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The Roles of Introduced Eucalyptus in the Conservation and Expansion of Ethiopian Orthodox Church Forests in the Northern Ethiopian Highlands

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ABSTRACT

Species of the genus *Eucalyptus* (common name eucalyptus) are widely planted all across Ethiopia – including on large areas of land previously allocated to food production. In recent decades eucalyptus has also increasingly been planted on lands around and within “church forests,” sacred groves of old-aged Afromontane trees surrounding Ethiopian Orthodox Tewahido churches. These revered holy sites have long been recognized for their cultural values and also for their ecosystem services – including their potential to support species conservation and restoration, as church forests are some of the only remaining sanctuaries for many of Ethiopia’s indigenous and endemic plant and animal populations. Ethiopian Orthodox church communities have a long history of planting and nurturing indigenous tree seedlings to sustain church forest groves. However, due to the fast-growing nature of eucalyptus combined with its widely recognized socio-economic benefits (as fuelwood, charcoal, construction wood, etc.), this introduced species has been widely planted on cropland around church forests – in some cases even replacing native tree species within church forests themselves. In many developing country contexts the introduction of exotic eucalyptus has been shown to have ecological impacts ranging from soil nutrient depletion, to lowering water tables, to allelopathic effects. This thesis examines the expansion of eucalyptus planted in and around church forests, as well as the ecological and social impacts of this expansion on the vitality of the natural forests, surrounding land, and church communities.

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INTRODUCTION

Throughout much of the tropical and subtropical regions of the world, the genus *Eucalyptus* (common name eucalyptus) has been both revered and despised. Originating in Australia and surrounding islands, eucalyptus has now been planted widely in most low-income countries (Stanturf et al., 2013). In areas where forests and other natural resources have been degraded, eucalyptus serves as a fast-growing alternative fuel and construction wood source, and can be a very profitable crop for smallholders (Jagger & Pender, 2003; Sunder, 1993). However, the same characteristics that allow eucalyptus to thrive in environments with degraded natural resources also present competitive advantages over indigenous tree species. In comparison to native species, eucalyptus uses disproportionate amounts of water and rapidly depletes soil nutrients (Tadele et al., 2014; Yitaferu et al., 2013; Jagger & Pender, 2003). Moreover, while indigenous trees are often intercropped with food crops, eucalyptus is usually planted in a dense monoculture, displacing food crops (Mengist, 2011). The ongoing debate on the potential economic benefits and the detrimental ecological costs of this introduced species is a source of major controversy, as it pits natural biodiversity against the livelihoods of many people in developing nations.

Eucalyptus trees were first introduced to Ethiopia in the late nineteenth century to supply fuel wood and timber to Addis Ababa, the rapidly expanding capital city (Teshome, 2009; Pankhurst, 1995). Being fast-growing and requiring little care, eucalyptus is able to provide ample fuel wood and construction wood for community-level and commercial uses (Jagger & Pender, 2003). Electric transmission poles, fencing, and building posts are all important eucalyptus products in Ethiopia, as almost all power and telephone lines, wooden houses and fences rely on eucalyptus poles (Dessie & Erkossa, 2011). Uses of non-timber products from eucalyptus including applications in medicine, honey production, and perfumery are also widely appreciated in East Africa (Teshome, 2009). As a high value cash crop, by 2011 eucalyptus accounted for approximately 25% of all Ethiopian farmers' income (Dessie & Erkossa, 2011).

In many places, the economic and social benefits of eucalyptus far outweigh the costs, but in and around natural forest fragments there may be additional costs, such as biodiversity loss, that are not fully recognized or considered in farmers' decisions to plant this exotic tree

crop. These costs, albeit often unintentional, are important considerations given the recent dramatic expansion of eucalyptus surrounding the small amounts of indigenous forest remaining in Ethiopia. Today eucalyptus is widely planted all across Ethiopia – including on lands around and within "church forests," sacred groves of old-aged Afromontane trees surrounding Ethiopian Orthodox Tewahido churches (Wassie et al., 2004). These revered holy sites have long been recognized for their extraordinary potential to support conservation efforts, as they are some of the only remaining sanctuaries for many plant and animal populations that have disappeared elsewhere in the country (Wassie et al., 2007). In response to deforestation and continuing demand for fuel and construction materials, church communities have a long history of planting and nurturing tree seedlings to sustain their church forests. But due to the fast-growing nature of eucalyptus and its widely recognized socio-economic benefits, this introduced species has become the dominant response to the deforestation of native tree species (Yitaferu et al., 2013; Kidanu et al., 2005). A large body of pre-existing literature across many tropical and sub-tropical regions has shown that eucalyptus can outcompete native trees (Kidanu et al., 2005; Harrington & Ewel, 1997; Bean & Russo, 1989). Furthermore, the planting of eucalyptus can manipulate environmental conditions such as water availability and soil fertility, rendering it less suitable for future growth of crops and natural forests alike (Palmberg, 2002). Particularly in northern Ethiopia where native tree populations are already scarce, eucalyptus expansion may adversely affect the function of what little natural forest remains.

This thesis uses spatial analysis, ecological and social surveys to holistically assess the roles and expansion of introduced eucalyptus trees in church forests and communities in the Amhara Region. The first chapter provides a literature review of deforestation and reforestation in Ethiopia, as well as the recent expansion of eucalyptus species. The second chapter uses spatial data analysis to determine the change in total church forest cover in the last 30 years in a subset of sacred natural groves in South Gondar, East Gojjam, and West Gojjam Zones. Additional present-day eucalyptus data is accounted for in order to interpret the difference in indigenous forest cover change, as much recent forest growth is made up of fast-growing eucalyptus stands. The third chapter of this thesis compares soil properties within the indigenous groves of the church forest, adjacent eucalyptus plantations, and surrounding agricultural land to assess the degree of ecological impact eucalyptus has on

neighboring land types. Lastly, a series of social science tools were implemented in the fourth chapter to reveal the preferences and uses of community members of the forest and eucalyptus plantations alike, and how these preferences may be driving eucalyptus expansion.

CHAPTER ONE: DEFORESTATION AND THE INTRODUCTION OF *EUCALYPTUS SPP.* IN THE NORTHERN ETHIOPIAN HIGHLANDS: A REVIEW OF EXISTING LITERATURE

Deforestation and Reforestation in Ethiopia

The decline in forest cover in Ethiopia has been mainly attributed to agricultural land expansion as a response to population growth and the decline of agricultural productivity, as widely reported by farmers (Assefa & Bork, 2014; Bishaw, 2001). Exploitation of forests for fuel wood and construction materials without replanting has enhanced the deforestation problem in Ethiopia. Additional social and political challenges, such as weak land tenure and inconsistent enforcement of government forest policies, have further exacerbated deforestation and failed to promote re-planting of native forests (Assefa & Bork, 2014; Lemenih & Kassa, 2014; Bishaw, 2001).

Historical Changes in Forest Cover

Many papers in the past have stated that in the year 1900 natural coniferous and broad-leaf forests covered nearly 40% of Ethiopia – the first published instance of this claim being in a 1961 FAO publication, *Agriculture in Ethiopia* (McCann, 1997). It is thus widely believed that the country went from having 40% to less than 3% forest cover in a mere hundred years (Dessie & Christiansson, 2008; Bishaw, 2001; Yirdaw 1996; Wood, 1990; Kuru, 1990; Breitenbach, 1961). However, deforestation is by no means a problem confined to the last century – and a growing body of literature has shown that the "40% forest in 1900" figure was largely conjecture, accepted to be based in science, but in reality, likely an overestimate (Nyssen et al., 2015; Boerma, 2006; McCann, 1997). While little concrete information exists on the state of Ethiopia's forests prior to colonization by Italy in 1890, the evidence that is available based on historical documents and observations from archival terrestrial photographs shows that many forest resources were already quite scarce in the nineteenth century (Nyssen et al., 2015; Meire et al., 2013; Boerma, 2006; Pankhurst, 1995), and this trend of deforestation has continued since and in recent decades (Assefa & Bork, 2014).

Historical observations offer that present-day Addis Ababa was devastated in ancient times (Pankhurst, 1995). Archival research suggests exhaustive deforestation may have been

taking place over the last 3,000 years (Bishaw, 2001). As early as the 1500s, there has been documentation by foreigners of the perceived deforestation in Ethiopia (Pankhurst, 1995). Travelers reported that there was little or no forest cover in the country; the only forest cover was found in a few areas, such as the Gojjam region and in the areas surrounding churches (Assefa & Bork, 2014; Melaku, 2003). In the seventeenth century, Portuguese Jesuit Manuel de Almeida noted upon arrival in Ethiopia that there was not much woodland in the country (Pankhurst, 1995). He attributed the lack of forest not to poor soil or climatic conditions, but to people cutting down trees for their houses and fuels, but to the people having neither "the energy nor the will to replant a single one" (pp. 120). A century and a half later, Scottish explorer James Bruce encountered a similar narrative; in then-capital Gondar people had extirpated the wood from forests and resources were scarce (Pankhurst, 1995).

Though the processes leading to forest depletion in Ethiopia span much more than the last century, deforestation certainly continues to be a problem, in large part driven by the booming population. Recent settlement and agricultural expansion has resulted in massive clearing of forests in some regions. A study by Assefa & Bork (2014) estimated that of the remaining natural forest in the Chencha and Arbaminch areas of Southern Ethiopia, there was a 23% decline in forest cover between 1972 and 2006, and that the most significant change occurred between the years of 1986 and 2006. There is a great need to afforest the land in order to address issues of food security, environmental degradation and economic development (Mengist, 2011; Bishaw, 2001; Pankhurst, 1995). In part owing to this sense of urgency, the government has promoted rapid reforestation of historically forested land with mono-species plantations, such as eucalyptus (Leminh & Kassa, 2014). These efforts have improved the sheer amount of forest cover in recent decades (Assefa & Bork, 2014), but have greatly shifted the ecological and social dynamics of those forests.

Drivers of Deforestation

Deforestation in Ethiopia cannot be attributed to a singular cause. Over the years, rapid deforestation rates have been a result of a combination of biophysical and social conditions. Geography, population growth, agricultural development, socio-political factors, and insecure land tenure have all affected deforestation in the country (Assefa & Bork, 2014; Dessie & Christiansson, 2008; Bekele, 2001). Even still, contributors of deforestation vary

from region to region, influenced by both local socio-economic backgrounds and national policy trends.

Demographic Drivers of Deforestation

The chief underlying cause of deforestation in Ethiopia is rapid population growth, bringing about an increasing demand for cropland, grazing land, and wood for construction and fuel (Assefa & Bork, 2014; Bekele, 2001). Historically the establishment of new settlements has instigated events of rapid large-scale forest clearing. The destruction of forests in the establishment of Addis Ababa in 1886 was particularly well documented (Dessie & Erkossa, 2011; Bishaw, 2001; Pankhurst 1995). When the French Scientific Mission arrived in the 1840s, the area that was to become Addis Ababa was covered with juniper (*Juniperus africana)* and wild olive *(Olea europaea*) (Pankhurst, 1995). As the city developed, the search for timber for construction and fuel wood for cooking and heating became more and more difficult. At the turn of the century, British traveler A.B. Wylde observed that the territory surrounding Addis Ababa was barren and treeless, and many believed that the end of the booming capital city was near (Pankhurst, 1995).

As the demand for wood products increases, deforestation continues to be a problem based on the sheer size of the country's population. The current population in Ethiopia is estimated at 97 million and increasing at a rate of 2.5% each year (The World Bank, 2014), and thus increasing settlements and urbanization in historically forested areas continues to be a burden on the forests of Ethiopia (Bekele, 2001). As settlements continue to emerge and urbanization escalates, the demand for products like fuel wood, construction wood, fodder, and even non-timber forest products such as honey and medicine, can cause further deforestation. Fuel wood demand is one of the principal causes of deforestation in Ethiopia, especially in rural areas where it serves as the primary source of energy (Assefa & Bork, 2014). The income from fuel wood sales is often used to supplement income from agricultural production, especially during times of crop failures (Jagger & Pender, 2003).

High population growth and declining agricultural productivity are forcing additional deforestation in the conversion of forests to agricultural land (Assefa & Bork, 2014). The subsistence agricultural sector makes up nearly 85% of Ethiopia's work force, consequently Ethiopia relies heavily on agriculture to not only feed its people but also for economic

development (Bekele, 2001). As new settlements and urbanization in historically forested areas is becoming increasingly relevant, more conversion of forested land into other land use systems is occurring. For example, presently, the few remaining natural highland forests are under pressures from investors to be converted to coffee or other cash crop plantations (Tadesse et al., 2014; Bekele, 2001) – practices that would ultimately harm the remaining, surrounding Afromontane forests (Hundera et al., 2013). Deforestation is also a major cause of soil degradation in Ethiopia, limiting agricultural production and contributing to food insecurity and poverty (Assefa & Bork, 2014; Reusing, 1998; Mekonnen, 1998; Teketay, 1992).

As human populations increase, livestock populations follow the same trend, leading to similar pressures in forest conversion to pasturelands as in conversion to agricultural lands (Bekele, 2001; Pankhurst, 1995). Ethiopia is highly dependent on livestock, with livestock contributing to the livelihoods of roughly 60-70% of the population (Halderman, 2004). Though primarily used to feed the growing population of the country, livestock also attributes to the transportation, security system, cash income, and acts as an indicator of wealth for many Ethiopians (Halderman, 2004). The country's dependency on livestock has generated a demand to expand livestock production, in order to feed and support the rising population. In addition to the direct conversion of forest to pastureland, overgrazing is believed to contribute substantially to land degradation and desertification (Dregne et al., 1991). Indirect effects of livestock include trampling, which ultimately leads to soil compaction and may cause run-off and gully erosion (Dregne et al., 1991). Additionally, natural regeneration of herbaceous plants and woody tree species are scarce due to the high levels of disruption by livestock (Thomas & Bekele, 2002; Pankhurst, 1995).

In burning of dry grass to improve grazing land for their livestock, herdsmen can unintentionally burn areas of natural forests, and both burning and grazing prevent natural regeneration (Pankhurst, 1995). Fires have also happened for other reasons in Ethiopia, notably to kill or drive off wild animals and mosquitos, to flush out rebels, or to rid decaying matter considered the cause of disease (Pankhurst, 1995). With increased settlements also comes greater likelihood for accidental burning of forests, in many cases due to the failure to extinguish campfires or fires in the process of smoking out bees for their honey (Pankhurst, 1995).

Living in a largely subsistence economy, the pressure of population growth has exacerbated poverty, leaving the population more vulnerable to hunger, disease and famine (Halderman, 2004). Continued reliance on wood for fuel and construction timber, among other things, has characterized deforestation not just as a matter of forest policies but also as a component of broader development strategies and challenges.

Social-Political Drivers of Deforestation

Deforestation has also been attributed to dynamic economic, political, and social conditions in Ethiopia. Historically, political events and upheavals have played a large role on the status of forests in Ethiopia (Assefa & Bork, 2014; Dessie & Christiansson, 2008; Boerma, 2006; Pankhurst, 1995). With minimal interest in the protection of natural resources, large areas of forest have been cut down during periods of political transition. Land rights and ownership has also been complex in Ethiopia's history. Long-term management of forests has been obstructed by uncertain land security throughout various political periods (Dessie & Christiansson, 2008). The lack of sustainable land use policy and viable forestry laws has continued to aggravate the rate of deforestation in the last century (Bekele, 2001).

Ethiopia had among the most complex land tenure systems in Africa prior to 1975 (GeBreegziabher, 2009; Crewett et al., 2008; Jemma, 2004). Leading up to and in the nineteenth century, the social and political situation in Ethiopia was based on a caste system. Though there was no scarcity of land at this point in the country's history, the religious sanctity of forests was very significant. Thus, second-class citizens were given land that was situated on the steep slopes of mountains, largely uncultivable, and were told not to encroach on forests and woodlands (Assefa & Bork, 2014; Jemma, 2004).

At the end of the nineteenth century, numerous land tenure systems were introduced, one of the more widely spread systems being the *gabbar* or *gulti* tenure system (GeBreegziabher, 2009; Jemma, 2004). These tenure systems had a large impact on forest exploitation, conversion of forests for agricultural uses, and social stratification into the twentieth century (Assefa & Bork, 2014; Crewett et al., 2008; Jemma, 2004). Large tracts of land, primarily forested land, were given to *gult* holders, such as government officials, priests, civil servants, and members of the military. *Gult* rights were also given to organizations, most notably the Orthodox Church (Crewett et al., 2008). The system also created a class of landless tenant

farmers (called *gabbar*), and created enormous inequalities in wealth and power along class and ethnic groups (Crewett et al., 2008; Jemma, 2004). While this tenure system was widely spread, other schemes were more prevalent in other various areas of Ethiopia, including the highlands.

In the north, the *risti* system was frequently used (GeBreegziabher, 2009; Jemma, 2004). The *risti* system was based on the principle that land use was allowable for all descendants of people from a common ancestor and in an ambilineal manner, essentially on the basis of one's inclusion in a community (Jemma, 2004). This communal land was distributed among individuals, and descendants were able to claim the legal right to use the land through proof of relation to the original landholder (GeBreegziabher, 2009). However, *risti* landholders had no rights to transfer to family members or to others by way of sale, rather, the land would be redistributed by way of a lottery. With weak individual user rights, the *risti* system de-incentivized proper and sustainable land use by farmers, and resulted in land degradation (GeBreegziabher, 2009).

Forests were also heavily exploited during periods of colonial administration. In the first decade of Italian colonial rule (1936-1941), large amounts of timber were used for firing bricks, building railway ties, and providing timber and fuelwood for military quarters (Boerma, 2006). These impacts were mostly localized, but nevertheless acted as a cause of deforestation in the country. The Italian administration also disbanded the existing tenure system, in hopes of gaining local popularity (though the systems were reinstated by Haile Selassie after Ethiopia gained independence) (Assefa & Bork, 2014). Farmers who had previously not been able to possess their own land were now given that privilege, and also the ability to obtain permits to expand their farmland by clearing forests, furthering aggravating the deforestation problem. The British had no permanent interest in Ethiopia when Italy surrendered the region to the allies in World War II, ultimately restoring independence to Ethiopia. In the short time that the British were present in Ethiopia, however, timber was exploited extensively in the forests and woodlands that still existed, to export in the form of logs or charcoal to British colonial territories (Boerma, 2006).

In 1975 the Derg, a Marxist military regime led by Menistu Haile Mariam, overthrew Haile Selassie and ended the landlordism associated with imperial rule (Keeley & Scoones, 2000; Hoben, 1995). Following the Derg revolution all land was seized by the military,

eliminating any existing land rights, and redistributed among peasant communities with the aim of transforming rural institutions and spurring agriculture development, increasing food security, and tackling environmental problems such as deforestation (Hoben, 1995). In most areas, however, land reform did not solve the problem of acute land shortage. As new households pressed their claims to land, the size of peasant holdings dwindled, and still in some cases the lack of land and the growing population left many completely landless (Hoben, 1995). Over time, the repeated redistribution of land for a series of new government programs under the Derg regime weakened the security of land ownership, thus de-incentivizing good land management practices, and ultimately contributing to further land degradation and decreased food security (Hoben, 1995; Cohen & Isaksson, 1988).

The Derg regime was overthrown and replaced by the elected Ethiopian People’s Revolutionary Democratic Front (EPRDF) in 1991, a coalition led by the Tigray People's Liberation Front (Keeley & Scoones, 2000). Since the EPRDF’s rise to power and to this day rural and urban land alike has remained owned by the state, but administratively reorganized around ethnically-based regions (Keeley & Scoones, 2000). As a result of EPRDF reforms, forest and woodlot management has been decentralized and community management reinstated. Although EPRDF has stepped away from the centralized control put in place by the Derg, the lack of well-defined and well-enforced policy surrounding land tenure makes it an enduring political issue, and deforestation remains a persistent problem (Crewett et al., 2008).

Prevention of Deforestation

In Ethiopia’s history, there have been several attempts to prevent deforestation, with limited success. The issue of deforestation was of personal concern to Emperor Menelik II (1889-1913). The emperor was a self-proclaimed “lover of trees” and lamented the devastation of forests taking place (Pankhurst, 1995). Recognizing the scarcity of fuel wood and timber, observed largely in the translocation and construction of government facilities, he turned all forest lands into state property and gave orders prohibiting the cutting of trees without his permission, but these regulations were difficult to enforce and largely ignored (Assefa & Bork 2014, Pankhurst 1995). It became clear that attempts to regulate the use of

forest were no longer sufficient in rehabilitating Ethiopia's land and forests, but rather, initiatives to reforest and afforest areas of the country would be necessary.

Afforestation and Reforestation Efforts

Various reforestation and afforestation efforts have been instated, with varying levels of success, throughout the country's history, as a means of restoring the natural environment and supporting the growing population (Lemenih & Kassa, 2014). In urban areas, where timber and fuel wood was used extensively, the occurrence of household-level planting of trees has been observed in historical records (Pankhurst, 1995). *Wanza* trees (*Cordia abyssinica*) surrounded most houses in the Gondar area in the eighteenth century, and likewise in many other urban areas in the country at that time (Pankhurst, 1995). These trees were used to replenish the private needs of the households that planted them. However, in the same time period, afforestation efforts were limited in more rural areas. Aside from sacred church forest sites, there is no record of traditional policy surrounding reforestation or afforestation in the countryside. Because forest use was not as extensive in these areas, there was believed to be less of an imminent need to replenish the sources of construction and fuel wood – however, the gradual use and lack of reforestation ultimately led to a steady decline in the natural forests of these areas (Pankhurst, 1995).

In the 1890s, in addition to his efforts to prevent deforestation, Emperor Menelik introduced re-greening efforts though reforestation and afforestation, the first formal reforestation attempt by government in the history of Ethiopia (Lemenih & Kassa, 2014). Reforestation efforts were again tested during the Italian occupation from 1936-1941 (Assefa, 2008; Boerma, 2006). Over twenty new forest decrees were issued, including forest protection and standards for resource use (Assefa, 2008). With ambitious infrastructural development goals for the country and the intentions of creating an agriculturally prosperous colony, legislation to protect the existing forests of the highlands became increasingly strict over time (Boerma, 2006; Assefa, 2008). Italian settlers and local communities alike were coaxed or coerced to plant trees, while the government itself established large tree plantations in areas adjacent to major towns in the highlands (Boerma, 2006).

The Derg recognized growing environmental threats and widespread unemployment, and introduced extensive conservation initiatives throughout the country. Those who were left

landless by the land redistribution were put to work implementing vast state-run conservation projects, including tree planting. These conservation efforts, including food-for-work programs used to coerce citizens to plant trees on government land (Sawa, 2010), were seen by the people of Ethiopia as the result of centralized, top-down rule (Hoben, 1995). As a consequence, much of the land that had been reforested were cleared once more without replacement following the end of the Derg regime (Keeley & Scoones, 2000). This may have satisfied the people's yearning for a revolt against the centralized regime, but ultimately led to further land degradation and may have attributed to the devastating famine of 1984 (Sawa, 2010).

Perhaps the most successful period of reforestation efforts in Ethiopia's history occurred after the famine of 1984 (Lemenih & Kassa, 2014; Assefa & Bork, 2014). Both the Ethiopian government and international donors associated the famine with deforestation and soil degradation (Assefa & Bork, 2014). In response, a massive afforestation program, known as the "Green Campaign," was instigated in the late 1980s (Assefa & Bork, 2014; Wooldridge, 2014). A mass mobilization of the people, including many of those employed through food-for-work programs, took on the afforestation of approximately 400,000 hectares of hilly areas and tracts of degraded land (Assefa & Bork, 2014; Vletter, 1991). The majority of trees planted in these community forests were exotic species, with *Eucalyptus globulus*, *Pinus patula*, *and Cupressus lusittanica* being three of the species most abundantly planted (Assefa & Bork, 2014). *Juniperus procera*, a native tree that is popular in monoculture plantations, was also a dominant species. This project accounted for 9% of the total natural forest area – roughly 0.3% of Ethiopia's total land area (Vletter, 1991), and the accomplishments of this afforestation effort were by and large praised as a colossal success in regards to the forest management history of the country (Assefa & Bork, 2014).

However, the program was not without its flaws. Prior to the planting of trees, much of the land was grassland that served as a source of pastures for livestock grazing. Many Ethiopians did not have a positive view towards communal woodlots due to their impacts on the availability of pastureland (Assefa & Bork, 2014). Illegal tree chopping in community woodlots was also reported at this time, due to the dissatisfaction towards the reforestation program in failing to consider and fulfill needs prioritized by the community. The lack of true community participation was apparent; the Green Campaign held on to a top-down approach

that had been tried and failed by previous reforestation programs (Assefa & Bork, 2014; Zewdie, 1998). As a result, it failed to gain popular support within the country and deforestation continued to occur. State ownership of the land also diminished people's desire to plant a sufficient number of trees out of fear that the government would repossess and redistribute the land to others. This situation did not encourage long-term forest management (Assefa & Bork, 2014; Wassie et al., 2004).

Afforestation and reforestation programs continue to be widely important in Ethiopia today, as the nation remains at risk of food insecurity and famine (Hadley et al., 2012; Ramakrishna & Demeke, 2002). The EPRDF regime is committed to addressing environmental problems such as deforestation and stresses the importance of community-level participation, though the extent to which it has escaped old customs is unclear (Jagger et al., 2004; Hoben, 1995). In December of 2011, the Government of Ethiopia included in its strategy document a goal of two million hectares of afforestation, one million hectares of reforestation, and improved management of an additional three million hectares of natural forests and woodlots by 2030 (FDRE, 2011). The forestry sector is a pillar of the green economy that the country is developing, as they hope to achieve 50% of its total domestic greenhouse gas emissions abatement potential in the next 15 years (FDRE, 2011).

Particularly in northern Ethiopia where the EPRDF is especially strong, there have been notable increases in forest cover in recent decades, unlike examples in the south where forest cover continues to decrease rapidly (Assefa & Bork, 2014). In the area of Tigray, where the EPRDF was born, the regime has actively mobilized local peasant associations to promote terracing and reforestation projects. Smallholders are also required to devote 20 days of uncompensated labor to various land reclamation and tree planting initiatives every year (Jagger et al., 2004). Recent changes in legal frameworks have strong potential to positively affect re-greening efforts. The Rural Land Administration Proclamation is a legal instrument that has recently improved tenures security among farmers through agricultural land registration (Lemenih & Kassa, 2014). As tenure insecurity was a major disincentive for tree planting in the past, land certification has improved the sense of land security, which in turn has led to more re-greening efforts (Lemenih & Kassa, 2014). The Tigray Regional State now boasts 19% forest cover, as of 2008, a great increase compared to the 5% forest cover in the late 1800s and early 1900s (Meire et al., 2013). A study done by Nyssen et al. (2014)

showed a general tendency towards a recent increase in vegetation cover in the last 145 years, as well as improved environmental indicators in recent years (2006-2011), as a result of intense rehabilitation activities as well as initiatives by farmers. Similar findings of improvement in biomass production in the Tigray Highlands between 1975 and 2000 have also been cited in past literature (de Muelenaere et al., 2012; Nyssen et al., 2009; Munro et al., 2008), as well as in the Amhara Region (Girmay, 2003; Bewket, 2002; Crummey, 1998; Woien, 1995).

The long-term sustainability of these programs and the ultimate expansion of forests in Ethiopia are reliant on local involvement in natural resource management and the existence of fair land and tree tenure policies (Assefa & Bork, 2014). Rural development programs include tree planting in order to provide communities with food, fuel wood, income, and environmental benefits (Bishaw, 2001). Other efforts seek to increase public awareness and education on forestry and natural resource conservation as a means for maintaining Ethiopia's remaining natural forests and biodiversity (Bishaw, 2001).

Introduction and Expansion of Eucalyptus

With strides being taken in efforts to re-green Ethiopia and replant trees in areas that have been deforested, it is important to distinguish how afforestation and reforestation efforts may differ from the original forests that occupied the land. As previously mentioned, many of the afforestation and reforestation programs in Ethiopia in the past and present have focused their efforts on planting fast-growing, exotic plantation species, such as eucalyptus, in order to quickly replenish biomass production (Assefa & Bork, 2014).

When Emperor Menelik recognized the need to reforest the lands as the country was facing shortages of fuel wood and timber, in particular due to the expansion of the capital city of Addis Ababa, he introduced eucalyptus as a plantation species (Assefa & Bork 2014; Dessie & Erkossa, 2001). The Australian eucalyptus tree became known as *bahr zof*, meaning, "tree from across the sea" (Pankhurst, 1995). As town development and natural forest preservation in the absence of any alternative measure would be impossible, Menelik incentivized landowners to plant this fast growing exotic tree through tax reliefs and the distribution of seeds and seedlings at no cost (Zegeye, 2010). The eucalyptus tree was so fast-growing that people immediately began to see its potential in meeting the goals of

bolstering fuel wood and construction supplies, fortifying its place as a widely planted plantation species.

In fact, the majority of reforestation that has been implemented in Ethiopia to date includes vast planting of this exotic species (Assefa & Bork, 2014; Lemenih & Kassa, 2014; Pankhurst, 1995). During the Italian colonial administration afforestation efforts, the government established large plantations of eucalyptus in the towns of the highland plateau (Boerma, 2006). Especially since the 1970s, eucalyptus trees have been introduced as an alternative to endemic species for building purposes (Nyssen et al., 2009; Jagger & Pender, 2003). The mass afforestation program that took place in the 1980s following the famine of 1984 also consisted predominantly of eucalyptus (Assefa & Bork, 2014). In parallel with the large-scale reforestation efforts of the 1980s, the majority of smallholders assigned plots of their land for the planting of tress, predominantly eucalyptus, usually where the soil was less fertile and the land had been abandoned for cultivation (Assefa & Bork, 2014). Farmers also planted eucalyptus along roads and paths, and along and inside gullies.

Communities and households have exhibited strong preferences for eucalyptus as a species for planting, with its various benefits in comparison to indigenous trees. Above all, the short period of time between harvests – eucalyptus can be coppiced every three to seven years (Matthies & Karimov, 2014; Assefa & Bork, 2014; Dessie & Erkossa, 2011) – is extremely attractive to landowners. Additionally, eucalyptus' ability to grow in poor environments with minimum care is appealing in a country where much of the land has been degraded. Local communities in many parts of the country have become increasingly dependent on eucalyptus for uses like fuel wood and timber for construction, contributing to the steady expansion of eucalyptus in Ethiopia (Zegeye, 2010). In addition to being grown for fuel wood and construction material at the household level and to sell, both in large-scale plantations and small woodlots, eucalyptus also provide shelterbelts for farmland from winds and erosion, and form shady groves in and around villages, churches, and homes (Dessie & Erkossa, 2011; Zegeye, 2010). Ethiopian farmers also recognize the ability of eucalyptus for soil conservation and gully stabilization, and to drain marshy land that could otherwise become a breeding ground for malaria (Dessie & Erkosa, 2011). Planting eucalyptus, in many instances, can ensure land security that is otherwise hard to come by in Ethiopia (Dessie & Erkossa, 2011; Deininger & Jin, 2006; Holden & Yohannes, 2001). The

dominance of exotic species in plantation developments is also related to legal constraints (Lemenih & Kassa, 2014). Policies that manage natural forests are principally conservation-oriented, and therefore communities are not allowed to use wood from natural forests for commercial purposes.

As one of the pioneer African countries to introduce eucalyptus, Ethiopia currently has the largest area of eucalyptus plantations in all of East Africa (Dessie & Erkossa, 2011). Since its introduction in the 1890s, eucalyptus has expanded from about 5,000 hectares to an estimated 894,240 hectares in 2011 (Leminh & Kassa, 2014) (Figure 1.1). With the encouragement of academic, research and development institutions, eucalyptus cultivation has gradually spread throughout Ethiopia (Amare, 2002), occurring nearly everywhere in the country where rainfall is above 400mm annually (Friis, 1995). Today, it is the single most common tree species in northern Ethiopia (Jagger & Pender, 2003), with roughly 55 subspecies of eucalyptus, the most common including *Eucalyptus globulus* and *Eucalyptus camaldulensis*, species most preferred by farmers (Dessie & Erkossa, 2011; Zegeye, 2010, Teshome, 2009; Zerfu, 2002; Friis, 1995).

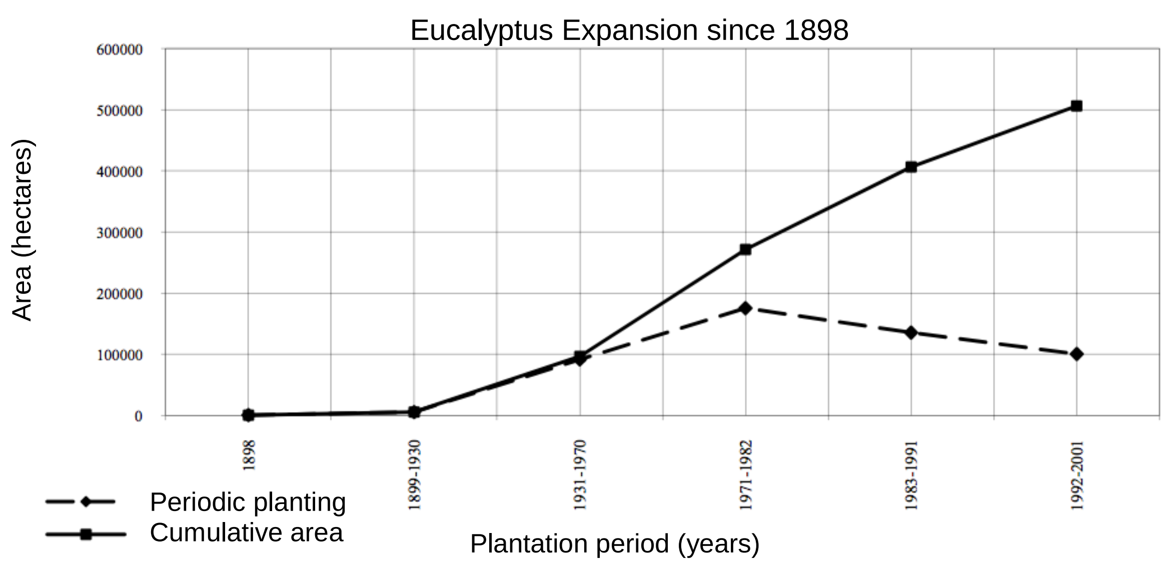

Figure 1.1 History of eucalyptus expansion since its introduction to Ethiopia (Amare, 2002).

With increasing population density and demand for construction wood and fuelwood, local communities have become more motivated to protect vegetated areas and start reforestation programs. However, as forest cover increases throughout northern Ethiopia, it is important to recognize that a large proportion of afforestation and reforestation efforts have

been targeted at planting exotic eucalyptus species. Presently, eucalyptus occurs everywhere in the landscape – planted as individual trees or small hedges by farmers or smallholders, or introduced as plantations on a community basis (Meire et al., 2013).

Moving Forward: Concerns and Hesitations

Despite the widespread popularity of eucalyptus trees among landowners and farmers, concerns have raised about the potential negative impacts of eucalyptus plantations on the environment. This apprehension resulted in bans and regulations of eucalyptus in areas of the country not long after its introduction at the turn of the nineteenth century (Dessie & Erkossa, 2011). Planting eucalyptus was prohibited on farmland, stream banks and catchment areas, and in 1913, a directive was issued to remove half of the eucalyptus that had been planted in the capital city Addis Ababa (Dessie & Erkossa, 2011; Jagger & Pender, 2003; Hagos et al., 1999). Since then, regional bans on eucalyptus have been put in place in order to keep farmland primarily utilized for food production, and also to fend off any negative environmental externalities associated with eucalyptus. Despite the potential for eucalyptus to improve rural livelihoods, the Regional Government of Tigray has imposed a ban on eucalyptus on farmland since 1997 (Jagger & Pender, 2003). Some of the main concerns of eucalyptus presence are high levels of water consumption, the depletion of soil nutrients, the suppression of growth of crops, grass, and other plants, which can in turn have implications for human food security as well as cattle grazing (Assefa & Bork, 2014; Dessie & Erkossa, 2011; Zegeye, 2010). However, the regional government allows and encourages the planting of eucalyptus in community woodlots, community wasteland and steep hillsides, where ecological impacts would have a lesser net effect (Jagger & Pender, 2003).

The concerns of planting eucalyptus are widespread and have persisted up to now in Ethiopia (Dessie & Erkossa, 2011; Jagger & Pender, 2000). As a result, eucalyptus tree planting is increasingly concentrated in areas where the land has been abandoned due to poor soil quality or soil erosion, particularly on steep slopes (Assefa & Bork, 2014). Restrictions on eucalyptus planting in resource poor regions may harm communities in their pursuit of abundant forest resources, wood products, and income opportunities for smallholders (Jagger & Pender, 2003), but eucalyptus are thought to impose significant environmental costs due to their ability to outcompete crops and other vegetation for water and nutrients. The potential

trade-offs between socio-economic benefits and environmental risks associated with planting this exotic species in a resource-deficient country such as Ethiopia have begun to be evaluated in existing literature (Chanie et al., 2013; Zegeye, 2010; Jagger & Pender, 2003), and will be examined in the following chapters of this thesis, as well.

CHAPTER TWO: *EUCALYPTUS SPP.* EXPANSION IN THE CHURCH FORESTS OF THE NORTHERN ETHIOPIAN HIGHLANDS

Church Forests: Conservation Hotspots

In Ethiopia, natural Afromontane forests have largely disappeared, with the remaining fragments of natural forest found almost exclusively in “church forests” (Bongers et al., 2006). The churches are governed by the Ethiopian Orthodox Tewahido Church, one of the oldest Christian churches in the world (Wassie & Teketay, 2006). The Orthodox Church has a long history of conserving the forest resources found in the ring of Afromontane forest that surrounds each individual church (Wassie & Teketay, 2006). In addition to serving as a place of worship, church forests also offer valuable habitat for plants, animals and microorganisms. Church compounds serve as in situ conservation sites and hot spots for biodiversity, hosting numerous indigenous trees and plant species of Ethiopia (Wassie, 2002).

Sacred natural sites are likely the oldest form of habitat protection and conservation. Many sacred natural sites exist inside officially protected areas, but many more form a “shadow” conservation network that have only recently been recognized for their conservation potential (Dudley et al., 2009). Unlike traditionally protected areas, which are often resented in their formal management, religious-based management systems can inspire the protection of the natural world through their philosophy, teachings, and actions (Dudley et al., 2009; Bhagwat & Rutte, 2006). Protected by local traditions and often situated within agricultural landscapes, natural sacred sites can play an important role in biodiversity conservation because of their long history, their religious ties, and the local people’s willingness and involvement in protecting them (Bhagwat & Rutte, 2006).

Deforestation and Degradation in Church Forests

In spite of their conservation potential, as well as additional cultural and spiritual benefits, church forests – like many other sacred natural sites – have been degraded due to a combination of economic, ecological and social factors (Reynolds et al., 2015). Some church communities have chosen to clear forest in order to erect new church buildings or expand burial sites, traditional practices that now exceed the forests’ regenerative capacity (Bongers et al., 2006). Due to livestock grazing and fuelwood harvesting pressures, there has also been great loss in the biodiversity of church forests (Wassie et al., 2010). As forest fragments are

continuously damaged and degraded, edge effects such as light intensity, wind and temperature variability, and reduced soil moisture and humidity create further pressures on forest biodiversity (Aerts et al., 2006). These problems will likely be accentuated as a result of climate change (Cardelús et al., 2013); and can have major implications for the restoration of church forests.

Church forests have also been found to be decreasing in size and density (Wassie et al., 2010), which can have further implications for the restoration of these forest fragments. A study by Cardelus et al. (2013) found that church forests are vulnerable to loss because the majority of the sacred natural sites are small (~5.2±0.44 ha) and isolated (with a distance of ~2.10±0.03 km between forests). Small forests are more vulnerable to edge effects, and isolated forests have lower exposure to seed sources (Cardelus et al., 2013). Management practices should therefore focus on minimizing disturbance to the church forests and, if possible, increasing church forest patch size (Berhane et al., 2013). Additionally, limiting tree harvesting (Wassie et al., 2010), and using techniques like seed sowing, planting seedlings, and soil scarification (Wassie et al., 2009) can all contribute to the viability of church forest restoration.

Eucalyptus Expansion in Church Forests

In conjunction with the degradation of natural forests, shifts in economic incentives and cultural norms have led communities to plant cash crop trees such as eucalyptus in church forests rather than the traditional planting of indigenous seedlings, leaving forests even more impoverished in terms of floristic diversity (Reynolds et al., 2015; Bongers et al., 2006). The presence of eucalyptus may complicate the restoration efforts in these sacred natural sites. First and foremost, eucalyptus can induce a number of negative ecological impacts, as outlined in Chapter Three. Competition for water and nutrients can disturb not only surrounding crops and agricultural land, but has the potential to impose the same impacts on surrounding indigenous trees on church sites. Due to the relative ease of growth, church communities may choose to focus reforestation efforts on eucalyptus, and as a result, native species that are crucial for conserving the natural biodiversity of the area, may be ignored in planting. However, eucalyptus can provide an alternate source of wood for church members

(if permissible by church authorities) and church use. This may eliminate the need to cut down the existing indigenous trees in the church forest.

As recent studies show that forest cover has been consistently increasing in the northern highlands of Ethiopia over the past few decades (de Muelenaere et al., 2012; Nyssen et al., 2009; Munro et al., 2008; Girmay, 2003; Bewket, 2002; Crummey, 1998; Woien, 1995), it is important to distinguish between the change in forest cover of native species and the expansion of exotic eucalyptus plantations that may not provide the same biological and ecological benefits as its indigenous counterparts. Church forests are no exception to eucalyptus planting. In this thesis chapter the extent to which eucalyptus has accounted for forest cover change in the last 30 years is explored. The implications of eucalyptus expansion will be explored further in Chapter Three and Chapter Four.

Methods

Study Sites

Eucalyptus expansion and overall forest cover change was studied in the church forests of three zones in the Ethiopian highlands using Google Earth, ArcGIS version 10.3.1 (ESRI, 2015), and the statistical package R version 3.1.2 (2014). Using Google Earth, 2,560 church forests were identified in the South Gondar, East Gojjam, and West Gojjam zones of the Amhara Region. These church forests were traced in Google Earth and their areas quantified in ArcGIS. Additionally, any eucalyptus plantation within the church forest boundaries were traced and quantified separately.

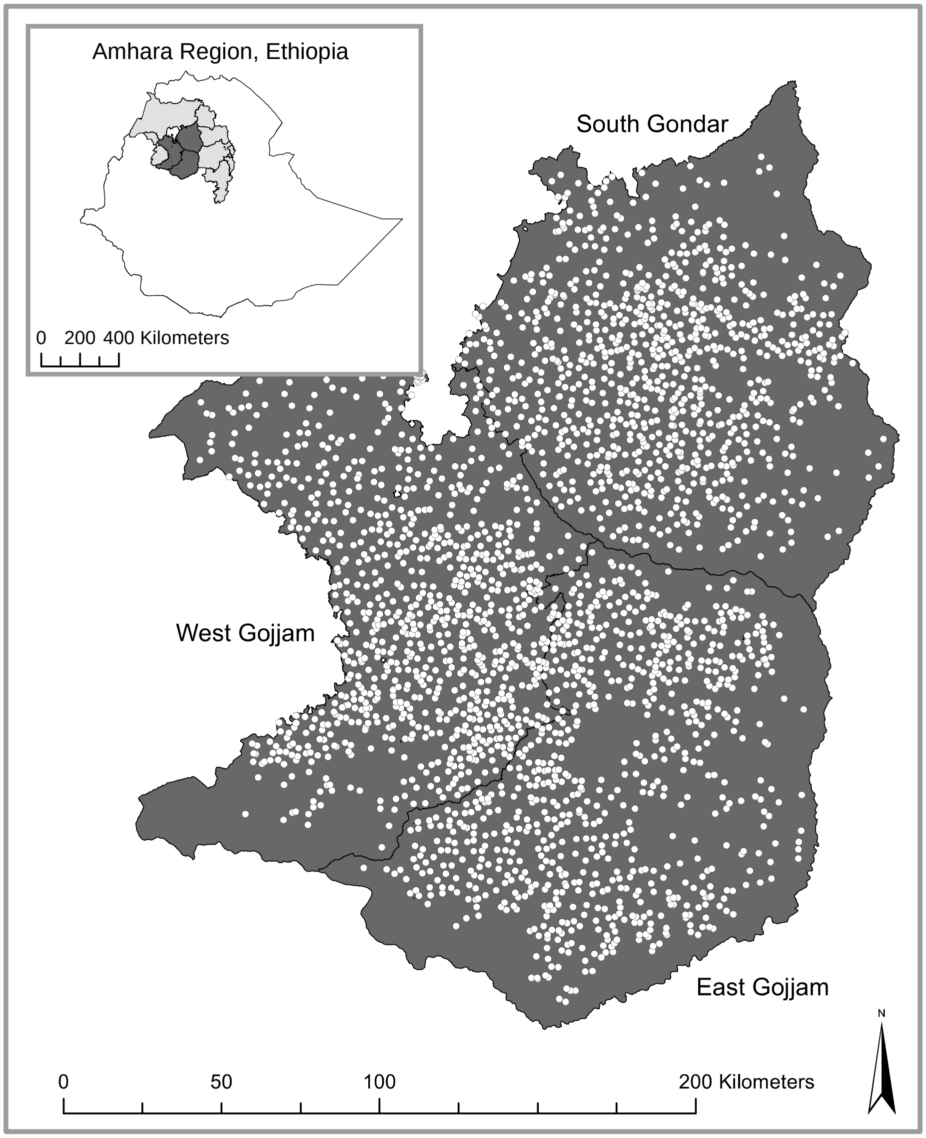

Figure 2.1. Map of South Gondar, East Gojjam, West Gojjam and zones in the Amhara region, and the church forests and neighboring eucalyptus plantations and agricultural lands visited for soil collection in each zone, represented by the points.

Google Earth Polygon Tracing

In Google Earth, the polygon tool was used to trace both the entire church forest and the eucalyptus patches within the entire forest of 2,560 forests in the South Gondar, East Gojjam, and West Gojjam zones (Figure 2.2). When tracing the total forest, any signs of roads, hedgerows, or other clear boundaries were also used to distinguish where the church forest ended. If clear boundaries were not present, tracings were made using the rule that if a patch of forest were 10m or greater apart from the adjacent church forest, it would not be counted as part of the church forest. For the eucalyptus cutouts within the entire forest, any forest

patches with the distinct regular pattern of eucalyptus growth were traced. If it was difficult differentiating eucalyptus from indigenous forest due to poor imagery or slope and elevation changes in the landscape, the history tool in Google Earth was used to look at past images of the same forest. If trees appeared within the matter of years, or there were a lot of distinguishable changes due to plantation harvest, it was likely that the patch was eucalyptus, which grows much more quickly and is harvested much more often than indigenous trees.

Figure 2.2. An aerial photo from Google Earth (image from 2/21/2015) of Simadibera Mariam (church ID #2558), one of the 2,560 churches identified in the three study zones of South Gondar, East Gojjam, and West Gojjam. The white outline represents the entirety of the church forest, as defined in the methods, and the red outlines depict the eucalyptus patches within the total forest area.

The eucalyptus cutouts were named with the same identification number as the entire forest tracings. These numbers were then merged using the "join" function and the church identification numbers in R. The areas of all of the polygons were calculated, so that each forest had a determined total area, and total eucalyptus area. The ratio of eucalyptus area to total forest area was also calculated for all church forests with eucalyptus present.

Landsat Imagery and NDVI Processing

Land cover analyses were performed using geospatial data from the USGS Landsat program. The Landsat program, sponsored by the National Aeronautics and Space Administration (NASA) since the early 1970s, provides 30-meter by 30-meter resolution satellite imagery of the earth's surface (USGS, 2015). There is a large literature base demonstrating the use of satellite imagery to analyze temporal land cover change (de Muˆelenaere et al., 2012; Munro, 2008; Girmay, 2003). This chapter uses similar methods to analyze land cover change over time. The Landsat imagery was downloaded from USGS to create vegetation maps of the landscapes that scattered church forests persist in. Landsat data were taken from 1984 and 2014 imagery.

The Landsat scenes were processed using R version 3.1.2 (2014) to calculate the Normalized Difference Vegetation Index (NDVI) (Figure 2.3). NDVI is an index of plant “greenness”, or green biomass of a landscape, and is one of the most commonly used vegetation indices (Huete et al., 2002). NDVI is used to understand the extent and density of vegetation of a region. Photosynthetic vegetation reflects poorly in the visible part of the spectrum but strongly in the near-infrared (NIR) part of the spectrum. This unique characteristic allows us to quantify the amount of plant biomass using remote sensing imagery. NDVI combines the energy absorbed by chlorophyll in the red sector of the electromagnetic spectrum (RED) with NIR. NDVI is computed by the calculating the difference between RED and NIR bands and normalizing this difference using the following equation: NDVI = (NIR-RED)/(NIR)+RED). The NDVI value can range from -1 to 1 with values closer to 1 indicating high green vegetation content.

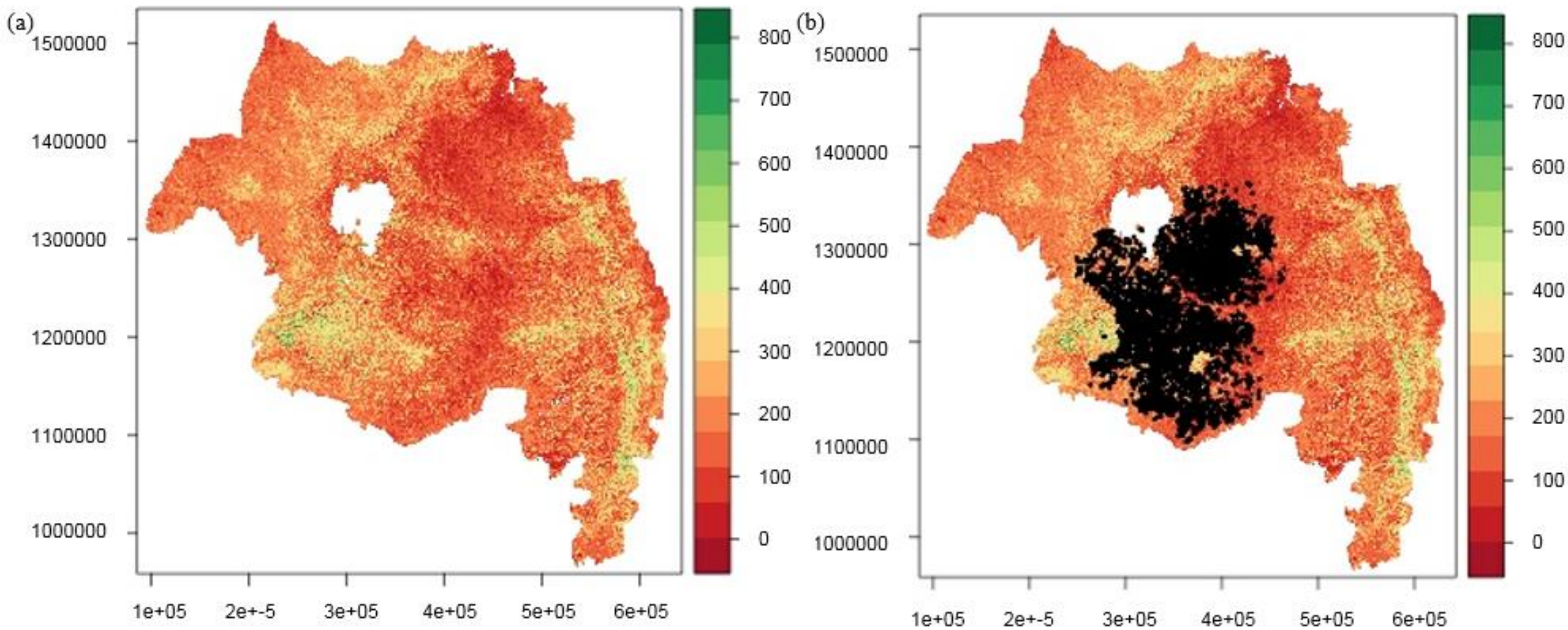

Figure 2.3. (a) The NDVI values were rescaled to integers covering a range of -1000 to 1000 to reduce data storage requirements (for example, an NDVI value of 0.500 is represented by 500 in this scale) for the Amhara Region. (b) The black clusters are the church forest polygon tracings. By pulling the NDVI values from the pixels within these tracings, a cut-off NDVI value for differentiating forest vs. non-forest pixels was determined.

Total Forest Cover Change and Church Forest Area Analysis

Once all of the NDVI scenes were processed for both time periods the NDVI values were pulled from the extent of each eucalyptus polygon and each indigenous forest polygon (determined by subtracting the eucalyptus polygon from the total forest polygon drawn in Google Earth). The NDVI values within these polygons were used to determine a suitable cut-off level for determining what is forest and what is not based on NDVI, and whether or not there was a distinguishable difference in NDVI value between indigenous forest cover and eucalyptus plantation cover (Appendix 1). It was determined that there was no significant difference between the range of NDVI values for eucalyptus and indigenous, and that the general forest cut-off NDVI value was approximately 0.250. This value was used to create a binary output raster, where anything that was equal or greater than 0.250 was designated as "1," indicating a forested pixel, and anything less than 0.250 was designated as "0," indicating a non-forested pixel. The raster was first clipped to the extent of the study sites – the three zones (South Gondar, West Gojjam, and East Gojjam) that contain the 2,560 church forests identified, and the overall forest cover change in these zones was calculated.

Raster pixels with a value of "1" were then converted into a polygon layer. Buffers of 0.01 meters were created around these new polygons to cope with error associated with pixel resolution and the resulting adjacent or bordering pixels were dissolved to create a single, contiguous polygon. This was done for both the 1984 NDVI raster and the 2014 NDVI raster. A 100-meter buffer was created around the present day church forest tracing created in Google Earth, and the forest area within the buffer was calculated in the 1984 NDVI polygon layer and the 2014 NDVI polygon layer within the buffer. This 100-meter buffer of the present-day church forest tracing limits the capture of non-church associated forest, while creating a standard scope of study between the 1984 and 2014 layers. However, it is possible that greater amounts of forest existed in 1984, but was clipped off by the buffer. In that regard, our calculations may be conservative figures for forest cover in 1984.

The difference between 2014 and 1984 forest pixel areas was said to be the difference in total vegetation cover in three decades. These data were merged by forest identification number to the data with eucalyptus traced polygon areas, and eucalyptus polygon areas were subtracted from the difference between NDVI areas to get the total difference in indigenous

forest when eucalyptus is accounted for as non-indigenous forest pixels. Data were further analyzed using R version 3.1.2 (2014).

Results and Discussion

Total Forest Cover Change from 1984-2014

The NDVI binary raster layer was used to determine the overall forest cover change in the three study zones (South Gondar, East Gojjam, and West Gojjam). The percentage of forested area in these three zones was found to have decreased from 19.4% in 1984 (7,800,000 hectares) to 14.5% in 2014 (5,830,000 hectares), losing approximately 1.97 million hectares of forest in the last 30 years (Figure 2.4).

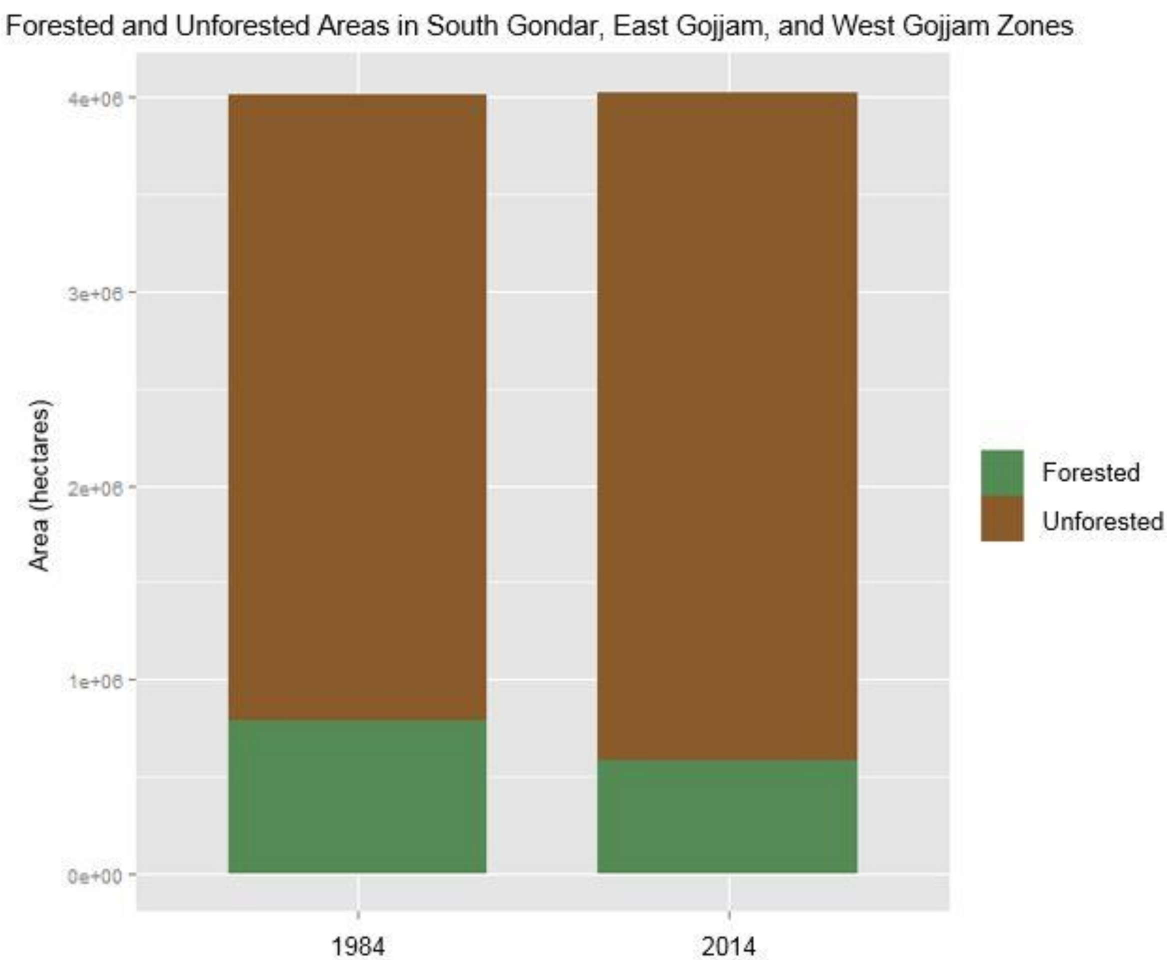

Figure 2.4. A graphical representation of the amount of forested and unforested areas in 1984 and 2014. There has been an increase in deforestation in the overall region in the last 30 years.

A previous study by Mekonnen et al. (2016) used SPOT (5-meter resolution) satellite imagery to quantify the present-day forest cover of the entire Amhara Region. Their work indicates that the forest cover of the Amhara region is roughly 8.2%, accounting for natural dense forests, woodlands, riverine forests, as well as plantations. Including bushlands into that mixture, the total forest cover in the Amhara region was estimated at 13.85%. This percentage is similar to the 14.5% forest cover in 2014 that was computed in this study in the South Gondar, East Gojjam, and West Gojjam zones of the Amhara region, and also coincides with the FAO (2010)'s estimate of Ethiopia being among countries of the world with forest cover of 10-30%. In further analysis from the work of Mekonnen et al. (2016), it was found that, similarly to our results in three zones within the Amhara region, there was a 2.65% decrease in forest cover in the entirety of the Amhara region from 1990 to 2010, losing approximately 2.91 million hectares in this twenty-year span.

Church Forest Change from 1984-2014

Using the same NDVI binary raster, the total church forest area was determined to be 11,400 hectares in 1984 and 14,600 hectares in 2014. Unlike in the total forest cover change in our three study zones, the forest area associated with church forests has increased by 3,200 hectares, roughly 28.1% of the amount of forest in 1984, in the last three decades. It is also estimated that church forests accounted for roughly 2.5% of the total forest cover in the three study zones in 2014.

Church forests in 1984 ranged from 0 to 141 hectares, with the interquartile range spanning from 0.991 to 5.20 hectares (Figure 2.5). The mean church forest area was 4.45 hectares in 1984, and the median value was 2.52 hectares. In 2014, church forests areas ranged from 0 to 133 hectares, with a mid-50% range from 1.53 to 7.11 hectares (Figure 2.5). The mean and median church forest areas in 2014 were 5.71 hectares and 3.71 hectares, respectively.

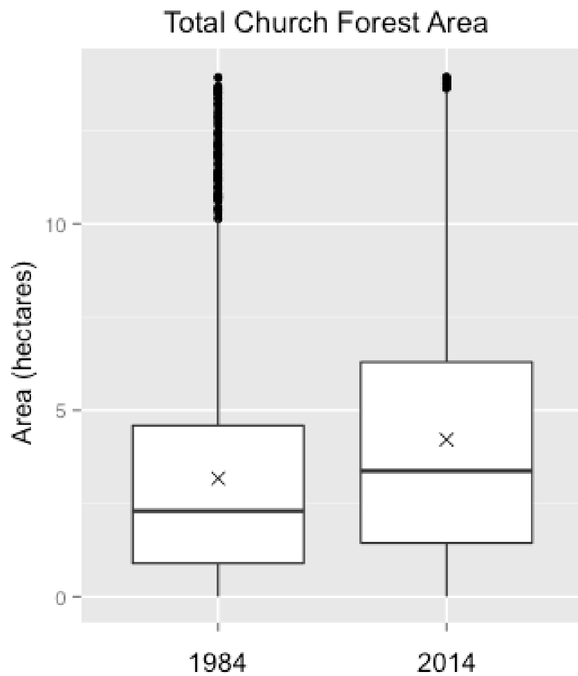

Figure 2.5. The range of church forest areas in 1984 and 2014. The horizontal line in the boxplot represents the median church forest area, and the "x" represents the mean.

On average, church forests in 2014 were 1.26 hectares larger than church forests in 1984 (Figure 2.6), though there were a few large church forest areas that created a right skew in the data. The median value indicated that individual church forests were, on average, 0.630 hectares larger than church forests in 1984. The inter-quartile range of the difference in church forest area spans from -0.090 to 2.19 hectares (Figure 2.6).

The fact that the total church forest area increased from 1984 to 2014 while the total forest area in the three study zones decreased indicates that there could be greater conservation practices within church forests and communities than in other forest types, such as state forests or plantations. As shown in previous studies, religion-based management systems can motivate and encourage the protection of the natural world through philosophy and teachings (Dudley et al., 2009; Bhagwat & Rutte, 2006). Sacred natural sites are protected by local tradition, and therefore play an important role in conservation because of their long history, their religious ties, and the local people's willingness and involvement in protecting them (Bhagwat & Rutte, 2006).

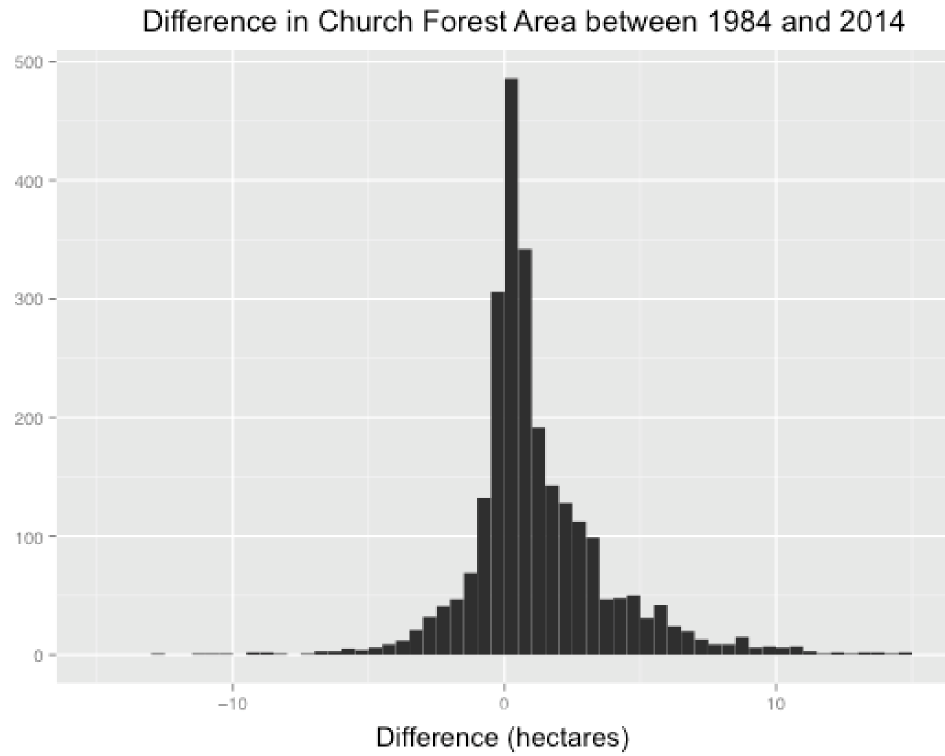

Figure 2.6. A histogram of the difference in church forest areas between 1984 and 2014.

However, given that there has been widespread planting of plantation species such as eucalyptus in the last few decades, as cited in the literature (Assefa & Bork, 2014; Lemenih & Kassa, 2014; Nyssen et al., 2009; Jagger & Pender, 2003; Pankhurst, 1995), much of the expansion is likely due to non-indigenous forests, like eucalyptus and other fast-growing plantations. In the Amhara region, plantation forests are mainly found in Awi, North Shewa, South Gondar, South Wollo, East Gojjam, and West Gojjam zones (Mekonnen et al., 2016), three of which were our studied areas.

Quantifying Eucalyptus Cover in Present-Day Church Forests

856 of the 2,560 church forest study sites had eucalyptus visibly surrounding or mixed into the indigenous forest. This accounts for roughly 33.4% of all church forests in the South Gondar, East Gojjam and West Gojjam zones. Subtracting the eucalyptus area values from the forested areas in 2014 (using the NDVI method), the inter-quartile range shifted slightly to a range of 1.44 hectares to 6.96 hectares. The mean church forest area accounting for only indigenous forests was 5.54 hectares, and the median value was 3.65 hectares, 0.17 hectares

less than the previous mean church forest area when eucalyptus was included in the area, and 0.06 hectares less than the median church forest area. Accounting for eucalyptus also decreased the mean difference between 1984 and 2014 indigenous church forest areas, with church forests in 2014 averaging a mean area of 1.09 hectares greater than church forests in 1984, and a median area value of 0.540 hectares greater than church forests in 1984.

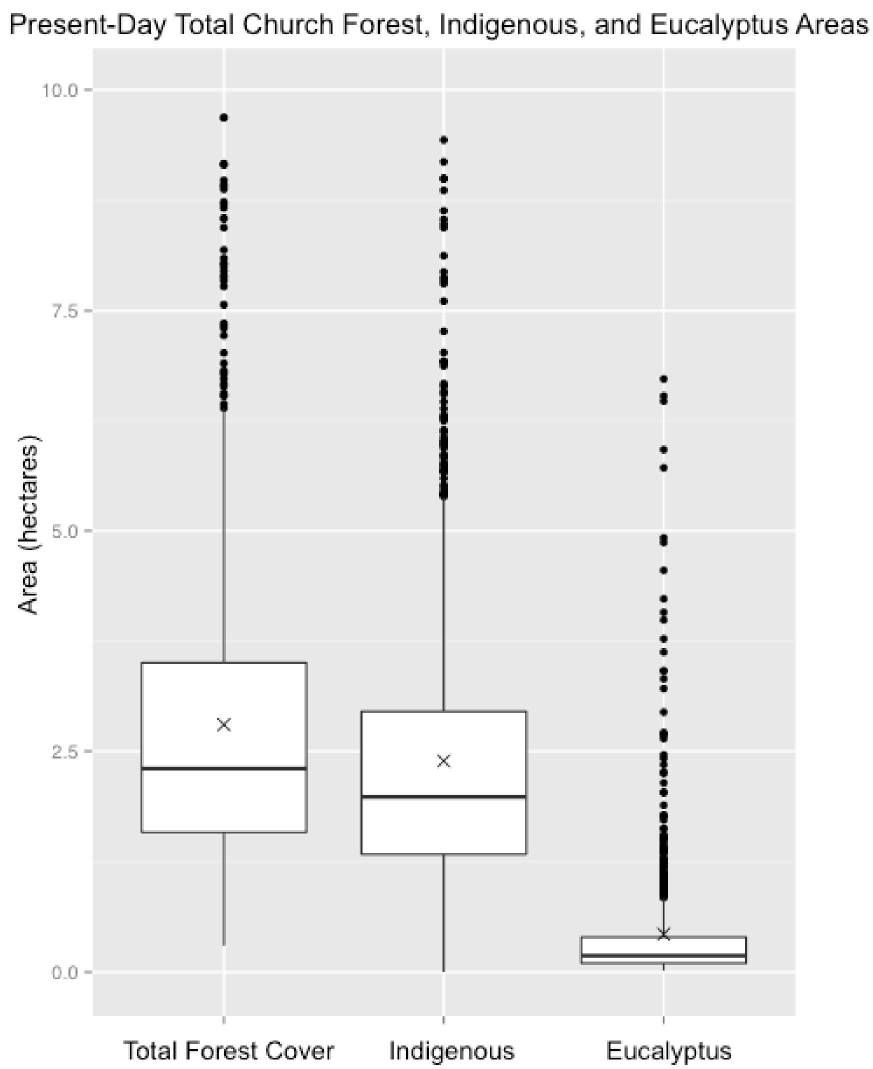

Figure 2.7. The ranges of total church forest cover, indigenous forest within the church forest, and eucalyptus plantation area associated with the church forests.

Of the 856 churches with eucalyptus stands, the range of eucalyptus area ranged from 0.018 to 34.6 hectares, with the inter-quartile range spanning from 0.09 to 0.398 hectares (Figure 2.7). The mean is heavily skewed by a few outliers, valuing at 0.489 hectares, much greater than the 0.186-hectare median. Proportionally, the eucalyptus stands in these 856

churches range from approximately 0.355% of the total forest cover to 100% of the total forest cover, with the inter-quartile range spanning from 4.31% to 17.4% (Figure 2.8). The mean percentage of eucalyptus cover in the forest was 14.9%, and the median value was 8.2%. 24 of the 856 forests, or 2.8%, are made up of entirely eucalyptus, with no value for indigenous forest. In total, there was 419 hectares of eucalyptus accounted for in the church forests of South Gondar, East Gojjam, and West Gojjam zones, making up 30.7% of the 2,790 hectares of the 856 church forests in which eucalyptus was present, and 5.05% of the 8,290 hectares of all 2,560 studied church forests.

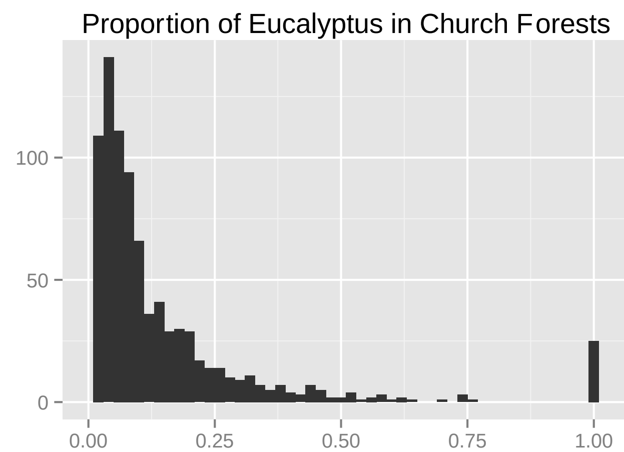

Figure 2.8. A histogram of the proportion of eucalyptus amongst the 856 of the studied church forests with eucalyptus present.

Although church forests are showing higher rates of reforestation than the larger areas encapsulating all surrounding lands, shifts in economic incentives and cultural norms have influenced church communities to plant cash crops such as eucalyptus (Bongers et al., 2006; Reynolds et al., 2015). The expansion of eucalyptus across Ethiopia has by no means excluded church forests, with some newer churches (in this study, 24 of the 2,560) even choosing to plant their surrounding forests using only eucalyptus trees.

Future Study Recommendations

The NDVI buffering method used in this thesis chapter showed that forest cover has changed in three zones of the Amhara Region in the last thirty years, while church forests in the same area have increased in size. Though the NDVI methods used were held consistent between the 1984 and 2014 imagery, using a 100-meter buffer around the 2014 church forest

tracing to assess church forest change, the implementation of other methods could improve the accuracy of these findings. For instance, one potential source of error in the current method is that from church to church, the buffering method could include additional forest that is not associated with the church, or not include the entirety of the church forest. With the existing Google Earth traced polygons for representing present-day church forests, it could be beneficial to do similar historical tracings using higher resolution images. The comparison of 1984 to present-day church forest area using tracing methods for both images would be more labor-intensive, but yield a more accurate result.

Another improvement that could be made by manually tracing historical images of church forests is the ability to account for any eucalyptus plantations in or around church forests in 1984. Although the majority of church forests likely did not have eucalyptus plantations until recently, this assumption may not apply to all church forests in the area, and therefore manually tracing both the church forest and surrounding eucalyptus for the historical images could account for any additional error in change in indigenous forest area and expansion of eucalyptus over time.

A less time-intensive practice that could be used in future studies over larger geographic areas would be to apply maximum likelihood classification to land cover in historical and present-day images. Using this method, it would be possible to estimate vegetation and land cover throughout a larger image by designating "training areas" or regions of interest, essentially telling the computing software that specific pixels were native forest or eucalyptus. Once a sufficient quantity of pixels were marked, algorithms could then be run to analyze the spectral signatures of the regions of interest, and then all pixels in the Landsat image could be classified as belonging to the land cover type whose spectral category they most resembled.

Conclusion

Deforestation has been a problem in Ethiopia for centuries. The utilization of natural forests for fuel wood and construction materials, as well as additional social and political challenges throughout the country's history, have exacerbated deforestation (Assefa & Bork, 2014; Lemenih & Kassa, 2014; Bishaw, 2001). Unlike recent literature declaring greater levels of biomass production in both the Tigray Highlands and the Amhara Region in recent

decades (de Muelenaere et al., 2012; Nyssen et al., 2009; Munro et al., 2008; Girmay, 2003; Bewket, 2002; Crummey, 1998; Woien, 1995), this thesis chapter indicates that there has been an overall decrease in forest cover in the last three decades in the South Gondar, East Gojjam, and West Gojjam zones of the Amhara Region. This finding is important because it suggests that deforestation continues to present itself as a prominent issue in the northern Ethiopian Highlands. However, when honing in on church forests exclusively, there was found to be an overall increase in forest cover from 1984 to 2014, therefore this thesis chapter also suggests that reforestation efforts may be more prominent in and around church forests than in regional forests in the same area. The Ethiopian Orthodox Church has a great influence on forest management in church forests, and with their positive philosophies and teachings regarding nature, they have great potential to encourage and inspire forest conservation (Dudley et al., 2009; Bhagwat & Rutte, 2006).

However, the presence of eucalyptus in over one third of the studied church forests indicates that even in areas where forest conservation is of foremost importance, the exploitation of natural forests and socio-political challenges has failed to promote reforestation of native forests. Rather, developing nations such as Ethiopia have turned to fast-growing monoculture plantation species, such as eucalyptus, to fill the void of missing indigenous trees. This pattern does not exclude church forests, with some newer church forests even being made up entirely of exotic eucalyptus species. But alleged negative ecological consequences of planting eucalyptus species indicate that communities should be cautious when planting the stands around natural church forest fragments or agricultural land. Greater focus should be given to encouraging reforestation efforts that utilize indigenous tree species, therefore benefitting natural biological diversity, general ecosystem health, and the ecosystem services provided to humans by the natural environment.

CHAPTER THREE: EFFECTS OF EXOTIC *EUCALYPTUS SPP.* PLANTATIONS ON SOIL PROPERTIES IN AND AROUND SACRED NATURAL SITES IN THE NORTHERN ETHIOPIAN HIGHLANDS

Background

Eucalyptus dominates most of the natural forests in their natural habitat, growing in a range of diverse climates and soil types (Pohjonen, 1989). In Ethiopia, eucalyptus tends to outperform other exotic species and native species alike in terms of production and farmer income generation – this can be attributed to a number of biological and physiological characteristics including high fecundity (Stanturf et al., 2013), rapid growth rates (Leicach et al., 2012), allelopathic properties (Zhang & Fu, 2009) and a tolerance for a wide range of soil and climate niches (Yitaferu et al., 2013; Zegeye, 2010; Pohjonen, 1989). Eucalyptus species are also tolerant of severe periodic moisture stress and low soil fertility with xeromorphic leaves (structural modifications that enable the reduction of water loss) and specialized ecto- and endomycorrhizae systems that increase nutrient uptake (Zegeye, 2010; Bean & Russo, 1989; Davidson, 1989). Furthermore, eucalyptus leaves contain oils and phenolic compounds that increase resistance to insects and non-palatability to grazers (Dessie & Erkossa, 2011; Zegeye, 2010). Perhaps most importantly, many eucalyptus species are easy to cultivate for fuel wood, timber, and charcoal due to their ability to coppice readily, tolerance for low quality sites, and low maintenance requirements. In addition to wood products, eucalyptus trees are useful for non-wood products such as honey, and can also act as shelterbelts, erosion control, land reclamation and drainage (Dessie & Erkossa, 2011; Palmberg, 2002). Collectively, these characteristics contribute to the efficacy of eucalyptus as a major production tree species grown by smallholder farmers on depleted and deteriorated agricultural land in the northern Ethiopian Highlands (Jagger & Pender, 2003).

On the other hand, with many of the traits that allow eucalyptus species to thrive in degraded environments also come potentially negative ecological effects, such as soil nutrient depletion and soil degradation. The potential negative impacts of eucalyptus plantations on soil quality and other ecosystem services have been intensively studied. Studies conducted across many tropical and sub-tropical regions cite high demand for soil nutrients as an important drawback to eucalyptus plantations (Kidanu et al., 2005; Harrington & Ewel, 1997; Bean & Russo, 1989). High rates of soil nutrient uptake in *Eucalyptus spp.* are

due in part to the combined effect of fast growth and the inability to fix nitrogen (Zegeye, 2010); consequently in both the short- and long-term eucalyptus plantation establishment has been shown to have detrimental effects on soil quality and fertility (Lemenih & Kassa, 2014; Chanie et al., 2013). By degrading soils, eucalyptus may render land less suitable for future growth of crops and natural forests alike (Palmberg, 2002). However, the ultimate impacts of eucalyptus production on degraded agricultural land remains fiercely debated – indeed, a small, more recent literature has indicated that eucalyptus may even have the potential to have positive impacts on soil fertility in degraded and treeless lands of Ethiopia, by increasing decayed litter content (Yitaferu et al, 2013; Dessie & Erkossa, 2011; Zegeye, 2010; Kidanu et al., 2005; Jagger & Pender, 2003; Yirdaw, 2001).

Impacts of Eucalyptus on Soil Nutrient Depletion and Fertility

In order to keep up with their fast growth and to substitute for their inability to fix nitrogen, eucalyptus species have specialized nutrient uptake systems of ecto- and endomychorrhizae that can greatly increase rates of nutrient uptake (Zegeye, 2010). In areas where there are crops nearby, this can make eucalyptus a problematic competitor. For instance, Chanie et al. (2013) found that eucalyptus decreased both soil nutrients and crop (maize) yield up to 20 meters away from the eucalyptus trees in the Lake Tana Plain of Ethiopia, and additionally, soil hydrophobicity (water repellency) became a problem. Fast growing and short rotation tree plantations such as eucalyptus also use escalated amounts of nutrients from the soil in comparison to slow-growing species (Dessie & Erkossa, 2011; Heilman, 1997). Monoculture forest activities such as eucalyptus plantations may further affect soil chemical characteristics if the organic litter is continuously raked, prohibiting nutrient recycling (Zewdie, 2008).

In addition to soil fertility and nutrient content, eucalyptus has been found to have impacts on topsoil retention and soil erosion (Dessie & Erkossa, 2011; Jagger & Pender, 2003; Palmberg, 2002; Sunder, 1993; Poore & Fries, 1985). Some studies have concluded that eucalyptus can worsen soil erosion as an indirect result of frequent disturbance from repeated harvesting and reduced understory cover (Nyssen et al., 2004; Poore & Fries, 1985). Others argue that eucalyptus plantations can help control soil erosion on sloped or degraded sites, but their efficacy depends on environmental factors such as intensity of rainfall, soil

condition, slope and the presence of ground vegetation and litter cover (Sunder, 1993). Though few Ethiopia-specific case studies exist, the limited evidence available suggests that eucalyptus may be an ineffective choice for erosion control (Nyssen et al., 2004; Sunder, 1993) – rather, eucalyptus trees are generally expected to lead to an increase in soil loss due to the reduced understory cover in densely planted eucalyptus areas (Nyssen et al., 2004; Pohjonen & Pukkala, 1990).

Potential Positive Impacts of Eucalyptus on Soil Properties

Other recent evidence from the literature suggests that eucalyptus may not always have negative effects on topsoil retention and soil nutrient availability. If planted properly, for example, eucalyptus can act as shelterbelts for crops (Zegeye, 2010; Jagger & Pender, 2003). Wind erosion is especially prominent in dry areas with light soils where there are few tree roots or other vegetation to hold the topsoil (Zegeye, 2010). The extensive lateral root systems of eucalyptus species can make them good candidates for wind barriers even in dry, sandy soils (Dessie & Erkossa, 2011). *Eucalyptus globulus*, for instance, has a strong tap root and lateral root system that makes it a very reputable species protection from erosion in catchment areas, and has been widely planted for this purpose (Teshome, 2009; Teketay, 1992).

Evidence is also mixed on the circumstances under which eucalyptus plantations will have a negative impact on soil nutrients. A study done by Yitaferu et al. (2013) examined the impacts on soil when eucalyptus plantations were converted to cropland in the Amhara region of Ethiopia. The results of this study showed that with the exception of available phosphorus, the measured nutrient content and soil quality was higher in areas where land use had changed from eucalyptus to cropland in the last three years than in areas that were permanently under food crops. Yitaferu et al. (2013) concluded that it may be possible to convert eucalyptus woodlots to cropland without detrimental effects on soil fertility and the productivity of the subsequent crop growth. It has even been argued that eucalyptus could positively impact soil fertility through decayed litter in areas where the land has been previously degraded by intensive agriculture (Zegeye, 2010).

Case Study of Ethiopian Orthodox Church Forests in the Northern Ethiopian Highlands

In northern Ethiopia, where native tree populations are already scarce, there is concern that eucalyptus expansion may adversely affect the function of what little natural forest remains. Afromontane forests have largely disappeared in the northern Ethiopian Highlands, with the remaining fragments of natural forest found almost exclusively in thousands of "church forests," small fragments of indigenous forest governed by followers of the Ethiopian Orthodox Tewahido Church (Aerts et al., 2016; Reynolds et al., 2015; Bongers et al., 2006). In addition to serving as places of worship, church forests serve as in situ conservation sites and hotspots for biodiversity, hosting numerous indigenous trees and plant species of Ethiopia (Wassie et al., 2010). Sacred natural sites such as church forests also provide unique opportunities for future restoration of indigenous forests in the degraded Ethiopian Highlands (Wassie, 2007). But the land surrounding these natural forest fragments is increasingly eucalyptus-dominated (Reynolds et al., 2015; Bongers et al., 2006), as church communities recognize the socio-economic benefits tied to eucalyptus including its roles as a fast-growing supply of fuelwood and timber and a key source of income (Chanie et al., 2013; Yitaferu et al., 2013; Dessie & Erkossa, 2011; Mengist, 2011). To the extent that the introduction of eucalyptus to land around and within church forests increases nutrient depletion and land degradation, there is concern that eucalyptus expansion may complicate current and future forest restoration efforts in and around these sacred natural sites. In adjacent agricultural land, impacts on crops and livelihoods can also be linked to the introduction and expansion of eucalyptus to church forests affecting the environment in which food crops are able to grow (Chanie et al., 2013).

This study adds to the increasing literature surrounding the debate on the ecological impacts of eucalyptus stands in Ethiopia by analyzing the impacts of eucalyptus on soils in comparison to agricultural land and indigenous church forest fragments. The objective of this work was to 1) quantify organic matter, pH, total nitrogen, and total phosphorus in 80 sampling points across 20 rural agrarian communities in the Amhara National Regional State, and 2) observe the effects of *Eucalyptus spp.* on these soil parameters in comparison to other land uses.

Methods

Study Sites

To examine the possible impacts of eucalyptus planting on soils around indigenous forest fragments in northern Ethiopia, soil samples were collected from 20 different church forest communities, including samples within native forest vegetation, at the edge of natural forests, in adjacent eucalyptus plantations, and in surrounding agricultural land. The sample of 20 church forests was comprised of 11 in South Gondar Zone, three in East Gojjam Zone, two in West Gojjam Zone, one in Awi Zone, and one in Bahir Dar Liyu Zone (Figure 3.1, Table 3.1).

Study sites were identified using aerial images from Google Earth and the following criteria:

- The forest must have at least one patch of eucalyptus bordering the indigenous forest, and that eucalyptus patch must border the indigenous trees of the church forest for at least 10 consecutive meters.
- Forests that were completely eucalyptus, as many newer church forests are, were not considered. Rather, the forests selected must have sufficient indigenous forest area to have a 10-meter by 10-meter plot of indigenous trees towards the core of the forest that would not overlap with a 10-meter by 10-meter plot of indigenous forest bordering the eucalyptus.
- There must also be agricultural land in close proximity to the church.

On the ground, accessibility was also considered. Churches that were more than three kilometers from the main road were not easily accessed due to lack of efficient transportation. Some church leaders or priests also refused access to their forest upon arrival. Some of the Google Earth images were taken during the wet season, in which much of the image was very green it was difficult to distinguish trees from small shrubs or grass, resulting in some of the forests being much more degraded upon arrival than anticipated. With these additional considerations, 20 church forests were included in the final sample for soil collection.

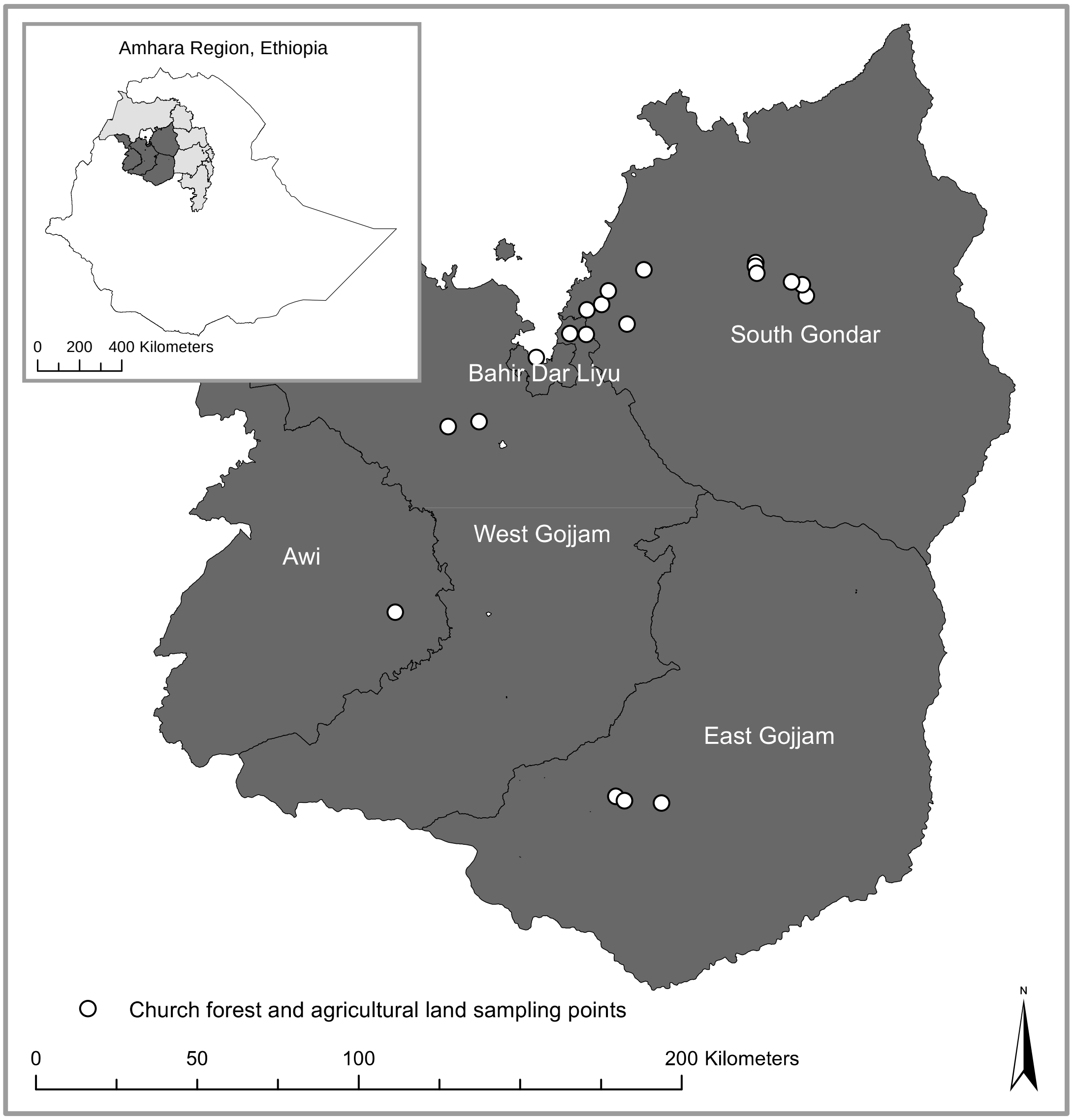

Figure 3.1. Map of South Gondar, East Gojjam, West Gojjam, Awi, and Bahir Dar Liyu zones in the Amhara region. The church forests and neighboring eucalyptus plantations and agricultural lands visited for soil collection in each zone are represented by the points.

Table 3.1. Church identification by name, zone, GPS coordinates (decimal degrees), elevation, and annual rainfall. Total forest area, eucalyptus area within the total forest area, and percent cover of eucalyptus in the total forest area are also shown.

Church Name	**Zone**	**Latitude**	**Longitude**	**Elevation (m)**	**Annual Rainfall (mm)**	**Total Forest Area (ha)**	**Eucalyptus Area (ha)**	**Percent Eucalyptus Cover (%)**
Abagerima Mariam	West Gojjam	11.678	37.506	1907	1075	5.05	2.28	45.07
Addis Mariam	East Gojjam	10.371	37.620	2411	890	3.98	0.398	10.0
Asketes Teklehai-manut	East Gojjam	10.366	37.724	2409	887	7.67	1.52	19.8
Azawar Kidana Miharet	South Gondar	11.790	38.131	2900	729	5.35	0.268	5.01
Bale Xavier	Awi	10.897	36.969	2543	1047	5.48	0.497	9.07
Bata Lemariam	Bahir Dar Liyu	11.613	37.364	1798	1076	4.64	0.339	7.31
Debrasena Mariam	South Gondar	11.852	37.990	2650	866	11.9	0.204	1.71
Enkuhar Micahel	South Gondar	11.861	37.668	1883	1089	6.03	0.850	14.1
Fisa Michael	South Gondar	11.747	37.507	1873	1097	7.03	0.827	11.8
Idonga Mariam	West Gojjam	11.432	37.203	2023	1195	2.03	0.085	4.18
Mashenkoro Giorgis	South Gondar	11.708	37.621	2046	1045	4.71	0.351	7.45
Robit Bata	West Gojjam	11.680	37.459	1857	1075	7.99	0.983	12.3
Sarna Mariam	South Gondar	11.820	38.120	2777	743	3.73	0.238	6.38
Simadibera Mariam	West Gojjam	11.417	37.114	1991	1196	7.45	1.46	19.6
Tsegur Kidana Miharet	South Gondar	11.881	37.986	2622	866	3.63	0.872	24.0
Tsegur Michael	South Gondar	11.871	37.985	2659	866	5.07	3.25	64.1
Wadebuko Giorgis	South Gondar	11.828	38.088	2670	743	3.84	0.821	21.4
Wonchet Mariam	South Gondar	11.763	37.548	1933	1097	7.11	0.107	1.51
Woynima Mariam	East Gojjam	10.383	37.595	2252	890	1.96	0.107	5.46
Zahara Michael	South Gondar	11.800	37.567	1907	1152	9.09	0.115	1.27

Soil Sampling Methods

Four soil sampling sites were identified at each forest: one within the interior of the indigenous forest, one at the edge of the indigenous forest bordering the eucalyptus stands, one within the eucalyptus stands, and one in the agricultural land adjacent to the church forest (Figure 3.2).

Figure 3.2. An example of the locations of each 10-meter by 10-meter plot at Debrasena Mariam Church: one in the interior of the forest, one on the edge of the forest, one in the eucalyptus plantation, and one in the surrounding agricultural land.

At each location, a 10-meter by 10-meter plot was approximated, and five 10-centimeter cores were taken using a soil core. Samples were taken from depths of 0 to 10 centimeters from the surface of the ground. The five cores taken at each location were mixed into one sample to be analyzed. The cores were taken randomly, with each core being no less than two meters away from the other core locations (exceptions were made when instructed not to sample on or near grave sites, forcing cores to be taken closer to one another). Coring near the roots of trees was avoided to the extent possible in order to avoid microhabitat effects under particular species of trees. At all four sites, canopy cover was also recorded at the center of each plot. Using a spherical densiometer (Robert E. Lemmon forest densiometers, Model-C), the raw number of quarter squares not covered by canopy (where the light hit the

densiometer and there was no forest cover) was recorded in the four cardinal directions (north, east, south, and west).

The interior forest soil sample was taken as close to the center of the church forest as possible, but outside of the central clearing in the church forest, as this is a spiritual area where the church building sits. The edge sample was taken at the intersection of the indigenous forest and alongside a eucalyptus patch. Eucalyptus sampling plots were only done in the plantations bordering the indigenous forest; eucalyptus in mixed forests was not sampled, but where applicable its presence was recorded. In the eucalyptus plots, the average diameter at breast height (DBH), eucalyptus age, ownership of the plantation (by the church or by adjacent private smallholders), and the landuse type present prior to the eucalyptus plantation were all recorded as well. The agricultural sample was taken at least 20 meters away from any eucalyptus to minimize influence.

Soil Analysis Methods

Soil samples were analyzed at Brookside Laboratories for organic matter, Olsen's phosphorus, available nitrogen (nitrate and ammonium), and pH. Organic matter was measured using loss on ignition at 360° C, a method described by Schulte and Hopkins (1996). This procedure estimates soil organic matter by the loss of weight in a sample heated at a temperature high enough to burn organic matter but not high enough to decompose carbonates. The sample is first dried to remove moisture, then weighed, heated to 360° C for two hours and weighed again after the temperature cools down to below 150° C. Soil pH was determined using a 1:1 soil to water extract of the soil using deionized water (McClean, 1982). Available nitrogen was approximated by the summation of nitrate and ammonium concentrations, both of which were extracted from soils using KCl (Dahnke, 1990). Available phosphorus was measured using the Olsen method, due to the low acidity associated with soil in the Ethiopian Highlands, generally between 5.5 and 6.7 in the Lake Tana area (Schlede, 1989). This method estimates the availability of phosphorus in soils by extraction using alkaline sodium bicarbonate solution and determining the phosphorus concentration in the extract colorimetrically (Olsen & Sommers, 1982).

Statistical Analysis Methods

Using R version 3.1.2 (2014), data were submitted to non-parametric tests, including a Kruskal-Wallis one-way analysis of variance test. If analysis of variance showed statistically significant differences among the four treatments ($p \leq 0.05$), additional analysis was conducted to assess the differences between each pairing of treatments using Mann-Whitney-Wilcoxon tests. Additional multiple regression analyses were run using R to explore the effect of several independent predictor variables on our measured soil properties.

Results

Soil Quality by Sampling Location

There were significant differences found across the 20 sampled church forests between the interior, edge, eucalyptus, and agriculture plots for each of the measured soil properties: organic matter, pH, total nitrogen (N), and total phosphorus (P) (Figure 3.3).

Organic Matter

Organic matter content differed significantly between the interior, edge, eucalyptus, and agriculture plots of the 20 study sites ($p<0.001$) (Figure 3.3). The mean organic matter contents of the interior (16.5%) and edge (15.4%) plots were not significantly different (Table 3.2). Both the mean organic matter contents of the interior and edge plots were, however, significantly different from the mean organic matter content of the eucalyptus (7.71%) and agriculture plots (4.83%). Soils in eucalyptus stands also had significantly higher organic matter content than agricultural soils ($p<0.001$). Additional analysis amongst only the church forest sites where eucalyptus plots were known to previously have been

Table 3.2. The differences in soil property values (first location minus second location) between each pairing of the interior, edge, eucalyptus, and agriculture plots. The significance of results was calculated using Whitney-Mann-Wilcoxon tests.

	Organic Matter (%)	pH	Nitrogen (mg/kg)	Phosphorus (mg/kg)
Interior-Edge	1.10	0.255	-0.585	1.40
Interior-Eucalyptus	8.75***	0.695*	19.5***	14.1
Interior-Agriculture	11.6***	0.725**	25.8***	29.8**
Edge-Eucalyptus	7.74***	0.440	19.9**	12.7
Edge-Agriculture	10.6*	0.470	26.4***	29.4*
Eucalyptus-Agriculture	2.88***	0.030	0.0993	15.8

Signif codes: *p<0.05, **p<0.01, ***p<0.001

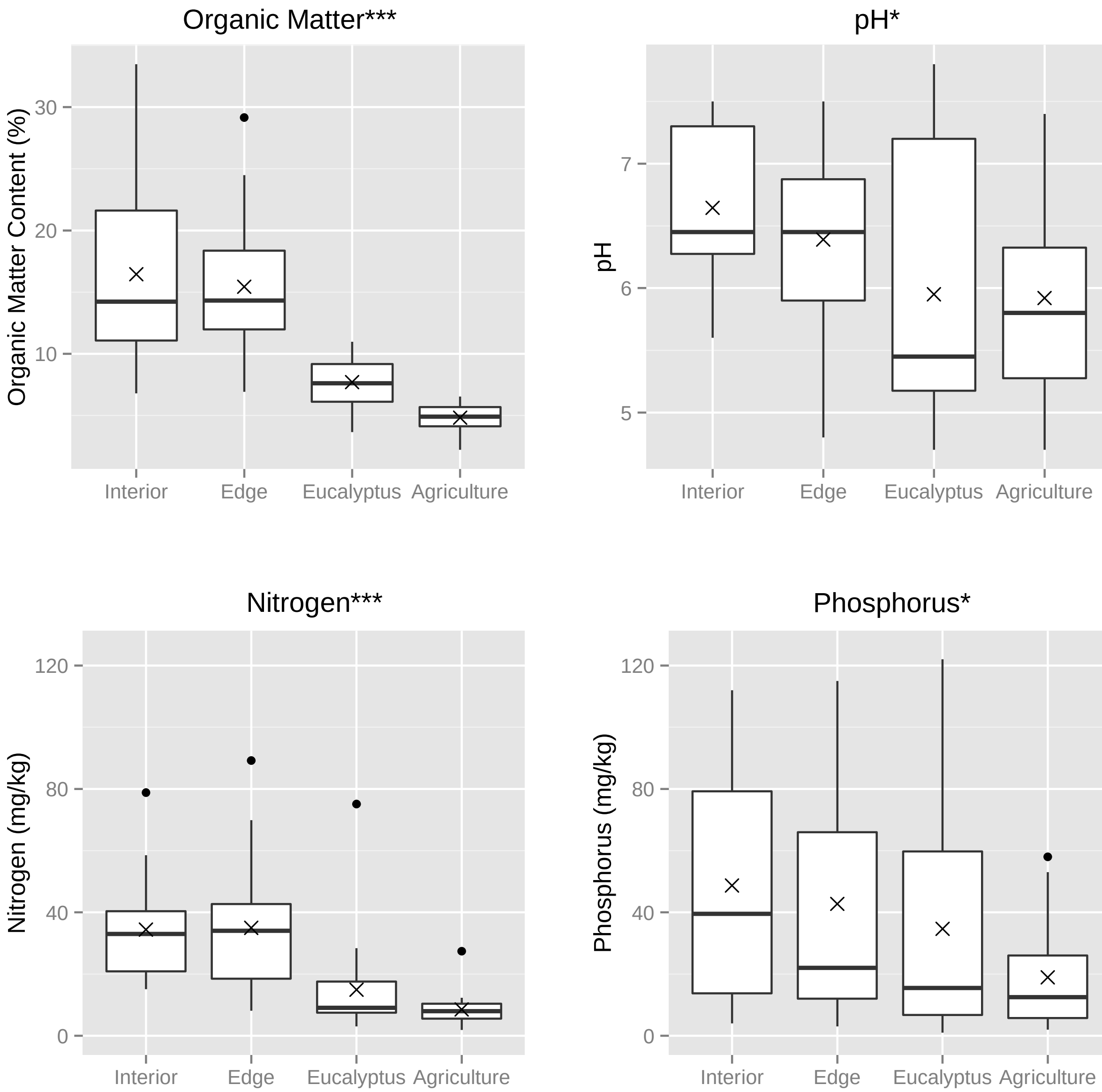

Figure 3.3. The distribution of organic matter content (%), pH, nitrogen (mg/kg), and phosphorus (mg/kg) among the 20 sampled church forests. The line within each boxplot indicates the median value for that plot location (interior, edge, eucalyptus, or agriculture), and the "X" marks the mean value. Significance levels (denoted with asterisks) reflect the results of Kruskal-Wallis one-way analysis of variance tests and identify where there were significant differences between locations of the measured soil properties (*p<0.05, **p<0.01, ***p<0.001).

farmland (n=7) yielded a significant difference between the mean organic matter content across the eucalyptus plots (8.70%) and the agriculture plots (5.13%, $p<0.01$).

Soil pH

The samples collected in our study reflect a moderately weak acid range, with mean pH values of 5.92-6.65 at the four plot locations (Figure 3.3). There was a significant difference found in the mean pH levels of the interior, edge, eucalyptus, and agriculture plots ($p<0.05$) (Figure 3.3). Pairwise significant differences in pH occurred between the interior (pH of 6.65) and eucalyptus plots (5.95, $p<0.05$), and the interior and agriculture plots (5.92, $p<0.01$) (Table 3.2). The edge plots also had a greater mean pH value (6.39) than both the eucalyptus and agriculture plots, following the predicted trend, but the differences were not significant. The mean pH levels of the interior and edge plots were not significantly different from each other, nor were they significantly different in the eucalyptus and agriculture plots.

Nitrogen

Similar patterns in significant differences were observed between interior, edge, eucalyptus, and agriculture plots for measured nitrogen content ($p<0.001$). The mean nitrogen levels were not statistically different between the interior plots (34.4 mg/kg) and edge plots (35.0 mg/kg), nor between the eucalyptus plots (14.9 mg/kg) and agriculture plots (8.55 mg/kg) (Table 3.2). However, there were significant differences in nitrogen levels between the interior and agriculture plots ($p<0.001$), the interior and eucalyptus plots ($p<0.001$), the edge and agriculture plots ($p<0.001$), and the edge and eucalyptus plots ($p<0.01$) (Table 3.2). Across our church forest study sites, nitrogen was also positively correlated with organic matter content, by a factor of 1.83 mg/kg for every percent increase in organic matter ($p<0.001$).

Phosphorus

Finally, there was a statistically significant difference between the phosphorus levels of the interior, edge, eucalyptus, and agriculture plots of the sampled church forests ($p<0.05$). Unlike total nitrogen and organic matter, the eucalyptus plots did not have a mean phosphorus level (34.7 mg/kg) that was statistically different from either of the indigenous

plots (interior and edge) (Table 3.2). The mean phosphorus content of the agriculture plots (18.9 mg/kg), however, was significantly lower than the interior plots (48.7 mg/kg, $p < 0.01$), as well as the edge plots (47.3 mg/kg, $p < 0.05$). Phosphorus levels also shared a strong positive correlation with nitrogen levels across all soil samples ($p<0.01$). Additionally, phosphorus had a positive correlation with organic matter content ($p<0.01$).

Additional Factors Associated with Soil Quality

Multiple regression analyses controlling for additional factors that could partially explain differences in soil properties between the interior, edge, eucalyptus, and agriculture plots at the 20 church forest study sites largely support the results of bivariate analyses.

Elevation is a factor that could impact the soil properties at the study sites. Across the indigenous forest plots (both the interior and edge plots), there is an increase in organic matter as elevation increases ($p<0.05$). There is also a significant negative correlation between elevation and pH ($p<0.05$). The species of eucalyptus is another source of potential variability that is in part accounted for by controlling for elevation: in our sample *E. globulus* was exclusively grown above 2500 meters (2504-2900 meters in our study sites), and *E. camaldulensis* at elevations lower than 2500 meters (1788-2429 meters in our study sites), consistent with published geographical distributions of these two major species (Dessie & Erkossa, 2011). Rainfall is also highly correlated with elevation (adjusted R-squared=0.769, $p<0.001$). For this reason, elevation is included in our final regression model, but eucalyptus species and rainfall are not.

Canopy cover is another possible explanatory variable, varying dramatically across the interior (93.2%), edge (86.9%), eucalyptus (70.5%), and agriculture (0.00%) plots ($p<0.001$). All paired statistical tests for average canopy cover across the four sampling locations were statistically significant with a p-value of less than 0.001. Consequently, canopy cover was tightly correlated with the four categorical locations (adjusted R-squared=0.942, $p<0.001$). Because these two variables were strongly associated, our final regression model (Table 3.3) includes sampling location only. A notable positive relationship also exists between canopy cover and organic matter content ($p<0.01$) when excluding the agriculture plots (which all had a canopy cover of 0%).

Our final regression model also groups interior and edge values into a single category of "indigenous forest," as the interior and edge plots have statistically insignificant mean differences for nearly all soil properties.

Table 3.3. Multiple regression models for organic matter, pH, nitrogen, and phosphorus based on elevation and location of the plot. Interior and edge have statistically insignificant mean values for all soil properties, so they are combined in this model, and the combined "indigenous forest" is used as a reference level. The agriculture and eucalyptus locations are included as dummy variables.

	Coefficient			
	Organic matter (%)	**pH**	**Nitrogen (mg/kg)**	**Phosphorus (mg/kg)**
(Intercept)	6.62 (±3.15)*	8.13 (±0.599)***	40.4 (±11.3)***	11.05 (±25.1)
Elevation	0.0041 (±0.001)**	-0.001 (±0.0003)**	-0.003 (±0.005)	0.016 (±0.011)
Location – Eucalyptus	-8.21 (±1.21)***	-0.574 (±0.230)*	-19.8 (±4.33)***	-13.2 (±9.65)
Location – Agriculture	-11.1 (±1.21)***	-0.599 (±0.230)*	-26.1 (±4.24)***	-29.1 (±9.65)**
Adj. R-squared	0.575	0.153	0.342	0.097

Signif. codes: *p<0.05, **p<0.01, ***p<0.001

The final regression model suggests that controlling for elevation, soils in eucalyptus plots have 8.21% less organic matter (p<0.001) than indigenous forest (interior and edge plots) and soils in agriculture plots have 11.1% less organic matter content (p<0.001). Soil pH decreases by 0.574 (p<0.05) in the eucalyptus plantations and by 0.599 (p<0.05) in the agricultural land in comparison to the indigenous forest. Eucalyptus plots have 19.8 mg/kg less nitrogen (p<0.001) and agriculture plots have 26.1 mg/kg less nitrogen (p<0.001) than the indigenous forest. The difference in phosphorus between eucalyptus and the indigenous plots is insignificant, but there is a significant 29.1 mg/kg decrease in phosphorus in the agricultural plots in comparison to the indigenous forest plots.

Discussion

Comparison of Soil Quality in Different Landuse Types

As there is much economic incentive to plant eucalyptus, it is important to understand the potential environmental impacts eucalyptus species may provoke. The degradation of soil by eucalyptus is of one area of particular concern; some studies have highlighted cases in which eucalyptus plantations have rendered soils unfit for future agricultural use, therefore reducing future economic benefits (Palmberg, 2002; Sunder, 1993). In this study of 20 church forests and their surrounding eucalyptus plantations and agricultural land, indigenous forest soils were of overwhelmingly higher quality amongst four soil properties than either eucalyptus or

agricultural soils. Organic matter, pH, and soil nutrients are all important considerations of soil health, as there needs to be enough organic matter and nutrients and a favorable pH range to ensure plant growth (Brady, 1990). These soil characteristics are all interdependent and closely related. Soils in the natural Afro-montane forests were more abundant in organic matter, nitrogen, and phosphorus, and were less acidic than soils in the adjacent eucalyptus stands, as well as surrounding cropland. Consistent with past research this suggests that native trees, though requiring greater time and care than introduced eucalyptus species, serve an important role in soil nutrient upkeep and fertility (Mekonnen et al., 2009; Jagger & Pender, 2003).

However, in comparison to the soil in neighboring agricultural fields, eucalyptus soils yielded similar or superior levels of the measured soil properties. The results of this study indicate that eucalyptus plots had a greater abundance of organic matter than agricultural fields, suggesting that agriculture may be a less beneficial landuse for accruing soil organic matter. There was no significant difference in pH between the eucalyptus and agriculture plots, suggesting that in comparison to agricultural practices, eucalyptus may have comparable effects on soil acidity, consistent with recent work by Chanie et al. (2013). Likewise, there was no significant difference in nutrient levels between the eucalyptus and agriculture plots.

Impacts of Environmental Factors on Soil Quality

The greater levels of organic matter in the indigenous forests in comparison to the eucalyptus plantations and agricultural fields can be partially attributed to extended canopy cover and increased productivity in dense, indigenous forests. There are many layers of vegetation in the understory of natural forests in comparison to monoculture species like eucalyptus plantations, and greater numbers of animal organisms contributing additional organic material (Singwane & Malinga, 2012; Palmberg, 2002). Though lower than natural forest soils, the organic matter content found in eucalyptus plantations is nevertheless significantly greater than in agricultural lands, in part because there is notably more canopy cover in the eucalyptus stands. This difference in canopy cover may lead to increasing volumes of leaf litter and other organic material available to the soil in eucalyptus plantations relative to agricultural fields with few shade trees.

In addition to improving soil structure, soil water, soil aeration, and soil temperature, organic matter supplies essential nutrients to the soil (Singwane & Malinga, 2012; Brady, 1990). As organic matter input increases in the soil due to increased litter falling from the forest or plantation canopy, micro-organisms break down the organic matter, generating more nutrients, including nitrogen and phosphorus (Bot, 2005). Both nitrogen and phosphorus are associated with the amount of organic matter found in our soil samples, as organic matter acts as a major source of nutrients to the soil (Brady, 1990). Nitrogen and phosphorus levels were higher in the indigenous forest than in the eucalyptus and agricultural areas, where there are also significantly higher amounts of organic matter.

Elevation is another environmental factor that may impact the soil properties at each church forest site. Across the indigenous forest plots (both the interior and edge plots), there is an increase in organic matter as elevation increases. Soil organic matter accumulation at higher elevations is likely driven by a reduction in decomposition rates rather than an increase in primary productivity (Griffiths et al., 2009, Garten et al., 1999; Sims & Nielsen, 1986). Decreased soil temperature at higher elevations generally results in decreased litter decay and soil organic matter decomposition rates, often resulting in higher organic matter content, but subsequently lower soil nutrient levels as there is less soil microbial activity (Garten et al., 1999). Elevation can also play a role in the pH of soil, as our results demonstrated that higher elevation corresponds to a more acidic pH (Griffiths et al., 2009).

Decreased rainfall may also have had an influence on soil health. Changes in precipitation can affect vegetation, which in turn has impacts on soil organic matter cycle (Ruiz-Sinoga & Romero-Diaz, 2010). Low levels of precipitation can also influence the runoff rate and formation of surface crusts, which can affect erosion and cause additional land degradation (Ruiz-Sinoga & Romero-Diaz, 2010).

Effect of Agricultural Management Practices on Soil Properties

The more degraded status of the soils in agricultural fields and eucalyptus plantations in comparison to natural forests may also be indicative of the varying management practices of these different sites. Constant tillage and continuous cultivation for food crops and similarly the frequency of cultivation and harvest of plantation species such as eucalyptus can negatively impact the quality of soils (Singwane & Malinga, 2012; Poore & Fries, 1985). The

repeated cultivation of crops exhausts soils of their available nutrients, and the constant tending of agriculture fields leaves very little organic material on the ground to break down into available nutrients. Harvesting and site preparation within eucalyptus plantations can increase the loss of nutrients occurring, as well, via erosion, leaching, and transfer to the atmosphere (Raison et al., 1982). Monoculture forest activities such as eucalyptus plantations may prohibit nutrient recycling if the organic litter is frequently raked, therefore limiting the amount of organic material that can be broken down into organic matter in the soil (Zegeye, 2010; Zewdie, 2008; Davidson, 1989).

Stable or higher nitrogen and phosphorus levels in the eucalyptus plots in comparison to the agriculture plots, could also be explained by the significantly different quantities of organic matter, due to the obvious difference in leaf litter. Agricultural fields, which are cultivated and harvested more frequently than eucalyptus plantations, can lose a lot of additional nutrients and organic matter in its topsoil (Reganold et al., 1987). Though fertilizers can add large amounts of nitrogen and phosphorus to the soil in agriculture lands, it is expensive and generally uncommon to use in Ethiopia, except in cases of the government granting fertilizer subsidies. Where it is applied, fertilizer is also being actively used by the crops and at times cannot compensate quickly enough for the amount of nutrients being taken up by the crops, and the soil can become impoverished.

In cases in which it is present, the addition of fertilizer can simultaneously affect the pH of the soil. Soil acidity intensifies with exhaustive farming over a number of years with the use of fertilizers or manures (Ravina da Silva, 2012; Singwane & Malinga, 2012). The agricultural land surrounding all of the church forests sites have been cultivated for long periods of times, and where available, fertilizers and manure have been used to maximize crop production, potentially reducing acidic pH levels in agriculture plots relative to indigenous forest plots. Likewise, the afforestation of eucalyptus species can also acidify soil, as indicated in multiple studies in the past (Mengist, 2011; Berthrong et al., 2009; Faria et al., 2009). Eucalyptus species can influence the acidity of soil with their fast-growing ability, as growth is a function of nutrients extracted from the soil (Mengist, 2011; Lemenih et al., 2004, Turner & Lambert, 2000).

Eucalyptus Plantation Management Considerations

With significantly higher levels of organic matter, and comparable pH and nutrient levels to agricultural soils, this case study in the church forests of the northern Ethiopian Highlands offers that eucalyptus may not always be as detrimental to soil properties as previous studies have suggested. On the contrary, our findings are more consistent with studies suggesting that revegetation, even with an exotic plantation species, might have the potential to restore soil fertility through improvement in soil organic matter content, available nutrients, cation exchange capacity, increased biological activities as well as improvement in physical conditions of the soil (Mensah, 2015). The soil of eucalyptus plantations that were planted on land that was previously used for agriculture fared better than present-day agricultural land neighboring the present-day eucalyptus plantations. This suggests that it is possible that eucalyptus planting could have a positive influence on soil organic matter, and subsequently nutrient availability, in areas that have been previously degraded through the cultivation of food crops. Yitaferu et al. (2013) have made similar speculations, as they suggested that future conversion of eucalyptus to cropland could potentially increase the productivity of subsequent crops. Additionally, there is a practical application of using eucalyptus plantations as a manner of claiming land that cannot be overlooked in a country where land insecurity continues to be a problem. If the planting of a long-term species does not occur, the land will continue to be used for exhaustive agricultural purposes. Even if eucalyptus does not improve soil conditions, the management application of using eucalyptus plantations to put a halt to the continuous cultivation of agricultural land for crop production could have beneficial effects on organic matter and subsequently soil fertility in the area. The possibility of eucalyptus plantations rehabilitating degraded agricultural soils also provides a potential stepping stone for re-introducing indigenous species in mixed eucalyptus stands, especially leguminous species such as *Acacia* that form natural associations with eucalyptus.

However, in employing eucalyptus in whole or in part as a solution for improving previously degraded agricultural soils for either future crop use or forest restoration, there is also an array of management strategies to consider. The ultimate impact of eucalyptus on soils is a product of both species-specific characteristics and management-related decisions. In the case of eucalyptus plantations where the trees are regularly harvested after coppicing, as is common practice in northern Ethiopia and our church forest study sites, there is a

substantial loss of soil nutrients over time (Mengist, 2011). Both soil nutrient levels and soil pH tend to decrease after the first eucalyptus coppice, after the initial establishment of the eucalyptus plantation (Mengist, 2011). In comparison to other plantation type trees, like the indigenous *Juniperus procera*, eucalyptus species, specifically the species *Eucalyptus globulus* that is commonly found in the Ethiopian Highlands, typically have lower soil nutrient contents (Michelsen et al., 1993). With short cropping rotations and lack of intercropping, like with most other crops, the loss of nutrients must be made up for through the addition of fertilizers (Sunder, 1993). However, fertilizer use remains low in northern Ethiopia (Endale, 2011) and the need to purchase and apply fertilizers reduces the economic benefits of the species. A possible alternative to monoculture eucalyptus stands as a means of soil improvement is planting mixed stands, particularly with leguminous *Acacia* or *Albizia* trees. These species have been shown to form associations with eucalyptus species in their natural habitat (Zegeye, 2010), and *Acacia* trees in particular were observed in the eucalyptus plantations of several near church forests sampled. These trees' nitrogen-fixing capacity not only improves the ability of eucalyptus to grow, but can greatly improve soil fertility and nutrient availability.

Litter management is another consideration that shapes the ultimate soil impacts of eucalyptus production and alternative land-use management. Our study showed that there were significant correlations between litter on the ground, as reflected in canopy cover, and subsequent organic matter and nutrient levels. In many places across Ethiopia, especially more developed areas, the litter is collected as fuel or removed to reduce fire risk. Removal of the organic material that accumulates in eucalyptus stands in addition to disturbance by humans and livestock can compound the inefficacy of eucalyptus as a barrier to soil erosion (Zegeye, 2010; Palmberg, 2002; Sunder 1993). Additionally, litter collection further robs soils of nutrients (Dessie & Erkossa, 2011; Zegeye, 2010). If left alone, the accumulated litter under eucalyptus stands can be incorporated into the soil system to slow down runoff and improve soil infiltration, and shelter loose soil from being easily eroded (Zegeye, 2010, Teshome, 2009). Likewise, frequent cultivation and harvesting can make the soils more prone to runoff and erosion (Valentin et al., 2008), so limiting human disturbance and tillage in eucalyptus plantations could also prove to be beneficial for soil quality. However, some recent studies have shown that no-till practices may not have as positive of an impact on soil

organic matter and nutrient retention as previously cited (Janeau, et al., 2014; Mailapalli, 2013). Rather, conservation practices may be more dependent on the density and type of plant cover present, the soil's physical and chemical properties, the slope, and microbial utilization rates (Janeau et al., 2014).

Study Limitations

Eucalyptus may have some additional drawbacks that are not considered in this study. Though increased levels of organic matter should function as a source of food for soil microbes and thereby help enhance and control their activities (Brady, 1990), the toxins found in eucalyptus leaves and litter can inhibit microbes from getting the intake that they need (Dessie & Erkossa, 2011). Eucalyptus is alleged to affect the diversity and abundance of plantation understory species, including negatively impacting the productivity of crops through the release of allelochemicals from eucalyptus leaves and litter (Zegeye, 2010; Lisanework & Michelsen, 1993; Poore & Fries, 1985). These allelochemicals found in eucalyptus species can significantly reduce the seed germination, radicle elongation, and growth of crops (Lisanework & Michelsen, 1993). Eucalyptus plantations have also been proven to be unsuitable habitat for herbaceous annual species in the understory (Bean & Russo, 1989). The toxins present in the eucalyptus leaf litter can impede on the growth of forbs and grasses and decrease the natural biodiversity of the area.

Eucalyptus trees also take up a great amount of water from the soil and as a result can affect water availability, competing with crops and other vegetation for water and depleting the water table (Dessie & Erkossa, 2011; Zegeye, 2010; Jagger & Pender; 2003). Their high water requirements and deep root systems can give them a relative advantage over other plants in terms of water usage, which can be particularly damaging if eucalyptus trees are planted in arid regions (Jagger & Pender, 2003; Palmberg, 2002). Other studies argue that eucalyptus is in fact more efficient at using water than many crops and plants, consuming less water per unit of biomass produced (Joshi & Palanisami, 2011; Zegeye, 2010; Prabhakar, 1998; Davidson, 1989). However, it is acknowledged that the sheer density of eucalyptus planting can aggravate water depletion (Joshi & Palanisami; 2011), regardless of the species' potential efficiencies in water use.

Further research should be done to determine the overall impact of eucalyptus on surrounding soil and crops, particularly when taking into account effects on soil chemicals through its allelopathic qualities and water availability. Rigorous future experimental design in both lab and field settings could be used to assess the effect of eucalyptus on indigenous forest restoration. One possibility of an experiment to determine the allelopathic effects of eucalyptus on surrounding native vegetation would be to plant native seeds within eucalyptus plantations and at varying distances from eucalyptus plantations, noting which indigenous species are able to germinate and at what distances. To avoid confounding factors such as time since agricultural disturbance has ceased, a long-term experimental design in which agricultural plots are left untouched or planted with eucalyptus could also yield valuable results. After a period of allowing some agricultural plots to sit untouched by further agricultural use, and planting other agricultural plots with eucalyptus, indigenous species could be planted within all experimental plots and more conclusive results on whether or not eucalyptus improves soil conditions and could allow for indigenous forest restoration.

Conclusion

Soil quality and composition is a significant indicator of ecosystem health, and thus the impacts of smallholder eucalyptus planting on agricultural land can have great implications for larger development issues such as food security (Lal, 2007; Wiebe, 2003). The impacts of eucalyptus species on soil health remain hotly debated among scientists and development practitioners (Yitaferu et al., 2013; Jagger & Pender, 2003; Palmberg, 2002). Our results indicate that soils in eucalyptus stands surrounding Ethiopian Orthodox church forests are more acidic and have lower levels of organic matter and nutrients than soils in adjacent indigenous forest. However, there is also evidence that eucalyptus plantations exhibit higher organic matter and nutrient levels in comparison to nearby agricultural land, and no significant decrease in soil pH. With a small sample size and possible differences in management, it is not possible to say conclusively that the replacement of agricultural crops with eucalyptus stands in particular can improve soil quality. But these findings suggest that while eucalyptus stands are less favorable for soil quality than indigenous forest, eucalyptus planting could potentially benefit, or at least cause no additional harm to, soil fertility on land that has been previously degraded by extensive cultivation.

Though in our analysis eucalyptus stands appear to be more favorable than agricultural crops in terms of the four observed soil properties, this conclusion is not without significant caveats. There are other ecological effects of eucalyptus on agricultural land that are not tested in this study, but nevertheless are important considerations in eucalyptus systems, such as water use and the allelopathic impact of eucalyptus trees on neighboring crops and forests (Jagger & Pender, 2003; Palmberg, 2002; Lisanework & Michelsen, 1993; Poore & Fries, 1985). It should also be strongly emphasized that indigenous trees – as represented by both the interior and edge plots in this study – were found to play even more significant roles in soil quality, providing far greater advantages in all four studied characteristics than eucalyptus stands. Indigenous tree planting would also have less detrimental effects on other environmental properties in the long term, and therefore preference should be given to planting indigenous tree species where possible.

In addition to potential agricultural soil improvement, our study emphasizes the management considerations surrounding eucalyptus planting around church forests—some of the last fragments of natural forest in Ethiopia—where changes in soil fertility may have both short- and long-term implications for native forest regeneration. Further research needs to be done to understand the roles eucalyptus planting might play as part of integrative strategies for natural forest restoration in the degraded highlands of Ethiopia.

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CHAPTER FOUR: SOCIO-ECONOMIC DRIVERS OF *EUCALYPTUS SPP.* EXPANSION IN CHURCH COMMUNITIES IN THE NORTHERN ETHIOPIAN HIGHLANDS

Background

Despite the lack of empirical evidence and the uncertainty of net ecological effects of eucalyptus on its surroundings, eucalyptus continues to be expanded upon in Ethiopia by smallholder farmers, in the central highland landscape in particular (Yitaferu et al., 2013; Kidanu et al., 2005). Even in areas where the once productive land has been exhausted by the presence of eucalyptus, farmers insist on planting eucalyptus for the raw material and cash income it can provide (Chanie et al., 2013). Others argue yet that while eucalyptus may indeed have negative environmental influences, it is possible to manage and plant the species in a manner that is advantageous for both the people and the land (Zegeye, 2010). Although the observed ecological harms eucalyptus procures may have negative socio-economic consequences in the long run by degrading the land further, there is no denying that the immediate socio-economic impacts of eucalyptus can be positive for farmers and smallholders in rural Ethiopia.

Eucalyptus as a Natural Resource and Source of Income

Even with the potential negative ecological impacts of eucalyptus, the fact of the matter is that under the current status quo in Ethiopia natural forests continue to be converted to cropland, which in turn is converted to eucalyptus wood lots (Yitaferu, 2013). This is due to two primary reasons: eucalyptus has an attractive economic return with minimal labor and capital inputs, and there is fear that crop yield would be further reduced due to the adjacent eucalyptus woodlots that are already present, and thus to maximize economic gains one should follow the example of their neighbor and convert surrounding lands to eucalyptus woodlots (Yitaferu, 2013). Chanie et al. (2013) executed a study that showed experimentally that eucalyptus negatively impacted adjacent maize crops. This effect was reiterated by interview responses from twenty-five farmers that eucalyptus trees were indeed exhausting the once productive land. Despite the experiential corroboration of the experimental results, the respondents insisted that they would continue to plant eucalyptus because of the cash income generated (Chanie et al., 2013).

At present, eucalyptus species are produced commercially as a commodity for multiple uses. As a monoculture tree production with short rotation periods, eucalyptus plantations can be easily used for things like fuel wood and raw materials for pulp products (Mengist, 2011). The major factors driving farmers to plant eucalyptus were the increasing demand for wood products, the lack of wood from natural forests due to deforestation, their high rate of biomass production, ease of cultivation and adaptability, non-palatability to livestock, the decline in agricultural land productivity, and the decline in off-farm employment opportunities (Jenbere et al., 2011; Mekonnen et al., 2007). Eucalyptus has generated substantial revenue for rural households, yielding greater incomes than other exotic trees and even better than some agricultural crops (Chanie et al., 2011; Dessie & Erkossa, 2011; Amare, 2002). In addition, large-scale eucalyptus plantation projects provide employment for unskilled laborers, and support community development projects such as roads, schools, and health centers (Dessie & Erkossa, 2011). Regions with lower wage rates will likely be most attracted to tree planting investments, but high wage rate areas may also favor tree planting when compared to more labor-intensive activities (Jagger & Pender, 2003).

The ability to survive in low nutrient and low moisture environments relative to native species can also be critical to smallholders. In conditions under which crops are destroyed by drought or are unproductive on infertile land, eucalyptus trees, which are able to tap deep-water sources with their roots, are able to survive, thrive, and provide much needed income (Jagger & Pender, 2003). The resistance of eucalyptus to insects, pathogens and livestock, fire, climate variability and other risks also improve its ability to survive in harsh conditions. Eucalyptus that is planted as shelterbelts or windbreaks are also able to retain topsoil moisture by conserving surface ground water and reduce erosion, allowing existing crops to fare better in drying wind, high temperatures and intense rainfall (Jagger & Pender, 2003; Huchu & Sithole, 1993; Stiles et al., 1991).

Land Tenure Security

Another important contribution of eucalyptus, and other fast-growing monoculture plantation species, in Ethiopia has been in providing smallholders land tenure security. Property rights that are both secure and transferable have been identified as key elements in allowing economic diversification and growth (Deininger & Jin, 2005; Holden & Yohannes,

2001). With changing economic, political, and social conditions in Ethiopia, complex land rights and insecure land tenure throughout various political periods has obstructed the possibility of long-term, sustainable management of forests, and instead has allowed for extreme land degradation (Dessie & Christiansson, 2008).

As land is owned by the state, it is at constant risk of being repossessed and redistributed by the government (Assefa & Bork, 2014). By planting trees on their land, it is possible for farmers and smallholders to feel more secure in their claim on the land on which their trees are planted. Where tenure rights are ambiguous, trees can provide a means to prolong the current occupant's possession of a parcel of land (Bruce, 1989). Planting eucalyptus can decrease the incentive for land to be redistributed, as eucalyptus species can introduce deteriorating effects on the land, deeming it less desirable (Jagger & Pender, 2003). Farmers may also choose to plant eucalyptus to maintain the ownership of their rural land while living in urban areas (Dessie & Erkossa, 2011; Amare, 2002). Though securing ownership of land is not a benefit specific to eucalyptus species, eucalypts present an additional advantage by keeping the land productive while farmers are away, as the species requires minimal care. Additionally, eucalyptus poles have been extremely important in the construction industry of East Africa, and as a consequence, some banks have accepted eucalyptus stands as collateral for loans (Dessie & Erkossa, 2011).

Negative Socio-Economic Effects of Eucalyptus

Eucalyptus has been cited for a range of socio-economic problems, but few of these issues are unique to eucalypts. The major criticisms include the loss of agricultural land for food production, the reduction in rural employment due to the lack of labor-intensive activity, diversion of forest products form local markets to large-scale industrial users, and the transfer of public or common land to private corporations (Palmberg, 2002). All of these concerns foster the imbalance in the distribution of wealth in rural communities. Moreover, the high expectations have sometimes led to dissatisfaction when the wrong species was planted, or where there was insufficient planning and consultation prior to planting (Palmberg, 2002). Despite these flaws, which are not the result of special features of eucalypts, social pressures on household land usually dominate decision-making and thus

poverty rates and land tenure insecurity continue to drive the planting of eucalyptus both on a large scale and on smallholder lots (Jagger & Pender, 2003; Holden & Yohannes, 2001).

Planting Eucalyptus as a Form of Church Forest Restoration

Sacred natural sites are likely the oldest form of habitat protection and conservation. Many sacred natural sites exist inside officially protected areas, but many more form a "shadow" conservation network that have only recently been recognized for their conservation potential (Dudley et al., 2009). Additionally, the institutional goals of the Orthodox Church line up well with conservation ambitions. Tree seed collection, traditional medicine collection, and using the forest as a space for reflection are generally permitted uses of the church forest, while collection of fuel wood, construction wood, and fodder are generally forbidden for the community (Bongers et al., 2006). There is a high level of trust and respect in the local community in regards to the church organizations and their rules, making church forests likely sites to succeed in enforcing conservation guidelines (Bongers et al., 2006). Because of these beliefs, church forests have begun to be perceived as beacons of conservation and a hopeful start for forest restoration projects.

However, recent restoration efforts have increased efforts to reforest areas with exotic plantation species, such as eucalyptus. In a paper by Bongers et al. (2006), three different modes of restoration of a degraded ecosystem are outlined: natural, intermediate and domesticated (Figure 4.1). Natural restoration, using indigenous species, recreates the original structure of the forest and maintains high biodiversity. Sometimes, plantations may be mixed with natural species, creating an intermediate ecosystem with more structural development and diversity than domesticated ecosystems, but less still than naturally-restored ecosystems. To a greater extreme, domesticated restoration relies on exotic species, such as eucalyptus, and creates a simple structure with low biodiversity. However, domesticated restoration does result in high productivity, as exotic plantation species are often fast-growing. This characteristic has motivated the spread of plantations through private initiatives and community-based plantations, in both the surroundings of towns as well as rural areas, where the demand for wood resources has increased at alarming rates (Mekonnen, 2016). Moreover, plantations have become a main source of income for many people. This has influenced many church members to prefer planting eucalyptus to other tree

species. In a survey of 122 followers surveyed in churches of the South Gondar region, 32.8% of respondents preferred eucalyptus to be planted in their church forests to indigenous species (Bongers et al., 2006).

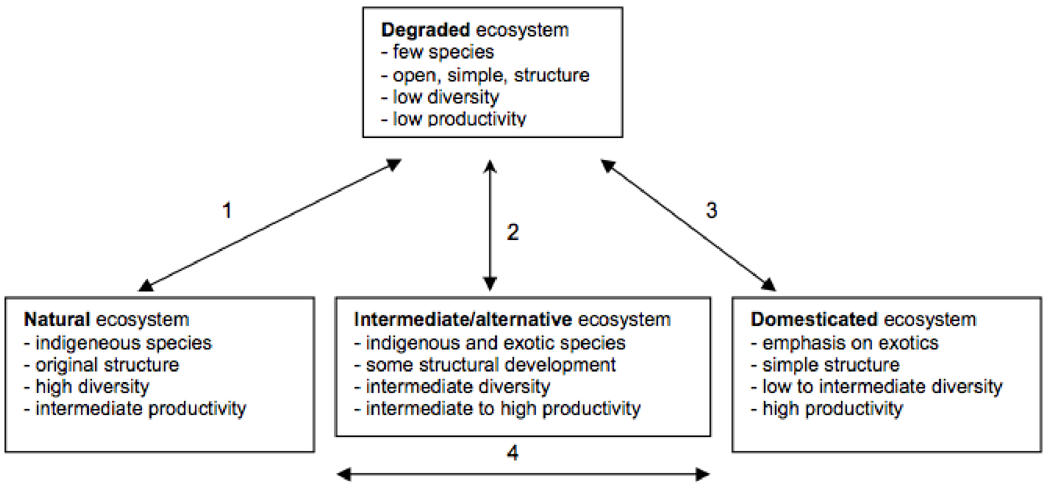

Figure 4.1. The various modes of restoring a degraded forest ecosystem (Bongers et al., 2006).

The recorded attitudes towards planting eucalyptus have been perceived to be generally positive in developing nations where natural resources are scarce. Similarly, church communities have benefitted from the growth of eucalyptus species on church properties. If permissible by the church, eucalyptus can act as a source of fuelwood or construction wood for community members (Bongers et al., 2006). Eucalyptus also serves as an abundant mode of income for the church. This thesis chapter seeks to identify the heterogeneous mix in attitudes toward eucalyptus plantations in church forests and analyze the drivers of eucalyptus-planting within church forest communities.

Methods

Study Sites

In the summer of 2015, household surveys and focus groups with church leaders and community members were conducted at six different church forests in South Gondar and West Gojjam zones in the Amhara Region. The churches visited were Debrasena Mariam, Woji Abuna Aragawi, Abalibanos, Alember Quosquam Mariam, Robit Bata, and Gombat Michael.

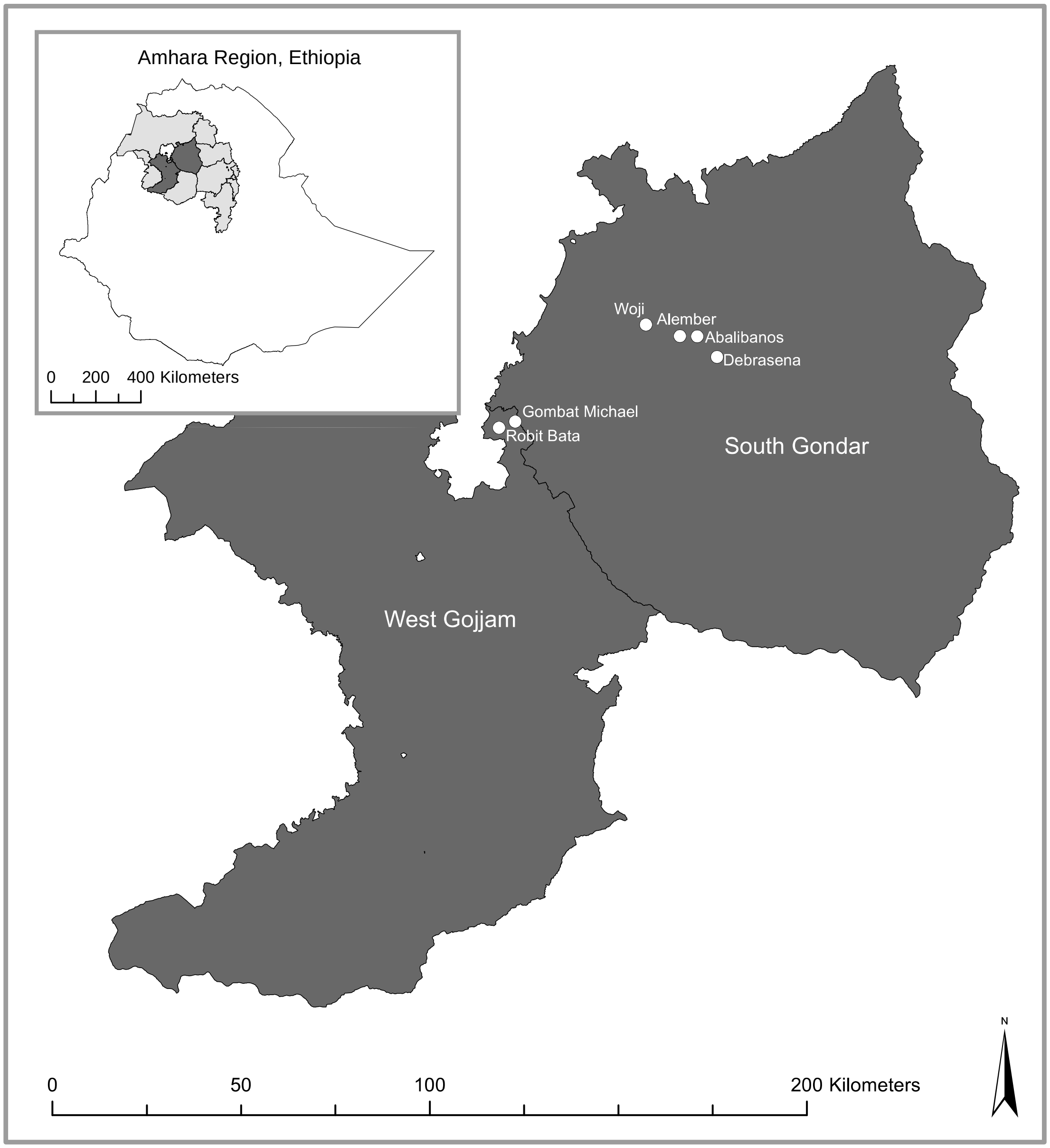

Figure 4.2 Map of South Gondar and West Gojjam zones in the Amhara region. The church forests and visited for household surveys and focus groups in each zone are represented by the points.

Household Survey

Household surveys were administered in six church forest communities in the Amhara Region. Over the span of four weeks in the summer of 2015, 138 subjects were interviewed near Debrasena Mariam, Woji, Alibanos, Alember, Robit Bata, and Gombat Michael (though a varying number of respondents answered each question). Survey questions were written in English and translated into Amharic, and administered by Ethiopian students from Debre

Tabor University. Respondents were randomly selected as they were working outside their homes or walking out of the church.

The survey consisted of basic demographic information, such as age, gender, whether the individual was the head of their household, education level, occupation, monetary income, and livestock owned as a substitute for income (Table 4.1). Additionally, the survey asked if the respondent held a position of leadership at his or her church. The respondents were then asked a series of questions related to the trees in their church forest, the benefits gained from the forest, and any rules pertaining to forest use.

Table 4.1. Summary of household survey data including the sample size, sex, average age, primary occupation, average income, average number of livestock, and average area of land owned among the six different church forest communities (Debrasena, Woji, Abalibanos, Alember, Robit Bata, Gombat Michael).

	Debrasena	**Woji**	**Abalibanos**	**Alember**	**Robit Bata**	**Gombat Michael**
Sample Size (n)	29	25	12	19	24	29
Sex	70% Male 30% Female	68% Male 32% Female	67% Male 33% Female	74% Male 26% Female	88% Male 12% Female	74% Male 26% Female
Median Age Range	40-49	40-49	40-49	40-49	40-49	40-49
Average Number in Household	6.7	5.6	4.8	5.3	5.2	5.4
Head of Household	92%	96%	92%	95%	96%	96%
Occupation	59.1% Farmer 27.3% Farmer and Herder 4.5% Religious Service 4.5% Day Laborer 4.5% Merchant	54.2% Farmer 33.3% Farmer and Herder 8.3% Merchant 4.2% Religious Service	40% Farmer 60% Farmer and Herder	47.1% Farmer 41.2% Farmer and Herder 5.9% Merchant 5.9% Day Laborer	57.1% Farmer 33.3% Farmer and Herder 9.5% Merchant	46.2% Farmer 42.3% Farmer and Herder 3.8% Herder 3.8% Merchant 3.8% Government
Education Level	41.7% Adult school 25% Elementary School 21% None 12.5% Other	24% Adult School 24% Elementary School 24% None 8% Other	16.7% Adult School 16.7% Elementary School 66.7% None	26.3% Adult School 26.3% Elementary School 36.8% None 10.6% Other	33.3% Adult School 41.7% Elementary School 25% None	6.9% Adult School 3.4% Elementary School 62.1% None 24.1% Religious School
Median Income (Birr)	10,000 to 20,000	10,000 to 20,000	5,000 to 10,000	10,000 to 20,000	10,000 to 20,000	5,000 to 10,000
Average Number of Livestock	5.3	6.5	5.8	NA	6.5	8.8

In addition to asking about church forest use, governance, and conservation, four questions were directed at the respondent’s perception of eucalyptus as a species to grow in their church forest. Questions included the uses of eucalyptus, whether or not the amount of eucalyptus in their church forest is sufficient, and who makes decisions about and who is

allowed to use the eucalyptus on the church compound. Risk aversion questions were also posed to evaluate how open to risk respondents were, and how that might correlate to their opinions of eucalyptus being planted over slow-growing indigenous tree species.

Focus Groups

Focus groups were also conducted at each of the six churches. At each church, three different focus groups were conducted – one with priests, one with farmers, and one with women. For the majority of the focus groups, there was an English enumerator, an American student from the Colby College REU, and an Amharic enumerator, a student from Debre Tabor University or a master's student from another Ethiopian university, present. Each focus group had 6-8 participants, and followed a protocol for questions and participatory activities. The participants were asked to discuss amongst themselves each of the topics and questions presented, and the conversation was recorded, written down in Amharic, and translated to English.

In all of the focus groups, with priests, farmers, and women, the participants were asked very broadly about the advantages and disadvantages of eucalyptus. Because of time constraints and different survey interests, only the famers were presented with more specific questions about eucalyptus, because they are generally the ones planting and growing eucalyptus trees as a crop or plantation species on their own properties. In an effort to better understand regeneration capabilities and potential for indigenous seedling growth amongst eucalyptus stands, farmers were asked about harvest rates, presence of indigenous seedlings in eucalyptus stands, presence of eucalyptus seedlings in the indigenous forest, and eucalyptus regeneration.

Additionally, in the famer and women focus groups, the participants were asked to participate in an activity in which they would rank their preference for six different church forests based on aerial maps. The first time around, they were simply shown the maps with no information given, and asked to rank the forests and explain their choices (Figure 4.3). The presence of eucalyptus in each map was then disclosed to the participants, and they were asked if they would like to change their rankings (Figure 4.4). If they did, they were asked to re-rank the church forests and again, explain their decisions.

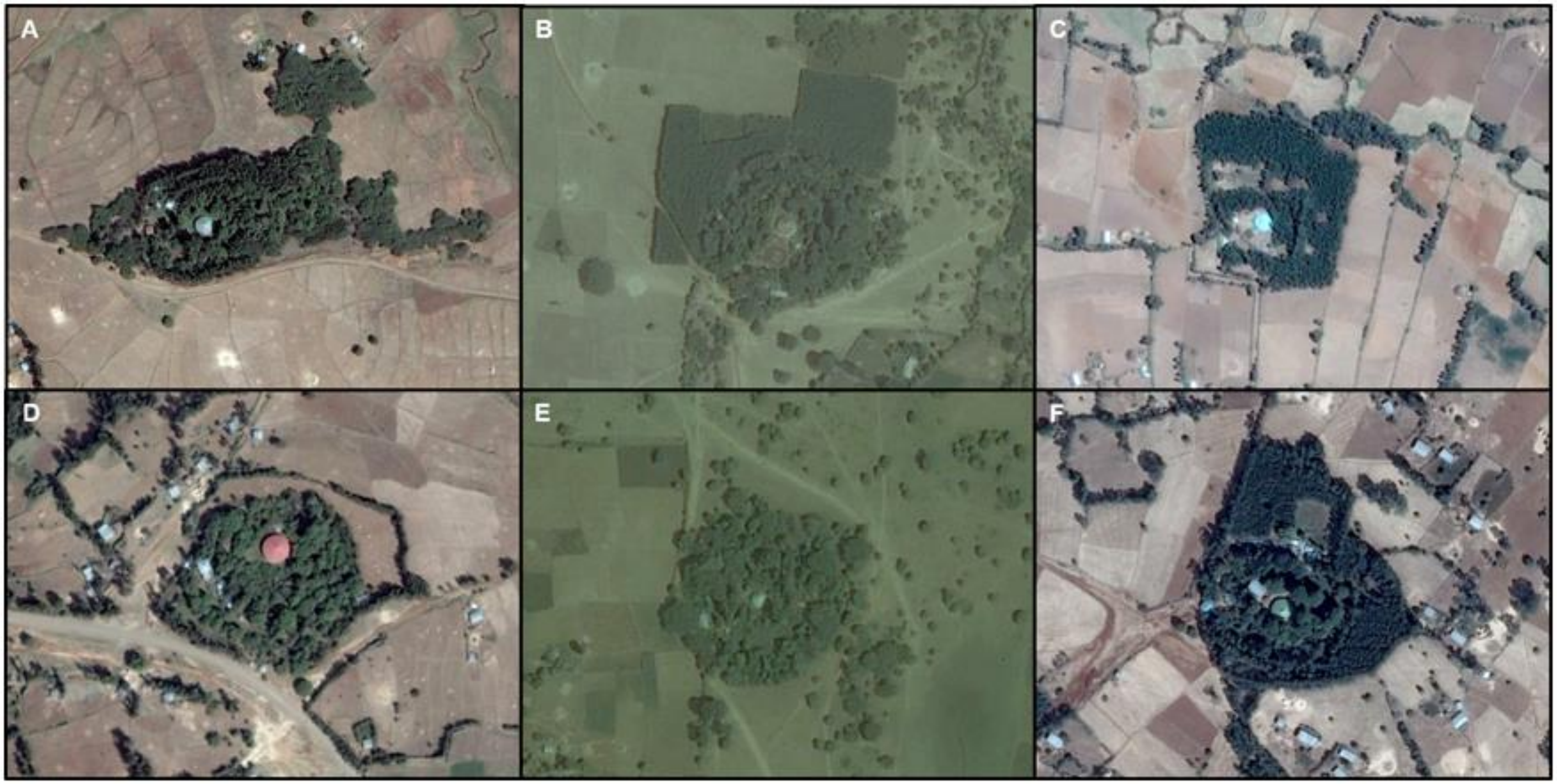

Figure 4.3. Map activity images; 6 church forests were chosen to represent varying degrees of eucalyptus presence in church forests: A) eucalyptus interspersed in the forest, B) a large eucalyptus plantation outside of the forest, C) eucalyptus making up the entire church forest, D) eucalyptus forming a boundary around the indigenous forest, E) no eucalyptus in the church forest, and F) a eucalyptus plantation that borders more of the indigenous forest than Map B.

Figure 4.4. In this figure, the eucalyptus areas from the map activity images are outlined in white for greater clarity in identifying eucalyptus patches.

Priest Meeting Workshop

A priest meeting was hosted at the Deb Anbesa Hotel and Bata Lemariam church in Bahir Dar. Similar to the focus group protocols, the priests in attendance were split into six groups of 8-10, each with an English and Amharic-speaking enumerator. Amongst a larger array of questions regarding the current state and future of church forest conservation, priests were asked to participate in the same eucalyptus map preference activity as the farmer and women focus groups.

Additional Data

Additional data on the presence and abundance of woody tree species was taken across 28 churches in the Amhara Region, from the work of Wassie et al. (2010). Detailed species composition and abundance data were collected from 28 forests spanning a range of sizes, altitudes, and grazing and tree harvesting intensities. The sample forests vary in areas from 1.6 ha to 100 ha, and are located at altitudes ranging from 1816 m to 3111 m. In each forest, 10-by-10 meter plots were established at 100m intervals along transects. The number of transects, and therefore plots, varied with forest size. To account for greater sampling effort in larger forests, species richness data were rarified to seven plots, the minimum number of plots sampled in any forest (Wassie et al. 2010).

Results

Eucalyptus Presence and Abundance

Using data from Wassie et al. (2010), eucalyptus species were observed in 11 of the 28 (39.3%) studied church forests (Figure 4.5), close to the figure of 33.4% of the 2,560 church forests studied using satellite imagery in Chapter Two. In comparison to indigenous species, such as *Juniperus procera* and *Olea europaea,* eucalyptus species were found in relatively few church forests. *Eucalyptus globulus* was found in 6 forests, and *Eucalyptus calmadulensis* was found in 7 forests. However, *Eucalyptus calmaldulensis* was the fourth most abundant tree species across all church forests, with a mean of 1.02 individuals in each church forest plot, following only *Coffee arabica*, *Juniperus procera*, and *Erica arborea*. *Eucalyptus globulus* was the fifth most abundant tree species with a mean of 0.825 individuals across all church forest plots. This suggests that though eucalyptus is found in

only a small portion of church forests, where it is found it may often be planted in high abundance.

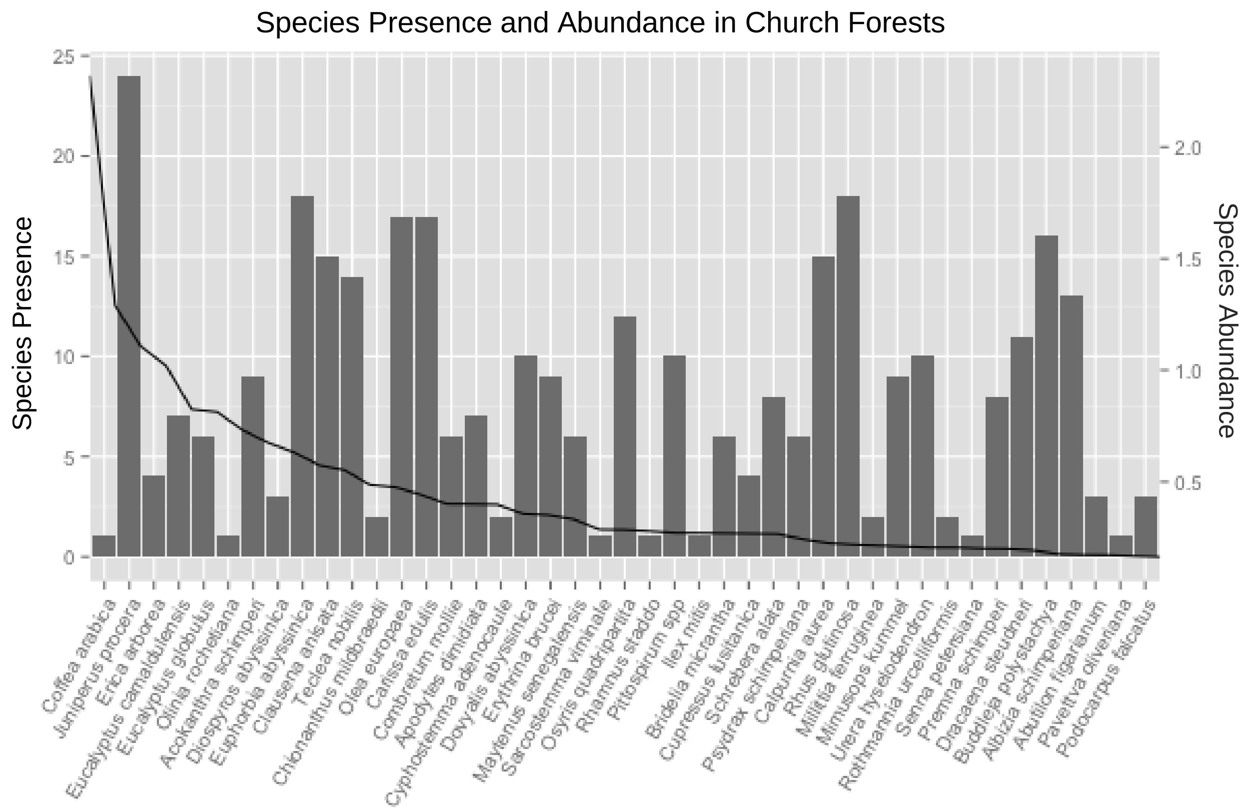

Figure 4.5. This figure displays the presence and abundance of each species across the 28 surveyed church forests. On the left axis, species presence indicates the number of churches that the species was observed in. On the right axis, species abundance indicates the mean number of individuals found across all 13 church forests.

Attitudes and Preferences as Told by Household Surveys

The preference of eucalyptus relative to indigenous species and the extent to which eucalyptus is regarded in net positive or negative light were assessed through two basic questions in the household survey: "What trees should be planted in the church forest (name five species)?" and "What do you think about the amount of eucalyptus in the church forest? Is there too much, too little, or just the right amount?"

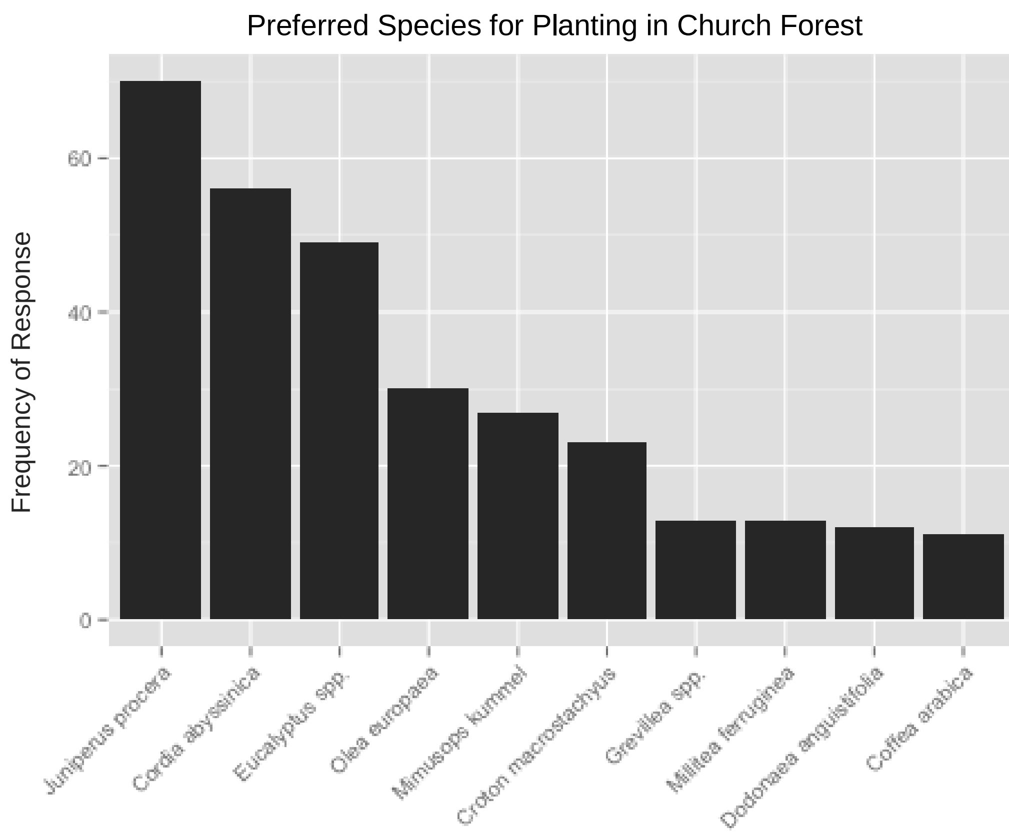

Figure 4.6. The ten most frequent responses when asked which tree species the respondents preferred for planting in the church forest. Eucalyptus ranks as the third most frequent response.

The ten most popular trees identified as preferred species for planting in church forests were *Juniperus procera*, *Cordia abyssinica*, *Eucalyptus spp.*, *Olea europaea*, *Mimusops kummel*, *Croton macrostachyus*, *Grevillea spp.*, *Militea ferruginea*, *Dodonaea anguistifolia,* and *Coffee Arabica* (Figure 4.6). Eucalyptus was given as the third most frequent response, with 39.5% of respondents saying that eucalyptus trees should be planted in the church forest. *Juniperus procera* and *Cordia abyssinica* were the only two species that were preferred by a greater percentage of respondents, with 56.5% and 45.2%, respectively.

The majority of respondents (60.2%) thought that there could be more eucalyptus in their church forest. 22.3% of respondents thought that there was too much eucalyptus in their church forest, and 17.5% of respondents thought that there was just enough eucalyptus in their church forest. These results did not differ significantly between many of the measured demographics including age, income, church position (leader or member), occupation, or

wealth. However, there was a statistically significant difference in the percentages of responses from male and female respondents (Chi-square, $p < 0.05$).

There was also a statistically significant difference in the way people felt about the amount of eucalyptus in their church forests depending on if they were more or less economically risk-averse (Chi-square, $p < 0.05$). Risk aversion was determined by an individual's preference of receiving a smaller amount of money (100 birr) immediately, or waiting one month to receive a larger amount of money (125 birr). Respondents who were more risk-averse, answering that they would rather receive a smaller sum of money immediately, were more likely to want more eucalyptus in their church forest, with 68.1% of respondents answering that there was not enough eucalyptus in their church forest. On the other hand, amongst respondents who were less risk-averse, and willing to wait a longer amount of time for a larger promised monetary unit, only 40.0% wanted more eucalyptus in their church forest.

Respondents were also asked in the household survey to list the uses of the church forest (as a whole), as well as the uses of exotic eucalyptus trees in or around the church forest. The most commonly stated use of the church forest was for worship, with 81 respondents (64.8% that answered this question) providing this answer (Figure 4.7). Collection of fruit, honey, water, medicine, and seeds and seedlings were also stated uses of the church forest. Construction and fuel wood were also listed as uses of the church forest, but with low frequencies of 3 and 4 people, respectively. A few individuals listed beauty and burial as additional uses of church forests.

Eucalyptus, on the other hand, was primarily used for income generation and construction wood. Income generation for the church was the most popular stated use of eucalyptus, with 85 respondents (66.9%) providing this answer. 73 individuals (57.5%) gave construction wood as a use, with 7 of those people specifying that eucalyptus was used only for construction on the church compound. Additional uses of eucalyptus in the church forest included fuelwood, charcoal, acting as a boundary for the church forest (both aesthetically and to keep illegal activity out), and preventing soil erosion.

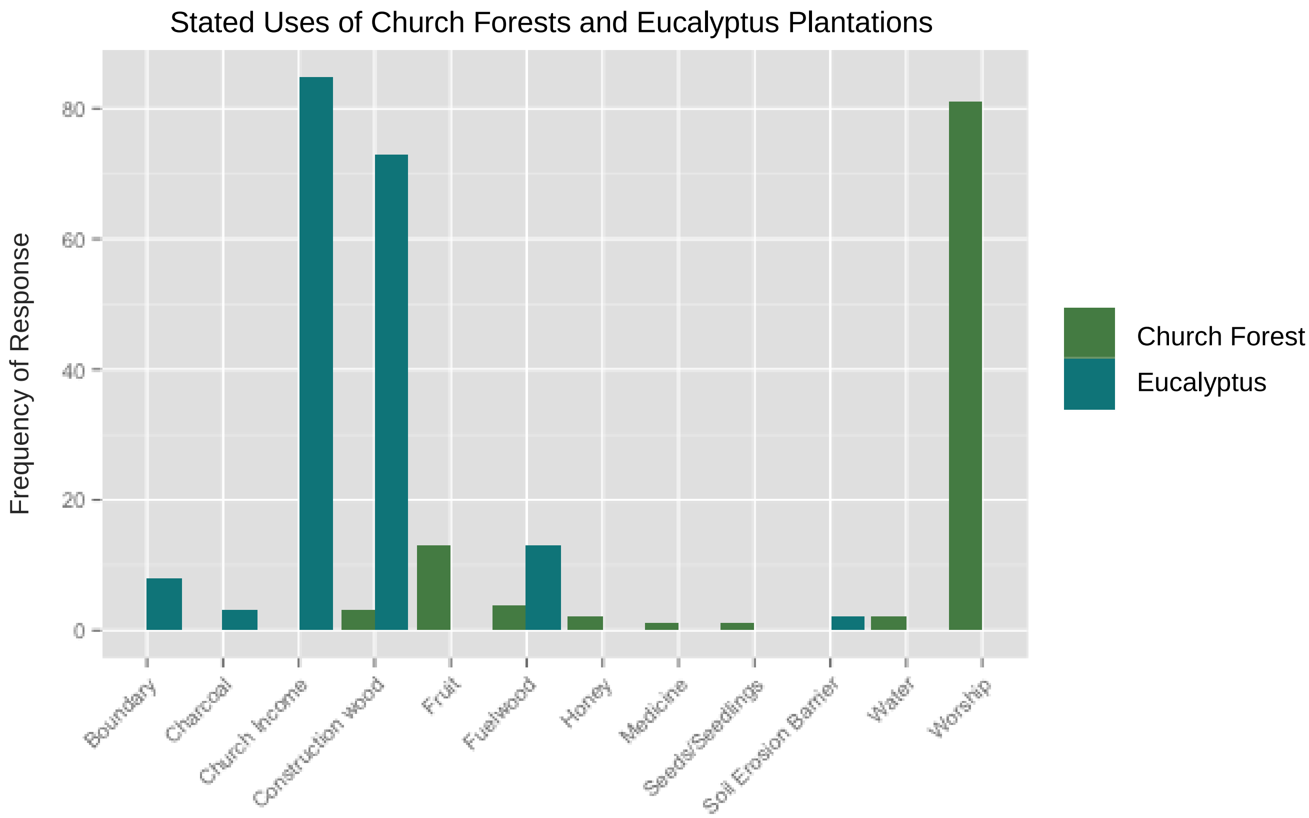

Figure 4.7. The uses most commonly stated by respondents of church forests and eucalyptus plantations. The uses of the church forest are illustrated in green, and the uses of the eucalyptus plantations are illustrated in blue.

The uses of the church forest, for worship and the collection of non-timber forest products, were stated to be permissible for all church members, either freely or with permission from church leaders, by 56.4% of respondents. However, the vast majority of eucalyptus uses, typically for construction and income, were for strictly church use only, as indicated by 50.5% of the respondents. Another 26.3% stated that eucalyptus use was allowed by all church members with permission from priests or church leaders, but also that taking eucalyptus for products like construction wood would often incur a fee to be paid to the church.

According to 71.9% of the respondents, the church committee makes decisions regarding eucalyptus. Another 14.1% reported that the general church community makes these decisions. Only 7.00% of individuals reported that decisions regarding eucalyptus are made by the priests alone.

As previously mentioned, the final piece of information gathered from the household survey was a simple risk aversion analysis. Respondents were asked a series of questions regarding their inclination to accept a smaller sum of money immediately, or to wait a period of time before receiving a larger sum of money. 65.1% of respondents were more likely to take 100 birr (the equivalent of roughly 5.00 USD) today than wait a month to receive 125 birr. 57.0% of respondents were more likely to take 100 birr today than wait a month to receive 150 birr. Many respondents who chose to receive immediate compensation indicated that their decision was made based on the need for money in the present, and they trust in God and their faith to take care of them in the future. Other respondents stated that they simply did not trust that they would receive that amount of money in a month's time.

Anecdotal Evidence from Focus Groups and Map Activity

From the focus groups, using information primarily from the map activity, data was collected about how church community members perceive eucalyptus expansion in church forests in a group setting. Most commonly, church forests were said to be ranked by size, tree density, or even "greenness" in the first round of ranking, when eucalyptus patches were yet to be revealed. Churches A, B, and F were most likely to receive high rankings based on this set of criteria (Figure 4.3, Figure 4.8)

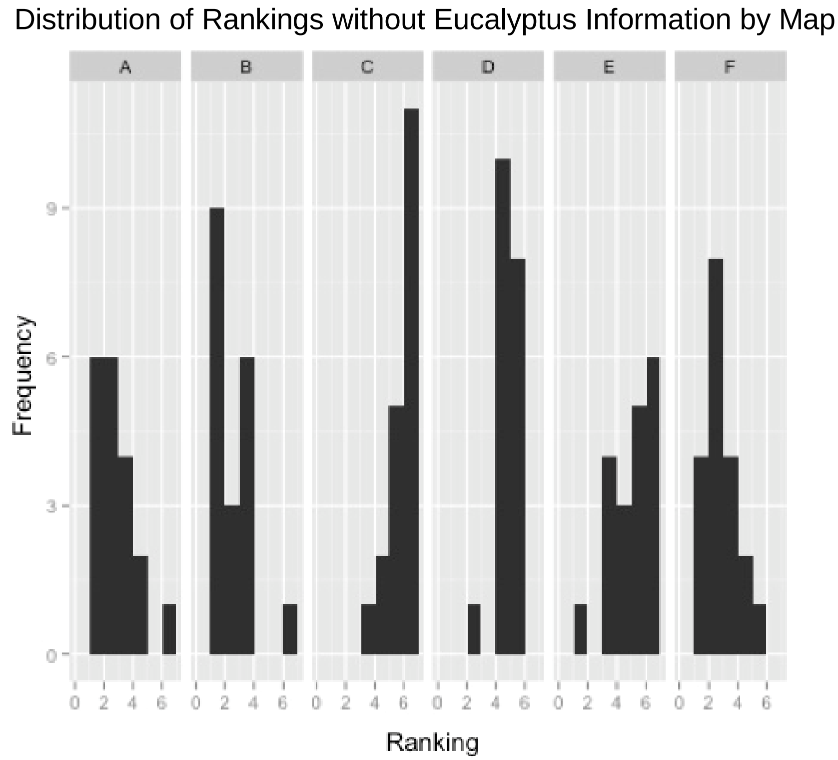

Figure 4.8. The rankings of the map activity church forests, with "1" indicating the "best" forest, and "6" indicating the "worst" forest, prior to providing the focus groups with eucalyptus information.

Eucalyptus patches in the church forests were then identified, and focus groups were given the option to re-rank the forests and provide a new explanation as to how they were ranked (Figure 4.4). Interestingly, all of the women focus groups chose not to re-rank the forests after eucalyptus was revealed. At Woji, the women noted that eucalyptus trees are a great source of income, house construction, and fuelwood. They also noted that there might be ecological disadvantages, but ultimately did not have any preference of indigenous trees over eucalyptus trees stating that "eucalyptus are trees, they still add area to the forest." Likewise, the women focus group at Abalibanos stated that "eucalyptus is useful and has advantages for the church," and for this reason they did not prefer indigenous tree cover to eucalyptus cover. At Debrasena, the women even considered eucalyptus expansion as a method of restoration, again viewing eucalyptus as a positive addition to the church forest.

On the other hand, the vast majority of priest and farmer focus groups, at our six studied church forests as well as at the priest meeting, chose to re-rank the forests after learning of the varying degrees of eucalyptus expansion at our six map activity church forests (Figure

4.9). Both groups prioritized the amount of indigenous tree cover in the church forest over the area of eucalyptus. Map C and F, which are completely eucalyptus and mostly eucalyptus, respectively, were widely ranked as the worst forests, and Maps A, B, and E jumped up in rankings. Map E, which is a smaller but completely indigenous forest, was previously ranked very low, but after identifying the eucalyptus in each church forest, many groups gave it a good ranking.

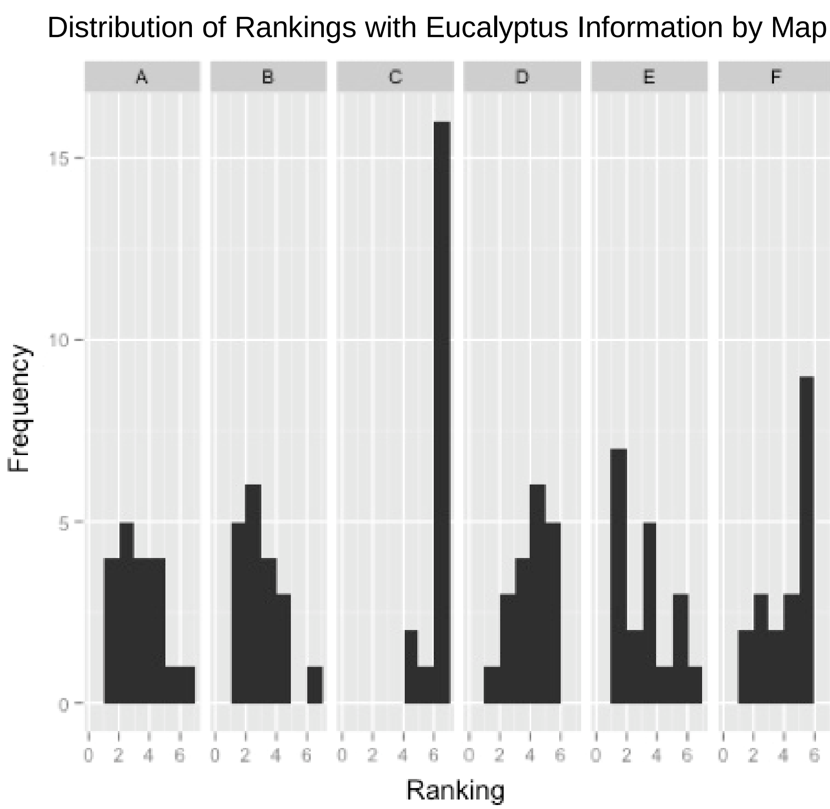

Figure 4.9. The rankings of the map activity church forests, with "1" indicating the "best" forest, and "6" indicating the "worst" forest, after providing the focus groups with eucalyptus information.

Farmers and priests had different reasons for prioritizing indigenous trees over eucalyptus trees in the church forest. Farmers primarily gave reasons against eucalyptus, such as decreasing the fertility of the soil and water resources and shading out their crops. Priest focus groups cited the values of conserving the indigenous forests as a reason to prioritize indigenous trees over eucalyptus expansion. Additionally, they too recognized the negative effects of eucalyptus, including toxicity to crops and indigenous trees, drying up the

landscape, and the replacement of natural forest. Despite these negative consequences, they admitted that ultimately the economic benefits of eucalyptus were great and for that reason their church forest would continue to let the eucalyptus plantations grow.

Discussion

Eucalyptus species are not as widespread as many of the indigenous species observed. The small number of churches that have planted eucalyptus is unlikely to be due to environmental constraints, as eucalyptus trees are capable of growing across a wide range of environmental niches. Rather, the small number of church forests in which eucalyptus are found may suggest that some church leaders or community members prefer other indigenous tree species over exotic plantation species in their forests, or that there are perceived negative consequences of eucalyptus that deter churches from planting them. However, the results also show that eucalyptus trees are relatively abundant in the forests in which they are found. This suggests, as cited in literature, that eucalyptus species are capable of growing quickly and in large quantities without being labor-intensive or incurring a great monetary cost (Yitaferu, 2013; Jagger & Pender, 2003). Further analysis of household surveys and focus groups attempts to tease apart community perceptions of the benefits and negative impacts of eucalyptus and resultant attitudes and preferences in planting eucalyptus in church forests.

The contrast between focus group and household survey responses indicate that the social norm continues to favor indigenous tree planting over eucalyptus planting, as indicated by the group responses to prioritizing indigenous species, while the household survey results showed that economic motives still influence individuals to allow eucalyptus planting, as it serves as a great source of income and construction wood for the church. In a focus group setting, there may be a greater social pressure for individuals to show their dislike of eucalyptus. This shows that the social norm amongst most church communities is to continue to voice one's preference of indigenous trees over eucalyptus. The attitude of the women focus groups towards eucalyptus, which seems to favor the positive economic benefits of eucalyptus over indigenous trees, could be because women generally spend less time experiencing the direct effects of eucalyptus on crops, like farmers, or on surrounding natural forests, like priests.

Though farmers and priests voice their concerns over eucalyptus expansion in the focus groups, an overwhelming majority of household survey respondents, including many farmers and some priests, indicated that there was not enough eucalyptus in their church forest. This suggests that individual economic motives continue to drive the expansion of eucalyptus. However, these motives are not necessarily out of sheer preference, but rather, due to economic need. It is clear through the risk-aversion questions in the household survey that the majority of respondents (65.1%) would rather have a smaller monetary sum now than wait any period of time for a larger sum of money. Many of these individuals stated that they simply needed the money immediately because they were struggling in the present. How could they worry about how much money would be offered to them in a month's time if they do not even have enough money to feel secure right now? This implies that with the majority of our respondents there is great economic concern, and therefore the growth of a plantation species, which are more likely to promise short-term economic return in comparison to indigenous tree species. This is observed in the fact that there was a statistically significant difference between respondents who were more or less economically risk-averse, with more risk-averse people, who were also typically poorer, more likely to want eucalyptus over indigenous trees.

The stated uses highlight the different values that church forests and eucalyptus plantations hold in the eyes of the church community members. It is clear from Figure 3.6 that church forests and eucalyptus plantations serve very different purposes in the church compound. While church forests have a lot of provisional services, mostly non-timber forest products, they primarily serve as a place of worship. It appears that the cultural service of the church forest is greater than the use value; people simply appreciate the presence of the forest, as it has deep roots in religion and culture. Eucalyptus on the other hand, exists in and around church forests primarily to supply construction wood and income for the church. Regardless of any potential environmental hindrances, the use value of eucalyptus plantations is undeniable and continues to drive eucalyptus expansion in and around church forests.

Conclusion

The recorded attitudes towards planting eucalyptus have been perceived to be generally positive in developing nations where natural resources are scarce. Similarly, church

communities have benefitted from the growth of eucalyptus species on church properties, as a source of fuelwood, construction wood, and income for the church (Bongers et al., 2006). However, results from the focus groups suggest that there are different attitudes towards eucalyptus plantations in church forests. Specifically, farmers, who bear the brunt of the environmental impacts on their crops, and priests, who may be more concerned with church forest conservation than others, have made it clear that there is a preference for indigenous tree species over eucalyptus plantations.

However, though participants were aware of the negative consequences of eucalyptus through their own experiences, there is still a tremendous desire for eucalyptus plantations, as demonstrated by the results of the household surveys. The ability of eucalyptus to produce large quantities of construction wood, fuelwood, and charcoal makes eucalyptus an appealing species to plant. Even within church forests, where indigenous trees are of great religious and cultural value, priests have indicated that the economic benefits of eucalyptus are simply too great to resist in a time when income and wood supply shortages are frequent. Economic constraints have led to continued domestic restoration using eucalyptus in church forests.

SYNTHESIS AND FUTURE RESEARCH OPPORTUNITIES

Deforestation remains a prominent issue in Ethiopia, with the total amount of forest cover across my three study zones of the Amhara region having had decreased in the last three decades, despite claims that reforestation programs have been effective (Assefa & Bork, 2014; Jagger et al., 2004). Primarily due to economic constraints and a lack of natural resources, eucalyptus continues to be expanded upon. Even in church forests, where local traditions and religious philosophies encourage conservation of the natural world and reforestation rates have surpassed that of regional forests in the last 30 years, the economic advantages of eucalyptus is still taking precedent in some churches over the restoration of indigenous forest. Priests, farmers, and women alike claim that there are many advantages to planting eucalyptus in their church forests, namely as a source of income, construction wood, and fuelwood, and that the economic benefits are far too great to dismiss.

With the almost certain future expansion of eucalyptus, it then becomes most important to understand the ecological consequences of eucalyptus. Much of the existing literature cites eucalyptus as using disproportionate amounts of water and rapidly depleting soil nutrients, among other negative environmental impacts (Tadele et al., 2014; Yitaferu et al., 2013; Jagger & Pender, 2003). However, this thesis shows that eucalyptus may actually not be as harmful to soil fertility as areas that have been heavily degraded by exhaustive agricultural use. With further research, it is possible that eucalyptus could potentially serve as a stepping stone for natural forest conservation and restoration, as 1) eucalyptus could help lessen the need to deforest more indigenous forest for timber and revenue, 2) it is possible that eucalyptus could improve soil conditions in places previously degraded by agricultural use to a condition in which native tree species could then regenerate and grow (with significant caveats and management stipulations), and 3) eucalyptus could have a nursing effect on shade-intolerant indigenous species by providing a reduced canopy cover compared to dense, indigenous forest.

Preliminary results from focus groups found that many native trees, most notably leguminous trees such as *Acacia* species, are found in natural association with eucalyptus stands at the church forest study sites. This presents an opportunity to study the ability of native trees to flourish in areas of current or past eucalyptus growth, and how these

indigenous species may impact soil quality in conjunction with the already-present eucalyptus. Extirpating an area of eucalyptus and planting native seedlings to see if they are then able to grow and regenerate could also yield valuable results. If the results from these future studies prove to be positive, there is a plausible application that could be used in the restoration of church forests. However this conjecture comes with the caveat that soil is only one of many ecological factors that needs to be assessed, and therefore much more research needs to be done on the ecological impacts of eucalyptus. Additionally, more research needs to be done on the long-term ecological and socio-economic effects of eucalyptus on surrounding agricultural land and indigenous church forest fragments.

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APPENDICES

Appendix A: Determining an NDVI Cut-Off Value

The following R-script was created using R version 3.1.2 (2014-10-31) “Pumpkin Helmet.”. The goal of this script was to extract the NDVI values within the polygons traced in Google Earth to determine a cut-off NDVI value for distinguishing between indigenous forest, eucalyptus plantation, and non-forest.

```
##Load libraries
library(raster)
library(rasterVis)
library(rgeos)
library(rgdal)
library(GISTools)

##Load the NDVI file
NDVI.2014 <- raster("2014NDVIproj.tif")

##Define color scheme for displaying raster layers
myTheme <- rasterTheme( region=brewer.pal('RdYlGn', n=10))

##Indigenous forest only NDVI summary##
#Load the indigenous only layer
indig <- readOGR(".", "OnlyIndigenousFINAL")

#Add the point layer to the raster.
p1 <- levelplot(NDVI.2014, par.settings=myTheme,  margin=FALSE)

#Add the polygon layer to p
p1 + layer(sp.polygons(indig, pch=20, cex=1.3))

#Collect all NDVI values that fall within polygon into a list.
NDVI_indig <- as.vector( extract(NDVI.2014, indig, na.rm=TRUE))

#View boxplot and summary of all NDVI values
boxplot(unlist(NDVI_indig))
summary(unlist(NDVI_indig))

##Eucalyptus only NDVI summary##
#Load the eucalyptus only layer
euc <- readOGR(".", "EucalyptusFINAL")

#Add the point layer to the raster.
p2 <- levelplot(NDVI.2014, par.settings=myTheme,  margin=FALSE)

#Add the polygon layer to p
p2 + layer(sp.polygons(euc, pch=20, cex=1.3))

#Collect all NDVI values that fall within polygon into a list.
NDVI_euc <- as.vector( extract(NDVI.2014, euc, na.rm=TRUE))

#View boxplot and summary of all NDVI values
boxplot(unlist(NDVI_euc))
```

```
summary(unlist(NDVI_euc))

#Side by side boxplots of indig and euc NDVI values
boxplot((unlist(NDVI_indig)/1000), (unlist(NDVI_euc)/1000),
        horizontal=T,
        names =c("Indigenous", "Eucalyptus"),
        main="NDVI Values")

##Do all of the above with the combined indigenous and eucalyptus polygons (use total forest polygon)
total <- readOGR(".", "EntireForestFINAL")
p3 <- levelplot(NDVI.2014, par.settings=myTheme,  margin=FALSE)
p3 + layer(sp.polygons(total, pch=20, cex=1.3))
NDVI_total <- as.vector( extract(NDVI.2014, total, na.rm=TRUE))
saveRDS(NDVI_total, file="NDVI_total_2014.Rds")
boxplot(unlist(NDVI_total)/1000)
hist(unlist(NDVI_total)/1000, main="Range of Total Forest NDVI Values",
     xlab="NDVI")
summary(unlist(NDVI_total)/1000)

##Repeat with 1984 NDVI raster by inputting the below and repeating all steps above above
NDVI.1984 <- raster("1984DVIproj.tif")
```

Using the NDVI raster layers from 2014 and traced eucalyptus and total forest polygons from Google Earth, the range of NDVI pixel values for our traced forest areas was extracted for both eucalyptus stands within and surrounding church forests as well as the indigenous forest around the church (by clipping out the eucalyptus polygons from the total forest polygons). It was determined that it was not possible to distinguish between indigenous forest and eucalyptus plantations based on NDVI; the range of NDVI values for the eucalyptus polygons and the indigenous forest polygons were not significantly different (Figure A.1, Table A.1). The range for the combined forest and eucalyptus NDVI values was 0.002 to 0.769, with the midrange falling between 0.305 and 0.501 (Table A.1). Using this information, a trial and error method was applied to test different NDVI cut-offs in order to determine what NDVI value minimum best fit our present-day forest area tracings from Google Earth. A cut-off NDVI value of 0.250 was determined to best encapsulate the most true forest pixels as forest, without overcompensating and incorrectly identifying a large amount of non-forest pixels as forest.

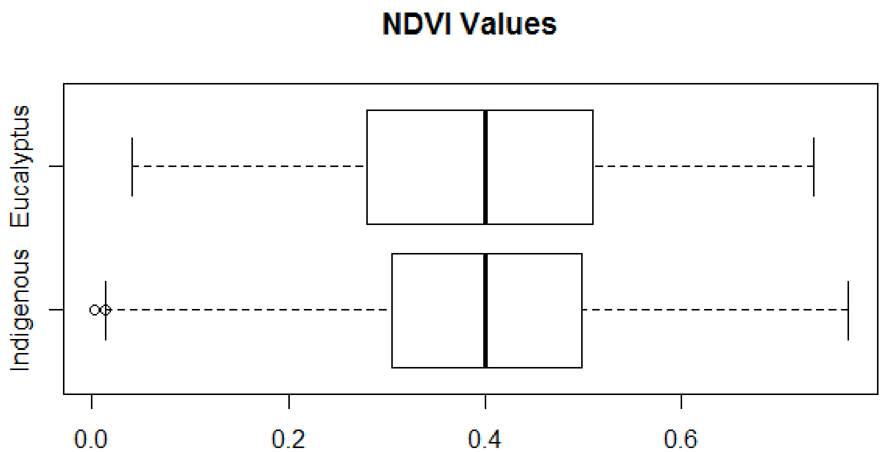


Figure A.1. This side-by-side boxplot depicts the range of NDVI values found within the traced polygons for eucalyptus plantations within and around the church forest study sites, and the range of NDVI values found within the indigenous forest polygons (extracted by subtracting the traced eucalyptus polygons from the traced total forest polygons).

Table A.1. Range of NDVI values for indigenous forest and eucalyptus plantation polygons.

	Minimum	1st Quarter	Median	Mean	4th Quarter	Maximum
Indigenous	0.002	0.305	0.401	0.402	0.499	0.769
Eucalyptus	0.040	0.280	0.400	0.393	0.509	0.734
Total Forest	0.002	0.305	0.402	0.403	0.501	0.769

Neither the median or mean values of the indigenous NDVI values and eucalyptus NDVI values proved to be significantly different (Table A.1). In fact, the range of the mid 50% was extremely similar, with NDVI values varying from 0.305 to 0.499 for the indigenous forest clippings and 0.280 to 0.509 for the eucalyptus clippings. This means that this NDVI cut-off method would not be effective in distinguishing eucalyptus and natural forests.

This NDVI binary output method provides us with a measure of forest area, but as it is based on an arbitrary cut-off point, it is not the most accurate. When subtracting the 2014 NDVI binary raster forest areas from the present-day traced polygons in Google Earth, the median difference was -12.1 hectares, with a mid-range of -40.7 to -0.0248 hectares. This suggests that the NDVI method generally outputted a much larger area than the tracing method, catching additional forest in the 100 meters outside of the tracing area. However, a larger NDVI cut-off tended to miss the pixels within the forest tracing, so a trade-off exists between the range of NDVI used and the accuracy of the forest area cover. It is also possible that our NDVI index is not sensitive enough to differentiate between forests and bushlands.

Appendix B: Creating NDVI Polygons in ArcGIS

The following steps were performed in ArcGIS version 10.3.1. The goal of the following steps was to identify and calculate the areas of church forests in both 1984 and 2014. The steps below are to be repeated for each the raster from each year.

1) Clip NDVI rasters to extent of the study sites (South Gondar, East Gojjam, and West Gojjam zones)
2) Set binary output using 250 NDVI cut-off (NDVI index is scaled to 1000)
3) Set null for "0" values in binary output
4) Use the "Raster to polygon" function for the new layer with only outputs of "1" remaining
5) Select and export polygons within 500-meers of church forest points (in order to speed up the buffering process) to a new layer
6) Create a 0.01 meter buffer around new polygons (from step #5) in order to join touching pixels
7) Dissolve touching polygons to create single polygons
8) Create 100-meter buffer around church forest tracings (uploaded from Google Earth kml file)
9) Clip out only binary output raster within 100 meter buffer
10) Use "Spatial join" to assign the same church ID to the binary polygons as used in the original church forest tracings from Google Earth
11) Dissolve by church ID
12) Calculate area of polygons

Appendix C: R-script for Merging NDVI Polygons and Google Earth Tracings

This R script was created using R version 3.1.2 (2014-10-31) “Pumpkin Helmet.” The goal of this script is to merge the1984 and 2014 NDVI polygon data and Google Earth traced polygon data into one table for further data manipulation and representation.

```
##Load libraries
library(dplyr)
library(ggplot2)
library(tidyr)

##Load data
dat.1984 <- read.csv("1984_NDVITracingBuff_Apr8.csv")
dat.2014 <- read.csv("2014_NDVITracingBuff_Apr8.csv")
dat.tracing <- read.csv("Forest&EucAreas.csv")
names(dat.tracing)[names(dat.tracing) == 'Euc.Area'] <- 'EucRatio'

##Merge 1984 and 2014 NDVI files
dat.NDVI <- full_join(dat.1984, dat.2014, by="Name_1") %>%
  mutate("Name"=Name_1) %>%
  select(Name, Area1984, Area2014)

##Merge NDVI polygons with traced polygons
dat <- left_join(dat.tracing, dat.NDVI, by="Name")

##Make all NA values equal to zero
dat[is.na(dat)] <- 0

##Computing difference between 2014 and 1984 NDVI buffered areas, not isolating eucalyptus
dat.dif <- dat %>% mutate("diff"=Area2014-Area1984)
ggplot(dat.dif) + aes(diff/10000) + geom_histogram(binwidth=.5) + xlim(-15,15) +
  ggtitle("Difference in Church Forest Area between 1984 and 2014") + xlab("Difference (hectares)") +
  ylab("")
summary(dat.dif$diff)

##Side-by-side boxplots of 1984 and 2014 areas, without isolating eucalyptus
dat.w <- dat %>% select(Name,Area2014, Area1984) %>%
  gather(key = "Year", value = "Area" , 2:3) %>%
  mutate("Year"=ifelse(Year=="Area1984", "1984", "2014"))
ggplot(dat.w) + aes(x= Year, y=Area/10000) + geom_boxplot()  +
  ggtitle("Total Church Forest Area") + ylab("Area (hectares)") +
  stat_summary(fun.y=mean, geom="point", shape=4, size=3, show_guide=F) +ylim(0,14)

##Histogram of 1984 and 2014 areas, without isolating eucalyptus
ggplot(dat) + aes(Area2014) + geom_histogram(binwidth=2000 )+ xlim(1,100000)
ggplot(dat) + aes(Area1984) + geom_histogram(binwidth=2000 )+ xlim(1,100000)

##Computing difference between 2014 and 1984 NDVI buffered areas, subtracting eucalyptus,
dat.euc <- dat %>% mutate("Area2014.Euc" = Area2014-EucArea) %>%
  mutate("Difference" = Area2014.Euc-Area1984)
ggplot(dat.euc) + aes(Difference/10000) + geom_histogram(binwidth=.5) + xlim(-15,15) +
  ggtitle("Difference in Church Forest Area between 1984 and 2014, Excluding Eucalyptus") +
  xlab("Difference (hectares)") + ylab("")

##Boxplots of 1984 and 2014 areas (subtracting eucalyptus)
```

```
dat.euc.w <- dat.euc %>% select(Name,Area2014.Euc, Area1984) %>%
  gather(key = "Year", value = "Area" , 2:3) %>%
  mutate("Year"=ifelse(Year=="Area1984", "1984", "2014"))
ggplot(dat.euc.w) + aes(x= Year, y=Area/10000) + geom_boxplot()  +
  ggtitle("Total Church Forest Area, Excluding Eucalyptus") + ylab("Area (hectares)") +
  stat_summary(fun.y=mean, geom="point", shape=4, size=3, show_guide=F) +ylim(0,14)

##Only church forests with eucalyptus
sum(dat$EucArea!=0)
dat.856 <- dat %>% filter(EucArea!=0) %>%
  mutate("Indigenous"=Area-EucArea) %>%
  mutate("Proportion"=EucArea/Area) %>%
  mutate("Proportion"=ifelse(Proportion>1, 1, Proportion))

##Histogram of eucalyptus proportion in 856 forests
ggplot(dat.856) + aes(Proportion) + geom_histogram(binwidth=.02, origin=-0.01) + xlim(0,1.02) +
ggtitle("Proportion of Eucalyptus in Church Forests") +
  ylab("") + xlab("")

##Side by side boxplot of indigenous, eucalyptus, and total ranges, with mean marked by "X"
dat.long <- gather(dat.856, key="AreaType", value="Area", Area, Indigenous, EucArea)
ggplot(dat.long) + aes(AreaType, Area/10000) +
  geom_boxplot() + ggtitle("Present-Day Total Forest, Indigenous, and Eucalyptus Area") +
  labs(x="", y="Area (hectares)") + stat_summary(fun.y=mean, geom="point", shape=4, size=3, show_guide=F)
+  ylim(0,10) + scale_x_discrete(breaks=c("Area", "Indigenous", "EucArea"),
                            labels=c("Total Forest Cover", "Indigenous", "Eucalyptus"))
```

Appendix D: R-script for Soil Property Figures and Statistics

This R script was created using R version 3.1.2 (2014-10-31) “Pumpkin Helmet.” The goal of this script is to create the figures and run the statistical tests for the soil property data from Chapter Three. All data files are available upon request from the author.

```
##Load libraries
library(dplyr)
library(ggplot2)

##Install multiplot and load required libraries
library(grid)

multiplot <- function(..., plotlist=NULL, file, cols=1, layout=NULL) {
  library(grid)
  plots <- c(list(...), plotlist)

  numPlots = length(plots)

  if (is.null(layout)) {
    layout <- matrix(seq(1, cols * ceiling(numPlots/cols)),
                    ncol = cols, nrow = ceiling(numPlots/cols))
  }

  if (numPlots==1) {
    print(plots[[1]])

  } else {
    grid.newpage()
    pushViewport(viewport(layout = grid.layout(nrow(layout), ncol(layout))))

    for (i in 1:numPlots) {
      matchidx <- as.data.frame(which(layout == i, arr.ind = TRUE))

      print(plots[[i]], vp = viewport(layout.pos.row = matchidx$row,
                                      layout.pos.col = matchidx$col))
    }
  }
}

##Load data
dat <- read.csv("SoilData_Feb18.csv")

##Plot: spread of each soil property by location##
dat <- dat %>% mutate("LOCATION"= ifelse(LOCATION=="INT", "Interior",
                                  ifelse(LOCATION=="EDGE", "Edge",
                                         ifelse(LOCATION=="EUC", "Eucalyptus", "Agriculture"))))
dat$LOCATION <- factor(dat$LOCATION, levels=c("Interior","Edge","Eucalyptus", "Agriculture"))

#Organic matter
om <- ggplot(dat) + aes(LOCATION, ORGMAT) +
  geom_boxplot() + ggtitle("Organic Matter***") +
  labs(x="", y="Organic Matter Content (%)") +
  stat_summary(fun.y=mean, geom="point", shape=4, size=3, show_guide=F) +
  theme(plot.title = element_text(size=12))
```

```
#Nitrogen
n <- ggplot(dat) + aes(LOCATION, TOTALN) +
  geom_boxplot() + ggtitle("Nitrogen***") +
  labs(x="", y="Nitrogen (mg/kg)") + stat_summary(fun.y=mean, geom="point", shape=4, size=3,
show_guide=F) +
  ylim(0, 125) + theme(plot.title = element_text(size=12))

#Phosphorus
p <- ggplot(dat) + aes(LOCATION, OLSENP) +
  geom_boxplot() + ggtitle("Phosphorus*") +
  labs(x="", y="Phosphorus (mg/kg)") + stat_summary(fun.y=mean, geom="point", shape=4, size=3,
show_guide=F) +
  ylim(0, 125) + theme(plot.title = element_text(size=12))

#pH
ph <- ggplot(dat) + aes(LOCATION, PH) +
  geom_boxplot() + ggtitle("pH*") +
  labs(x="", y="pH") + stat_summary(fun.y=mean, geom="point", shape=4, size=3, show_guide=F) +
  theme(plot.title = element_text(size=12))

multiplot(om,n,ph,p, cols=2)

##Mean values for each soil property, by location

#Organic matter
aggregate(dat$ORGMAT, by=list(dat$LOCATION), FUN=mean)

#Nitrogen
aggregate(dat$TOTALN, by=list(dat$LOCATION), FUN=mean)

#Phosphorus
aggregate(dat$OLSENP, by=list(dat$LOCATION), FUN=mean)

#pH
aggregate(dat$PH, by=list(dat$LOCATION), FUN=mean)

##Kruskal-Wallace test, by soil property
#Organic matter
kruskal.test(ORGMAT ~ LOCATION, data = dat)

#Nitrogen
kruskal.test(TOTALN ~ LOCATION, data = dat)

#Phosphorus
kruskal.test(OLSENP ~ LOCATION, data = dat)

#pH
kruskal.test(PH ~ LOCATION, data = dat)

##Mann-Whitney Mancoxon Test for each location pairing, by soil property
#Select interior and edge plots
dat_intedge <- dat %>% filter(LOCATION=="INT"|LOCATION=="EDGE")
wilcox.test(ORGMAT ~ LOCATION, data = dat_intedge)
wilcox.test(TOTALN ~ LOCATION, data = dat_intedge)
wilcox.test(OLSENP ~ LOCATION, data = dat_intedge)
```

```
wilcox.test(PH ~ LOCATION, data = dat_intedge)

#Select interior and eucalyptus plots
dat_inteuc <- dat %>% filter(LOCATION=="INT"|LOCATION=="EUC")
wilcox.test(ORGMAT ~ LOCATION, data = dat_inteuc)
wilcox.test(TOTALN ~ LOCATION, data = dat_inteuc)
wilcox.test(OLSENP ~ LOCATION, data = dat_inteuc)
wilcox.test(PH ~ LOCATION, data = dat_inteuc)

#Select interior and agriculture plots
dat_intag <- dat %>% filter(LOCATION=="INT"|LOCATION=="AG")
wilcox.test(ORGMAT ~ LOCATION, data = dat_intag)
wilcox.test(TOTALN ~ LOCATION, data = dat_intag)
wilcox.test(OLSENP ~ LOCATION, data = dat_intag)
wilcox.test(PH ~ LOCATION, data = dat_intag)

#Select edge and eucalyptus plots
dat_edgeeuc <- dat %>% filter(LOCATION=="EDGE"|LOCATION=="EUC")
wilcox.test(ORGMAT ~ LOCATION, data = dat_edgeeuc)
wilcox.test(TOTALN ~ LOCATION, data = dat_edgeeuc)
wilcox.test(OLSENP ~ LOCATION, data = dat_edgeeuc)
wilcox.test(PH ~ LOCATION, data = dat_edgeeuc)

#Select edge and agriculture plots
dat_edgeag <- dat %>% filter(LOCATION=="EDGE"|LOCATION=="EUC")
wilcox.test(ORGMAT ~ LOCATION, data = dat_edgeag)
wilcox.test(TOTALN ~ LOCATION, data = dat_edgeag)
wilcox.test(OLSENP ~ LOCATION, data = dat_edgeag)
wilcox.test(PH ~ LOCATION, data = dat_edgeag)

#Select eucalyptus and agriculture plots
dat_eucag <- dat %>% filter(LOCATION=="EUC"|LOCATION=="AG")
wilcox.test(ORGMAT ~ LOCATION, data = dat_eucag)
wilcox.test(TOTALN ~ LOCATION, data = dat_eucag)
wilcox.test(OLSENP ~ LOCATION, data = dat_eucag)
wilcox.test(PH ~ LOCATION, data = dat_eucag)

##Regression model showing the relationship between canopy cover and location
M <- lm (CANOPY~LOCATION, dat)
summary(M)

#Kruskal-Wallace test
kruskal.test(CANOPY ~ LOCATION, data = dat)

##Regression model showing elevation and location, with int and edge lumped into indigenous forest
dat2 <- dat
levels(dat2$LOCATION) <- c("INT", "INT", "AG", "EUC")
#Organic matter#
eucmod<-lm(ORGMAT~ELEVATION+LOCATION, dat2)
summary(eucmod)
#Nitrogen
eucmod<-lm(TOTALN~ELEVATION+LOCATION, dat2)
summary(eucmod)
#Phosphorus
eucmod<-lm(OLSENP~ELEVATION+LOCATION, dat2)
summary(eucmod)
```

```
#pH#
eucmod<-lm(PH~ELEVATION+LOCATION, dat2)
summary(eucmod)

##Elevation range of eucalyptus species
ggplot(dat) + aes(x=EUCSPECIES, y=ELEVATION) + geom_boxplot()
dat_temp <- dat %>% filter(EUCSPECIES=="camaldulensis")
summary(dat_temp$ELEVATION)
dat_temp <- dat %>% filter(EUCSPECIES=="globulus")
summary(dat_temp$ELEVATION)

##Regressions
M <- lm(OLSENP~TOTALN, dat)
summary(M)
M <- lm(ORGMAT~PH, dat)
summary(M)
M <- lm(ORGMAT~OLSENP, dat)
summary(M)
M <- lm(ORGMAT~TOTALN, dat)
summary(M)
M <- lm(CANOPY~LOCATION, dat)
summary(M)
M <- lm(ELEVATION~PH, dat)
summary(M)

#Elevation vs. precipitation
elev_precip <- read.csv("elev_precip.csv")
M <- lm(Precip~Elev, elev_precip)
summary(M)

##Correlation matrix##
dat.cor <- dat %>% select(ORGMAT,PH,TOTALN,OLSENP) %>%
  rename('Organic Matter'=ORGMAT) %>%
  rename('pH' =PH) %>%
  rename('Nitrogen' =TOTALN) %>%
  rename('Phopshorus' =OLSENP)
mcor <- cor(dat.cor)
mcor
library(corrplot)
col <- colorRampPalette(c("grey100","grey0"))
corrplot(mcor, type="upper", method="circle", col=col(100),
         tl.col="black", tl.cex=0.8, tl.srt=0)
```

Appendix E: R-script for Species Presence and Abundance Data

This R script was created using R version 3.1.2 (2014-10-31) “Pumpkin Helmet.” The goal of this script is to analyze the species presence and abundance data from Wassie et al. (2010) in Chapter 4. All data files are available upon request from the author.

```
data <- read.csv(“Species By Forest Data.csv")
library(ggplot2)
library(dplyr)
library(tidyr)
library(grid)
library(gtable)

data2 <- data %>% gather(key="Church", value="Presence", 2:15)
data3 <- data2 %>% filter(Church=="Mekedesemariam")
species <- data3$Species
data2$Species <- factor(data2$Species, levels = species)
data3 <- data2 %>% filter(Church=="Mekedesemariam") %>% mutate("ID"=1:42)

grid.newpage()

p1 <- ggplot(data2) + aes(x= Species, y= Presence) + geom_bar(stat="identity", fill="gray50") +
  theme(axis.text.x = element_text(angle = 60, hjust = 1)) + labs(x="", y="Species Presence")

p2 <- ggplot(data3) + aes(x= ID, y=TOTAL) + geom_line() +
  labs(x="", y="Species Abundance") +
  guides(fill=guide_legend(ncol=2)) + scale_fill_grey() +
  theme(panel.background = element_blank(),
        panel.grid.minor = element_blank(),
        panel.grid.major = element_blank(),
        plot.background = element_blank()) +
  coord_cartesian(xlim=c(1,42))

# extract gtable
g1 <- ggplot_gtable(ggplot_build(p1))
g2 <- ggplot_gtable(ggplot_build(p2))

# overlap the panel of 2nd plot on that of 1st plot
pp <- c(subset(g1$layout, name == "panel", se = t:r))
g <- gtable_add_grob(g1, g2$grobs[[which(g2$layout$name == "panel")]], pp$t,
                     pp$l, pp$b, pp$l)

# axis tweaks
ia <- which(g2$layout$name == "axis-l")
ga <- g2$grobs[[ia]]
ax <- ga$children[[2]]
ax$widths <- rev(ax$widths)
ax$grobs <- rev(ax$grobs)
ax$grobs[[1]]$x <- ax$grobs[[1]]$x - unit(1, "npc") + unit(0.15, "cm")
g <- gtable_add_cols(g, g2$widths[g2$layout[ia, ]$l], length(g$widths) - 1)
g <- gtable_add_grob(g, ax, pp$t, length(g$widths) - 1, pp$b)

# draw it
grid.draw(g)
```

Appendix F: Household Survey Questionnaire

This household survey was a part of a larger church forest conservation project conducted in July and August of 2015 through the National Science Foundation funded *Research Experience for Undergraduates* at Colby College and Ethiopia. This survey has been approved by the Institutional Review Board at Colby College.

Household Survey Questionnaire
Colby College & Debre Tabor University
2015 NSF Research Experiences for Undergraduates Program

We are collecting responses to the survey below as part of a research project. The survey asks questions about your church, community, and livelihood, and takes approximately 40 minutes to complete. If you choose to complete the survey, your responses will be recorded anonymously and you are free to leave any of the questions unanswered. Thank you for participating!

Church Information

1) **REGION** Region: ______________________________
2) **ZONE** Zone: ______________________________
3) **WOREDA** Woreda: ______________________________
4) **KEBELE** Kebele: ______________________________
5) **CHURCH** Church name: ______________________________
6) **CHURCHID** Church map ID #: ______________________________

Household Information

7) **HOUSE** Number of people in your household: __________

8) **HEAD** Is the respondent the head of the household?
   a. 1=Yes
   b. 2=No

9) **SEX** Sex of respondent
   a. 1=Male
   b. 2=Female

10) **AGE** Age of respondent: __________
   (If exact age is unknown, ask respondent to estimate using the following categories)
   a. Under 20
   b. 20-29
   c. 30-39
   d. 40-49
   e. 50-59
   f. Over 60

11) **OCCU** Main occupation *(**circle** primary occupation and **check** all others that apply)*
   a. 1= Religious service ☐
   b. 2= Farmer ☐
   c. 3= Herder ☐
   d. 4= Farmer and herder ☐
   e. 5= Merchant ☐
   f. 6= Day laborer ☐
   g. 7= Government ☐
   h. 8= Student ☐
   i. 9= House duties ☐
   j. 10= Other: __________ ☐

12) **RELI** Religion *(do not ask if obvious or in church compound)*
   a. 1= Orthodox Christian
   b. 2= Muslim
   c. 3= Other __________

13) **POS** What is your position in the church?
   a. 1= Religious leader *(circle option below)*
      i. Priest
      ii. Monk
      iii. Deacon
   b. 2= Nun
   c. 3= Church community member
   d. 4= Guard
   e. 5= Other_________

14) **EDU** Educational level (years of schooling completed): __________
(Enter the number of years on the line. Then circle all the following schooling options that apply.)
   a. 1= None
   b. 2= Adult school
   c. 3= Elementary school
   d. 4= Religious school
   e. 5= Secondary school
   f. 6= Vocational school
   g. 7= Higher level education

15) **NAT** Place of birth
   a. 1= Near the church
   b. 2= Other *(region, zone, woreda)*____

16) **MOVE** If place of birth is different, when did you move here? __________
(If exact year is unknown, estimate using the following categories.)
   a. 1= Less than 5 years ago
   b. 2= 10-20 years ago
   c. 3= 20-30 years ago
   d. 4= More than 30 years ago

Income-Related Information

17) **INCOME** To the best of your ability, estimate annual household income: __________birr
   a. 1= 0-5,000 birr
   b. 2= 5,000-10,000 birr
   c. 3= 10,000-20,000 birr
   d. 4= 20,000-50,000 birr
   e. 5= 50,000 birr or more
   f. 6= Unknown or does not want to disclose information

18) **LAND** Do you own land?
   a. 1= Yes
   b. 2= No

19) **LANDAR** If yes, how much land do you own? __________units __________

20) **LANDUSE** How much of your land is used for the following activities this year? *(Fill out all that apply to respondent.)*
   a. Farming __________units __________
   b. Grazing __________units __________
   c. Farming and grazing __________units __________
   d. Woodlot, eucalyptus trees __________units __________
   e. Woodlot, non-eucalyptus trees __________units __________
   f. Other __________units __________

21) **LANDUSECROPS** *(If farming was given as a response to **LANDUSE**, ask participant to fill out the following table.)*

Crop	Area (units__________)	Yield (units __________)	Annual Income (birr)
Teff			
Maize			
Barley			
Eucalyptus			
Coffee			
Other crops *(Specify up to 3)*			

22) **LIVESTOCK** How much livestock do you own? *(Fill out all that apply.)*
  a. Number of cows __________
  b. Number of goats __________
  c. Number of horses __________
  d. Number of donkeys/mules __________
  e. Number of sheep __________
  f. Other ____________ __________

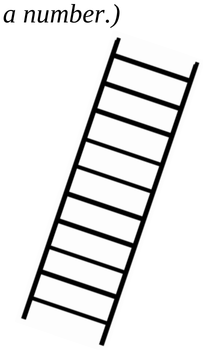
23) **FUEL** Where do you get firewood?
  a. 1= Own wood lot
  b. 2= Nearby natural forest
  c. 3= Nearby community forest
  d. 4= From the church compound
  e. 5= Buy from the market
  f. 6= From grazing land

24) **WATER** What is your main water source?
  a. 1= River in church forest
  b. 2= Spring/stream in church forest
  c. 3= River outside of church forest
  d. 4= Spring/stream outside of church forest
  e. 5= Shared well
  f. 6= Private well
  g. 7= Other: __________

25) **WATERCOL** Who is the primary water provider for your family?
  a. 1= Man
  b. 2= Woman
  c. 3= Helper / employee
  d. 4= Sons
  e. 5= Daughters
  f. 6= Other ____________

26) **LAD** Suppose we say that the top of a ladder represents the best possible life for you, and the bottom represents the worst possible life for you. Where on the ladder to you feel you stand at the present time? *(Circle a number.)*

10
9
8
7
6
5
4
3
2
1



General Church Community Characteristics

27) **MEM** How many members are there at your church? __________

28) **USESELF** What benefits does the church forest provide for you? *(Do not give options, circle all that apply.)*
  a. For worship
  b. Fuel wood
  c. Construction wood
  d. Fodder
  e. Seeds/seedlings
  f. Medicine
  g. Honey
  h. Fruit
  i. Water
  j. Other: __________

29) **USEOTHERS** What benefits does the church forest provide for others? *(**Circle** respondent's answers, read options, then **check** all others that apply.)*

a.	For worship	☐	f.	Medicine	☐
b.	Fuel wood	☐	g.	Honey	☐
c.	Construction wood	☐	h.	Fruit	☐
d.	Fodder	☐	i.	Water	☐
e.	Seeds/seedlings	☐	j.	Other: __________	☐

30) **ALLOWUSE** Which uses are allowed in your church forest? *(Give all options, circle all that apply.)*

a.	For worship	f.	Medicine
b.	Fuel wood	g.	Honey
c.	Construction wood	h.	Fruit
d.	Fodder	i.	Water
e.	Seeds/seedlings	j.	Other: __________

31) **ALLOWPPL** Who is allowed these uses of the church forest?
   a. 1= Church only
   b. 2= Priests, deacons, monks, and nuns
   c. 3= All members, with permission from priests
   d. 4= All members, freely
   e. 5= No one

32) **PUN** What happens if someone is caught grazing cattle in the church forest? *(Do not give options, circle all that apply)*
   a. Fines
   b. Labor for church
   c. Public apology
   d. Jail
   e. Excommunication
   f. No punishment
   g. Other: __________

33) **PUNSTRANG** What would you do if you witness a stranger cutting down a tree in the church forest?
   a. 1= Try to stop them
   b. 2= Inform the church leaders
   c. 3= Inform the kebele leaders
   d. 4= Do nothing
   e. 5= Warn them

34) **PUNNEIGH** What would you do if you witness a neighbor cutting down a tree in the church forest?
   a. 1= Try to stop them
   b. 2= Inform the church leaders
   c. 3= Inform the kebele leaders
   d. 4= Do nothing
   e. 5= Warn them

35) **PLANT** What trees should be planted in the church forest? (*Name at least 5 species.)*

__________________________ __________________________ __________________________
__________________________ __________________________

36) **TREE** What tree species are in the church and what are their uses?
(Give pre-determined options, circle species found in the church forest, ask about uses of those species only. Allow respondent to add additional species that are found in the church forest and go through their uses. Use the following use categories, circle the appropriate code: 0 = never use; 1 = sometimes use; 2 = often use)

Species	Firewood	Charcoal	Medicine	Food	Construction	Tools	Fodder	Shade	Fences
Species names in Amharic version	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2
	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2
	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2
	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2
Other species mentioned:									
	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2	0 1 2

37) **PLANTSEED** What is the best way to mobilize the community to plant seedlings?
   a. The priest organizes tree planting, with no payment for individuals
   b. The idder organizes tree planting, with no payment for individuals
   c. The government requires tree planting, with punishment for noncompliance
   d. An NGO organizes tree planting, with payment for individuals
   e. An NGO organizes tree planting, with payment to the church

38) **SIZE** How has the church forest changed in size:
   a. **SIZE1** When Haile Selassie was in power
      1= Increasing 2= Decreasing 3= No Change
   b. **SIZE2** During the Derg Regime
      1= Increasing 2= Decreasing 3= No Change
   c. **SIZE3** Since the EPRDF came to power
      1= Increasing 2= Decreasing 3= No Change
   d. **SIZE4** Over the past 5 years
      1= Increasing 2= Decreasing 3= No Change

39) *(If increasing over the past 5 years)*
INCREASE If it is currently increasing, how? *(Give all options, circle all that apply.)*
   a. New seedlings are being planted by the church
   b. New seedlings are naturally regenerating
   c. New forest areas are obtained by the church
   d. Other reason: ____

40) *(If decreasing over the past 5 years)*
DECREASE If it is currently decreasing, why? *(Do not give options, circle all that apply.)*
   a. Illegal encroachment by farmers
   b. Firewood collection
   c. Land use conversion by the church
   d. Extensive graveyards/monuments
   e. Natural disaster
   f. Eucalyptus growth
   g. Other reason: ____

Other Tree Species in and around the Church Forest

41) **EUCCHURCH** Does the church own any eucalyptus?
   a. 1= Yes
   b. 2= No

42) **EUCUSE**
[**If the church has eucalyptus:** What is the eucalyptus in the church forest used for? *(Do not give options, circle if options are stated, elaborate below as needed)*]
[**If the church has no eucalyptus:** What could eucalyptus be used for in the church forest? *(Do not give options, circle if options are stated, elaborate below as needed)*]

a. For worship
b. As a boundary, aesthetically
c. To reduce illegal encroachment on indigenous forest
d. To reduce soil erosion
e. Fuel wood
f. Construction wood
g. Medicine
h. Honey
i. Sold for the church
j. Other: __________

____
____

43) *(If the church owns any eucalyptus)*
EUCDEC Who primarily makes the decisions about the eucalyptus in the church forest? *(Give all options)*

a. 1= The priest
b. 2= The church committee
c. 3= The church community
d. 4= Other: __________

44) *(If the church owns any eucalyptus)*
EUCALLOW Who is allowed the uses of the eucalyptus in the church forest? *(Give all options)*

a. 1= Church only
b. 2= Priests, deacons, monks, and nuns
c. 3= All members, with permission from priests
d. 4= All members, freely
e. 5= No one

45) **PLANTEUC** What do you think about the amount of eucalyptus in the church forest?

a. 1= There is too much
b. 2= There is too little
c. 3= There is just enough

46) **SHRUB** Are there any thorny shrubs in the church forest?

a. 1= Yes
b. 2= No

47) **SHRUBF** What do you think about the amount of thorny shrubs in the church forest?

a. 1= There is too much
b. 2= There is too little
c. 3= There is just enough

48) **SHRUBP** What do you think about the amount of thorny shrubs in the pastureland?

a. 1= There is too much
b. 2= There is too little
c. 3= There is just enough
d. 4= There are no thorny shrubs in the pasture

49) **SEED** Are there any indigenous trees in your fields?

a. 1= Yes
b. 2= No

50) **CROPSEED** What have you observed about the total number of trees in your cropland?

a. **CROPSEED1** When Haile Selassie was in power
   1= Increasing 2= Decreasing 3= No Change
b. **CROPSEED2** During the Derg Regime
   1= Increasing 2= Decreasing 3= No Change
c. **CROPSEED3** Since the EPRDF came to power
   1= Increasing 2= Decreasing 3= No Change
d. **CROPSEED4** Over the past 5 years
   1= Increasing 2= Decreasing 3= No Change

51) **PASTSEED** What have you observed about the total number of trees in your pastureland?
   a. **PASTSEED1** When Haile Selassie was in power
      1= Increasing 2= Decreasing 3= No Change
   b. **PASTSEED2** During the Derg Regime
      1= Increasing 2= Decreasing 3= No Change
   c. **PASTSEED3** Since the EPRDF came to power
      1= Increasing 2= Decreasing 3= No Change
   d. **PASTSEED4** Over the past 5 years
      1= Increasing 2= Decreasing 3= No Change

52) **SEEDLESS** If there are less trees in the fields, why? *(**Circle** respondent's answers, read options, then **check** all that apply)*
   a. 1= Cutting for firewood
   b. 2= Cutting for wood sale
   c. 3= Clearing for more crop production
   d. 4= Clearing for livestock
   e. 5= They died
   f. 6= Other: __________

53) **MED** When you are sick how do you prefer to treat your ailment? *(Give options, circle one response)*
   a. 1= Medicinal plants
   b. 2= Western medicine
   c. 3= Other: __________

54) *(Skip if medicinal plants not answered in* **MED***)*
MEDPLANT Where do you prefer to get medicinal plants? *(Do not give options, circle all that apply)*
   a. 1= Medicinal plants from the church forest
   b. 2= Medicinal plants from your garden/fields
   c. 3= Medicinal plants from the healer
   d. 4= Medicinal plants from the market
   e. 5= Other: __________

Food, Water, and Security

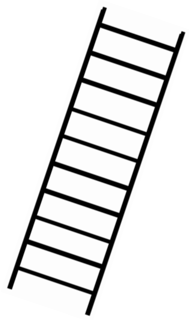
55) **WATERAVAIL** How has water availability changed in your lifetime/since you moved here?
   a. 1= Increased
   b. 2= Decreased
   c. 3= No change

56) **PLANT** Have you ever been required to plant trees?
   a. 1= Yes
   b. 2= No

57) *(If they have participated in a tree-planting program)*
DERG Was this program under the Derg regime?
   a. 1= Yes
   b. 2= No

58) *(If they have participated in a tree- planting program)*
LADPLANT Using the same ladder as earlier, how would you rate your quality of life before participating in the tree planting program? *(Circle a number on the left)* And how would you rate your quality of life after participating in the program? *(Circle a number on the right).*

10
9
8
7
6
5
4
3
2
1



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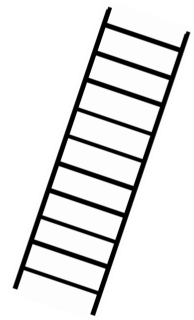

59) **RISKA** Would you prefer to be given:
   a. 1= 100 birr today
   b. 2= 125 birr in one month

60) **RISKB** Would you prefer to be given:
   a. 1= 100 birr today
   b. 2= 150 birr in one month

61) **RISKWHY** Briefly, why did you make these choices?
____
____

62) *(If response is "100 birr today" for both **RISKA** and **RISKB**)*
RISKC How much would you have to be given in one month for you to choose to wait?
__________birr

63) **RISKUSE** Rank the following in the order of what you would prefer to do if given a *kada* of land *(1 being most preferred, 4 being least preferred)*:
   a. Plant wheat, harvest after 4 months, worth 3,000 birr __________
   b. Plant teff, harvest after 5 months, worth 4,000 birr __________
   c. Plant eucalyptus, harvest after 5 years, worth 30,000 birr __________
   d. Plant eucalyptus, harvest after 10 years, worth 600,000 birr __________

64) **PROT** How do you think church forests should be protected?
(Do not give options, circle if options are stated, elaborate below as needed)
   a. Punishments given for misuse
   b. Stricter rules about forest uses
   c. More guards to enforce rules
   d. More community enforcement of rules
   e. Construct a wall around the forest
   f. Other______________________________
____
____

65) **PROT2** How do you think other forests or plantations should be protected?
(Do not give options, circle if options are stated, elaborate below as needed)

a. Punishments given for misuse
b. Stricter rules about forest uses
c. More guards to enforce rules
d. More community enforcement of rules
e. Construct a wall around the forest
f. Other________________________________

____
____

66) **WALL** Do you think a wall is effective in protecting church forests?

a. 1= Yes
b. 2= No

67) **IMPROV** Are there any improvements you wish to make to the church? Is there anything else you would like to say about your church forest? *(Leave room for elaboration)*

____
____

That concludes the questionnaire, thank you sincerely for you time. We are conducting this study to provide information for church leaders, communities, government and scientists to understand the benefits church forests provide. Thank you again for participating!

Appendix G: Farmer Focus Group

Focus groups with priests, farmers, and women were conducted as a part of a larger church forest conservation project in July and August of 2015 through the National Science Foundation funded *Research Experience for Undergraduates* at Colby College and Ethiopia. This survey has been approved by the Institutional Review Board at Colby College. The following is the script for the farmer focus group, which includes the same eucalyptus map activity instigated in each focus group.

Farmer Focus Group

Hi, my name is (   ). I am here to ask some questions about farming and church forests. Don't worry about your answers being right and wrong. I am interested in anything and everything you have to say. Your words will not be distributed with anyone outside of the research team.

1. *Tell me about being a farmer in this community:*

____

Neutral prompts:

Can you tell me more about (   )?
Can you explain how (   )?
Does (   ) bring anything else to mind?

Some of the questions I am going to ask you are going to seem a little repetitive, but please bear with me.

Crops

2. **CROP:** What are the best crops to grow? Why? *(Under income or resource limitations?)*

____

3. **CROPSOIL:** If soils are exhausted, what crops do farmers grow?

____

4. **CROPGEN:** What are women's crops? What are men's crops?
4.1 Women: ____
4.2 Men: ____

Eucalyptus

5. **EUC:** Do you grow eucalyptus? Why or why not?
a. (5.1) Reasons people say yes:

____

b. (5.2) Reasons people say no:

____

6. **EUCHAR:** How often should eucalyptus be harvested and why?

____

7. **EUCCHURCH:** Is eucalyptus a part of the church forest?

____

8. **EUCINDIG:** If eucalyptus is present in the church boundaries, do you see indigenous seedlings growing within the eucalyptus plots? *(Write number of individuals that answer Yes or No)*

a) Yes ______
b) No ______

8.2 If yes, what species?
____

9. **EUCSEED:** If eucalyptus is present in the church boundaries, do you see eucalyptus seedlings growing in the nearby indigenous forest or other nearby places (cropland, grazing land, etc.)? *(Write number of individuals that answer Yes or No)*

9.1 **EUCSEED1** In the nearby indigenous forest? a) Yes _______ b) No ________

9.2 **EUCSEED2** In other nearby places? a) Yes _______ b) No ________

10. **EUCSURVIVE: (**10.1) Do eucalyptus seedlings in the eucalyptus plots survive to adulthood where they are regenerated?
(10.2) Do you remove them and plant them elsewhere?
____

Seed Trees

11.1 **SEED1:** Are there any indigenous trees in the fields?
____

11.2 **SEED2** What types or species? (Legumes?)
____

11.3 **SEED3:** Why those species?
____

12. **SEEDBEN:** What are the benefits of having those trees on the farmland?
____

13. **SEEDPROB:** What are the problems of having those trees on the farmland?
____

14. **SEEDTREE:** Are there any trees you would want to plant on the farmland?
____

15. **SEEDHAR:** How often do people harvest the indigenous trees on the farmland?
____

Livestock and Shrubs

16.1 **SPINESHRUB** What is your opinion on spiny shrubs in pastures in general (includes community pastureland)?
____

16.2 **SPINEPOS** If it is positive, why? *(Write answers and circle all options that apply but do not give options)*
____

a. They protect seedlings from being eaten
b. They hold soil in place
c. They provide shade for cattle
d. They are food for livestock
e. Wildlife live in them

16.3 **SPINENEG** If it is negative, why? *(Write answers and circle all options that apply but do not give options)*

____

a.	They are a waste of pasture space	d.	Livestock don't eat them
b.	They are competing with favorable species	e.	They harbor pests
c.	They harm livestock	f.	They poke us and are annoying

Church Forest Facts

[Map activity]

17. **MAPPREF:** You have been presented with six church forest maps. Which forests do you prefer? *Arrange the maps in order of preference.*
Why?
____

18.1 **EUCPREF:** Would your preferences change if I told you these *(point out eucalyptus trees)* are eucalyptus

(Y/N)? ___________

18.2 Which forests do you prefer? *Rearrange the maps in order of preference.*
____

18.3 Why?
____

18.4 What are the advantages to growing eucalyptus?
____

18.5 What are the disadvantages to growing eucalyptus?
____

18.6 Where did you get this knowledge of eucalyptus?
____

[End map activity]

20. **SPECIES:** Which tree species from your church forest are most used by the community?

____________ ____________ ____________ ____________ ____________

22.1 **FORBEN:** What benefits does a forest provide?
____

22.2 **CHUFORBEN:** What benefits does a church forest provide?
____

23. **RESUSE:** Will church forest resources be available to your children and your children's children?
____

Rules and Norms

24. **RULES:** Who makes the rules norms about church forest resources?
____

25. **ENF:** Who enforces the rules of the church forest?

___

26. **USEPROH:** Are there certain uses of the church forest that are prohibited to everyone? Fuel wood

a. Construction wood
b. Fodder
c. Seeds/seedlings
d. Medicine
e. Honey
f. Fruit
g. Water
h. Other: ___

27. **PUNGRAZE:** What happens if someone is caught grazing cattle in the church forest?

a. Fines
b. Labor for church
c. Public apology
d. Jail
e. Excommunication
f. No punishment
g. Other: ___

28. **HEALTH:** How healthy do you think your church forest is?

a. Very healthy
b. Healthy
c. Neutral
d. Unhealthy
e. Very unhealthy

29. **HDET:** How do you determine if your church forest is healthy?

a. Number of tree species
b. Number of animal species
c. Water quality
d. Forest size
e. Abundance of fruit
f. Abundance of pollinators
g. Other: ___

30.1 **ENVDEG** Do you see environmental degradation happening in your church forest? (Y/N) ___

30.2 **ENVDEGWHY:** (If answer (**ENVDEG**) is Yes) Why do you think that may be?

___

31. **DAMSOL:** Do you have any solutions to prevent or fix environmental damage in your church forest?

___

Conservation

32. **CONSDEF:** What types of activities, specific to your church, do you think of when I say "conservation"?

___

33. **CONSPROJ:** Has your church forest ever been part of a conservation project?

___

34. **CONSPRI:** In your opinion, is conservation of the church forest a priority for the community?

___

35. **PLANTTREES:** Do you think that the church members should be willing to plant trees for the church without compensation?

___

That concludes the focus group, thank you sincerely for you time. We are conducting this study to provide information for church leaders, communities, government and scientists to understand the benefits church forests provide. Thank you again for participating!