees can be found in a variety of settings throughout Kenya. Its use for fuelwood and timber products as well as its rapid maturation time contributed to its proliferation throughout the nation. Tea plantations in the western highlands depend on *Eucalyptus* as a fuelwood source for drying the fresh tea leaves. Due to the high demand for *Eucalyptus*, it can now be found on even the smallest farming plots. On these smaller farm plots, the income generated from the sale of the wood represents a considerable proportion of the family's annual income (Dessie 2011).

While the immediate positive socio-economic impacts indicate that *Eucalyptus* is beneficial to the lives of individual Kenyan farmers and their immediate families, the ecological impacts of *Eucalyptus* plantations are less clear. The full impact on the culture of the indigenous people of Kenya is also unknown.

Claims against the species include the possibility that (1) the tree reduces or changes the habitat for native species (Belnap et al. 2012), (2) is characterized by a higher level of water use than native species, and (3) the trees compete directly with crops and native plants for soil resources (Otieno 1998).

Degradation of the soil in localities where *Eucalyptus* occurs is another possible concern. This can be realized by decreasing soil moisture, loss of nutrients and changes in the pH. These concerns can contribute to how a farmer uses the land. Changes that may occur by incorporating *Eucalyptus* into the farming regime could affect productivity of other crops by decreasing crop yeilds. Currently, there is considerable concern about planting *Eucalyptus* because of the possible negative environmental impacts. This study examined the reasons the small plot farmer has for continuing the *Eucalyptus* planting practice.

Eucalyptus trees depend upon the establishment of ectomycorrhizal (fungus-tree) associations for optimal growth. Very little is known about the species of fungi that have formed this symbiotic relationship in Kenyan populations of *Eucalyptus* (Díez et al. 2001). It is also unknown if indigenous people harvest the fruiting bodies associated with some of these fungi for use as a food source.

1.1 History of *Eucalyptus* in Kenya

European expansion across the globe was well under way when Captain James Cook first landed on the east coast of Australia in 1770 (Doughty 1996). The west coast of the continent was well explored, but the conditions there did not generate a large influx of European colonization. Colonization thrived where temperate climate conditions matched those of Europe and were highly desired for new settlements. These areas allowed colonists to recreate their home environments by introducing European crops and livestock. This would have a profound ecological impact on the new lands they colonized but also allowed for the opportunity to introduce new species into Europe (Crosby 2007).

What Cook and his crew discovered on the eastern part of Australia, among other things, was a tall tree that produced a gum-like substance. At the time, the tree was mistakenly identified as the dragon tree. Samples were collected from the trees during this expedition and subsequent expeditions, and eventually these made their way back to London. It wasn't until eighteen years later that the samples were examined by a French plant expert, Charles Louis L'Héritier de Brutelle, who first coined the name *Eucalyptus* (Doughty 1996).

The discovery of new and exotic species from around the globe sparked a drive among British aristocracy to obtain them as ornamentals in their gardens. The first eucalypt seeds were introduced in the early 1800's, with some speculation as to their ability to survive. The harsh winters impeded the initial efforts of introduction but increased knowledge of the tree and different varieties of seeds found success in the milder southern counties of England (Doughty 1996).

From the 1840's to the 1860's the popularity of the *Eucalyptus* grew. Locally harvested seeds began to supply the growing demand in England. Gardening publications and professionals extolled the virtues of the tree not only for health benefits but also for fuelwood and timber (Doughty 1996). However, the French have been credited with the secondary expansion of *Eucalyptus* through other parts of the world and pushed for its planting in regions where deforestation had occurred (Zacharin 1978). European outposts throughout the world were experiencing shortages of timber due to rapid development and resultant deforestation. Increased harvest rates were depleting the native forests and a fast growing alternative was highly sought after. Colonial scientists in the 1800's recognized the effect of forest depletion on the local environment and climate. The introduction of managed forest harvest rates and managed woodlots were considered fundamental to protecting the landscapes in colonized parts

of the world (Brown 2003). It was out of this practice that the *Eucalyptus* tree found a foothold in many parts of the world, including California, India and North Africa (Doughty 1996).
It wasn't until 1902 that *Eucalyptus* was introduced to Kenya, which at the time was a British protectorate (Oballa et al. 2010). Until this time, the area was mostly free from British colonization. The expansion of the Uganda Railway, from Mombasa on the coast to Kisumu near the border of Uganda, would change this (Figure 1.3). An increased need for construction wood would encourage *Eucalyptus* planting (Gunston 2002). This would also mark the beginning of a pivotal time that would change the area from The East Africa Protectorate to the British colony of Kenya (Ojany and Ogendo 1982).

In order for the railway system in the protectorate to be sustainable, it needed crops to transport. This created the first push for British settlement in the western highlands (Figure 1.4). This cooler region with similarities in climate to England, allowed for the introduction of large scale farming. An increase in colonization and development also meant an increase in use for the railroad, allowing the crop harvests to be moved out of Kenya (Ojany and Ogendo 1982). This brought about the rationale for the introduction of the *Eucalyptus*; to serve as a fast growing source for the railway system (Oballa et.al 2010). *Eucalyptus* was important not only as a fuelwood but was also used for the construction of the railway (Figure 1.5). Sleepers and ties were constructed from these trees (Nduwamungu el al. 2007).

1.2 Current Uses

Today, *Eucalyptus* trees are primarily grown as a source of fuelwood (Figure 1.6). The *Eucalyptus* trees are cultivated in three main ways. The first consists of large private commercial woodlots. These woodlots are generally grown to provide fuelwood. For example, the tea plantations in the Western Highlands require a fuel source for drying the tea leaves after they are harvested. Tea plantations manage large *Eucalyptus* plots to provide that fuel source. Several other commercial industries use the tree as fuel, including tobacco. The second way the *Eucalyptus* tree is produced is in government woodlots. These trees are grown on a large scale for harvesting and research purposes. Lastly, the trees are grown in private woodlots. These woodlots are generally small in scale and usually comprise less than a hectare. It is common to find the trees planted on the perimeter of the owner's land to delineate property boundaries.

The most common uses for *Eucalyptus* in Kenya are for fuelwood and construction. The tree is also used for plywood, pulpwood, fencing and harvesting essential *Eucalyptus* oil (Kituyi et al. 2001). Larger trees are harvested for use as utility poles, while younger and smaller trees are harvested for use in construction and more recently, furniture (Maundu and Tengnans 2005). In Kenya, the *Eucalyptus* trees have been used as windbreaks and as a fast growing tree to help with erosion control. Current research is also exploring the possible benefit of carbon sequestration in *Eucalyptus* stands (Oballa et al. 2010).

Species of *Eucalyptus* in Kenya

Several species of *Eucalyptus* are grown throughout Kenya. By the 1950's approximately seventy species had been introduced, though only a few species are cultivated as a timber source today (Zacharin 1978). Nearly 100 species have been planted in Kenya, with more being added all the time. The development of hybrids has also increased the number of new introductions (Oballa, et.al 2010).

There are four primary species of *Eucalyptus* grown in Kenya. They are *E. grandis, E. saligna, E. camaldulensis* Dehnh. and *E. globulus* Labill. Some other common species found on a smaller scale in Kenya are *E. regnans* F. Muell., and *E. paniculata* Sm.

Figure 1.3. Photograph of early construction of the Kenya-Uganda Railway (photo obtained from ekitibwakyabuganda.wordpress.com).

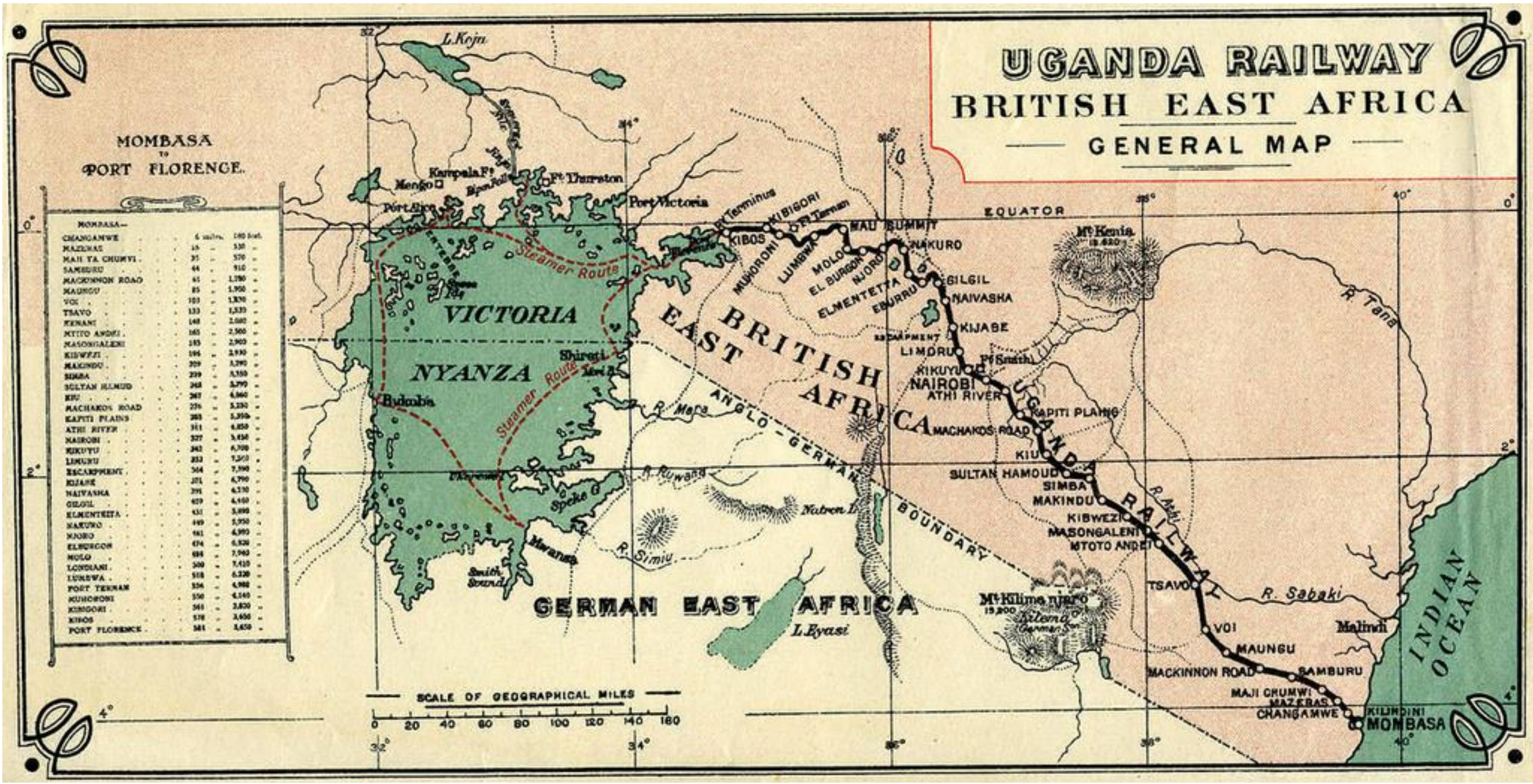


Figure 1.4. Early map of the Keny Uganda Railway (image from http://wwiafrica.ghost.io/wwi-uganda-railway/).

Figure 1.5. Early image of a *Eucalyptus* harvest. This is now a common sight throughout Kenya (image from fao.org).

Figure 1.6. *Eucalyptus* tree planted around the time of introduction to Kenya, based on information provided by local people. This tree is located near the railroad tracks and has a DBH (diameter at breast height) of 210 cm (photo by the author)

Hybrids produced from *Eucalyptus* growing in close proximity to each other are also found in suitable growing areas throughout Kenya (Oballa et. al 2010).

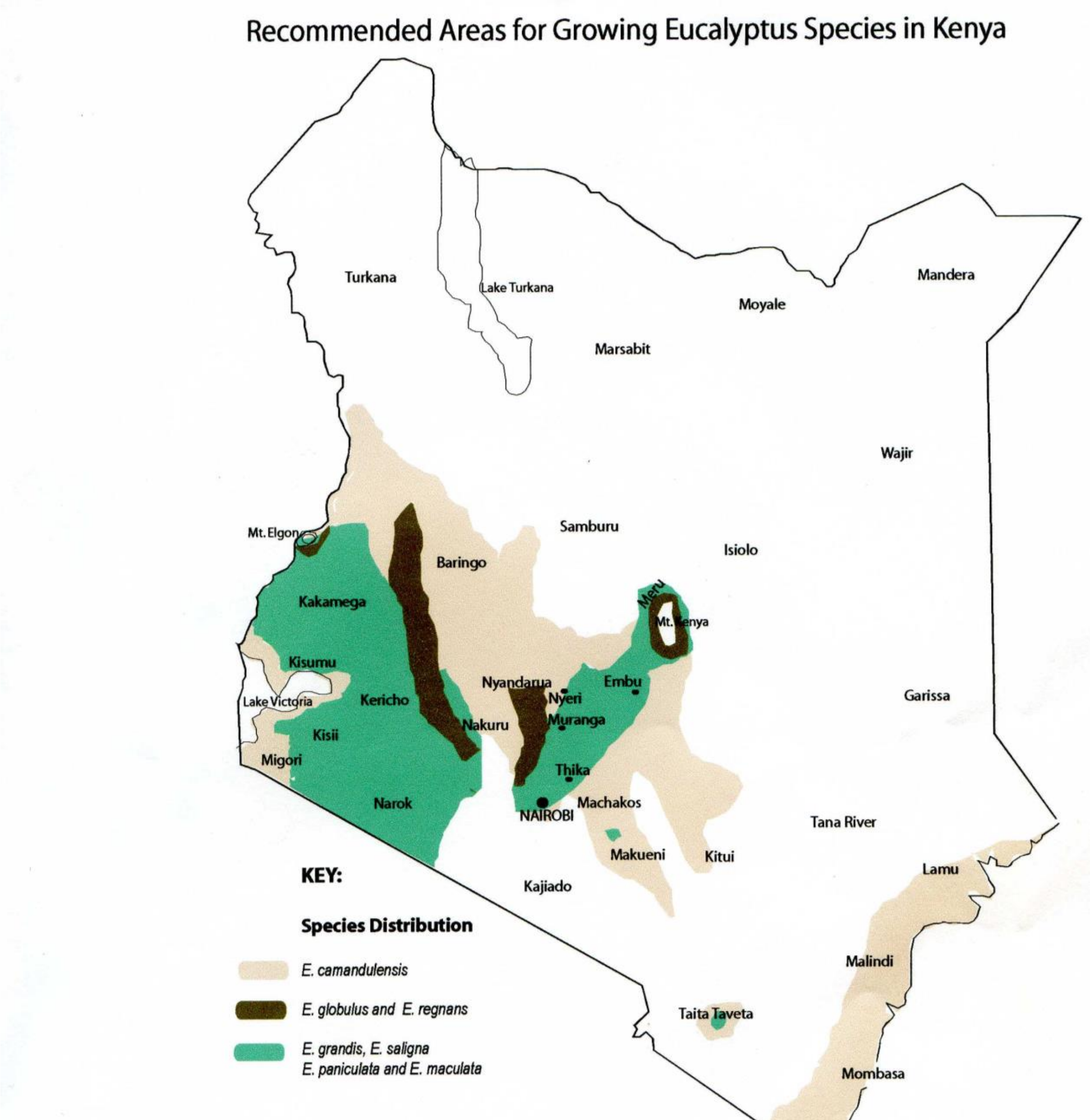
1.3 Distribution of *Eucalyptus* in Kenya

Eucalyptus trees can be found throughout Kenya but are concentrated in areas where environmental conditions are most suitable, especially with respect to moisture. The four most common species of *Eucalyptus* grown in Kenya are described below (Figure 1.7 and Figure 1.8).

Eucalyptus grandis, which is mainly grown for transmission poles, is concentrated in the Western Highlands area, which has an elevation range from 1400 m to 2200 m. This tree prefers well-drained soils but can adapt to many soil types. The mean annual rainfall in this area is 900 mm per year (Oballa, et al. 2010).

Eucalyptus saligna is used for a variety of purposes, including posts, timber, pulpwood and furniture. The optimal elevation is above 2200 meters above sea level, where *E. saligna* will grow at the highest rate but it can also be found at lower elevations. The average height is 40-50 m. but it can be as tall as 70 m if conditions are optimal (Oballa et al. 2010; Maundu and Tengnas 2005).

Eucalyptus camaldulensis favors the lowest elevations of the suitable environments in Kenya. It also can survive with less rainfall, a minimum of approximately 600 mm per year, than any of the other predominate species. This species is drought resistant but is also used to drain swampy areas because it can sustain growth in heavily saturated soils. It can also grow in poor and saline soils. This tree species is found along the coastal regions and the lower hill regions surrounding the Western Highland and also the Taita Hills region between Mombassa and Nairobi. The primary use for *Eucalyptus camaldulensis* is for utility poles, but it is also used for construction, fuelwood and windbreaks (Oballa et. al 2010).



Species	Altitude m	Minimum Rainfall mm
E. camandulensis	up to1400	600
E. hybrids	up to 1700	750
E. grandis	1400-2200	1000
E. paniculata and E. maculata	1600-2000	800
E. saligna	1600-2500	1000
E. globulus and E. regnans	2500-3000	1000

Figure 1.7. Distribution map of *Eucalyptus* in Kenya (Oballa et al. 2010).

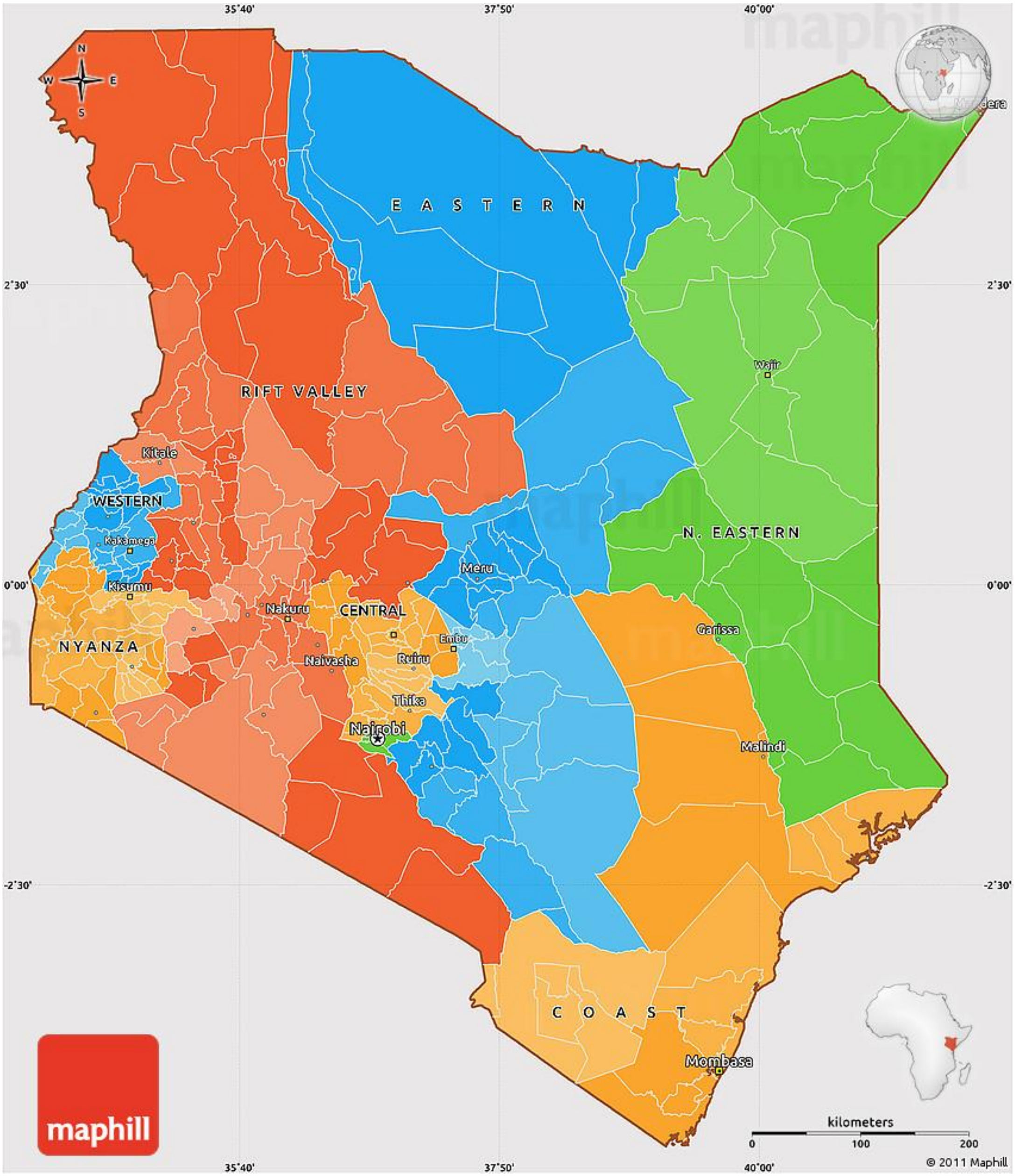


Figure 1.8. Geographic regions of Kenya (adapted from www.maphill.com).

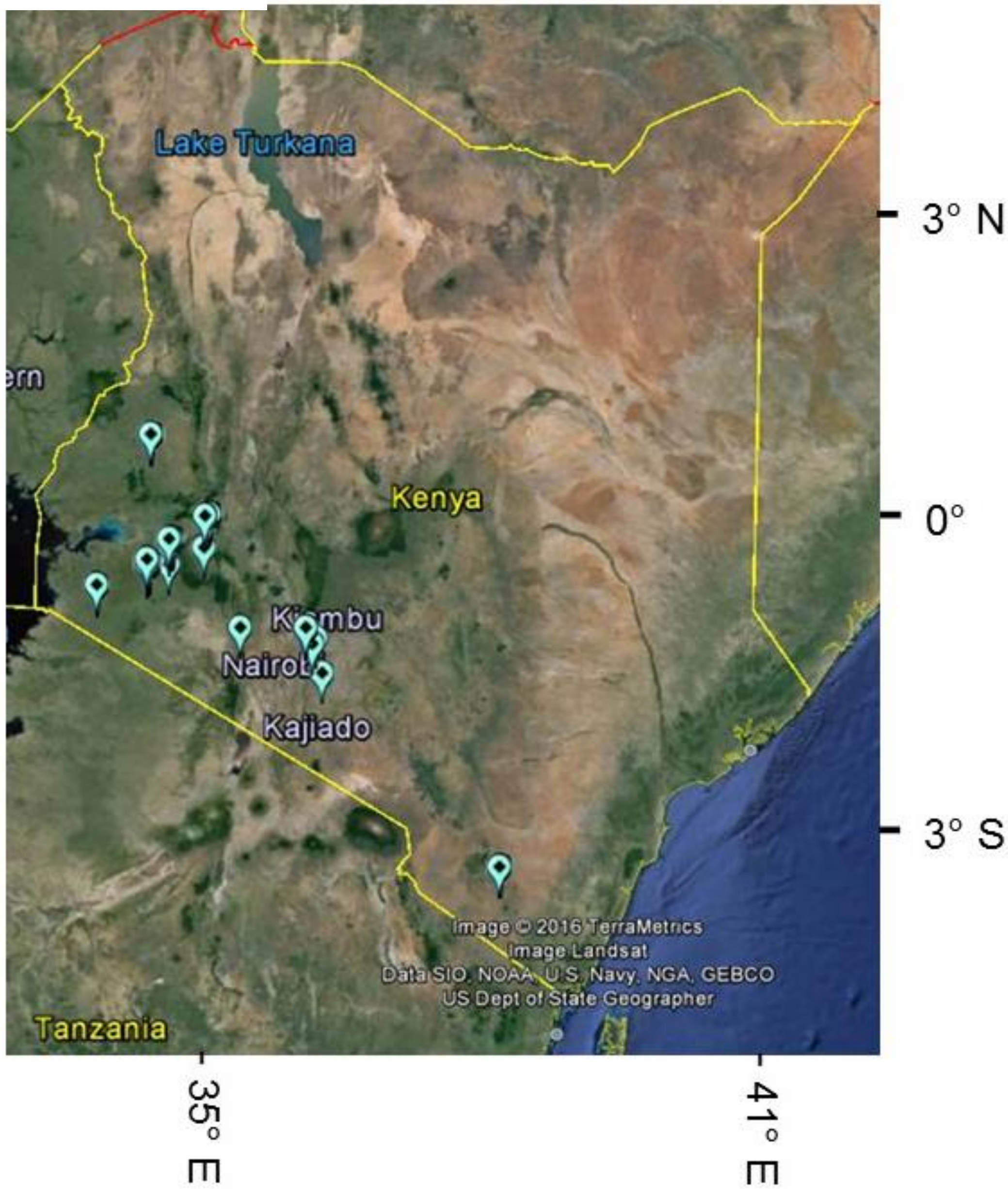


Figure 1.9. Data collection sites in Kenya.

Eucalyptus globulus occupies the highest elevations in Kenya, from 2000-3000 m above sea level. This species is commonly called the blue gum because of the blue-gray color of the juvenile leaves. The wood is used for poles, posts and veneer. The leaves are used to produce oil that is then used for pharmaceutical products as well as essential oil products such as soaps and perfumes. According to Oballa et al. (2010), the abundance of *E. globulus* has declined in recent years due to its susceptibility to predation by the *Eucalyptus* snout beetle, *Gonipterus scutellatus* (Gyllenhal 1833).

According the Kenya Forest Service, *Eucalyptus* planted in Kenya cover an estimated 200,000 ha, with 100,000 ha in plantations. They are planted primarily as an income-producing tree and can significantly enhance household incomes.

1.4 Objectives of this project

The *Eucalyptus* in Kenya is a fundamental element of many industries. It can be found in a variety of different environments. The abundance of the tree in the country attests to its survivability as an introduced species. The purpose of this study was to look at the introduction of *Eucalyptus* from a very broad approach to fully understand the impact it has had on both the environment and the people who cultivate it. The hypotheses for this study are listed below and data collection sites can be seen in Figure 1.9.

H1: *Eucalyptus* is an introduced species of tree in Kenya, and its introduction has changed the specific ecosystems in which it has been planted. This is reflected in an understory that is compositionally different from that of indigenous forests. This difference has ecological consequences for wildlife.

H0: *Eucalyptus* has not changed in the ecosystems where it has been introduced. There are no significant differences in the understory of a *Eucalyptus* forest when compared to indigenous forests.

H2: *Eucalyptus* forests are characterized by reduced levels of soil moisture compared with indigenous forests.

H0: *Eucalyptus* forests do not show a difference in soil moisture compared with indigenous forests

H3: *Eucalyptus* leaf litter is allelopathic and affects the growth of understory plants in forests in which the tree is present.

H0: *Eucalyptus* leaf litter does not affect the understory growth of plants in forests where the tree is present.

H4: The ectomycorrhizal fungi associated with *Eucalyptus* consist of taxa introduced along with the tree from Australia.

H0: The ectomycorrhizal fungi associated with *Eucalyptus* do not consist of taxa introduced along with the tree from Australia.

H5: Local villagers vary considerably in their views of the positive versus negative aspects of *Eucalyptus*, and these views are closely correlated with how the tree affects their own lives.

H0: The local villagers' views of *Eucalyptus* are not influenced by how the tree affects their own lives.

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Chapter 2. Forest Ecosystems

Kenya is located on the eastern side of the continent of Africa. The country has a total land area of approximately 582,646 square kilometers, which makes it a slightly smaller than Texas. Roughly two-thirds of Kenya is arid to semi-arid and not suitable for indigenous forests or for cultivating commercial woodlots. There are four major regions in Kenya that support forest ecosystems-the western part of Kenya which includes select areas in the highland, western Kenya, and Rift Valley forest communities and the coastal forest community (Figure 2.1). It is predominantly in these regions that both the indigenous and *Eucalyptus* forests can be found (Ojany and Ogendo 1982). According to the World Bank (2007), approximately 7.6% of Kenya is forested. This is up from the estimated 3.5% forest cover in 1963 (Ogendo 1966). Planted woodlots for commercial purposes probably account for the increase in forest cover. The increased demand for wood sources has increased the need to plant more trees to supply a growing population and wood material needs.

The highland plateau, consisting of the highland, western and Rift Valley, area is dominated by volcanic soils (Ojany and Ogendo 1982). The elevation ranges between 1500 m and 2500 m above sea level and there are two distinct rainy seasons (Mathu 2011). The rich soils and abundant rainfall make this area the agricultural center for Kenya and it is also where most of the tea plantations and *Eucalyptus* woodlots in the county are found.

Cultivated woodlots in Kenya are comprised mainly of pine, cypress and *Eucalyptus.* Woodlots are cultivated for economic purposes with the harvested trees going to the production of fuelwood, pulp wood, building materials, and transmission poles. *Eucalyptus* is the third most commonly cultivated tree in Kenya (Githiomi and Kariuki 2010). It was originally introduced from Australia as a fast growing tree to supply the wood needs in the country and to lessen the impact on harvested indigenous forests (Zacharin 1978). British expansion in the country increased the need for construction lumber both for buildings and to fuel the rail system.

This purpose of the study reported herein was to compare *Eucalyptus* woodlots and indigenous forests. It was hypothesized that the *Eucalyptus* woodlots would exhibit a significant difference in the soil mineral composition, moisture level, and understory growth when compared with indigenous forests. This would be demonstrated by the soils being less moist and fertile and the ground cover less abundant in the E*ucalyptus* woodlots.

2.1 *Eucalyptus* Ecosystems

The genus *Eucalyptus* has nearly 900 species according to the Centre for Australian National Biodiversity Research; these trees can be found in a wide range of habitats throughout the world and include several areas of Kenya (Figure 2.1). While concentrated in the highland and coastal areas, they are still found in a range of different soils and climates. Used predominately as a commercially harvested tree, *Eucalyptus* covers approximately 100,000 ha in Kenya (Oballa et al. 2010). It can be found in three primary settings, large commercial woodlots (35%), government woodlots (15%) and small private woodlots (50%).

A. Commercial woodlots

Large corporation commercial *Eucalyptus* woodlots cover approximately 35,000 ha in Kenya (Oballa et al. 2010). The driving force for commercial *Eucalyptus* woodlots observed was the tea industry (Figure 2.2). *Eucalyptus* trees are typically planted in a monoculture with 3 m spacing. The trees in tea plantations are generally harvested on a rotation of approximately 8-12 years (per personal communication with plantation manager 2013). Once harvested, the trees are dried and used as a fuel source for drying tea leaves. The remaining stumps can regenerate several stems. It is a common practice to have the tree regenerate from the stump then thin back

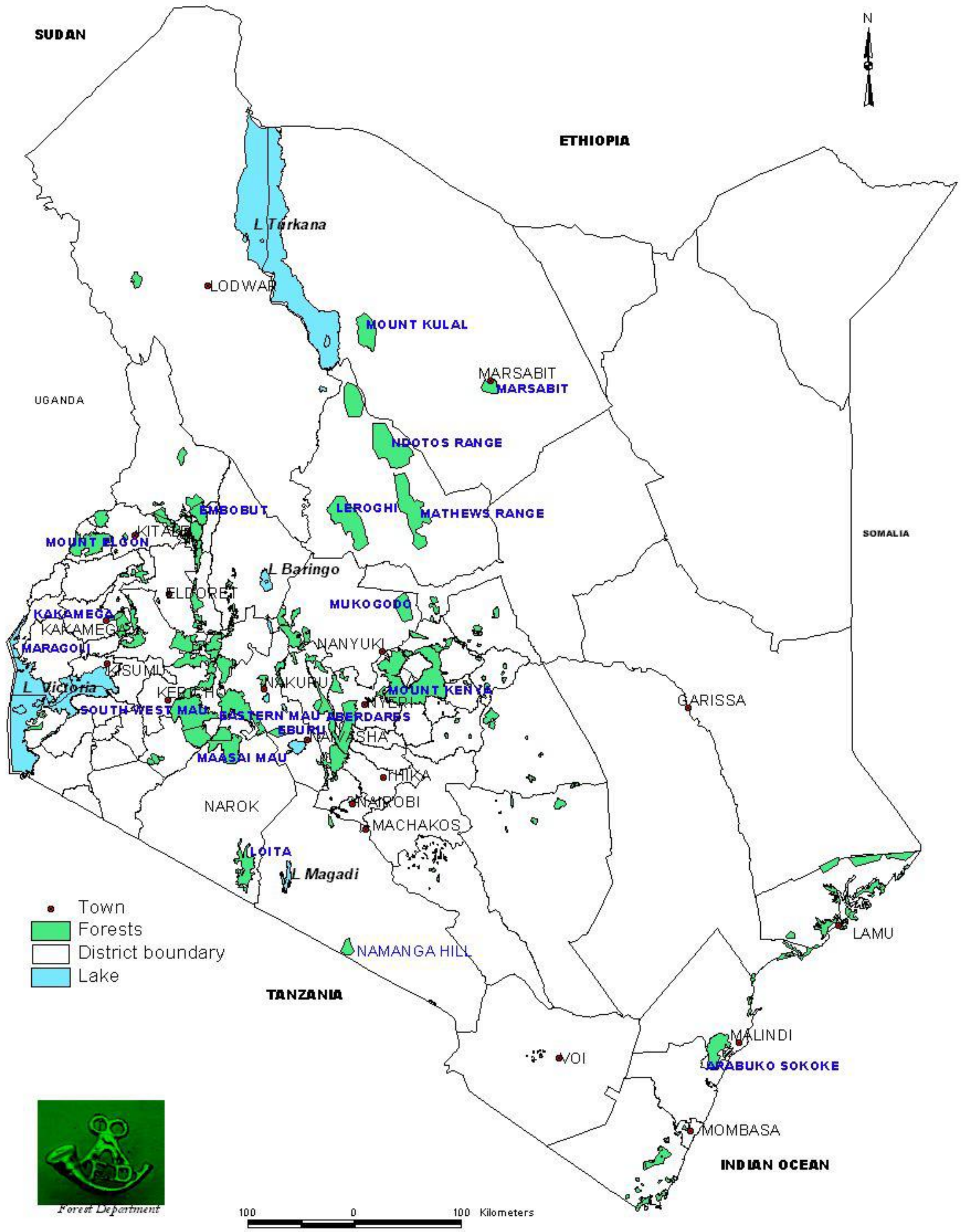

Figure 2.1. Forested areas in Kenya (after Mathu 2011).

Figure 2.2. A commercial tea plantation near Kericho, Kenya. Large tracts of land are used for growing tea plants as well as *Eucalyptus* woodlots (photo by the author).

Figure 2.3. Government managed woodlot. The woodlots are grown in a monoculture with specific spacing determined by wood use. The land is commonly leased to local farmers to graze their cattle (photo by the author).

Figure 2.4. Private, small plot woodlot. The location is not in an area that would be easily farmed and is generally small; this one was less than 0.25 hectares. (photo by the author).

to one stem. This stem can then grow into a full-sized tree. According to conversations with local woodlot managers, the regeneration time and size become diminished after the second time; therefore, most managers allow the tree to regenerate only twice before the stump is removed. The coppiced stems from the old trunk can also be used to generate new trees by placing them in a prepared planting soil. This practice is used more commonly in small private woodlots.

B. Government woodlots

Government woodlots cover approximately 15,000 ha in Kenya (Oballa et al. 2010). Government woodlots were established to supply the timber needs of the country and for exporting wood (Figure 2.3). *Eucalyptus* woodlots are planted in a monoculture with spacing determined by harvested wood use. For pulpwood, the spacing is 1 m by 1 m and for wood used in paper making, the spacing in 2.5 m by 2.5 m. The harvest age of *Eucalyptus,* as reported by Mathu (2011), is on average between 20-30 years. Government forest agencies monitor and manage the public forest land, including both exotic woodlots and indigenous protected forests. The land in production as harvestable woodlots is completely utilized and no additional land currently is available for woodlot production (Mathu 2011). This means that increased timber production in Kenya would come from small woodlot farmers or large corporate plantations.

C. Private woodlots

Private *Eucalyptus* woodlots, those owned by the community or small plot farmers comprise approximately 50,000 ha and represent the largest category of growers (Oballa et al. 2011). In terms of composition, size and planting regimes, this is also the most diverse category (Figure 2.4). While the Kenyan governmental agencies supply guidelines for planting, they are not always followed (Mathu 2011). Small farmer plots can comprise just a few trees or cover several hectares. On average, the small private woodlots observed and sampled were a half

Figure 2.5. Indigenous forest located within a corporate tea plantation. Many different species of trees and understory plants can be seen. This site was sampled to compare with *Eucalyptus* woodlots in the area (photo by the author).

hectare or less. Another type of woodlot that falls in this category is the community woodlot. This type of woodlot is generally larger than the small farmer woodlot and managed by a local community group. The spacing of *Eucalyptus* observed during this study ranged from 1 m by 1 m to the more common spacing of 3 m by 3 m. The harvest age of the trees varied by individual farmer but on average were between 10-15 years.

2.2 Indigenous Forests

Indigenous forests cover approximately 170,000 ha in Kenya. They can be classified into six distinct forest groups—high volcanic mountain, western plateau, northern mountains, coastal forests, southern hills and riverine forests. These forests are biologically diverse with species that are indigenous to Kenya (Figure 2.5). The composition of the forests generally includes both understory and canopy trees, along with a variety of small shrubs and groundcover plants that include a variety of different species (Pelterinne 2004). The indigenous forests in Kenya are found in small tracts and are fragmented in many places. These forests are not planted but instead are continuously growing forests that regenerate through natural processes. The indigenous forests found in Kenya today tend to be outside of protected areas on steep slopes where farming is unsuitable. Human disturbance is the primary threat to indigenous forests (Mathu 2011).

2.3 Sampling Methods

A. Site selection

Site selection was based on the availability of *Eucalyptus* woodlots representing each of the categories outlined previously. The majority of *Eucalyptus* woodlots are concentrated in the highland area, which is characterized by moderate temperatures of 22-27 °C, abundant rain (over 1000 mm/year) and fertile soils (Figure 2.6). Sample plots were established in several different

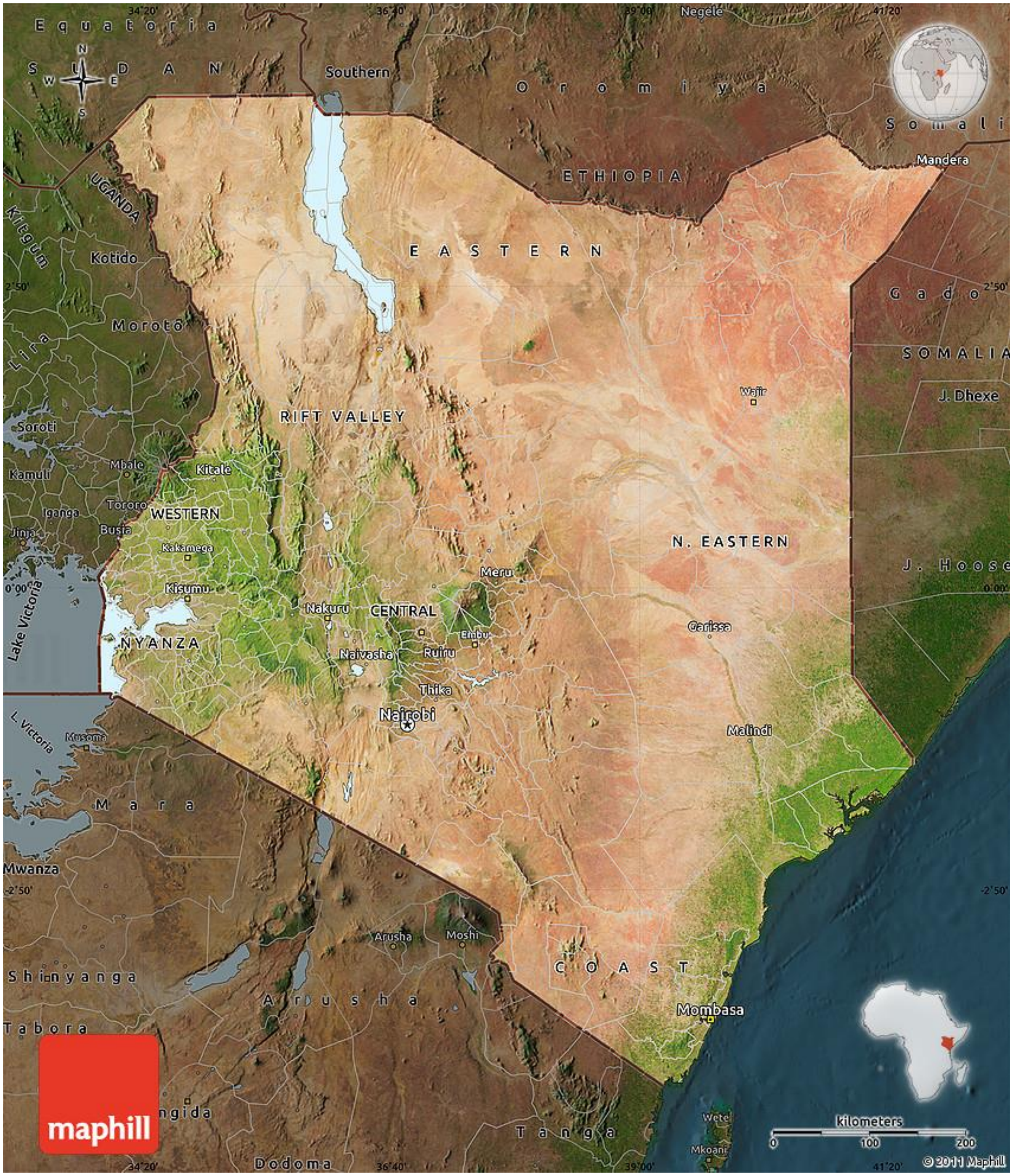

Figure 2.6. Satellite image of Kenya. The greener areas in the central to western parts of Kenya were the focus of the forest sampling in this study. This area is considered the highland area, with conditions suitable for *Eucalyptus* woodlots (http://www.maphill.com/kenya/maps/satellite-map/darken/).

large tea plantations, Kenya Forest Research Institute and Kenya Forest Service forests and on several local farming private woodlots.

B. *Eucalyptus* and Indigenous Forests

Sampling methods were the same for both the *Eucalyptus* sites and the indigenous sites. The data were recorded on field note forms and all measurements taken from field sampling devices were included for later analysis (Figure 2.7).

C. Data collection methods

Eucalyptus sites were selected based on size, composition and location. Indigenous forests were selected based on size and proximity to *Eucalyptus* sample sites. In order to compare the two forest types, it was necessary to collect data from areas that were geographically and geologically similar that would also have similar climate conditions. The woodlot or forest site needed to be large enough to accommodate a twenty-five meter transect without any edge effects influencing the data collected. Samples were collected from both *Eucalyptus* forests and indigenous forests. In the indigenous forest, it was important to try to find a site that was free of human disturbance; this included cultivation or introduction of *Eucalyptus* trees. For comparison purposes, the indigenous and *Eucalyptus* forests were in the same region and are similar in elevation to allow for comparison.

Several regions in Kenya were studied, but the measurements were the same for each sample plot. A portable GPS unit was used to determine the approximate elevation and GPS coordinates for each sample plot (The Magellan eXplorist 310 GPS). In addition, before entering the forest, the outside light intensity was measured using a digital light meter (Dr. Meter LX 1330B), which had a range of 20-200,000 lumens.

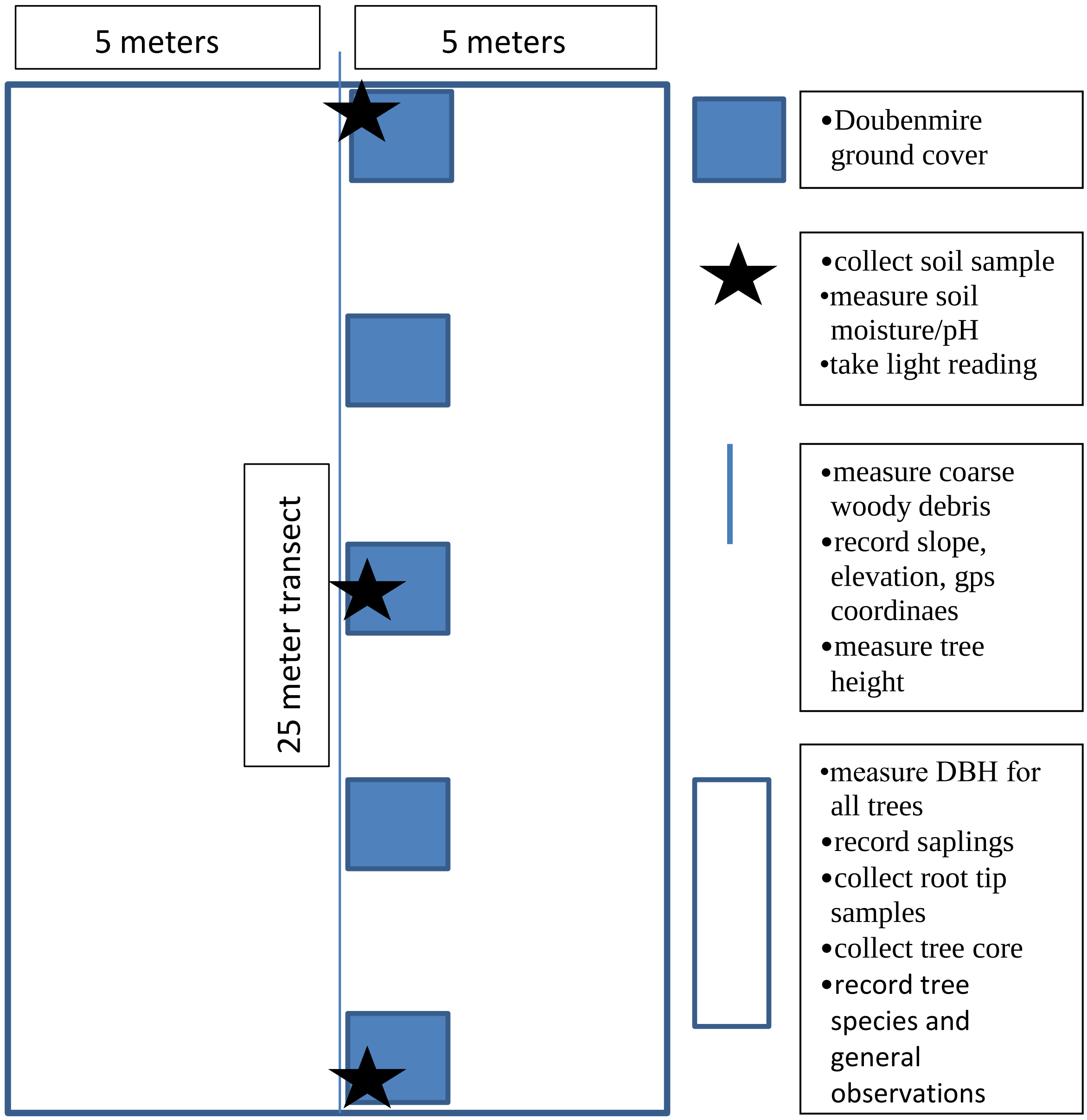

Figure 2.7. Diagram of data collected at each sample site.

Once an appropriate site was located, a transect was measured within the forest, more than 10 meters from the forest edge. The line transect sampling method was used and the slope and aspect of the transect was recorded (Anderson et al. 1978). The transect was delimited using a fiberglass measuring tape; this tape measured a 25 meter line with the tape laid out on the ground as a reference for further measurements and samples. This transect was perpendicular to the slope or hillside to minimize the amount of elevation change on the transect line (Figure 2.8). The actual slope of the area was measured perpendicular to the transect and was determined using a Suunto clinometer (Suunto PM-5/360). Using the same device, the tree heights were determined and recorded. Measurements were taken for both the primary canopy trees and any understory trees. A rectangular sample plot area was established using the transect as a baseline. This was done by measuring five meters out from the transect on both sides. This area became the sample area used for further measurements and data collecting.

Several measurements were taken along the transect. The first was estimating the extent of coarse woody debris on the forest floor. This was done by walking along the transect and any stem or branch greater than 1 cm in diameter was measured and recorded on the data sheet. Soil moisture and pH were measured using a soil moisture probe (Kelway soil tester, KEL Instruments Co., Inc.) which expressed moisture as a percentage. To use this device, a small hole was dug, the probe was placed in the hole and the soil then packed back around the probe ensuring that the soil made contact with the sampling plates on the side of the device. Measurements were recorded at the 0, 12.5 and 25 meter marks. Also at those marks, a soil sample was collected and the light intensity was recorded. The collected soil samples were processed for specific components at the Kenya Forest Research Institute lab using standard soil analysis procedures (Okalebo et al. 1993).

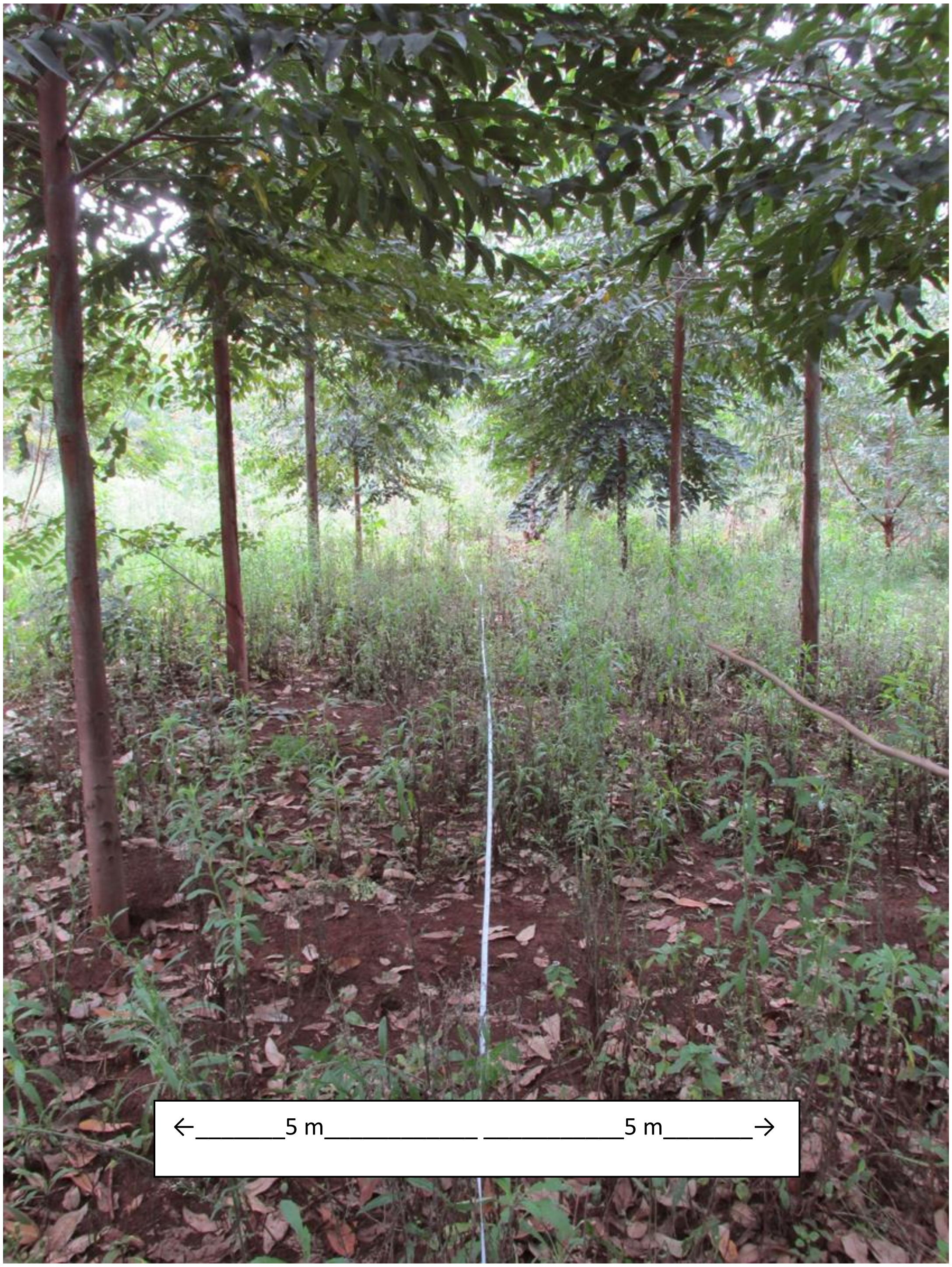

Figure 2.8. The line transect on the ground measured out 25 m. Measuring 5 m from each side of the line created a rectangular plot for sampling the forest or woodlot site (photo by the author).

Figure 2.9. The data collection method used to determine the amount and type of ground cover present in each of the five plots located along the transect involved measuring the distance along the tape intercepted by the plot in question. This method was used in both the *Eucalyptus* and indigenous forest site (photo by the author).

The Daubenmire cover value method was used along this transect. This method assigns a number that represents the range of each ground cover class observed in the sample plot. This number then translates to the midpoint percent cover for the combined data plots to give an estimate of the ground cover by class (Daubenmire 1959). Four different 1 meter by 1 meter plots were established at the 0 m-1 m, 5 m-6 m, 10 m-11 m 15 m-16 m and the 20 m-21 m marks along the transect. Cover classes recorded were forbs, grasses, woody shrubs and sedges (Figure 2.9).

Within the study plot, the diameter at breast height (DBH) on the trunk was recorded for every tree. The number of saplings in the study area was also recorded. Several root-tip samples were collected from *Eucalyptus* trees in each plot. The root-tip samples were later used to study the ectomycorrhizal fungi associated with the *Eucalyptus* trees, as described in chapter 4. In addition, one tree core was taken from one *Eucalyptus* tree in each plot. The tree height was recorded and the sample was used to determine the carbon content of the tree.

General characteristics of the plot were recorded. This included recording evidence of human activities inside the plots such as grazing of livestock or collecting branches. In several of the *Eucalyptus* plots, the age and species of *Eucalyptus* trees were known. This information was also recorded.

The results of the data samples from combined *Eucalyptus* sites and the combined indigenous sites were evaluated using the Mann-Whitney-Wilcoxon Test or the Welch's two sample t-test. The Mann-Whitney-Wilcoxon Test was used for the soil sample analyses, moisture, and for the outside and inside light measurements (Cox 2002). This was selected because the results were non-parametric and covered a large range of numerical results on a continuous scale. The ground cover, including coarse woody debris, was evaluated using the

Welch's two sample t-test. The R statistical software program was used for all statistical analysis (R core team 2013).

2.4 Results

The results of the soil analysis are indicated on Table 2.1.

A. Soils

The collected soil samples from the sampled plot sites for both *Eucalyptus* woodlots and indigenous forests were analyzed at the Kenya Forest Research Institute (KEFRI) soon after they were collected. The results were then sent to the University of Arkansas for further interpretation.

Soil pH

Soil pH is an index of the hydrogen ion concentration of a particular soil, and is based on a scale from 0-14 with 7 being neutral. Soil pH lower than 7 is acidic and soil pH higher than 7 is alkaline. The soil pH for both the indigenous and *Eucalyptus* forest were measured and recorded. The mean pH for the indigenous forest was 6.1 and the mean pH for the *Eucalyptus* woodlot was 5.5. Both samples were on the acidic side and did not show a statistically significant difference between the means as indicated by a p-value of 0.07796.

E.C. (mS/cm)

The electrical conductivity for these soil samples was measured in milliSiemens per centimeter. The indigenous forest group mean was 0.209 (mS/cm), while the *Eucalyptus* forest was 0.081 (mS/cm). This represents a significant statistical difference between the two means. This was indicated by the calculated p-value of 0.007994.

Percent Carbon

The carbon in the soil samples was measured as a percentage. The mean carbon percentage in the indigenous forest was 5.55 %, with the carbon content mean in the *Eucalyptus* forest measured at 4.34 %. The calculated p-value was 0.07765, indicating that there was not a significant difference between the means of the *Eucalyptus* or indigenous forest sites.

Percent Nitrogen

Nitrogen in the soil samples was measured in a percentage. The indigenous samples had a mean percentage of 0.525 and the *Eucalyptus* samples mean percentage was 0.405. The calculated p-value was 0.06216, which indicated that the sample means were not statistically different.

Phosphorus (ppm)

Phosphorus in the soil samples was measure in parts per million (ppm). The sample mean for the indigenous sites was 8.167 (ppm), with the *Eucalyptus* mean measured as 7.439 (ppm). The calculated p-value for the means was 0.3468 which indicated that there was not a statistical difference between the means of either group.

Potassium (ppm)

Potassium was measured in parts per million (ppm) in soil samples. The means of the measured potassium in the indigenous forest sample means was 790 (ppm). The means of the measured potassium in the *Eucalyptus* forests was 474 (ppm). The calculated p-value was 0.04186; this represents a statistically significant difference between the two sampled groups (Figure 2.10).

Calcium (ppm)

Calcium in the soil samples was measured in parts per million (ppm). The samples mean for the indigenous group was 3940 (ppm), with the sample mean of the *Eucalyptus* group measured at 1917 (ppm). The p-value was calculated as 0.03614 and this represented a statistically significant difference between the means of the two sampled groups.

Table 2.1. Calculated means for the *Eucalpytus* woodlot soil samples and the calculated mean for the indigenous forest soil samples. The range of results from all soil samples are included. The n indicates the number of soil samples analyzed. The p-value is given for each of the comparisons using the Mann-Whitney-Wilcoxon test. There were 44 samples analyzed, 38 from *Eucalyptus* sites and six from Indigenous sites.

Soil Analysis results using the Mann-Whitney-Wilcoxon Test

	Eucalyptus		Indigenous		n=44	
sample type	mean	range	mean	range	p-value	statistical diff.
pH H_2O	5.46	4.11-6.35	6.13	4.79-6.96	0.07796	no
E.C. (ms/cm)	0.08	0.04-0.21	0.21	0.05-0.31	0.007994	yes
pH $CaCl_2$	4.76	3.74-5.68	5.61	4.33-6.47	0.03291	yes
% C	4.34	1.9-7.6	5.55	3.5-7.9	0.07765	no
% N	0.41	0.17-0.72	0.53	0.34-0.75	0.06216	no
P (ppm)	7.44	2.1-25.8	8.17	4.3-13.9	0.3468	no
K (ppm)	474.23	139-945	790.03	341-1253	0.04186	yes
Ca (ppm)	1917.68	16-4308	3940.08	1111-5748	0.03614	yes
Mg (ppm)	534.20	27-881	765.48	274-1023	0.05628	no

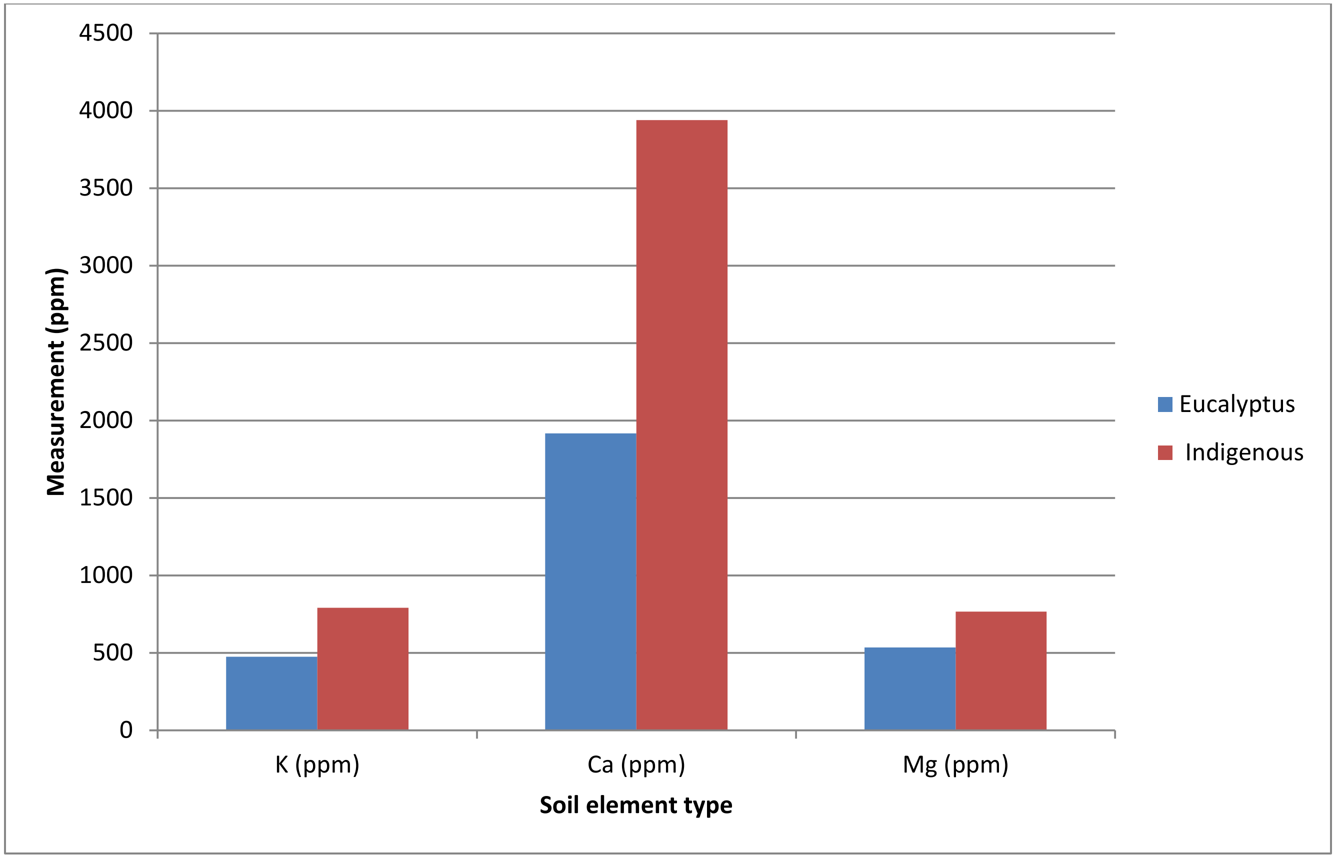

Figure 2.10. Values for three of the soil major soil elements tested in the samples from the *Eucalyptus* woodlots and the indigenous forests. Note that the potassium and calcium values were statistically different, but those for magnesium were not.

Magnesium (ppm)

Magnesium in the samples was measured in parts per million (ppm). The sampled mean for the indigenous group was 765 (ppm) with the sampled mean for the *Eucalyptus* sites calculated at 534 (ppm). The p-value was calculated as 0.05628, and while it was approaching a significant difference, the means of the two sampled groups were not statistically different.

Soil moisture

The soil moisture measurements were taken for both the indigenous and *Eucalyptus* sites. The mean soil moisture for the indigenous sites was 50 % and the mean soil moisture for the *Eucalyptus* was 25 %. The p-value for the samples sites was 0.01312. The calculated p-value indicated that there is a statistically significant difference between the indigenous site and the *Eucalyptus* sites.

B. Ground Cover

The Daubenmire ground cover estimation technique was used to determine the amount of ground cover found for four types of ground cover (Table 2.2). These were forbs, grasses, woody shrubs, and sedges. The midpoint cover percentage for each of the Daubenmire cover classes was averaged for the sum of the 1 m by 1 m plots along the transect in both the *Eucalyptus* woodlots and the indigenous forests sample sites (Daubenmire 1959).

The forbs in the *Eucalyptus* woodlots had an average cover of 18 percent, and the forbs in the indigenous forests had a cover of 25 percent. The p-value was 0.3237. The statistical difference between the two forest types was not significant.

The grasses in the *Eucalyptus* woodlots had an average cover of 21 percent, and the grasses in the indigenous forests had a cover of 9 percent. The p-value was 0.04347. The statistical difference between the two forest types was significant.

Table 2.2. Summary data for the results of the ground cover analysis using the Daubenmire (1959) coverage estimation technique. The comparison was calculated using Welch's two sample t-test. The results indicated that grasses, woody plants, sedges and seedling were all statistically different between the *Eucalyptus* woodlots and the indigenous forests. The forbs were not statistically different.

Ground Cover Results

	Eucalyptus	**Indigenous**		
sample type	**mean %**	**mean %**	**p-value**	**statistical diff.**
forbs	18	25	0.3237	no
grass	21	9	0.04347	yes
woody plant	2	23	0.006661	yes
sedge	1.83	0.08	0.01083	yes
seedlings	0.11	2.03	0.03991	yes
seedling cover estimate	44/ha	800/ha	0.03991	yes

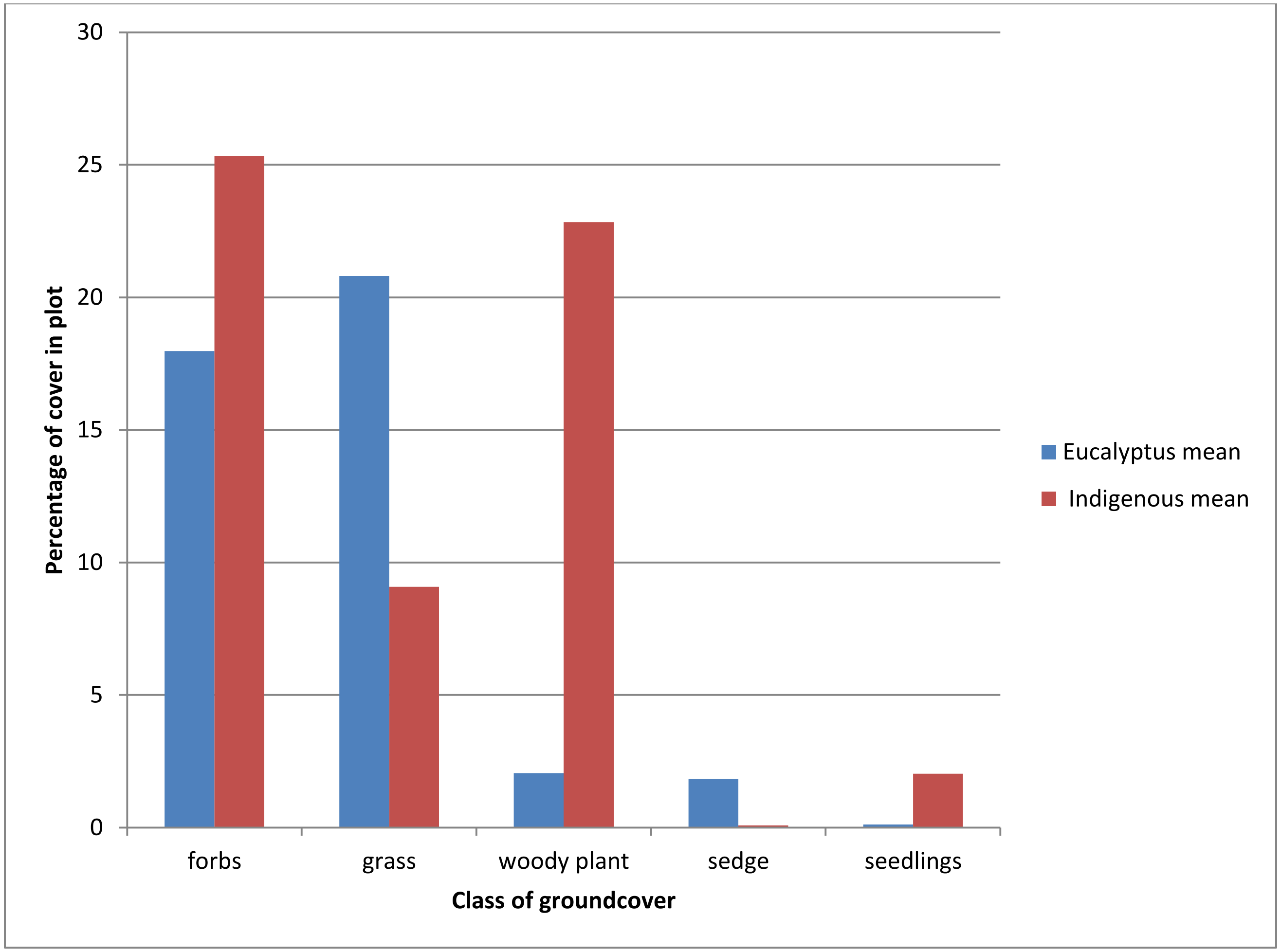

Figure 2.11. Ground cover results from *Eucalyptus* sites and the samples from indigenous sites. Forbs, grass, woody plant, and sedge are represented as mean percent cover. The seedlings are represented as mean seedling count in samples plots. With the exception of the forbs, all the other cover classes showed a statistically significant difference.

The woody shrubs in the *Eucalyptus* woodlots had an average cover of 2 percent, and the woody shrubs in the indigenous forests had a cover of 23 percent. The p-value was 0.006661. The statistical difference between the two sampled sites was significant.

The sedges in the *Eucalyptus* woodlots had an average cover of 1.82 percent, and the sedges in the indigenous forests had a cover of 0.08 percent. The p-value was 0.01083. The statistical difference between the two sampled sites was significant.

The seedlings were counted as number of actual seedlings found in the plot and not as percentage cover based on a maximum value of 100% for the entire plot. The average seedling count in the *Eucalyptus* sites was 0.11 or 44 seedlings per hectare. The average seedling number in the indigenous sites was 2 or 800 seedlings per hectare. The p-value was 0.03991. The statistical difference between the two sampled sites was significant. Table 2.2 and Figure 2.10 illustrate the results from the ground cover samples (Figure 2.11).

C. Light

Light measurements were taken both inside and outside of the sample plot. Outside measurements were taken under open sky conditions free from trees obstructing the light meter. The inside light readings were taken at regular intervals within the plots and averaged for each plot. The outside light intensity was calculated at 100 percent light for both the *Eucalyptus* wood lots indigenous forests. The p-value was 0.1406. The light intensity difference between the two types of systems was not statistically different.

The light intensity measurements taken inside the grouped *Eucalyptus* wood lots had a median of 8.3 percent, meaning that 8.3 percent of the total light reached the forest floor. The median of the indigenous sites was 1.7 percent. The p-value was 0.02097. The mean difference between the light intensities of the two sampled groups was statistically different. This is represented as a percentage of light reaching the forest floor in both forest systems (Table 2.3 and Figure 2.12).

D. Coarse woody debris

Coarse woody debris (CWD) was measured and these measurements pooled along the transect line in each plot for both the *Eucalyptus* and the indigenous forest sites. This mean of the CWD was calculated for each plot and for the combined plot totals. The Welch's two sample t-test was used to determine if there was a statistical difference between the *Eucalyptus* and indigenous plots.

The mean of the CWD in *Eucalyptus* plots was 0.09 percent of the total plot. The mean in the indigenous plots for CWD was 0.23 percent of the total plot. The p-value was 0.04665. This indicated that there was a significant difference between the amount of coarse woody debris on the forest floor between the *Eucalyptus* sites and the indigenous sites.

E. Discussion

The purpose of this study was to determine if the introduced *Eucalyptus* trees had an impact on the local physical environment. This was evaluated in several ways. The first was a comparison of soil samples collected from both *Eucalyptus* woodlots and indigenous forests. The soils comparisons included measures of pH, electrical conductivity, quantity of organic carbon, nitrogen, phosphorus, potassium, calcium, magnesium, and soil moisture.

From the samples analyzed, the electrical conductivity, potassium, calcium and soil moisture were the only variables that showed a significant difference between the two types of forest systems. The electrical conductivity in the soil is a measure of how well the soil can transmit an electrical current. It can also indicate the amount of solubles found in the soil water.

Table 2.3. The percentage of light reaching the forest floor for both forest types are represented in the table. The percent range for the *Eucalyptus* woodlots was 1-53 and the percent range for the Indigenous forests was 1-34. The outside light for the *Eucalyptus* sites and the indigenous sites were not statistically different. The light inside the two forest types were statistically different.

Percent of Light Inside and Outside of the Sample Plot

	Eucalyptus	**Indigenous**		
sample type	**median**	**median**	**p-value**	**statistical diff.**
light outside	100	100	0.1406	no
light inside	8.3	1.7	0.02097	yes

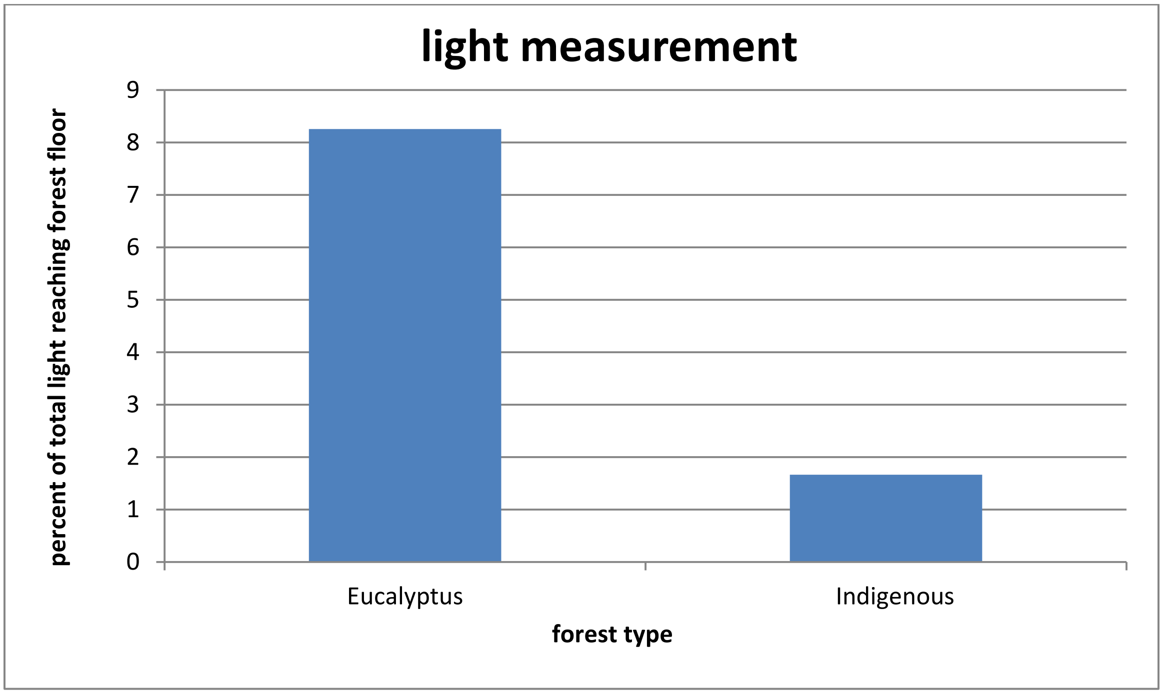

Figure 2.12. Median light intensity inside and outside of the sampled forest sites. The light intensity was statistically different inside the forest sites. There was more light reaching the forest floor of the *Eucalyptus* sites than reached the forest floor of the indigenous forest sites.

Solubles found in the soil water can be many different types of minerals but are most commonly a measure of the amount of calcium carbonate in the soil. Pure water is a poor conductor of electrical current and as the salinity of the soil water increases, the electrical conductivity also increases (Brady and Weil 1996). The *Eucalyptus* forests had an electrical conductivity level that was considered very low, and the indigenous forest has an electrical conductivity level that was considered low. This would not indicate a distinguishable level of salinity but may instead be a function of the soil moisture difference. Campbell (1990) found that as the soil moisture decreased there was also a decrease in the soil electrical conductivity.

The mean soil moisture for the two sampled forest systems showed a significant difference. Sampling of these different sites occurred during the same season and over a short period of time, usually within a few days of each other. Moisture differences would not be a result of seasonality but rather a result of another factor influencing the moisture level.

Introduced *Eucalyptus* in Africa has long been suspected of using large amount of water and putting water resources, such as ponds and streams, at risk (FAO 2011). In many regions of the world the enthusiasm for planting the fast growing *Eucalyptus* was commonly followed by ecological concerns (Bennett 2010). Removal efforts near water resources may mitigate some of the concerns. Studies have shown that removing the *Eucalyptus* from water ways and ponds can result in a return to previous water levels (Oballa el al. 2010). The water use by *Eucalyptus* has been heavily researched in some parts of the world and continues to be a concern as timber needs increase (Boden 1991; Jagger and Pender 2000). The fast growing time of *Eucalyptus* may be a result of its heavy water use. *Eucalyptus* plantations planted in water-scarce regions are the most vulnerable to criticism since the concern for the limited water resource is more evident (Albaugh et al. 2013).

The highland area, where the majority of the samples sites were located, benefits from regular rainfall. The results of the soil moisture in the *Eucalyptus* forests compared with the soil moisture in the indigenous forests indicated lower levels for the former, and this was statistically significant. This supports the hypothesis that *Eucalyptus* woodlots will have less soil moisture than indigenous forests and that *Eucalyptus* may have a negative impact on water resources in the region. Although this region receives abundant rainfall, changing global climate conditions could impact the rainfall patterns.

Potassium in the soil samples was found to be statistically different between the *Eucalyptus* sites and the indigenous forest sites. The mean results from both sites showed that while they were significantly different, the soil levels were still considered very high (Okalebo et al. 2002). Potassium is important for plant growth and development and is taken up in large quantities from the soil. Soils become depleted when crops or, in this case *Eucalyptus* trees, are harvested and removed. Removal of the vegetation prevents the potassium from being available through the breakdown of the organic material for the soil. Over time, continued harvesting of *Eucalyptus* trees could create a deficiency in potassium availability in the soil (Brady and Weil 1994).

Calcium in the two sample sites showed a statistical difference between the *Eucalyptus* and indigenous forests. The calcium content in the soils showed, for the *Eucalyptus* sites, a high level and for the indigenous sites a very high level (Okalebo el al. 2002). Changing calcium levels can influence the pH of the soil, and like potassium, can be leached from the soil through runoff or from plant production and subsequent harvest (Brady and Weil 1994).

The overall differences in the soils for the *Eucalyptus* and indigenous forest sites did not appear significant. Potassium and calcium were statistically different between the sites but they were still at very high levels in term of productivity. The lower levels of soil moisture, associated with *Eucalyptus* may be of more concern, reducing availability of water for plant growth. The difference was statistically significant and may also be having an effect on the electrical conductivity of the soils and the cause for its difference.

The light intensity measurements between the *Eucalyptus* and indigenous forest sites indicated a significant difference in the inside light. The light reaching the forest floor was statistically different inside the *Eucalyptus* woodlots than what was reaching the floor in the indigenous forests. The *Eucalyptus* sites were getting more sunlight while a more closed canopy in the indigenous forests was reducing the light reaching the forest floor. This became interesting and more relevant when compared to the Daubenmire ground cover study. In the ground cover comparison, forbs, grasses, woody shrubs and sedges were recorded for sampled plots, and the results showed that there was a significant difference in grasses, sedges, woody shrubs and the number of seedlings. Forbs did not show a significant difference. Diversity and abundance were higher in the indigenous forests even though it was getting less sunlight. The grasses were more abundant in the *Eucalyptus* forests. The nature of planting a monoculture woodlot would be expected to produce less diversity than an indigenous forest, but the age of the *Eucalyptus*, mostly five years and up, would allow for secondary growth on the forest floor. This may indicate an allelopathic trait exhibited by the *Eucalyptus.*

The results for the CWD from the *Eucalyptus* and indigenous forest sites showed a statistically significant difference. Several other factors may have influenced these results. The primary influence would be the collection of limbs and deadfall from the *Eucalyptus* sites. The *Eucalyptus* sites are closer to human activity and, especially in the small plot farmer areas, people collect the wood as a fuel source for cooking. Therefore, the two types of forest are not really comparable in this parameter.

Fuelwood extraction has been linked to a reduction in forest regeneration and forest floor plant diversity (Furukawa et al. 2011 and Chettri et al. 2002). Indigenous forest sites might have also been affected by limb and fuelwood collection, but probably less extensively. Furukawa et al. (2011) even suggested that the planting of *Eucalyptus* woodlots for fuelwood might help reduce the impact of limb collection and tree cutting in indigenous forests and help to preserve that resource.

The breakdown of CWD is important to the ecology of the forest ecosystems. Fungi and detritivores help to break down the wood and release the nutrients back into the soil. Insects and small animals use the fallen debris for protection, reproduction and food sources. Regeneration occurs when seed banks sprout on fallen trunks. The availability and breakdown of woody debris is important for a healthy forest ecosystem.

When considering the hypothesis that, *Eucalyptus* is an introduced species of tree in Kenya and that its introduction has changed the specific ecosystems in which it has been planted can be supported by the data presented herein. An examination of the results indicates that *Eucalyptus* and indigenous forests are structurally and compositionally different. This is reflected in an understory that is compositionally different for the two types of forest. This difference has ecological consequences for wildlife and people that utilize each forest type.

2.5 References

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Chapter 3. Allelopathy in *Eucalyptus*

Allelopathy is the chemical inhibition of growth of one species by another. The mechanism for inhibition can occur in a variety of ways. For the purpose of this study, the leaves of *Eucalyptus grandis* were used as the suspected mode for chemical release. These leaves were applied to the soil where tomato, corn and amaranth seeds were placed. These seed types were used because they are commonly grown on small farmer plots in Kenya and provide a food staple for the region. If *Eucalyptus* trees on rural farms are exhibiting allelopathic properties, then it could impact food production for the small plot farmers.

3.1 Introduction to allelopathy

Allelopathy is the ability of a plant to release chemicals, known as allelochemicals, which can influence growth and development in a nearby species (Whittaker and Feeny 1971). The chemical release can come from a variety of sources on the plants and not exclusively from any single source. Plant leaves, roots, fruit, flowers, nuts or stems can all be allelopathic. The recognition that plants can influence other nearby species has been recorded for nearly 2,000 years in an agricultural context in ancient cultures such as those found in China and India (Willis 2010). This property has been recorded as beneficial or harmful depending on the interactions observed.

One example of a well-known allelopathic plant is the black walnut tree (*Juglans nigra* L.). All parts of the black walnut have the allelopathic chemical juglone. Juglone is a respiration inhibitor that affects plants by causing the leaves wilt leading to the eventual death of the plant. Juglone, while present in the entire tree, is concentrated in the buds, nut hulls and roots (Angel et al. 1993; Jose 2002). More recently, some varieties of rice have shown negative allelopathic effects towards certain aquatic plants. This has generated interest in transferring those genes to help increase rice yields. This area of interest goes beyond rice to other areas where there is potential for genetically altering organisms to reduce the dependence on herbicides by incorporating allelopathic traits in a selected plant (Willis 2010).

Due to the large variety in allelochemicals, with over 100,000 identified to date, not all plants are affected the same way and it is important to note that allelochemicals can be beneficial or harmful to other organisms (Willis 2010). The allelochemicals can be both water soluble and degrade in the environment very quickly or they can build up in the soil layer over time as they are leached out from decaying leaves or dropped fruits. Environmental factors can also impact the allelopathic effects on other species (Jose 2002).

There is some indication that *Eucalyptus* may contain allelochemicals that negatively affect nearby plants by inhibiting growth and/or seed germination. A study of *Eucalyptus camaldulensis* Dehnh. in California found that there was a zone of limited growth surrounding the woodlot. Competition factors such as available sunlight, nutrient and water availability were ruled out with the finding of allelochemicals in the soil and tissues of the *Eucalyptus* that suppress growth (del Moral and Muller 1970).

Several species of *Eucalyptus* have been introduced throughout the world. The fast growing tree has become an important source of wood for many different industries globally (Bennett 2010). Farmers in Mexico have objected to the large scale *Eucalyptus* pulp wood plantations that have arisen since the 1990's due to possible effects on their crops (Espinosa-Garcia et al. 2007). In China, *Eucalyptus* has become one of the most widely propagated introduced trees and is also suspected of inhibiting crops near plantations (Zhang et al. 2010). This is a concern that is shared in many more countries where the *Eucalyptus* tree has been introduced, including Kenya.

This study examined one potential mode for allelopathic influence on crops, and this was leaf litter. One way for *Eucalyptus* to influence nearby crops is from the leaching of allelochemicals from leaves; these allelochemicals are then transported with runoff water to nearby farms. The practice of "trenching" was observed in *Eucalyputs* woodlots on tree plantionation in Kenya (Figure 3.1). This was presumably done to prevent the allelochemicals from influencing nearby crops.

Several studies have used samples of collected soils from various *Eucalyptus* species woodlots for greenhouse experiments assessing the possible effect of the tree on the germination and growth other plants (Espinosa-Garcia et al. 2008). Other studies have used leaf litter applied to the soil as a way to test the allelopathic effects of *Eucalyptus* on the growth and development of other plants. Predominately, the results have shown a negative effect on germination and growth, although the influence varied by tested species as well as by species of *Eucalyptus* used (Li et al. 2013; Bughio et al. 2013; Dadkhah 2013; Zhang and Fu 2010; Niakan and Saberi 2009).

Variation in allelopathic influence is highlighted in the study by Zhang and Fu (2010) who examined the effect of leaf litter on three common Chinese crops—cabbage, radish, and cucumber. They found that at lower leaf litter concentrations, cucumber actually experienced an increase in germination rates with two of the three *Eucalyptus* species. Conversely, cabbage and radish were negatively affected by the leaf litter, and the impact was more pronounced with an increase in concentration. These studies were the basis for developing the concentrations and protocols for the greenhouse experiment carried out in this study. The selections of seeds used were based on commonly grown crops in Kenya, where the *Eucalyptus* leaves were collected.

Figure 3.1. This image shows a trench that was dug around a *Eucalyptus* plantation to prevent runoff to nearby tea plants (photo by the author).

They included corn, tomato and amaranth. The latter is an indigenous plant widely consumed in Kenya while corn and tomato are introduced crop species (Ndenge et al. 2013).

3.2 Leaf litter greenhouse experiments

A. Methods—field

Leaves from *Eucalyptus grandis* were collected near the Kenya Forest Research Institute, which is located approximately 10 km north of Nairobi, Kenya. Small stems were gathered from newly harvested trees (Figure 3.2). These stems were allowed to dry outside until the leaves were free of moisture. The leaves were then removed from the stem and packaged for shipment to the University of Arkansas.

B. Methods—greenhouse

The greenhouse component of the study examined the influence of chemicals in *Eucalyptus* leaves on the growth and development of the seeds of three types of plants—tomato, corn and amaranth. The leaves, shipped from Kenya, were ground up through a series of grinders to reach a consistency able to pass through a 1 mm filter (Figure 3.3).

Commercially available topsoil was purchased from a local seed co-op and air dried in the greenhouse. Once the soil was completely dry, it was sifted through a filter to remove large particles in order to create an even consistency. Planting pots and trays were obtained from a local greenhouse. The planting pots were black, plastic, six pack pots with a growing space of approximately five square centimeters. The three groups were (1) a control, (2) 1% *Eucalyptus* to soil mixture and (3) a 10% *Eucalyptus* to soil mixture. A total of one hundred and twenty seeds were used for each type of plant. Each pot contained four seeds. The soil was mixed in one hundred gram batches for each of the experimental groups. For the 1% group, one gram of

Figure 3.2. Harvested *Eucalyptus grandis* leaves drying outside before being removed from the stem. Once dry, leaves were packaged for shipment to the University of Arkansas (photo by the author).

Figure 3.3. Image showing manually crushed leaves and the grinder used to finish grinding leaves to a fine consistency. The finely ground leaves were then mixed with potting soil for the allelopathy greenhouse experiment. Some of the leaves were also used in preparing aqueous solutions for the seed germination experiment (photo by the author).

Figure 3.4. Image showing the different seed types planted in pots. Each setup had a different percentage of ground *Eucalyptus* leaf litter incorporated into the soil (photo by the author).

Figure 3.5. Example of a harvested corn plant being measured for height (photo by the author).

Figure 3.6. Image of corn plants prepared for determination of dry weight measurements (photo by the author).

ground *Eucalyptus* was added to 99 grams of soil. This was used to fill the pots and when the pots were half full then they were watered thoroughly. More mixed soil was added to fill each pot and then it was watered again. The seeds were then placed, four per pot, an equal distance apart. A small amount of mixed soil was then added to the top. The pots were placed in the tray and watered thoroughly. This same procedure was repeated for the 10% *Eucalyptus* to soil mixture. This resulted in three trays, consisting of one control, one 1% mixture and one 10% mixture. The trays consisted of ten filled pots for each seed type, with four seeds in each pot (Figure 3.4).

The pots were maintained in a greenhouse located on the campus of the University of Arkansas. The greenhouse was set at 89 degrees for a daytime high temperature and 52 degrees for the nighttime low temperature. The greenhouse was maintained at 38% relative humidity. The pots were watered every Monday, Wednesday and Friday, with seedling counts taken every Monday and recorded.

The corn was harvested 48 days after planting and the amaranth and tomato were harvested 68 days after planting. Before the plants were removed from the pots, a measurement of height was recorded for each plant (Figure 3.5). The plants were then harvested, with the excess soil removed from the roots. The plants were allowed to dry for 24 hours in the greenhouse then they were placed in paper bags and moved to a drying facility for 48 hours. The dry weight was recorded for (1) the whole plant and (2) just the above ground portion of the plant (Figure 3.6). The corn and tomato plants were measured individually, but the amaranth plants were measured in groups due to the small amount of plant material available.

C. Results of growth experiment

The results of the plant height greenhouse experiment using corn, tomato and amaranth seeds are recorded in Tables 3.1, 3.2, and 3.3. The corn germination rates for the control were 77.5 %, and 82.5% in the 1% *Eucalyptus* mixture and 67.5% in the 10% *Eucalyptus* mixture. These results are slightly lower than the germination study results. The mean corn plant height in the control was 20.18 cm, 18.38 cm in the 1% mixture and 14.94 cm in the 10% mixture. The dry weight results where 19.83 g in the control 23.03 g in the 1% mixture and 12.55 g in the 10% mixture (Table 3.4).

The tomato germination rates were not apparently different from the control or the different mixture concentrations with 15, 15, and 16, respectively, but the overall germination rate was at or under 40%. The oven dry weights were 0.46 g in the control, 0.33 g in the 1% *Eucalyptus* mixture and 0.15 g in the 10% *Eucalyptus* mixture. The mean height for the control group was 4.46 cm, with the 1% *Eucalyptus* mixture measuring 3.86 cm and the 10% *Eucalyptus* mixture measuring 2.97 cm.

The amaranth seeds germinated in the control and 1% mixture with 16 and 13 seeds, respectively, but no seeds germinated in the 10% *Eucalyptus* mixture. The mean height for the control group was 2.84 cm, with the 1% *Eucalyptus* mixture measuring 2.03 cm. The oven dry weight of the control group was 0.05 g, with the 1% *Eucalyptus* mixture weight at 0.04 g. The small amount of vegetative matter made it difficult to determine a difference between the above ground dry weight and the whole plant, so the above ground measurement was not taken.

Table 3.1. Summary data for the different mixtures of ground *Eucalyptus grandis* leaf litter. The numbers represent the height in centimeters of each corn plant grown.

control		**1% *Eucalyptus***		**10% *Eucalyptus***	
height (cm)	weight (g)	height (cm)	weight (g)	height (cm)	weight (g)
23	0.76	23.5	0.81	20	0.9
24.2	0.76	17.2	0.82	14.8	0.88
18	0.75	23.5	0.82	14.6	0.51
21.1	0.75	18.6	0.82	18.7	0.51
20.8	0.75	18.7	0.86	9.4	0.52
25.2	0.75	19.5	0.86	17.9	0.51
21.7	0.76	22.5	0.86	16.1	0.61
14.3	0.76	23.6	0.87	11.2	0.62
20	0.73	10.5	0.62	18.1	0.61
26.2	0.73	25.3	0.62	20.9	0.61
21.8	0.74	30	0.62	18	0.64
29.5	0.74	10.4	0.62	25	0.64
24.6	0.46	25.4	0.62	14.2	0.27
15.5	0.47	10.3	0.62	15.6	0.27
24.3	0.46	15.6	0.62	11.4	0.27
23	0.47	25	0.63	10.2	0.42
20.6	0.44	17	0.67	8.2	0.42
23	0.44	18	0.67	12.3	0.42
13	0.44	19	0.83	18.2	0.42
23	0.44	21.5	0.83	19.6	0.38
20	0.75	23.3	0.83	12	0.37
17.5	0.78	25.6	0.84	14.7	0.37
19	0.78	12.8	0.52	9.5	0.37
17.5	0.78	16.8	0.52	19.5	0.46
22	0.48	24	0.52	6	0.12
23.4	0.48	14.2	0.52	15.2	0.16
17.5	0.63	19.5	0.73	12	0.27
3	0.64	14.6	0.73		
23.5	0.69	16.6	0.74		
17.4	0.45	9.5	0.74		
12	0.77	12	0.55		
		8.3	0.55		
		14.1	0.55		
mean					
20.18	0.64	18.38	0.70	14.94	0.46

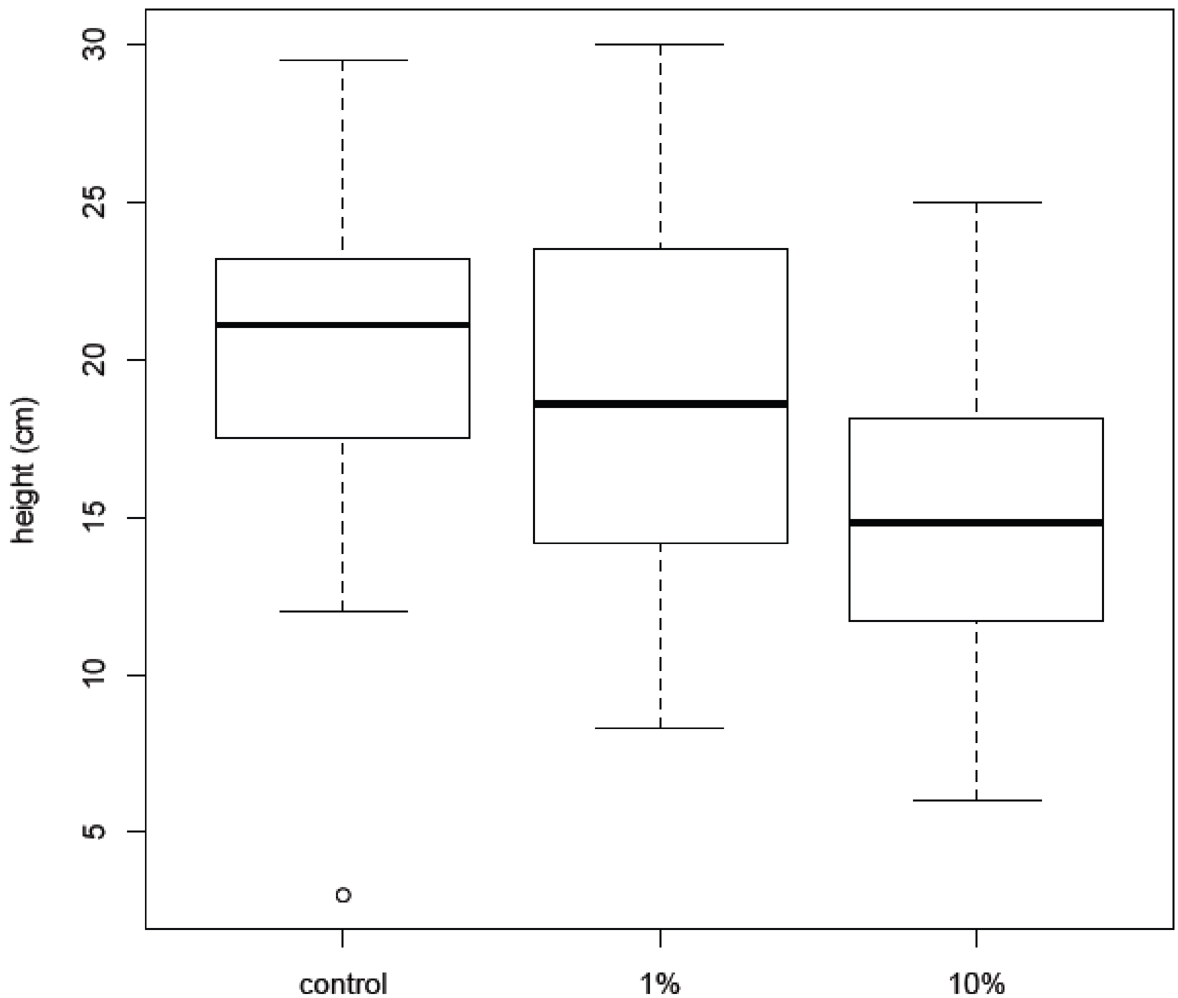

Figure 3.7. Results of the height of corn plants after harvest in each of the experimental growing conditions involving the effect of *Eucalyptus* leaf litter. The graph illustrates the median height, range and central 50% of the sample heights.

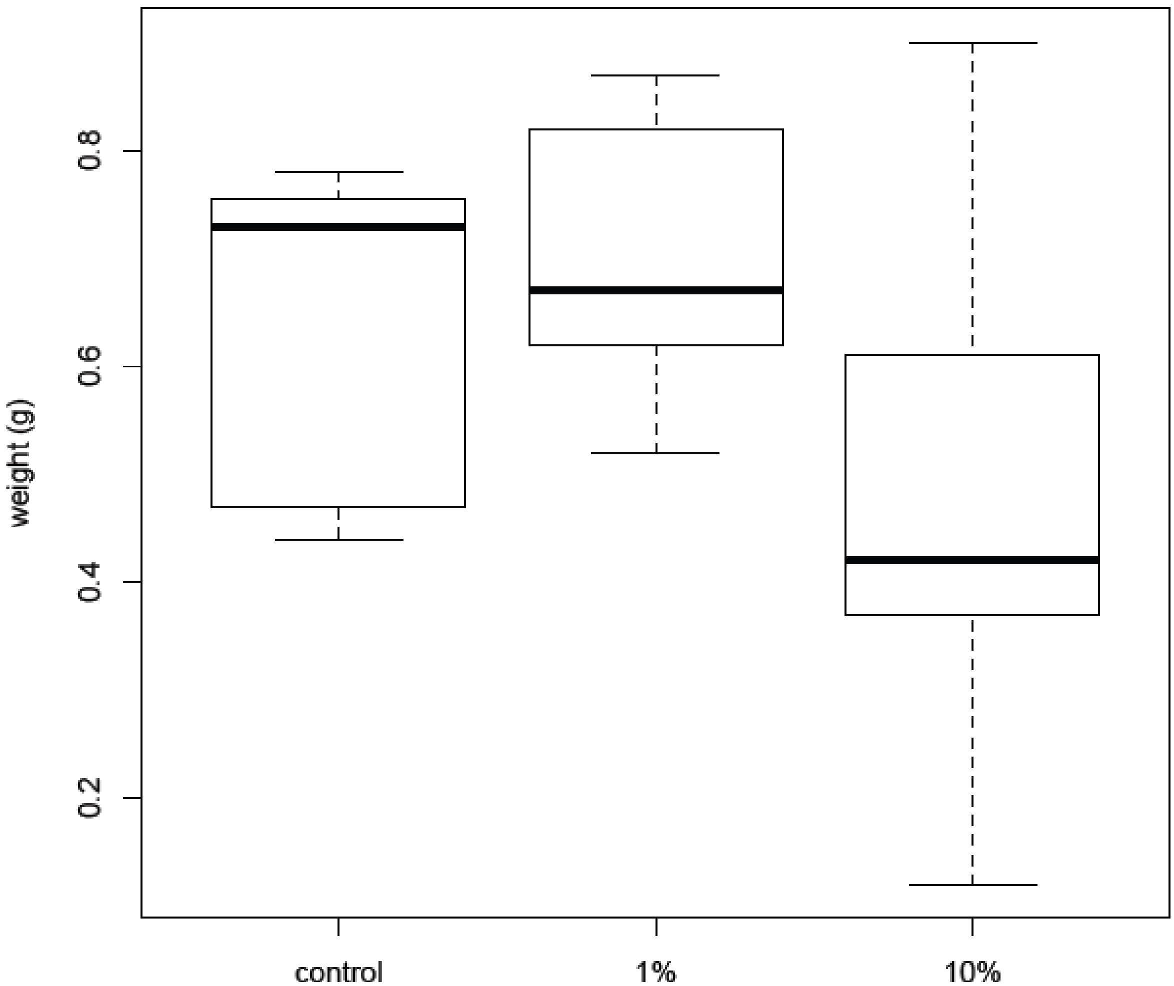

Figure 3.8. Results of the weight of corn plants after harvest and drying in each of the experimental growing conditions involving the effects of *Eucalyptus* leaf litter. The graph illustrates the median weight, range and central 50% of the sample weights.

Table 3.2. Summary data for the greenhouse experiment using tomato and different mixtures of ground *Eucalyptus grandis* leaf litter. The numbers represent the height in centimeters of each corn plant grown.

control		1%		10%	
height (cm)	weight (g)	height (cm)	weight (g)	height (cm)	weight (g)
5.6	0.03	3.4	0.04	2.5	0.01
4.3	0.03	3.5	0.02	3.5	0.01
5.1	0.04	4.5	0.02	4	0.01
5	0.02	3	0.01	1.1	0.02
4	0.01	4.1	0.02	3.4	0.01
5	0.03	3.3	0.03	3.7	0.01
3.8	0.03	3.6	0.02	3.1	0.01
3.8	0.03	3.7	0.02	3.5	0.01
5.2	0.04	5.3	0.01	2.5	0.01
5.3	0.03	4.5	0.07	2.3	0.01
4.1	0.04	3.8	0.01	2.3	0.01
4.2	0.05	4.6	0.01	3	0.01
4.3	0.01	4.8	0.01	3.2	0.01
4.2	0.06	3.9	0.03	2.5	0.001
4.5	0.01	1.9	0.01	3.5	0.001
				3.4	0.01
mean					
4.56	0.030666667	3.86	0.022	2.96875	0.0095

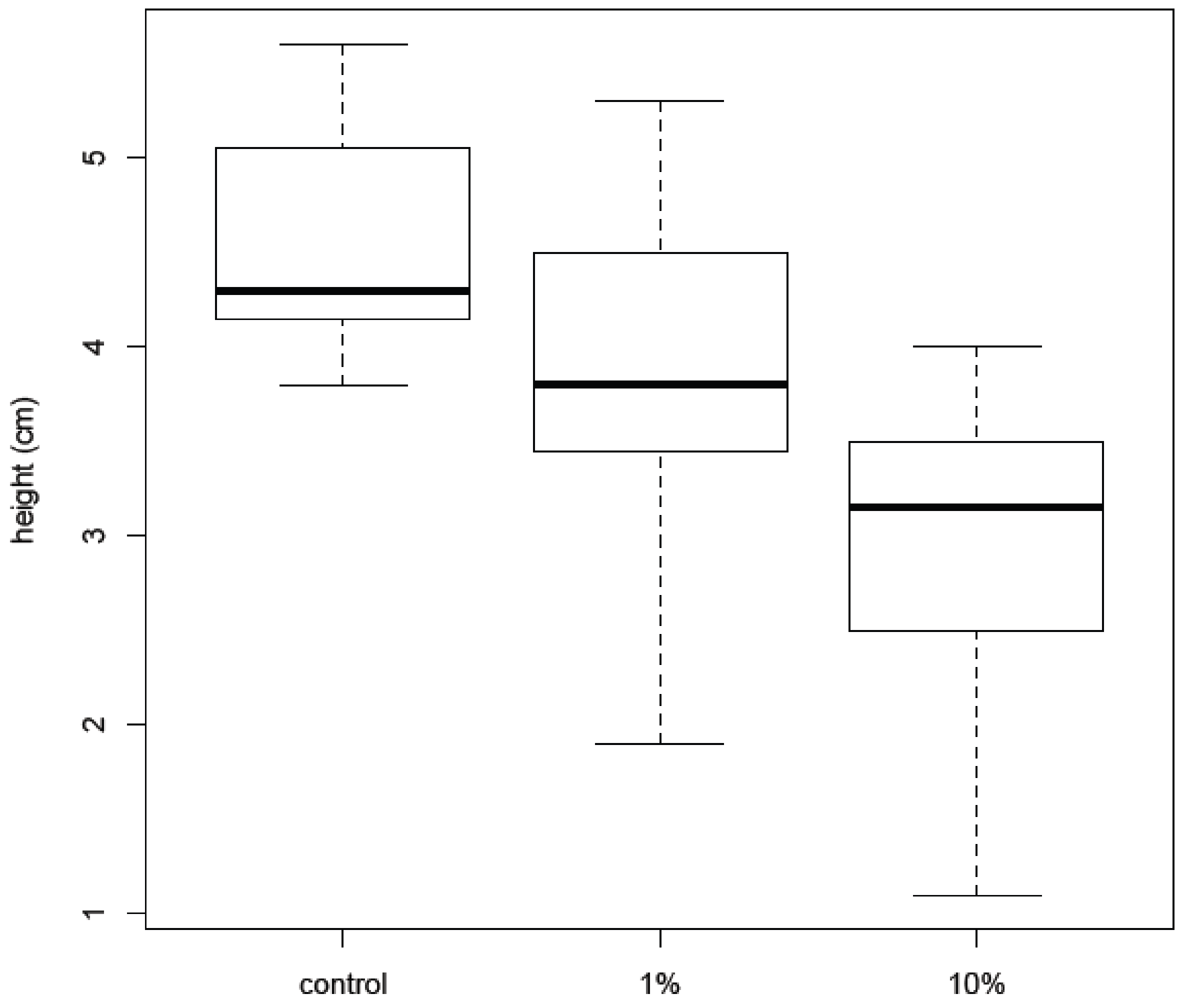

Figure 3.9. Results of the heights of the tomato plants after harvest in each of the experimental growing conditions involving the effects of *Eucalyptus* leaf litter. The graph illustrates the median height, range and central 50% of the sample heights.

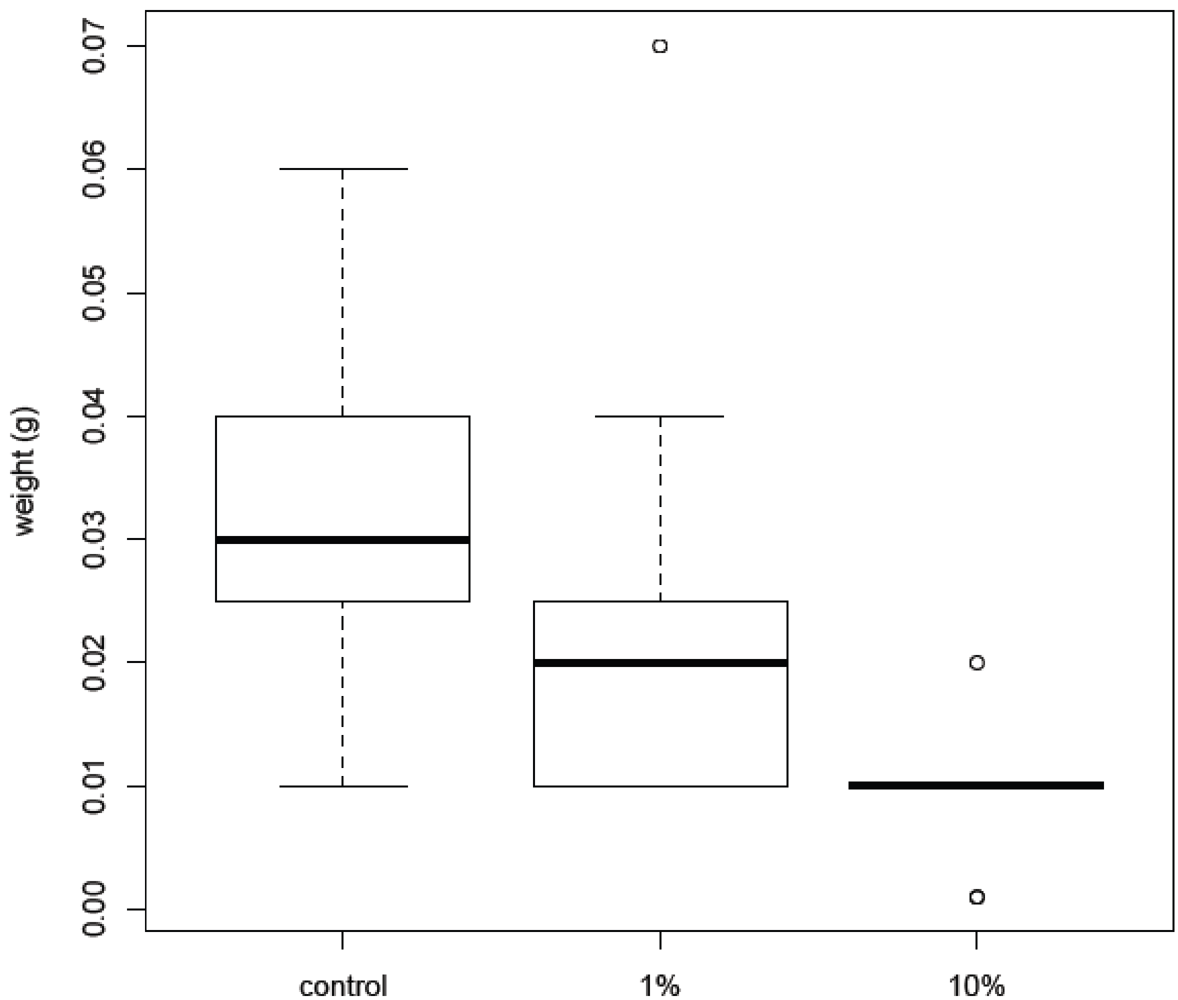

Figure 3.10. The results of the weights of tomato plants after harvest and drying in each of the experimental growing conditions involving the effects of *Eucalyptus* leaf litter. The graph illustrates the median weight, range and central 50% of the sample weights.

Table 3.3. Summary of data for the greenhouse experiment using amaranth and different mixtures of ground *Eucalyptus grandis* leaf litter. The numbers represent the height in centimeters of each corn plant involving the effects of *Eucalyptus* leaf litter.

control		1%		10%	
height (cm)	weight (g)	height (cm)	weight (g)	height (cm)	weight (g)
3.2	0.0050	1.7	0.0050	0	0
2.2	0.0050	2	0.0050		
2.7	0.0050	1.9	0.0050		
2.8	0.0050	2.5	0.0050		
2.6	0.0025	1.9	0.0025		
3	0.0025	2.1	0.0025		
2.5	0.0025	1.9	0.0025		
4.5	0.0025	2.3	0.0025		
7	0.0025	2.1	0.0025		
2.2	0.0025	2.3	0.0025		
2.1	0.0025	2.2	0.0025		
1.1	0.0025	1.3	0.0020		
2.4	0.0025	2.2	0.0005		
2.5	0.0025				
2.3	0.0025				
2.4	0.0025				
Mean					
2.84		2.03076923			

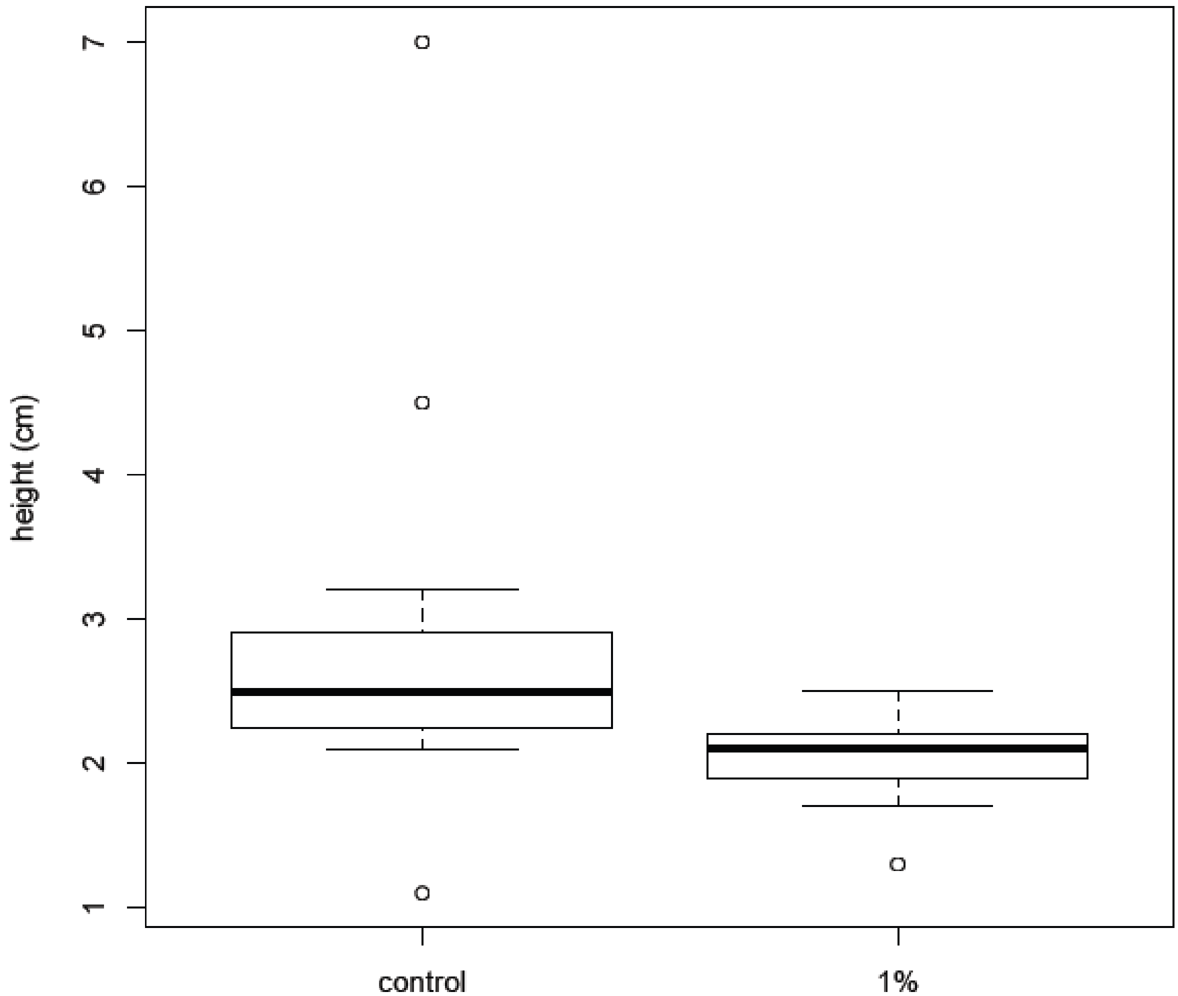

Figure 3.11. Results of the heights of the amaranth plants after harvest in each of the experimental growing conditions except for the 10% *Eucalyptus* leaf litter concentration, in which amaranth seeds did not germinate. The graph illustrates the median height, range and central 50% of the sample heights.

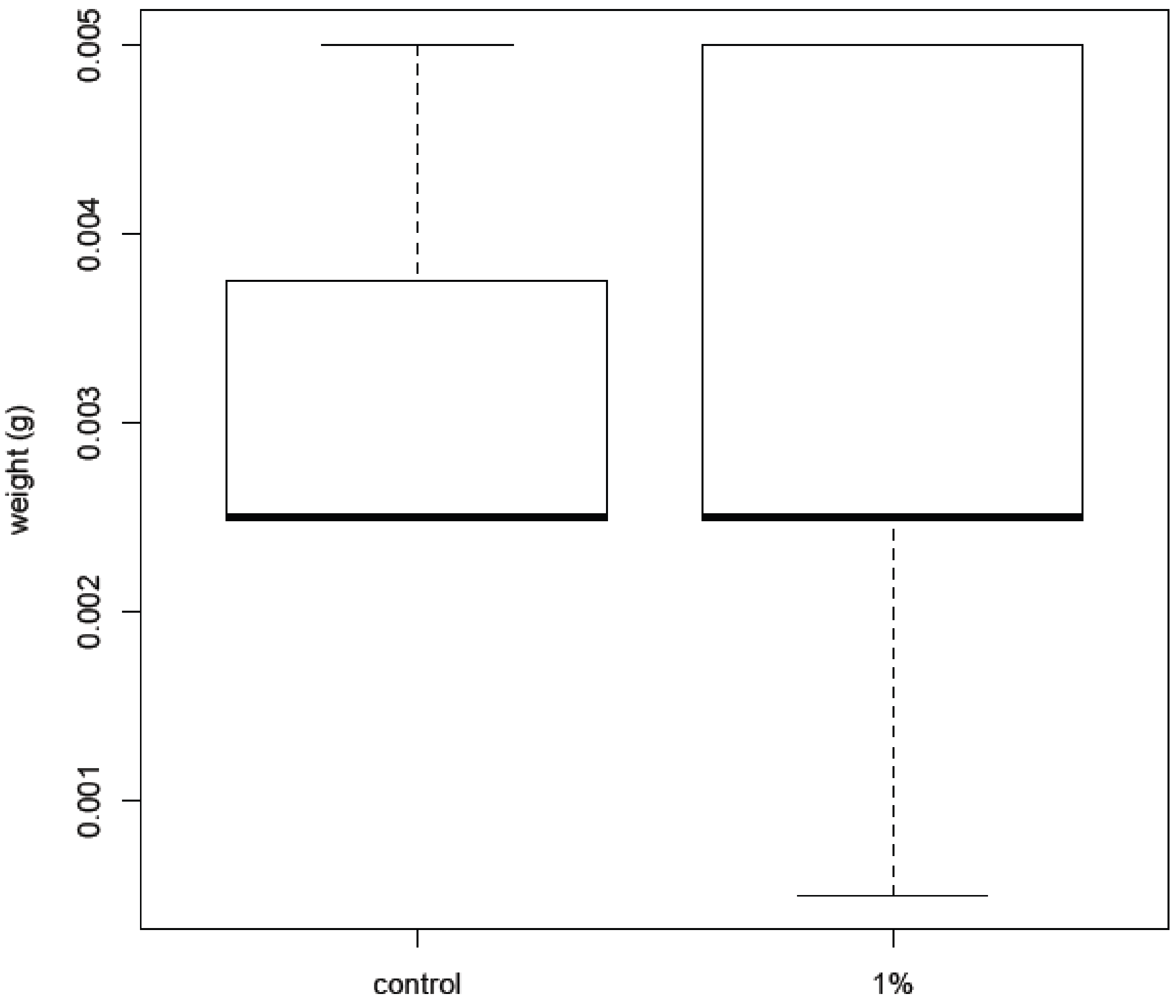

Figure 3.12. The results of the weights of the amaranth plants after harvest and drying in each of the experimental growing conditions except for the 10% *Eucalyptus* leaf litter concentration, in which the seeds did not germinate. The graph illustrates the median height, range and central 50% of the sample heights. The samples were so light that they were weighed in groups, reducing the sample size and resulting in little variation of weight between the control and 1% group. The 10% *Eucalyptus* leaf litter group did not germinate which indicate a significant different but was not included because there were no measurements to include.

Table 3.4. Summary data for the greenhouse study on the effects of *Eucalyptus* leaf litter of the growth and development of corn, tomato and amaranth plants. Included are the oven dry weights of the corn plants including the whole plant and just the above ground portion of the plant. Also included are the number of seeds that germinated and the percent germination rate, as well as the mean height of the plants before harvesting.

greenhouse results		control	1%	10%
whole plant dry weight (g)	corn	19.83	23.03	12.55
	tomato	0.46	0.33	0.152
	amaranth	0.05	0.04	0
above soil dry weight (g)	corn	4.46	4.49	2.17
	tomato	n/a	n/a	n/a
	amaranth	n/a	n/a	n/a
number of seed/40	corn	31	33	27
	tomato	15	15	16
	amaranth	16	13	0
percent germination	corn	77.5%	82.5%	67.5%
	tomato	37.5%	37.5%	40%
	amaranth	40%	32.5%	0%
mean height (cm)	corn	20.18	18.38	14.94
	tomato	4.56	3.86	2.97
	amaranth	2.84	2.03	0

D. Discussion

An ANOVA statistical test was carried out for each of the different plant treatment results, with a Tukey post hoc test performed to determine where there was a significant difference, if that was the case. For the corn experiment, both the height and weight showed significant differences with a 99% confidence interval for the data sets. The same results were reported for the tomato and amaranth data sets. Using the Tukey post hoc test it was possible to determine which data sets in each category showed statistical differences from others.

The corn data showed statistical difference between the 10% *Eucalyptus* mixture for both the height and weight measurements. The 1% *Eucalyptus* solution did not have a statistical difference between the height and weight of the corn plants when compared to the control. For the corn, the influence was more evident in the higher solution concentration.

The Tukey post hoc test also revealed that weight measurements for the both the tomato and amaranth did not have a significant difference between the 1% *Eucalyptus* concentration and the control. It is important to note that the sample size of plants that germinated in these groups was small. The amaranth plants were so small that they could not be accurately weighted individually and had to be weighed in groups to get a reading on the scale. A larger sample size might reveal a significant difference if the experiment was repeated.

The overall results of the greenhouse experiment demonstrate that *Eucalyptus* does have an effect on the growth and development of common crop seeds in Kenya. This supports the hypothesis that *Eucalyptus* tree are allelopathic and can influence the growth and development of nearby plants. This is similar to the results of greenhouse experiments using soil from *Eucalyptus* woodlots on agricultural crops conducted by Espinosa-Garcia et al. (2007), which found that the effect was the least on corn and greatest on the other vegetables tested.

The evidence from this study indicated that allelochemicals found in *Eucalyptus* could contribute to lower crop yields in rural farming areas and have a significant impact on food security for subsistence farmers.

3.3 Seed germination experiment

A. Plants used

The seeds used for this experiment were selected based on their use as a common crops by rural farmers in Kenya. They included two seed types that are introduced plants, corn and tomato, with one seed type that is an indigenous plant, amaranth.

B. Methods

Leaves from two species of *Eucalyptus* (*E. paniculata and E. grandis*) were collected and dried. The dried leaves were shipped to the University of Arkansas from Kenya. Aqueous solutions were prepared from these dried leaves for both species.

The solutions were prepared for a 10g/l solution and a 20g/l solution. The solutions were placed on a shaker table for 24 hours at 250 rev/min. The soaked leaf litter was strained through a filter and the remaining solutions were then placed in spray bottles to be used for application.

Disposable Petri dishes were used for the germination chambers. The bottom of each Petri dish contained 90 mm pieces of filter paper. This paper was sprayed with the particular solution concentration. Ten seeds were placed on top of the paper then another piece of 90 mm filter paper was placed over the seeds. The top filter paper was sprayed again to get an even moist environment. The lid of the Petri dish was placed on it, and the dish was placed in a dark cabinet. Each seed/concentration combination had 10 Petri dishes containing 10 seeds each. The Petri dishes were sprayed three times a week to maintain an even moisture environment. On the fourteenth day, the seeds were examined for germination and recorded. This was done with the

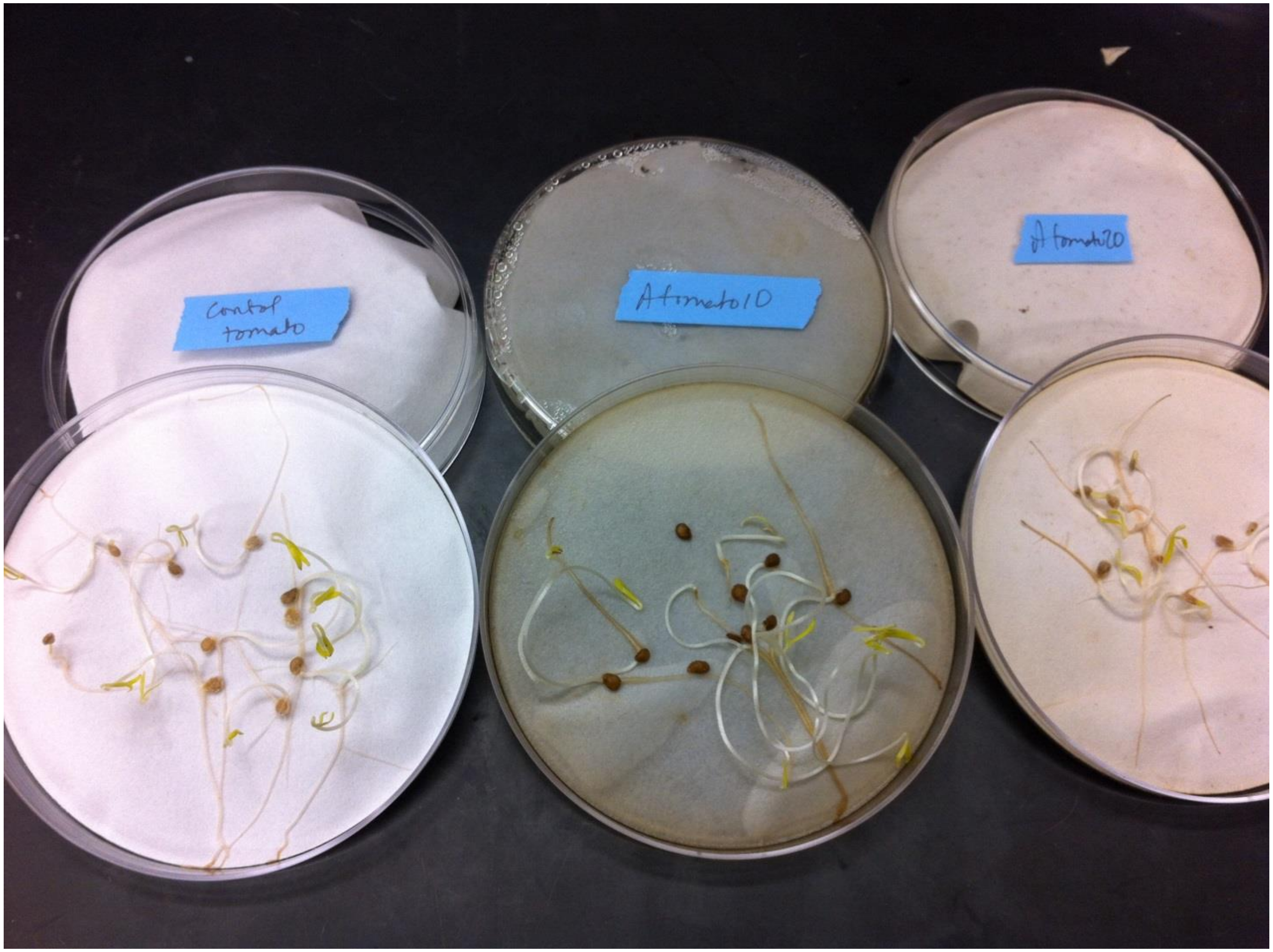

Figure 3.13. Seed germination experiment assessing the effects of different concentrations of *Eucalyptus* solution on tomato seeds (photo by the author).

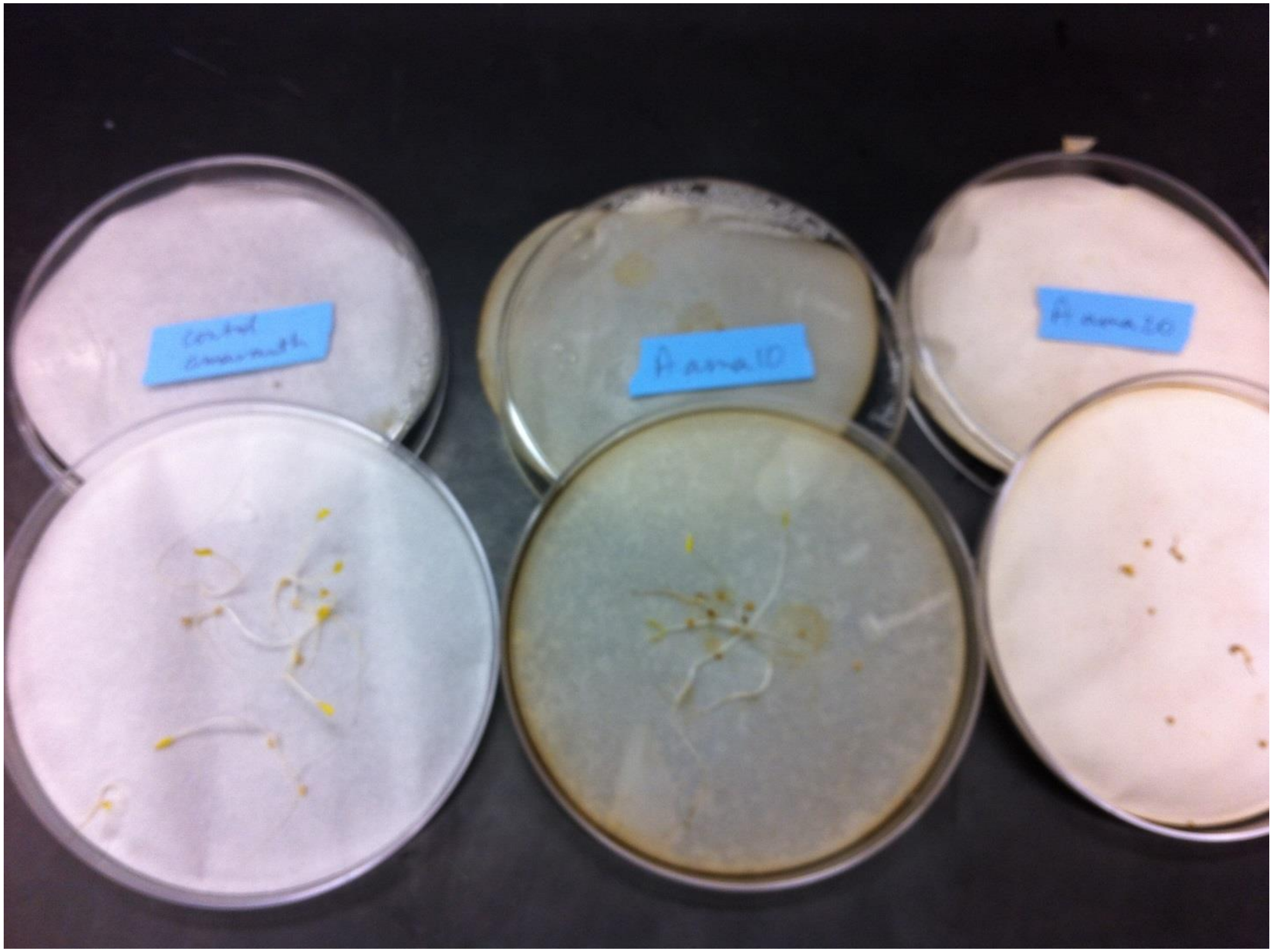

Figure 3.14. Seed germination experiment assessing the effect of different concentrations of *Eucalyptus* solution on amaranth seeds (photo by the author).

Figure 3.15. Seed germination experiment assessing the effect of different concentrations of *Eucalyptus* solution on corn seeds (photo by the author).

use of a stereomicroscope. A seed was considered to have germinated if there was a noticeable interruption in the seed coat. The results were recorded and reported in Table 3.4.

C. Results

The results of the seed germination numbers are presented in Table 3.5. With the 10 g/l solution of *E. paniculata,* 97 corn seeds germinated, and with the 20 g/l solution 95 seeds germinated. For the *E. paniculata* 10g/l solution 92 tomato seeds germinated and with the 20 g/l solution 89 seeds germinated. The amaranth seeds had the fewest germinated seeds with the *E. paniculata* solution. Under the 10 g/l solution 36 seeds germinated while 28 seeds germinated with the 20 g/l solution.

The results of seed germination under the *E. grandis* solution are given in Table 3.5. Ninety-six corn seeds germinated in the 10 g/l solution and 95 seeds germinate in the 20 g/l solution. The tomato seeds had 86 germinate in the 10 g/l *E. grandis* solution and the same number, 86, germinated in the 20 g/l solution. The amaranth seeds had 5 germinate in the 10 g/l *E. grandis* solution. In the 20 g/l *E. grandis* solution, none of the amaranth seeds germinated.

D. Discussion

The experiment to determine the effect of the aqueous *Eucalyptus* solution on the germination of seeds yielded some significant results. The corn showed very little effect from either the *E. paniculata* or the *E. grandis* solutions. The tomato displayed a slightly greater effect from both of the solutions but with little difference from the increased concentration. The amaranth seeds had the greatest effect from both of the *Eucalyptus* solutions. Approximately one third of the seeds germinated in the *E. paniculata* solution but only five seeds germinated in the 10 g/l *E. grandis* solution. In the 20 g/l *E. grandis* solution, none of the seeds germinated.

Table 3.5. Summary of the germination results for both of the *Eucalpytus* species used as well as the different concentrations used.

Eucalyptus paniculata

seed type	**control**	**10g/l**	**20g/l**
corn	100	97	95
amaranth	90	36	28
tomato	100	92	89

Eucalyptus grandis

seed type	**control**	**10g/l**	**20g/l**
corn	100	96	95
amaranth	90	5	0
tomato	100	86	86

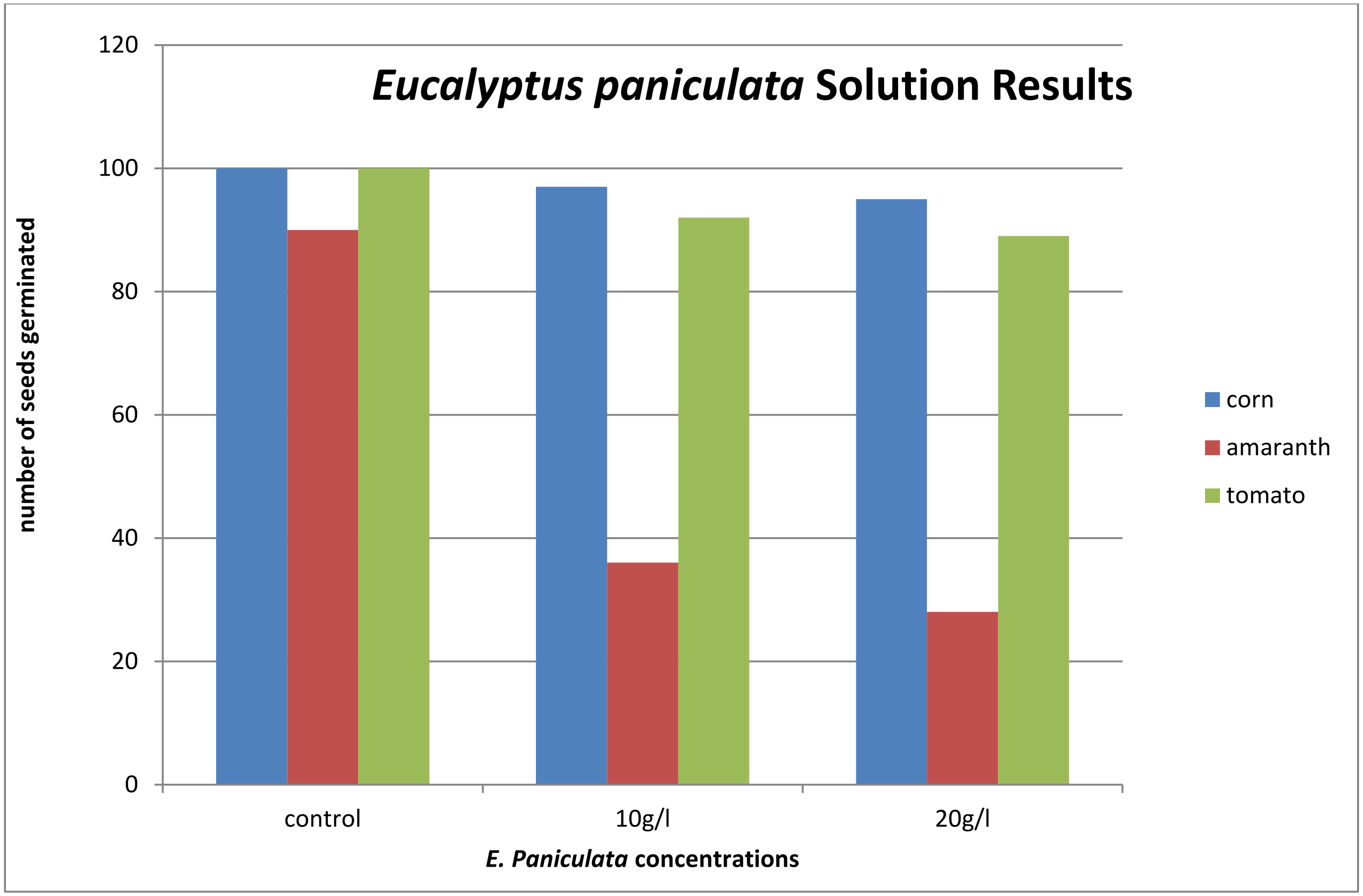

Figure 3.16. Seed germination results for the *Eucalyptus paniculata* solution on corn, amaranth and tomato seeds.

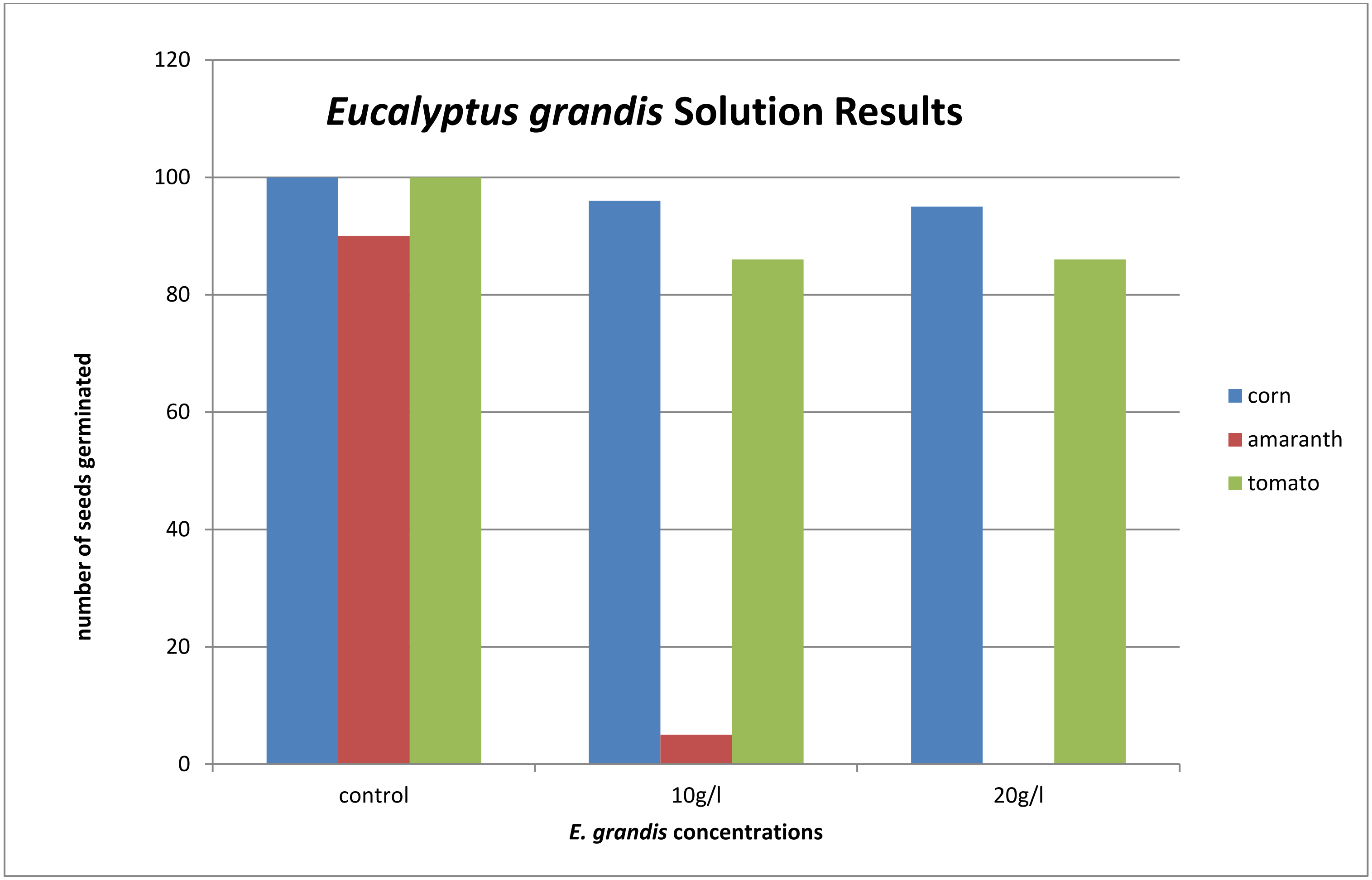

Figure 3.17. Seed germination results for the *Eucalyptus grandis* solution on corn, amaranth and tomato seeds.

Amaranth was the only seed that displayed a statistically significant difference in the germination percentages from the control group. This was verified using a chi-square analysis. The results were significant for both *Eucalyptus* species as well as in both concentrations.

Corn, tomato and *Eucalyptus* are all introduced species to Kenya, while the amaranth is a native species. This may provide some insight into the why the amaranth is more susceptible to the secondary metabolites that are found in the *Eucalyptus* leaves. The recent interaction between the two species has not been a long enough time for defense mechanisms to evolve to combat the allelopathic effects of the *Eucalyptus* tree (Stamp 2003).

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Chapter 4. Mycorrhizal Fungi and *Eucalyptus*

The origin of mycorrhizal fungi is estimated at about 460 million years ago, coinciding with the establishment of plants on land. The fungus-plant association was recognized by the scientific community in the late 1800's. Mycorrhizal fungi play an important role in ecosystems all over the world. They can be classified in several different taxa and include nearly 6000 species. The life cycles and host associations vary by type, but most are dependent on the fungus gaining nutrients from their host plant while providing minerals and water from the soils to the host. The importance of the symbiotic relationship is still actively studied today, both in field settings and in laboratories. Species of *Eucalyptus* are associated with mycorrhizal fungi and the relationship between the tree and the fungus is important for the survival and overall health of the trees. Understanding the fungal species associated with various species of *Eucalyptus* is important for management of woodlots (Chu-Chou and Grace 1982). In some cases, successfully establishing *Eucalyptus* woodlots in new locations requires the inoculation of seedlings with appropriate mycorrhizal symbionts (Malajczak et al. 1982).

4.1 Introduction to mycorrhizal fungi

Mycorrhizal fungi have been instrumental in their contribution to the diversity evident in terrestrial plant life seen today. There are indications that early associations with aquatic algae were fundamental for the establishment of plant life on land (Pirozynski and Malloch 1975). The symbiotic relationship formed with the plant host has been shown to be fundamental for the successful growth and development of both the fungus and plant (Smith and Read 1997). Mycorrhizal fungi contribute many other benefits to the ecosystems in which they occur such as providing a food source for other organisms.

Mycorrhizal fungi are a group of soil-dwelling fungi that form symbiotic relationships with the roots of other plants. These plants include angiosperms, gymnosperms, and some bryophytes. The relationship with the host plant is classified by how the fungus associates with the roots of the plant. Mycorrhizal fungi are found in the phyla Basidiomycota and Ascomycota (Stephenson 2010).

Mycorrhizal relationships are found in a variety of environments all over the world. They are found in nearly 90% of all of the land plants on earth. Their importance can be measured in both ecological and economic values. They are a vital component of many ecosystems including agricultural production.

Mycorrhizae in the soil serve an important function. The relationship formed with their host is dependent on the minerals the fungus supplies to the plant. These fungi are able to access the minerals that the host would otherwise not be able to obtain. While this is important for the plants' survival, it is also important for soil development processes. Mycorrhizal fungi secrete organic acids into the rhizosphere, helping to breakdown of both organic and inorganic substances. Ectomycorrhizal fungi also have the ability to break down complex organic molecules. This releases nitrogen, phosphorus and sulfur and aids in the weathering of soils. Minerals and nutrients that were once unavailable for use by living organisms are released back into the nutrient cycling system (Cardon and Whitbeck 2007).

Mycorrhizal fungi benefit from the nutrients they obtain from the host plant. This symbiotic relationship also allows the plants to contribute to the ecosystem by providing habitat and food for other organisms. Ectomycorrhizal fungi contribute an additional component to the ecosystem through the production of their fruiting bodies. The fruiting bodies are important food resources for both vertebrates and invertebrates. The collection method of these fruiting bodies also contributes to the ecosystem health by breaking up the leaf litter and soil, allowing moisture to enter. The animal vectors also aid in the propagation of the fungi by dispersing the spores (Johnson 1996; Lilleskov and Bruns 2005; Maser et al. 2008).

Just as mycorrhizae are important for natural forest ecosystems, they are also important for managed tree nurseries and woodlots. For example, early attempts at establishing exotic pine plantations in Australia failed due to the lack of pine-associating mycorrhizal fungi in the soil. Although the seedlings grew initially, they became stunted and quickly died without the input of minerals that were normally supplied by the mycorrhizal fungi. Once an understanding of the fungal relationship was incorporated into the tree planting regime, the trees quickly grew and flourished (Maser et al. 2008).

In mycorrhizal associations, the effective root area of the plant is greatly increased with the development of the fungi on the root-tips. This increases the plants' ability to obtain water and minerals while providing nutrient to the fungi. The fungus receives carbon-based nutrients from the host plant, while the host plant receives minerals from the fungi, completing the symbiotic relationship. In many instances, the survival of both the plant and fungus is dependent on the mycorrhizal association.

When the relationship is formed primarily on the outside of the roots, the fungi associated are classified as ectomycorrhizal. These types of fungi are found in the Basidiomycota and Ascomycota. Production of a Hartig net and fruiting bodies distinguish them from other mycorrhizae (Stephenson 2010).

Ectomycorrhizal fungi (ECM) are fungi that form symbiotic relationships with other vascular plants for the purpose of mineral and nutrient exchange. As the name implies, the association is found primarily on the outside of the root structure of the host plant. Their numbers are not as great as those of endomycorrhizal fungi, but they represent a group that is economically and ecologically important. ECM fungi form associations with major groups of trees including but not limited to pine, oak, beech and eucalyptus. They can be found in vastly different ecosystems all over the world (Tedersoo et al. 2010).

Ectomycorrhizal fungi predominately belong to the Basidiomycetes, accounting for 95 percent, with a few species also found in the Ascomycetes (Martin et al. 2001, Taylor and Alexander 2005). Most ECM reproduce sexually and produce fruiting bodies. The fruiting bodies can be found in a variety of forms and locations within the area, including in the soil, underneath litter and above ground (Tedersoo et al. 2010).

The ECM fungi form a symbiotic relationship with distinct hosts. These hosts will only allow specific species of ECM fungi to form the association, but each species of ECM fungi may be capable of forming a symbiotic relationship with a small range of different hosts (Martin et al. 2001). Once a symbiotic association is formed, structures like the hyphal network can take a variety of forms. Additionally, ECM can associate with the root-tips in a variety of ways, some penetrating only the outer layer while other will reach the cortex (Brundrett 2002). Given the diversity of ECM, there are still some general developmental processes that can be attributed to formation of this symbiotic relationship.

Recognition between the ECM fungi and host plant begins with a series of signals. Fungi propagules, either spores or hyphae found in the soil, will begin to produce hyphae that grow towards new root growth in an uninhabited host plant. Exudates released from the host will initiate a series of responses in the ECM. The chemicals, including flavonoids, make recognition and communication possible. The chemical signaling occurs from both the ECM and the host (Martin el al. 2001).

When contact has been made between the hyphae of the ECM and the cap cells of the root a series of events occurs. First, the hyphae penetrate the root cap cells and begin to grow through them. The hyphae will extend between the cells into the root until it reaches the epidermal cells (Martin et al. 2001). Depending on the species of ECM, the hyphae may continue to extend until reaching the cortex cells, once developed, is referred to as the Hartig net (Brundrett 2002). Simultaneously with the development of the Hartig net, the process of transforming the cap cells into the inner layer of the mantle begins. The mantle forms at the apex of the root. As the hyphae attach to the cells inside the root-tip, the outer layers begin to multiply and form layers. This is the beginning of the mantle. The mantle generally consists of an inner and outer layer. The inner mantle is generally not very dense and consists of a covering of hyphae containing extracellular sugars and proteins. These are believed to prevent the movement of molecules into the root from outside sources and for protection. The mantle also has a complex system of channels that allows movement of water and nutrients (Martin et al. 2001). This inner mantle layer does not have much, if any, contact with the soil. Water and mineral movement from the soil, through the mantle and ultimately into the host, depends on the hyphae that extend out from the outer mantle. This extends that amount of soil that can be utilized by the ECM (Agerer 2001).

The root structures formed from the ECM relationship are elaborate and take time to develop. Slow lateral growth in the host root is necessary to allow for the symbiosis to take place. In addition, the structures between the two begin to disintegrate in a fairly short amount of time, approximately two weeks. This requires that the host continually develop new root growth to continue the ECM partnership (Brundrett 2002).

Reproduction of ECM can happen by asexual means, simply by the spread of the vegetative mycelium from one host organism to another nearby host. However, ECM fungi reproduce predominately from sexual reproduction. Developing spores go through meiosis before they are dispersed. Once dispersed, they germinate and produce mycelia that fuse with those from another germinating, compatible spore. This process creates new individuals that are ready to form symbiotic relationships with host plants (Carriconde et al. 2008).

Mature spores can be developed in several different forms in the ECM and play an important role in the ecology of an area. As the name would imply, the fruiting body is the "fruit" of the fungi. Fruiting bodies house the spores; they can be found above ground, below ground or found in or on the litter layer on the ground. There is a great deal of variety in the forms of the fruiting bodies found in ECM (Cairney 2002).

Resupinate forms, produced in some ECM, are generally crust-like layers on the ground or other substrates. Each basidium will generally hold four individual spores, though there is some variation to this. This method for spore dispersal is thought to be from invertebrates in the soil that either feed on the spores or they inadvertently carry them on their bodies as they pass through the resupinate layer. The invertebrates then carry the spores to new environments within their range. The invertebrates could also be eaten by other organisms and the spores dispersed to new habitats as those organism defecate in a new area. The spores of this kind are generally very small with a thick outer layer that can protect them in the digestive tracts or in the soil for many months before germination (Lilleskov and Bruns 2005).

Fruiting bodies that form above the ground are termed epigeous. Though variation can be found in the actual structure for a variety of ECM, they are generally found with a cap and a stalk. The spores are produced on the underside of the cap where they stay until mature (Johnson 1996). Upon maturity, the spores are forcibly discharged from the cap. Wind dispersal takes the spores to a new location where they can germinate and find a new host plant. In some cases the fruiting body does not grow completely out of the leaf litter. This creates a problem for spore dispersal (Maser et al. 2008). Some fruiting bodies are termed subhypogeous. This is an intermediate form that produces a stalk and cap but the cap does not separate from the stalk. This form is usually only partially above ground. Spores cannot be ejected from the cap area so they must depend on another mode of transport from the fruiting body (Johnson 1996). Animal vectors are important for moving the spores of subhypogeous and epigeous fruiting bodies and constitute an important food source for these animals (Maser et al. 2008).

Hypogeous fruiting bodies are found below the surface layer of the ground. Their structure does not allow for forcible discharge of the spores. Their shape is ball-like with a thick protective outer layer. This type of fruiting body has arisen several times in evolutionary history, suggesting it may have a competitive advantage over the cap and stalk morphology in some circumstances. In areas where conditions are dry or prone to freezing, the fruiting bodies are protected underground. The peridium of the hypogeous body protects it from these environmental extremes as well as its location underground. Spore dispersal in this type of fruiting body depends heavily on animal vectors, done in one of two ways. The spores are released when the animal breaks open the fruiting body, sending them out for air dispersal or they are ingested and later passed in the feces. The distribution of ECM with hypogeous fruiting bodies also supports this concept of a selective advantage. Hypogeous fruiting bodies are found in alpine and subalpine environments as well as areas that are prone to both dry and freezing conditions (Johnson 1996).

Hypogeous fruiting bodies have developed an interesting way for animals to discover their location underneath the surface of the ground. Each species produces a distinct aroma. This also varies by the stage of spore development. When the spores are immature, very little odor can be detected. As the spore matures, so does the aroma until the spore is fully developed. This prevents animals from consuming or disturbing the fruiting body before the spores are ready to be released. The odor released comes from chemical compounds produced by the fruiting body. Animals can detect the chemicals and precisely dig up the fruiting body (Maser et al. 2008). This efficient method of digging and removal from the ground is also important for the health of the plant life in the area. Animals digging for the fruiting bodies or truffles break up the surface layer of the soil. This allows rainfall to leach into the soil, also increasing movement of minerals, instead of running off the surface of the litter.

Ectomycorrhizal fungi are important components of terrestrial ecosystems. Their associations with woody trees and shrubs throughout the world are of great ecological and economic importance (Cardon and Whitbeck 2007). The symbiotic relationships not only benefit the organisms involved, but are also vital to the ecology of an ecosystem. Ectomycorrhizal associations with trees that dominate boreal, temperate, and subtropical ecosystems illustrate the significance of the fungi and need to further understand their biology and ecology (Cairney 2000; Smithe and Read 1997).

A. Previous studies in Kenya

Research on the mycorrhizal associations of *Eucalyptus* in Kenya yields very little information. Even though the relationship has been long been recognized there are currently not many published works on the specific ectomycorrhizal fungi found in Kenya. Collection and identification of fungal fruiting bodies have been conducted since the late 1800's (Kost 2002). Specific ectomycorrhizal fungi associations with *Eucalyptus* in Africa have also been limited to identification through collection of the fruiting body (Ducousso et al. 2012). This highlights the importance of detailed molecular identification of fungal-*Eucalyptus* associations in Kenya.

4.2 Interactions with *Eucalyptus*

Mycorrhizal associations with *Eucalyptus* have been recognized for decades. Visual observations of fruiting bodies and hyphal structures on the roots have established the relationship with *Eucalyptus* in native habitats (Samuels 1926). Specificity of the relationship with particular host and fungus varies by species. Some subgenera appear to be able to interact with species of native soil fungi, while others appear to need a specific fungal partner. Early introductions of some important wood producing-species of *Eucalyptus* resulted in poor growth and ultimately the trees did not survive in the new environments. These trees were not able to form symbiotic relationships with native soil fungi. Later introductions that included inoculation with specific mycorrhizal fungi greatly increased the overall health and survivability of the trees (Pryor 1956).

The present study examined the ectomycorrhizal associations found with *Eucalyptus* trees in the various study sites. This was done by collecting root-tip samples and isolating the fungi. A comparison was done to find out if the fungi-tree relationship was from fungal taxa introduced from the *Eucalyptus* tree's native Australia or if it was associating with native taxa.

4.3 Identification

A. Collecting root-tips

Root-tip collection sites were selected at a variety of different localities. The sites included small farmer plots, government woodlots and large commercial plantations. The collection sites included the central, coastal, western and Rift Valley regions (Figure 4.1 and Figure 4.2).

Root-tips were collected by walking into a Eucalyptus woodlot and selecting a particular tree. From the base of the tree, a root was followed out approximately 20 cm. Using a trowel, the soil was removed from the root. Forceps were then used to collect the fine root-tips from the larger root (Figure 4.2). These were then preserved in a 2% CTAB (Cetyl Trimethyl Ammonium Bromide) solution in a 2 ml micro centrifuge tube (Figure 4.3). The preserved, collected root-tips were then mailed back to the University of Arkansas for processing.

B. DNA procedures

Processing of preserved samples began with removing the sample from the -20° freezer and then from the CTAB solution with sterilized forceps. The sample was rinsed with distilled water and viewed under a light microscope (Fig. 4.5). Colonized root-tips were selected, removed from the root and placed in a new, sterilized, 2 ml microcentrifuge tube. Each new tube contained samples from only one site. The isolated root-tip samples were then prepared, following the directions, with the Invisorb Spin Plant mini kit (Stratec Biomedical, Birkenfield, Germany). This nucleic acid purification kit allowed for the isolation of genetic material from the selected root-tip samples. The procedure involved seven steps. The first was the homogenization of the root-tip material. This step was completed by adding lysis buffer to the sample and manually rupturing the membranes using a plastic pestle.

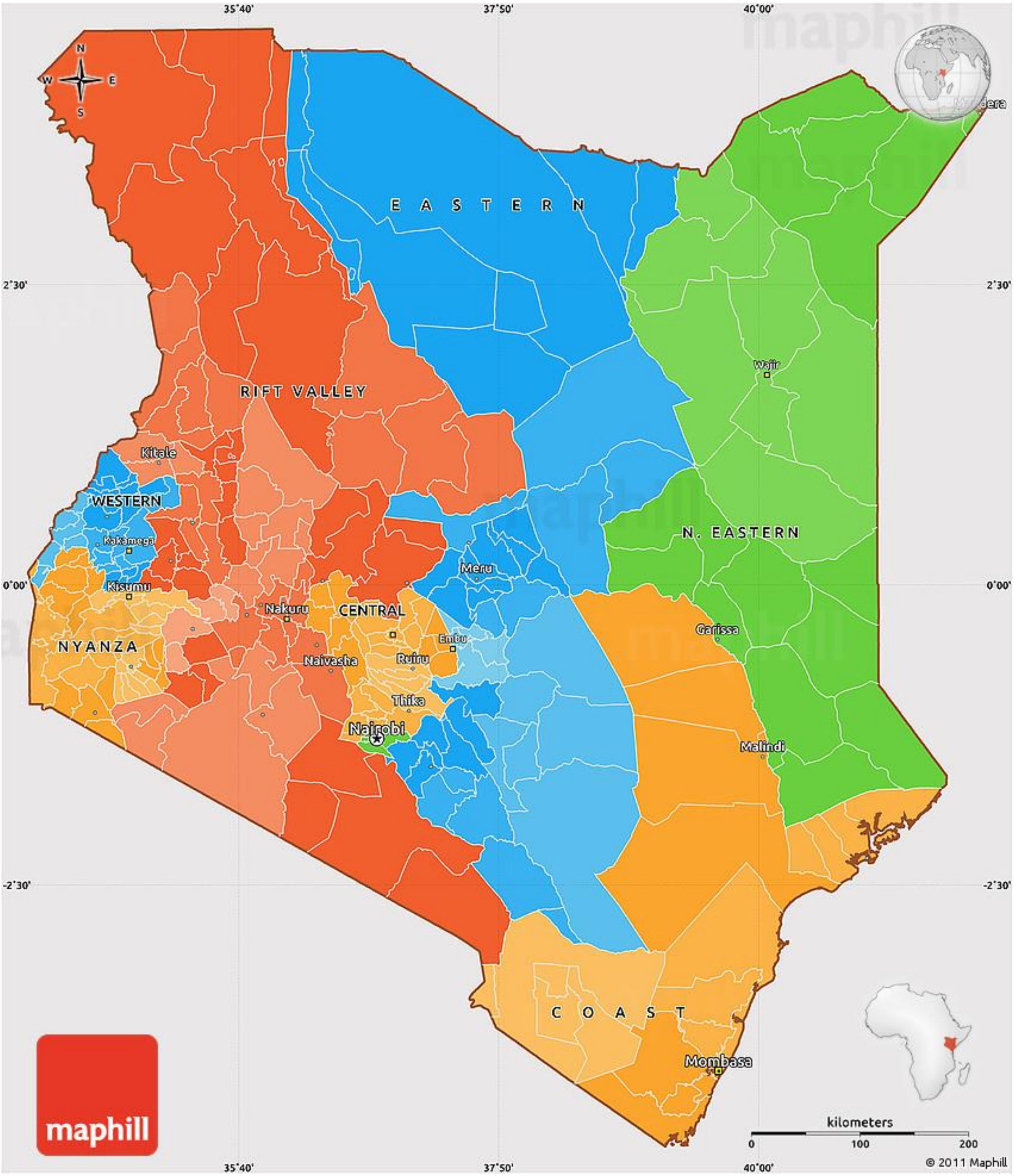

Figure 4.1. Geographic regions of Kenya. (edited from www.maphill.com)

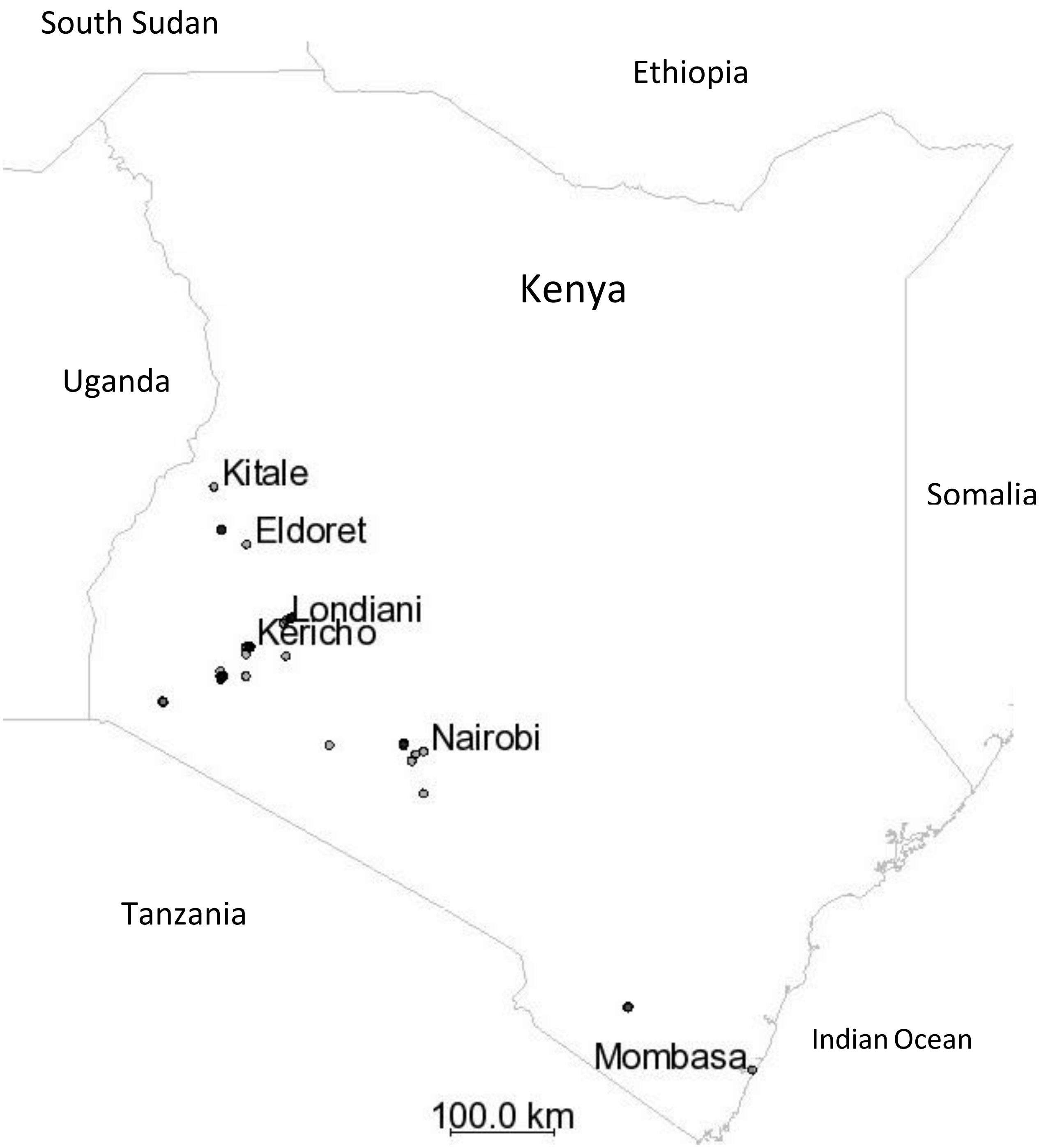

Figure 4.2. Localities in Kenya where *Eucalyptus* root-tips were collected.

Figure 4.3. *Eucalyptus* root-tips (photo by the author).

Figure 4.4. *Eucalyptus* root-tips in container with the CTAB preservative (photo by the author).

The following steps were used to isolate the genetic material and clean away the unneeded particles, such as proteins. What remained was a purified sample that was ready for amplification.

Each purified sample was then ready for amplification. The 25 µl sample was prepared of a solution that consisted of 50% GoTaq Green Master Mix 2x (Promega Corporation, Wisconsin), 5% ITS1F primer, 5% ITS4B primer, 32% double distilled water and 8% purified root-tip sample. The ITS1F and ITS4B primer pairs were used to amplify fungal DNA of basidiomycete and ascomycete fungi, both of which have known ectomycorrhizal species (White et al. 1999). The PCR amplification took place in a Bio Rad T100 Thermal Cycler (Bio Rad Inc., California) The protocol ran as follows; Step 1: 94°C for three minutes, Step 2: 94°C for one minute, Step 3: 54°C for forty-five seconds, Step 4; 72°C for one minute. This was repeated again from step 2 for thirty-six times followed by a ten minute period at 72°C. The amplification was finished and held infinitely at 4°C.

Verification of amplification was performed with a gel electrophoresis procedure. A 1% agarose gel was prepared, samples were loaded into the wells and the electrophoresis ran for approximately sixty-five minutes at 110v (Figure 4.6). The samples were then viewed for the presence of visible bands that indicate successful amplification of DNA product (Figure 4.7).

Samples that yielded strong bands were sent to Beckman Coulter Genomics (Danver, MA) for sequencing. Returned sequencing results were cleaned up using editing software (SeqMan Version 7.1.0) to correct mismatched base pairs. The cleaned up contigs were submitted to the NCBI database to look for potential species matches. A 97% match was considered a good species identification.

Figure 4.5. Image of *Eucalyputs* roots under a light microscope (photo by the author).

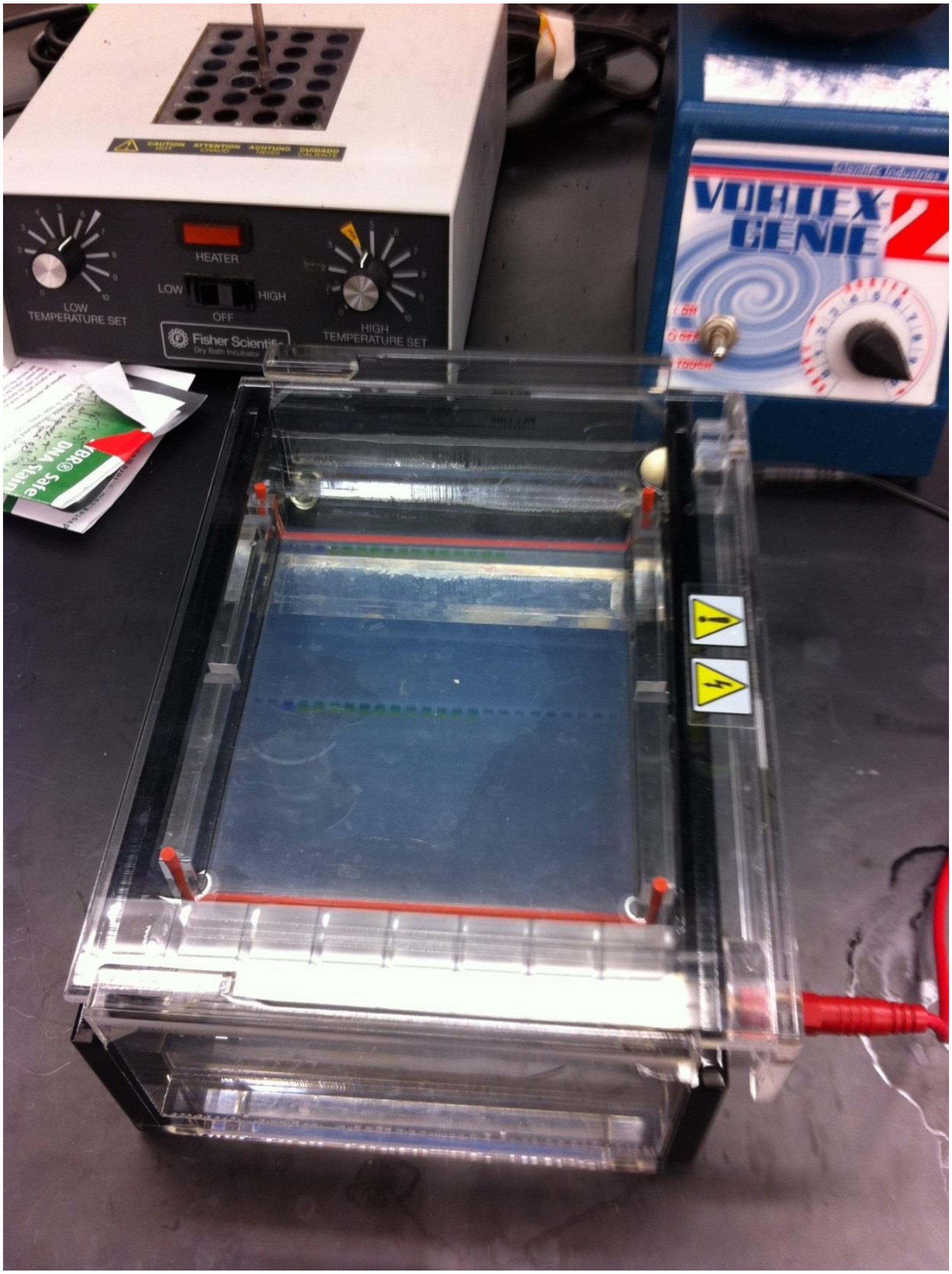

Figure 4.6. Prepared 1% agarose gel loaded with PCR products (photo by the author).

Figure 4.7. Image of DNA bands present from the amplification and gel electrophoresis procedure (photo by the author).

C. Results

Root-tip samples were collected during two field seasons. A total of 47 sites were established that yielded 121 root-tip samples. After extraction and amplification, 116 samples were sent off for sequencing. This included three fruiting bodies that were collected on three separate sites.

The results of the sequencing yielded 62 contigs that matched known species. Not all of these were fungal. There were 38 fungal samples with some repeated species. In total, the samples yielded 22 unique fungal species. The identified fungi are arranged by geographic location (Figure 4.8) and host *Eucalyptus* tree (Figure 4.9).

D. Discussion

The 22 species of fungi that were identified can be classified into two broad groups. One group would be the basidiomycota and the other group would be the ascomycota. Both of these groups include ectomycorrhizal species, but not all of these samples were ectomycorrhizal.

In the Basidiomycetes group, the species of *Laccaria, Descoleo, Pisolithus* and *Tomentella* are well documented ectomycorrhizal fungi found both in Australia and associating with *Eucalyptus* trees (Brundrett 2008). The species of *Laccaria*, *Descoleo*, and *Pisolithus* all produce above ground fruiting bodies. The species of *Tomentella* produces a crust like layer called resupinate. *Descomyces* is also an ectomycorrhizal fungi.

The identification of these ectomycorrhizal species in Kenya would support their introduction along with the introduction of *Eucalyptus.* These fungi were found across several regions of Kenya and several of the different collection sites. They were found on commercial tree plantations, government woodlots and in old growth *Eucalyptus* public lands. This would indicate that they were not necessarily inoculated when planted but that the fungi had already been introduced to Kenya and are now present in the soil where the trees are growing.

Table 4.8. List of fungi identified through molecular analysis listed by geographic region. FB=fruiting body

Geographic region	Fungi identified	Phylum
Coastal region	*Mycena pura*	basidiomycetes
Voi sites	*Scleroderma sinnamariense*	basidiomycetes
Central region	*Pisolithus microcarpus*	basidiomycetes
Nairobi and KEFRI sites	*Meyerozyma guilliermondii*	ascomycetes
	Mycena plumbea	basidiomycetes
	Descomyces sp.	basidiomycetes
	Lactarius chichuensis (FB)	basidiomycetes
Western region	*Hydnangium carneum*	basidiomycetes
Turbo sites	*Laccaria* sp.	basidiomycetes
	Psathyrella (FB)	basidiomycetes
Rift Valley	*Mycena plumbea*	basidiomycetes
Western Highlands	*Beauveria bassiana*	ascomycetes
Londioni, Sotik, and Finley sites	*Purpureocillium lilacinum*	ascomycetes
	Leotiomycetes	ascomycetes
	Isaria amoenerosea	ascomycetes
	Pezizomycetes	ascomycetes
	Myxotrichum sp.	ascomycetes
	Helotiales	ascomycetes
	laccaria cf. *lateritia*	basidiomycetes
	Tomentella parmastoana	basidiomycetes
	Hydnangium carneum	basidiomycetes
	Descomyces sp.	basidiomycetes
	Descolea tenuipes	basidiomycetes
	Hydnangium carneum	basidiomycetes
	Trechispora sp.	basidiomycetes
	Laccaria glabripes	basidiomycetes
	Agaricus subrutilescens (FB)	basidiomycetes
	Hydropus sp.	basidiomycetes
	Tomentella sp.	basidiomycetes

Table 4.9. List of fungi identified through molecular identification by host *Eucalyptus* species.

***Eucalyptus* species**	**Fungi identified**	**Phylum**
Eucalyptus grandis	*Hydnangium carneum*	basidiomycetes
	Laccaria sp.	basidiomycetes
	laccaria cf. *lateritia*	basidiomycetes
	Mycena plumbea	basidiomycetes
	Descomyces sp.	basidiomycetes
	Descolea tenuipes	basidiomycetes
	Trechispora sp.	basidiomycetes
	Laccaria glabripes	basidiomycetes
	Leotiomycetes	ascomycetes
	Isaria amoenerosea	ascomycetes
	Pezizomycetes	ascomycetes
	Helotiales	ascomycetes
	Myxotrichum sp.	ascomycetes
	Purpureocillium lilacinum	ascomycetes
	Hydropus sp.	basidiomycetes
	Meyerozyma guilliermondii	ascoycetes
Eucalyptus globulus	*laccaria* cf. *lateritia*	basidiomycetes
	Tomentella parmastoana	basidiomycetes
Mixed *Eucaluptus* species	*Trechispora* sp.	basidiomycetes
	Descomyces sp.	basidiomycetes
Eucalyptus camaldulensis	*Pisolithus microcarpus*	basidiomycetes
	Scleroderma sinnamariense	basidiomycetes
Fruiting bodies		
collected near *E. grandis*	*Lactarius chichuensis*	basidiomycetes
collected near *E. grandis*	*Agaricus subrutilescens*	basidiomycetes
	Psathyrella	

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Chapter 5. *Eucalyptus* and Humans

The western world did not discover *Eucalyptus* until the late 1700's when Captain James Cook's crew collected specimens from the east coast of Australia to take back to England (Doughty 1996). In its native home of Australia, this tree has occurred along with humans for nearly 60,000 years (Allen and O'Connell 2003). Indigenous aboriginal tribes of Australia had a long history of using *Eucalyptus* for medicinal purposes as well as for everyday use. Boiled bark from the *Eucalyptus* was used as a treatment for diarrhea. This was taken internally while a topical treatment was made for use as an antiseptic. A common everyday use of the *Eucalyptus* wood would be for cooking over open fire (Web 1969). The rapid expansion of *Eucalyptus* to other parts of the world did not necessarily mean the translation of the uses of the tree beyond the use of its wood for burning and building.

5.1 History of Human use

A. Before introduction

Prior to the European colonization of Kenya, *Eucalyptus* trees were not found in the country. Vast tracks of land that would appear relatively undisturbed were utilized by many different ethnic groups. These indigenous people comprised three main categories, agrarian, pastoral and a combination of the two. The agrarian groups farmed the land, while the pastoral group primarily grazed livestock (Ndege 2009).

European colonization in Kenya not only changed the ecology but also had a detrimental impact on indigenous societies. Prior to settlement, different ethnic groups moved across the terrain unhindered and interacted with each other for trade. European settlers moved into the central highlands and began to cultivate the land for both livestock and grain production. The establishment of territories and property boundaries upset the lifestyle of pastoral groups such as the Maasai, who depended upon trade with the agrarian groups and unhindered movement with their livestock. European settlement in the fertile highlands area divided the trade routes and pushed both pastoral and agrarian societies into less productive areas. This resulted in higher population densities in areas that were less able to sustain the population. The restricted movement resulted in disputes among ethnic groups, both with each other and with the European settlers (Ndege 2009).

Fundamental changes in how ethnic groups lived were further influenced by the agricultural practices introduced through European colonization. The primary purpose of these practices was to generate income and produce large quantities for export (Doughty 1996). Instead of small farming plots or a few livestock, large expanses of land were planted in monoculture crops such as wheat (Buckley 1903). Previously, the indigenous societies relied on a subsistence culture where surplus was redistributed among group members, most of whom were blood related, or used for trade with other groups (Ndege 2009).

Later introduction of coffee and tea plantations again changed the agriculture in the western highlands of Kenya. Today, large tracts of land, over 150,000 hectares, are currently in productions for tea, with approximately sixty percent coming from small landowner farms. The curing process of the tea involves a large input of fuelwood. *Eucalyptus* was originally cultivated for its rapid rate of growth in the construction sector but quickly became the preferred fuelwood source on tea plantations (Ojany and Ojendo 1982; Taku 1999).

With a rising demand for fuelwood, smaller plot farmers planted *Eucalyptus* trees for their potential economic benefits. The promotion of *Eucalyptus* as a fast growing wood source increased is prominence in agricultural settings in Kenya and many parts of the world (Doughty 1996). This rise in cultivation also came with concerns from farmers who noticed that water sources were becoming compromised and crops growing near *Eucalyptus* exhibited poor growth (Bennett 2010). The objective of this study was to assess the small plot farmer's view of the *Eucalyptus* as it pertains to its effect on the environment and their farm in particular.

B. Farmer survey

In order to assess the farmer's impressions of the *Eucalyptus* trees in their woodlots and elsewhere, a survey was carried out. This survey included questions about the trees they plant, the uses of the trees, other things they find in the woodlot and their general impression of how the *Eucalyptus* affects with the surrounding environment (Figure 5.1). Surveys were carried out in the Eastern, Central, Rift Valley and Western Regions of Kenya. Surveys were mainly conducted in central gathering places of villages and were done randomly. Some farmers were also surveyed when *Eucalyptus* woodlot sampling took place in their personal woodlot (Figure 2). Both men and women of various ages were surveyed. The initial question asked before conducting a survey was to determine if the person farmed and if they also grew *Eucalyptus* trees. Only one survey was conducted per family unit. If the survey respondent was fluent in English then the survey was conducted in English. If the respondent was not fluent in English then an interpreter conducted the survey in the local language. At times it was necessary, in the English surveys, to provide clarification on a question. Special care was taken to ask the questions as written except in the case of not understanding what a particular word meant. A total of 17 farmer surveys were completed. These surveys were then evaluated for developing an overall interpretation of farmer impressions of *Eucalyptus* (Martin 1995).

When possible, responses were recorded according to emic categories, those defined by the interviewee, and not categories defined by the interviewer. The open ended question at the end of the survey allowed for participants to add further thoughts and comments not previously addressed. The numbered questions were analyzed in a descriptive format to provide a general impression of the combined responses (Martin 1995).

C. Implications

The farmers surveyed had a diverse range of ages from the early 20's to late 60's. Of the respondents, the majority were male with only two mid 50's aged women participating. In several instances, the wives of respondents were present but the men provided the answers. The planting regimes for the *Eucalyptus* varied but were all small scale. The size of the plots ranged from 1000 square meters to one hectare with the exception of one who was the caretaker for a larger plantation that was approximately nine hectares. All of the respondents planted their woodlots from seedlings, with 76% purchasing seedlings from government or private nurseries. The remaining farmers collected seeds and germinated them in pots or temporary beds before out planting the seedlings to the woodlot. All of the respondents reported planting blue gum, which is a local name for *Eucalyptus* and is the common name for *Eucalyptus globulous.* Most of the *Eucalyptus* trees observed in the survey areas were *Eucalyptus grandis,* followed by *Eucalyptus saligna* as the second most observed tree species. It appears that the term blue gum is now commonly used to refer to most species of *Eucalyptus* in Kenya and may not accurately reflect the actual tree species planted.

The farmers had some varied responses with respect to the seedling spacing in the woodlot. About half of the farmers planted their seedlings one meter apart. Several of the farmers added that they would thin out the seedlings when they reached a certain size to an approximate three meter spacing, which was consistent with the remaining responses. When asked how long they would let the trees grow, 65% responded that they would harvest in 10-15

Farmer Survey

Date Location who helped

1. Farmer/villager age and gender

2. What is the approximate size of your woodlot?

3. How far apart to do you plant your trees? What is planted?

4. Do you use seeds or seedlings?

5. Where do you get your seeds or seedlings?

6. After how many years do you harvest your woodlot? How do you harvest

7. Do you collect the limbs and leaves that fall in the woodlot? Yes No

    a. If yes, what do you do with this?

8. Have you tried to plant other things in the woodlot? Yes No

    a. If yes, what have you tried to plant?

    b. How successful was this new crop you planted?

9. Do you collect anything from nearby forest? Yes No

    a. What items do you collect and for what purpose?

10. Do you collect anything that is only found with Eucalyptus?

11. Do you think Eucalyptus trees affect other plants that grow close them?

12. Do you think Eucalyptus used more water than other trees?

13. Do you see the same kinds of birds and animals in eucalyptus forests and native forests?

14. What else can you tell me about Eucalyptus?

Figure 5.1. Farmer survey form used to interview farmers in several regions of Kenya to assess their impressions and uses of *Eucalyptus* trees.

Figure 5.2. Collecting limbs from both *Eucalyptus* and indigenous forests is important for cooking fuelwood (photo by the author).

Figure 5.3. A small farm cassava plot; it is evident that the cassava plants grew smaller near the *Eucalyptus* woodlot (photo by the author).

years. The remaining farmers were split between approximately five years and more than 30 years.

The farmers were asked a series of questions about the use of the woodlot for other activities besides growing trees, including secondary agricultural and gathering activities. All of the respondents except one collected fallen branches from the *Eucalyptus* trees for firewood. Three of those respondents also used larger limbs for light construction as well. None of the farmers gathered anything else that grew or lived in the *Eucalyptus* woodlots. One farmer indicated that he would hunt an animal if it was found in the woodlot but did not specify the time when that occurred. A little more than half of the farmers had tried to plant other crops or trees in the *Eucalyptus* woodlots. With one notable exception, the farmers were not successful planting maize, cassava, beans, groundnuts, fruit trees or grasses for livestock. They reported that the plants either died directly or grew very poorly. The exception was with the manager of a larger *Eucalyptus* woodlot. His practice was to use the *Eucalyptus* trees, younger than three years, as a nursery for vegetable plants. He would germinate the vegetable plants in raised beds in the *Eucalyptus* woodlot. When the seedlings were of a certain size, they would be out planted outside of the woodlot. It is also important to note that *Eucalyptus* leaf litter was not allowed to accumulate on these planting beds and they were also regularly watered.

Although none of the farmers surveyed indicated that they gathered anything other than firewood from *Eucalyptus* woodlots, more than half of them gathered items found in indigenous forests. These items included grasses for livestock, firewood, mushrooms, seeds, fruits and wild animals from hunting. The farmers were asked if the same kinds of birds and animals were found in both indigenous and *Eucalyptus* forests and all responded no. A few gave examples of seeing monkeys or bats in the *Eucalyptus* forests. Many of the farmers reported that the indigenous forest had many more animals and birds, with some saying that no animals or birds could be found in the *Eucalyptus* forests.

The farmers were asked if the *Eucalyptus* tree had an effect on other plants that grew close to them. With the exception of the large woodlot manager, all of the farmers said they thought the *Eucalyptus* tree had a negative effect on plants growing near them. They volunteered that the ground would get very dry and that other plants would not grow well. One farmer replied that he grew the *Eucalyptus* only on hillsides where he could not grow crops. When asked about water usage, all of the farmers reported that they thought *Eucalyptus* used more water than other trees. Some gave examples of planting trees in wet areas that are now dry.

Each farmer was asked if that had anything else they would like to share about *Eucalyptus*. A few didn't have anything else to share, but of those that did fell into two main categories, ones that didn't know the effects of *Eucalyptus* and those that liked them for their monetary benefit.

The comments from the group that didn't know the side effects included their concern about water usage and the lack of other things growing around the *Eucalyptus.* A couple of farmers talked about the leaf litter and how it doesn't break down. They said it just keeps building up and doesn't allow the rain the reach the ground. Several farmers also indicated that even after the trees are harvested the ground does not grow well. One farmer talked about removing the stumps and then burning before anything would grow.

The other group that indicated they liked *Eucalyptus* mentioned that it was good because it grew faster than other trees and was good for building. During one conversation with a farmer, he spoke about why the harvest time was from 10-15 years. He said that when a man married and started his own farm he would plant *Eucalyptus* trees if he had the space. He would then leave the trees until it was time for his children to go to secondary school, which in many cases required boarding fees. He would then harvest his trees and have enough money for his children to continue their education. In a sense, the trees were acting as a saving account that accumulated interest as the trees grew in size and value.

D. Conclusions

The overall impression left by the farmer surveys in that they are aware that the *Eucalyptus* woodlots reduce diversity, affect nearby plants and use a lot of water. While some may not have initially been aware of these factors, they do now. The continued planting of *Eucalyptus* indicates that the monetary benefits outweigh the negative effects. Some farmers have indicated that they are using countermeasures to combat the negative effects by planting it in less desirable areas that are further from crop production. Some have switched their woodlots over to different trees and crops. The incentive, a saving plan for their children's' education, may be the biggest drive for continuing to plant *Eucalyptus.*

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Chapter 6. Carbon Sequestration Potential

Carbon dioxide emissions from the combustion of fossil fuels are a large contributor to increasing CO_2 concentrations in the atmosphere. This rise in atmospheric CO_2 has been linked to global climate change as a direct result of anthropogenic actions (Kongsager et al. 2013). In addition, the sea level has risen 15-23 cm during the last century. Ecosystem shifts, increases in drought and wild fires and loss of sea ice are being attributed to increased CO_2 levels in the atmosphere (Lal 2008).

Fossil fuels are not the only contributor to CO_2 emissions since changing land use constitutes approximately thirty-three percent of the carbon released into the atmosphere. This comes primarily from the expansion of agriculture in tropical regions. Tropical ecosystems contain huge reserves of carbon trapped in the organic material produced within them (Kongsager et al. 2013). It is estimated that tropical deforestation is already contributing approximately 1.5 billion tons of carbon to the atmosphere each year (IPCC 2007).

Concern over carbon dioxide levels in the atmosphere has led to expanded research on possible methods for trapping this gas and thus reducing these levels. Methods for trapping atmospheric carbon include abiotic sequestration and biotic sequestration. In the biotic sequestration methods, afforestation presents some feasible possibilities to capturing carbon. Restoration of tropical forests and better tree management practices may serve as an important carbon pool in the future (Lal 2008). Several studies have examined the carbon sequestering potential of trees. Carbon sequestration refers to the removal of atmospheric carbon and trapping it in a pool in which it can be stored for a period of time (Lal 2004). Photosynthesizing organisms remove the carbon from the atmosphere and transfer it into tissues and organic molecules for later use. The carbon is maintained in the organism even after it dies. The decaying organic matter is available for other organisms to break down and eventually will be recycled or become part of the soil carbon pool (Roxburgh et al 2006).

6.1 Introduction to carbon capture by *Eucalyptus* trees

Eucalyptus trees in Kenya were selected for this study due to the availability of large woodlots in which to establish study plots. It grows rabidly, which unquestionably results in superior carbon sequestration potential. As an introduced species, it has already been used extensively in the country to provide a wood source for construction and other practices.

Eucalyptus trees can be found in a variety of settings throughout Kenya. Species belonging to this genus are the predominant trees planted throughout Kenya due to their rapid growth and ability to survive in marginal environments (Dessie, 2011). Its use for fuelwood and timber products as well as its fast maturation time has contributed to an increased abundance. Tea plantations in the western highlands depend on the *Eucalyptus* as a wood source for drying the fresh tea leaves. It can now be found on even the smallest farming plots. In addition to *Eucalyptus* being abundant in the country, the plots are planted with equal spacing making them ideal for estimating carbon content in woodlots as opposed to the more natural and biodiverse native forests.

There are six pools that can be measured in Land Use, Land-Use Change and Forestry (LULUCF) activities. For this study, the above ground tree pool was used. This is the pool that accounts for the largest percentage of sequestered carbon in a forest system (Kongsager et al. 2013). The root mass was not estimated because it has the potential to grow new sprouts after the tree has been cut. This is a practice that is commonly used and can continue to serve as a carbon pool after the tree has been harvested. Coarse woody debris (CWD) is sometimes used to assess a component of the carbon content in a forest ecosystem but was not calculated in this study. Cultural practices in the area prevent CWD from staying on the ground very long because it is generally collected and used as firewood.

In order to calculate the carbon content in a woodlot it is necessary to determine the biomass of the tree; for this study just the above ground biomass (AGB) of representative trees in the woodlot was used. This can be obtained in different ways that can affect the accuracy of the results (Brown 1997). For example, calculations can be applied that use site sampled data and published densities for specific species of trees. These are based on regression equations that were derived from harvested trees in specific regions and by specific tree species. Density of *Eucalyptus maculata* was established using this method in New South Wales with a resulting density of 0.583 g/cm^3 reported (Ash and Helman 1990). Differences in temperature, elevation and annual rainfall could influence the density from one region to another. Githiomi and Kariuki (2010) reported a range from 0.414 g/cm^3 to 0.517 g/cm^3 in various aged *Eucalyptus grandis* in Kenya. For the purpose of this study, the density for each tree measured was calculated from tree core samples obtained at each sample site. The more information that can be obtained, the greater the accuracy of the calculations, and the more accurate value for the amount of carbon contained within the woodlot.

6.2 Tree core data.

Only species of *Eucalyptus* were measured and recorded. These included *Eucalyptus grandis, Eucalyptus saligna*, *Eucalyputs maculate, Eucalyptus globulous* and hybrid *Eucalyptus* trees. Tree core samples were taken with a Swedish increment borer (Figure 6.1) from 38 sites in Kenya (Figure 6.2). The core from each tree was packaged, labeled and shipped back to the University of Arkansas for later analysis.

Figure 6.1. A Swedish increment borer was used to take a core from a *Eucalyptus* at a sample site (photo by the author).

Figure 6.2. Map showing the collection sites where cores were collected from *Eucalyptus*.

A. Methods

Sampling sites were selected based on availability. Sites were in predominately large *Eucalyptus* plantations. The individual trees selected were chosen visually to ensure that they exhibited good health and were representative of the overall woodlot. The selected tree at each site was measured for diameter at breast height (DBH) and also for the height of the tree. This was done by measuring out 25 meters from the base of the tree. From this point a measurement was taken looking through a clinometer to the top of the tree. If the ground was level then the angle for the height of the tree was obtained. This could be used to calculate the tree height which was later used to calculate the carbon content of the tree. Wood cores were taken at the DBH level. Intact cores were stored in plastic straws that were slit for ventilation, labeled and shipped to the University of Arkansas. Upon arrival, they were placed in a -20°C freezer.

The samples were removed from the freezer when measurements were taken. They were allowed to completely thaw. Each length and diameter of each sample were measured and recorded while viewing under a stereoscope for accuracy. This step was done to validate measurements obtained from the water displacement method. Each sample was then placed in labeled weigh boats and left to soak for one hour (Figure 6.3). The samples were then measured for volume using the water displacement method (Chave 2005). This is done by placing a container of water on a scale. The next step was to zero out the scale then place the sample in the water. The sample was gently pushed under the water with a small needle (Figure 6.4). The recording on the scale gave the weight of the sample which is also equivalent to the volume of a particular sample. This can be cross checked against the previous measurements and may be helpful when the samples have multiple pieces. The water displacement method should be more accurate, especially when the samples are irregular in shape.

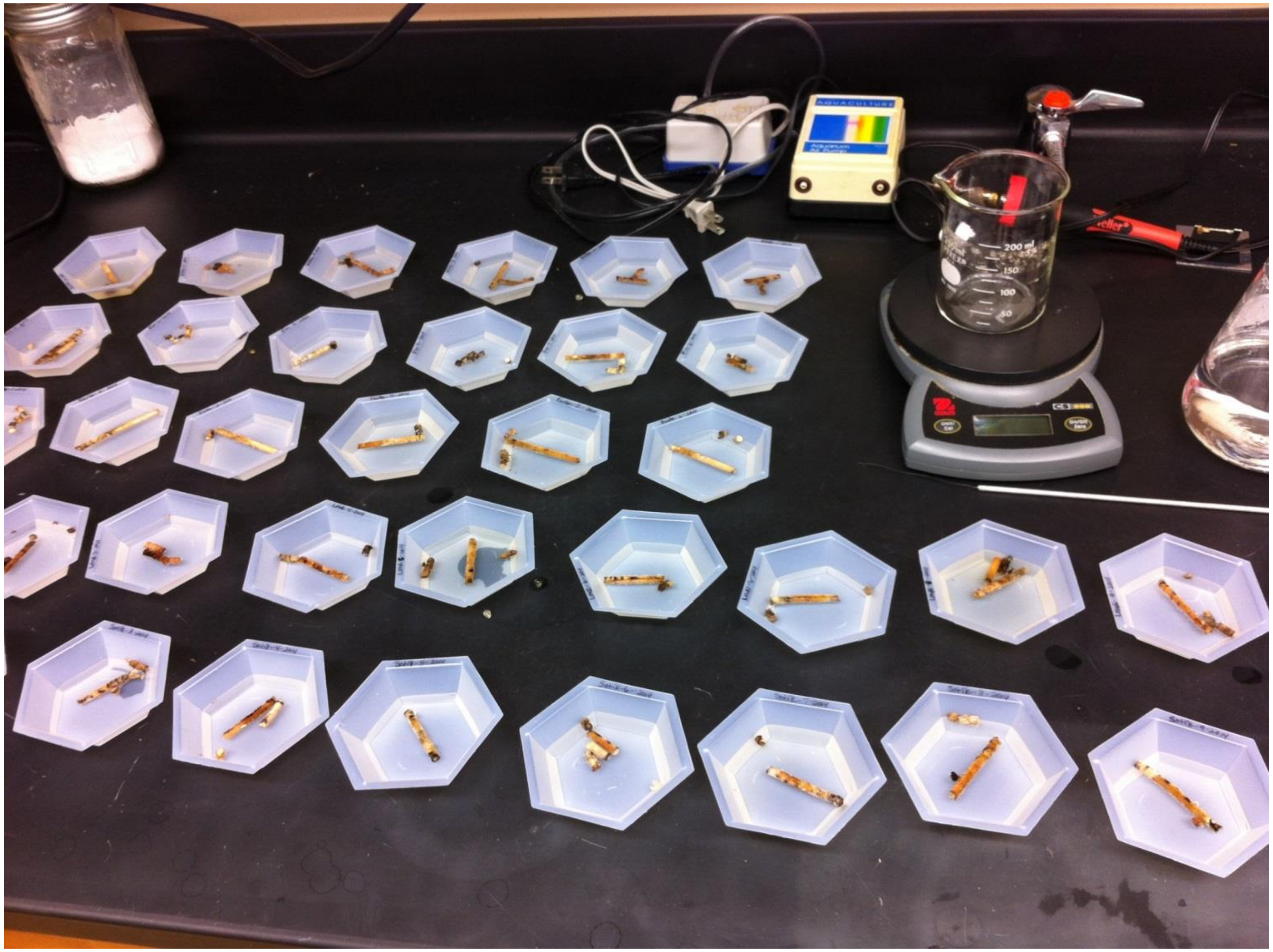

Figure 6.3. Individual tree core samples in weight boats (photo by the author).

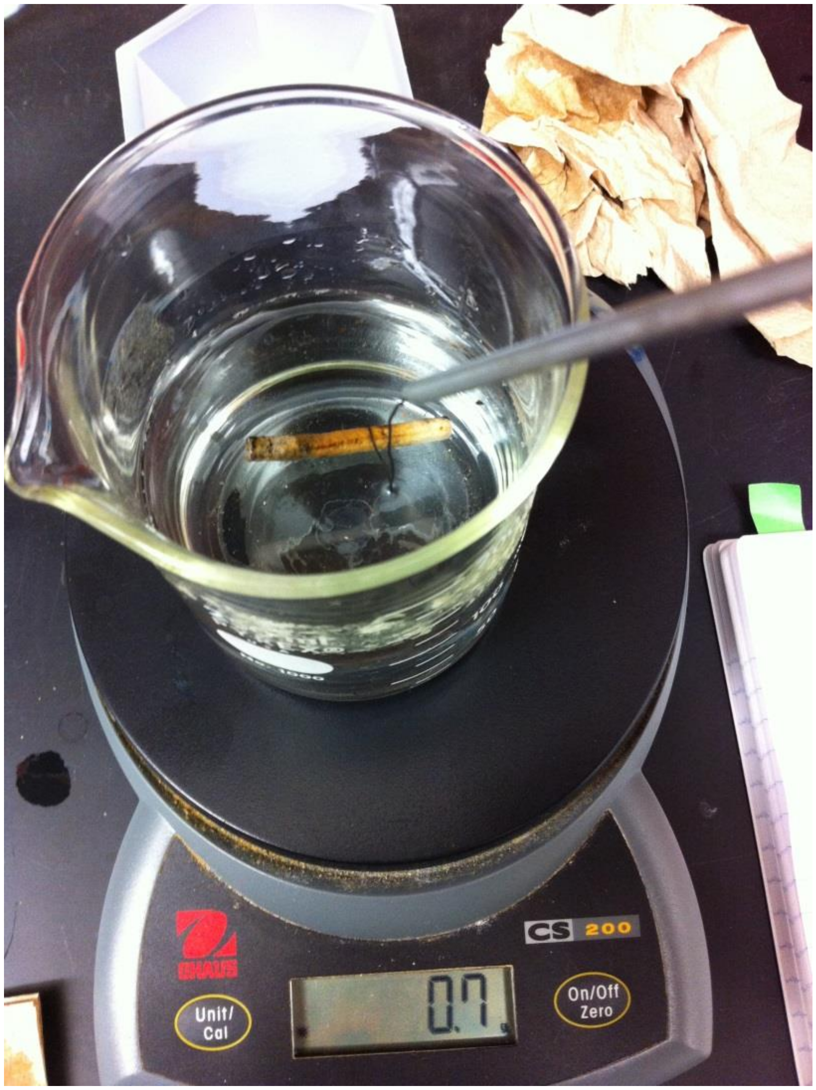

Figure 6.4. Image that shows the water displacement method (photo by the author).

Once the samples were weighed to generate the volume, they were then returned to their labeled weigh boat and placed in an oven dryer for 72 hours to remove all the moisture. Samples were then reweighed to obtain the oven dry weight. The density of each sample was then calculated as D (density) = M (mass)/V (volume). These values were then recorded for later use in calculating carbon content (Table 6.1).

For calculating the amount of AGB in Kenya's *Eucalyptus* woodlots, an equation based on allometric regression models was used. The specific formula was selected based on the work of Chave et al. (2005). The authors used tropical tree harvest data from the last several decades and compared it with published regression models to see which one was the most accurate in tropical forest woodlots. The formula is

$$\text{AGB (est)} = \exp(-2.977 + \ln(\rho D^2 H)) \equiv 0.0509 \times \rho D^2 H$$

where ρ is the wood density in (g/cm^3), D is the diameter at breast height in (cm) of the sampled tree and H is the height in (m) of the tree.

After the biomass was calculated for each sample, the carbon content could be determined. To determine the carbon content, the biomass is multiplied by 0.5 (Table 6.1). This is the recommendation from the Intergovernmental Panel on Climate Change's guide to good practice guidance for land use, land-use change and forestry (IPCC 2003). Table 6.1 also included the species of tree and age of the tree, if known. This was gathered from the woodlot manager or owner of the woodlot. When a sample species was unknown, it was recorded as a mixed species. If the age of the tree was unknown, it was recorded as unknown.

Table 6.1. Final density value and carbon total for each sample based on oven dry weights and water displacement volume measurements. The table includes the age and species of tree.

Sample site	vol (g/ml3)	dry weight g	density g/cm3	age	Species	AGB kg	Carbon Content kg
Kefri-1-2014	0.73	0.27	0.369863014	7	mixed	87.82131118	43.91065559
Kefri-2-2014	0.58	0.23	0.396551724	7	mixed	99.56776049	49.78388025
Kefri-3-2014	1.15	0.47	0.408695652	2	*E. grandis*	8.888072665	4.444036333
kefri-4-2014	0.87	0.41	0.471264368	11	*E. saligna*	291.8372077	145.9186039
Kefri-5-2014	0.6	0.23	0.383333333	11	*E. Saligna*	467.6887263	233.8443631
Kefri-6-2014	0.76	0.42	0.552631579	9	*E. saligna*	512.8364454	256.4182227
Fin-1-2014	1.02	0.36	0.352941176	4	*E. grandis*	74.18489185	37.09244593
Fin-2-2014	0.3	0.1	0.333333333	3	*E. grandis*	91.274898	45.637449
Fin-3-2014	0.43	0.15	0.348837209	6	*E. grandis*	159.8031352	79.90156762
Fin-4-2014	0.4	0.15	0.375	5	*E. grandis*	91.78784784	45.89392392
Fin-5-2014	0.79	0.36	0.455696203	7	*E. grandis*	401.8617467	200.9308733
Fin-6-2014	0.49	0.22	0.448979592	9	*E. grandis*	186.3772633	93.18863163
Lond-1-2014	0.34	0.2	0.588235294	10	*E. globulus*	106.9190429	53.45952147
Lond-2-2014	0.64	0.32	0.5	10	*E. globulus*	449.6751745	224.8375873
Lond-3-2014	0.56	0.25	0.446428571	10	*E. grandis*	430.5673992	215.2836996
Lond-4-2014	0.78	0.34	0.435897436	11	*E. grandis*	272.3841128	136.1920564
Lond-5-2014	0.58	0.32	0.551724138	12	*E. grandis*	920.5472728	460.2736364

Table 6.1. Continued.

Sample site	vol (g/ml3)	dry weight g	density g/cm3	age	Species	AGB kg	Carbon Content kg
Lond-6a-2014	0.61	0.29	0.475409836	11	mixed	375.785567	187.8927835
Lond-6-2014	0.7	0.29	0.414285714	11	*E. maculata*	329.6514917	164.8257459
Lond-8-2014	1.03	0.53	0.514563107	10	mixed	382.4038047	191.2019023
Lond-9-2014	0.73	0.37	0.506849315	10	mixed	161.492975	80.7464875
Lond-10-2014	1.12	0.61	0.544642857	unknown	*E. saligna*	438.8756633	219.4378317
Turbo-1-2014	0.7	0.16	0.228571429	8	*E. grandis*	71.96096571	35.98048286
Turbo-2-2014	0.83	0.34	0.409638554	8	*E. grandis*	316.540345	158.2701725
Turbo-3-2014	0.98	0.35	0.357142857	9	*E. grandis*	312.3305804	156.1652902
Turbo-4-2014	0.67	0.37	0.552238806	9	*E. grandis*	647.0186775	323.5093387
Turbo-5-2014	0.91	0.4	0.43956044	5	*E. grandis*	837.8699341	418.934967
Turbo-6-2014	1.1	0.32	0.290909091	10	*E. grandis*	363.59906	181.79953
Sotik-1-2014	0.99	0.43	0.434343434	16	*E. grandis*	100.0436177	50.02180886
Sotik-2-2014	0.54	0.22	0.407407407	13	*E. grandis*	213.5085333	106.7542667
Sotik-3-2014	0.62	0.29	0.467741935	12	*E. grandis*	261.7934774	130.8967387
Sotik-4-2014	0.65	0.35	0.538461538	11	*E. grandis*	350.17164	175.08582
Sotik-5-2014	0.55	0.2	0.363636364	5	*E. grandis*	194.9918808	97.49594042
Sotik-6-2014	0.6	0.29	0.483333333	8	*E. grandis*	249.3111644	124.6555822
Sotik-7-2014	0.56	0.25	0.446428571	9	*E. grandis*	396.6848235	198.3424118
Sotik-8-2014	0.68	0.28	0.411764706	unknown	*E. grandis*	154.9726934	77.48634669
Sotik-9-2014	0.72	0.34	0.472222222	2	*E. grandis*	7.23451371	3.617256855
Sotik-10-2014	0.78	0.36	0.461538462	9	*E. grandis*	353.9657417	176.9828708

B. Results

Calculations to determine the density of the sampled trees were carried out. This resulted in a density value for each species of tree as well as a density value for several different ages for each species sampled (Table 6.3). With the exception of *E. grandis*, all species had a small sample size and the trees did not span a large range in ages. The average density for each species was determined. The average density of all combined samples was 0.4545 g/cm^3.

The density determinations can be used to calculate the above ground biomass and total carbon content of individual trees as well as entire woodlots. This is possible if the acreage of the woodlot is known as well as the spacing of the trees. For example, if one hectare of *Eucalyptus* is planted with a 3 meter spacing, there would be approximately 1,111 trees in that woodlot. A representative tree similar to the other trees in the woodlot could be measured for DBH and height. Based on a density of 0.4545 g/cm^3, the established formula could be applied to calculate the entire biomass of the woodlot. If the DBH is 25 cm and the tree height is 46 m then the calculated biomass of the tree is approximately 665 kg with the carbon content calculated at approximately 332 kg. This could then be applied to the entire woodlot by multiplying the calculated number by the number of trees. For the example, the one hectare woodlot would contain approximately 368,852 kg of carbon stored within the trees in an even-aged woodlot.

Species and age specific calculations can increase the accuracy of the total carbon content in the selected woodlots. Regional information can also help assess the carbon content in an area. In the majority of Kenya's tea plantations, most trees are not older than 10 years of age, with the average country-wide harvest age between 8-12 years (Oballa et al. 2010). This gives a

Table 6.3. Density of each sample by species and age. Average by species is also included.

E. saligna		***E. grandis***		***E. globulous***		***E. maculata***		**mixed species**	
age(years)	density (g/cm³)	age (years)	density (g/cm³)	age (years)	density (g/cm³)	age (years)	density (g/cm³)	age (years)	density (g/cm³)
9	0.552631579	2	0.44045894	10	0.5	11	0.41428571	7	0.383207369
11	0.427298851	3	0.33333333					10	0.510706211
		4	0.35294118					11	0.475409836
		5	0.39273227						
		6	0.34883721						
		7	0.4556962						
		8	0.37384777						
		9	0.45119746						
		10	0.36866883						
		11	0.48717949						
		12	0.50973304						
		13	0.40740741						
		16	0.43434343						
average	0.489965215		0.41202897		0.5		0.41428571		0.456441139

general age for determining size of the trees over a large area of Kenya in order to calculate total carbon content held in *Eucalyptus* forests.

C. Discussion

Density can be calculated form tree core samples. The density data, along with DBH and tree height can be applied using the formula described by Chave et al. (2005) to determine the above ground biomass of a tree. This can then be used to calculate the total carbon content in a tree. Using the data collected from several species of *Eucalyptus* with varying ages, a total carbon content of large expanses of woodlots can be determined.

Kenya has approximately 100,000 ha of *Eucalyptus* forests (Oballa et al. 2010). With a conservative estimate of the trees being eight years of age, the total carbon pool in *Eucalyptus* forests in Kenya would be estimated at 36,978,825,906 kg.

With the larger sample size of *E. grandis,* a general trend towards a higher density with age is apparent (Table 6.3). This is consistent with the research by Githiomi and Kariuki (2010) who studied the density of *E. grandis* in the central Rift Valley of Kenya. They found that the density of the tree increased with age and height with the highest density at 10 years of age. This would indicate that to maximize the carbon capture of a tree, harvest should be at 10 years of age. Further sampling in the other *Eucalyptus* species could also reveal an optimal harvest age based on calculated density.

Kenya's *Eucalyptus* trees are grown predominately for commercial purposes. The harvested trees are used for transmission poles, construction and as a fuel source for drying tea leaves. Trees that are cut still hold the carbon they accumulated during growth. That carbon in trapped until the tree begins to decay or is burned. The trees that are burned will release carbon but not all of it. In the large commercial plantations where *Eucalyptus* are grown as a fuel source for drying tea leaves, the tree stumps are allowed to regrow the trees. This occurs on a three time rotation before the tree roots are removed and new seedlings are planted. During growth the tree is contributing to root development which also traps and stores carbon.

As a well-established tree in the country, the *Eucalyptus* tree also serves as a source of income for farmers who incorporate small woodlots on their land. Managed harvest rates by species and age can optimize carbon sequestration potential. The duel benefit of providing work and an income for rural farmers with the carbon sequestration ability of the *Eucalyptus*, make it a feasible possibility as an established carbon pool (Kongsager et al. 2013).

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Chapter 7. Summary and Conclusions

Just a little over a century ago a type of tree, the *Eucalyptus*, was introduced to Kenya, East Africa. The rapid expansion of this tree across the fertile highlands would have a profound impact on the society and environment of Kenya.

7.1 Conclusions

During two field season in Kenya, data were collected to determine the effects of *Eucalyptus* on the people and environment in Kenya. Field plots were established in *Eucalyptus* woodlots ranging from large corporate plantations to small plot farmer woodlots. These sites were compared with indigenous forests found in similar environments. Soil samples were collected for analysis. Leaves were collected, dried and shipped to the University of Arkansas for use in greenhouse experiments. Tree cores were taken from *Eucalyptus* trees of varying ages and species to determine wood density and ultimately the carbon content of *Eucalyptus* woodlots. Root-tips collected from *Eucalyptus* trees were shipped to the University of Arkansas, where the DNA from ectomycorrhizal fungi were isolated, amplified and identified. Lastly, farmer surveys evaluated the influence *Eucalyptus* had on the local people's lives.

It was hypothesized that *Eucalyptus,* as an introduced species of tree in Kenya, changed the specific ecosystems in which it was planted. This is now reflected in an understory that is compositionally different from that of indigenous forests. This is supported by the results of the ground cover comparison between the *Eucalyptus* and indigenous forests.

Sedges and woody plants were both significantly different in the *Eucalyptus* and indigenous forests, with both considerably more abundant in the indigenous forests. In contrast, the grasses showed a significant difference between the two forest types and were more abundant in the *Eucalyptus* forests. The number of seedlings was significantly different with indigenous sites having more seedlings present than the *Eucalyptus* sites. The forbs did not show a significant difference. These data begin to illustrate the difference found between each of the forest types. The understory growth and ability to regenerate is more abundant and diverse in the indigenous forests, while the *Eucalyptus* woodlots are less diverse, and what does grow are primarily grasses. This becomes even more evident when the light intensity results are included. There was a significant difference in the amount of light reaching the forest floor in the two types of forests. The *Eucalyptus* had significantly more light reaching the forest floor than the indigenous but showed less ground cover diversity.

Lower diversity in the understory of the *Eucalyptus* woodlots could be related to soil moisture levels. The soils in the *Eucalyptus* woodlots were significantly dryer than the soils in the indigenous forests. This supports the hypothesis that the presence of *Eucalyptus* does result in reduced soil moisture when compared with the indigenous forests.

The soil analysis revealed that the electrical conductivity in the soil was significantly lower in *Eucalyptus* woodlots when compared to indigenous forests. This may be a function of the lower soil moisture instead of an indication of salinity differences because both sites were considered to have low conductivity. The other soil parameters that showed a significant difference were calcium and potassium. Both of these elements were lower, and statistically significant, in the *Eucalyptus* woodlots than in the indigenous forests, but the levels in the samples were still considered high in both forest types. Harvesting of *Eucalyptus* trees appears to be reducing the amount of calcium and potassium in the soils but not at a rate that is seriously depleting the soils for future growth. However, increased harvest rates over an extended period of time may lead to further depletion detrimental to future growth.

The final consideration, when comparing the composition of the *Eucalyptus* and indigenous forests, was the amount of coarse woody debris (CWD) on the forest floor. The *Eucalyptus* woodlots were significantly lower, in term of the amount of CWD than the indigenous forests. This can have a big impact on the ecology of the site. Fallen trees and limbs provide protection and breeding sites for other species, including insects and small mammals. Fungi and detritivores depend on CWD for a nutrient source, and the forest as a whole depends on the breakdown of plant material to replenish the soils. These results are most likely impacted by local people, who collect fallen limbs in both types of sites as a source of fuelwood for cooking.

The largest and most significant differences between the *Eucalyptus* and indigenous forests were the diversity and abundance of understory growth and the difference in soil moisture levels, all reduced in the *Eucalyptus* woodlots. The reduction of understory vegetation may indicate the presence of secondary metabolites present in *Eucalyptus* woodlots. The hypothesis that *Eucalyptus* leaf litter is allelopathic and affects the growth of understory plants in forests in which the tree is present is supported by the greenhouse experiments.

Corn, tomato and an indigenous plant, amaranth, were grown in a greenhouse environment where ground *Eucalyptus* leaf litter was added to the soil. The results obtained for the height and weight of the plants was significantly different from the control plants. The leaf litter was influencing the growth in a negative way. The results in the seed germination experiment were slightly different. Both the *Eucalyptus grandis* and the *Eucalyptus paniculata* solutions had a significant impact on the germination of the amaranth seeds but did not have a significant impact on the germination of the corn or tomato seeds. This would indicate that the secondary metabolites have a more significant impact on growth than they do on germination.

The amaranth was significantly impacted by the presence of *Eucalyptus,* both in the germination and growth of the plant. Amaranth is a local plant that is grown for its leaves. It appears to be more susceptible to the *Eucalyptus,* which may be because it is indigenous and has not coevolved to combat the secondary metabolites found in *Eucalyptus.* All of the results support the hypothesis that *Eucalyptus* is allelopathic.

The root-tips from *Eucalyptus* trees in the samples sites were collected to see what species of ectomycorrhizal fungi were associating with this tree. *Eucalyptus* depends on associations with fungi in order to grow. As an introduced species in Kenya, it was hypothesized that the ectomycorrhizal fungi associated with *Eucalyptus* would consist of taxa introduced along with the tree from Australia. The results of the DNA extraction from the root-tip samples resulted in 25 fungi species identified. Of those identified, species of *Laccaria*, *Descoleo*, *Pisolithus* and *Tomentella* species were ectomycorrhizal (Stephenson 2010). These fungi have also been reported from Australia, thus supporting the hypothesis that they were co-introduced with *Eucalyptus.*

Eucalyptus was introduced as a way to mitigate the loss of indigenous forest and to provide a fast growing wood source. The question of environmental issues surrounding the introduction of *Eucalyptus* has been raised since soon after the introduction. The hypothesis that local villagers vary considerably in their views of the positive versus negative aspects of *Eucalyptus*, and these views are closely correlated with how the tree affects their own lives, was examined through the farmer survey. The results of the survey, conducted over a diverse array of respondents suggested that the farmers were similar in their impression of *Eucalyptus*. Overall, they thought it used more water and negatively impacted the growth of other plants on their farms. They noticed that the diversity in their *Eucalyptus* woodlots was less than in indigenous forests. This meant that they did not collect fruits, mushrooms or other edibles from the *Eucalyptus* woodlots. The continued use of *Eucalyptus* indicated that the profit generated was more significant than any negative effects.

The introduction of *Eucalyptus* to Kenya helped shape a new environment where the trees occur. Their presence, as an exotic species, changes the ecology of the area. This is also evident with the mycorrhizal fungi that were co-introduced. The slight changes in the soil properties may not be significant over all, but the drying of the soils may become a factor in the future. Currently, *Eucalyptus* is most abundant in areas that receive adequate rainfall. A changing climate in the region could pose a risk if the *Eucalyptus* competes with the needs of other plants.

Large stands of *Eucalyptus* may serve another important role in combating climate change. The tree cores from various species and ages of *Eucalyptus* were sampled to determine the density and carbon content of the tree. *Eucalyptus grandis* comprised the largest sample group and density calculations revealed that the density increased with age up to an age of ten years. Density determinations for different *Eucalyptus* species by age can help determine the maximize carbon content of a woodlot. This can be used as a tool to harvest trees when the carbon content is at a maximum. Small changes in harvest times could help reduce the amount of CO_2 in the atmosphere.

The benefits to the economy of Kenya and to the individual farmers producing *Eucalyptus* are also important considerations. *Eucalyptus* can be a resource to alleviate poverty and increase educational opportunities. Understanding how *Eucalyptus* can change the environment where it is planted can help counteract some of the negative aspects. Management plans should take into account the water usage, allelopathic properties and loss of diversity where *Eucalyptus* is planted, especially considering that it is now an important part of Kenya's ecology and economy.

7.2 Future research

There is still much to learn about *Eucalyptus* in Kenya. The present study focused on the pooled results from all of the study sites. Comparative studies could be expanded to see if there are regional differences and also differences among the species of *Eucalyptus.* This would apply to every research topic considered in this study.

Appendixes

Appendix A. IRB exemption letter

UNIVERSITY OF ARKANSAS

Office of Research Compliance
Institutional Review Board

February 11, 2016

MEMORANDUM

TO:	Brandy Garrett Kluthe Steven L. Stephenson
FROM:	Ro Windwalker IRB Coordinator
RE:	New Protocol Submission
Protocol Title:	*Eucalyptus in Kenya; Impacts on Environment and Society*

In reference to the request for IRB approval of your project titled *Eucalyptus in Kenya; Impacts on Environment and Society*, the IRB is not authorized to oversee and approve such research. This protocol does not meet the definition of research involving human subjects in the federal regulations. (See the citation below.) You are free to conduct your research without IRB approval.

45 CFR 46.102 (f)

(f) Human subject means a living individual about whom an investigator (whether professional or student) conducting research obtains

(1) Data through intervention or interaction with the individual, or
(2) Identifiable private information.

If you have any questions do not hesitate to contact this office.

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