FOREST COVER CHANGE AND AFFORESTATION POTENTIAL IN THE AMHARA REGION, ETHIOPIA

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Akira Shintani

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ABSTRACT

Degradation of natural vegetation has been a serious concern in northern highland areas of Ethiopia for a long time. It is believed that the country was originally 40% forested, which drastically decreased in extent throughout the 20th century. Major reasons for the forest decrease have been intensive uses of forest resources by people and livestock. The loss of woody vegetation has resulted primarily in soil erosion and fuelwood shortage. Therefore, there is urgent need to restore vegetation cover in the highland areas of Ethiopia.

Against this background, this project (i) determined important factors influencing on current distribution pattern of forests and other land cover types by using a Geographic Information System (GIS) and several thematic maps, (ii) estimated the trajectory of forest cover change through literature review and comparison of land cover maps in different years, and (iii) found practical modeling methods to identify suitable locations for common useful tree species in the Amhara Region, one of the National Regional States[1] located in the northern highland of Ethiopia.

Analysis of a land cover map in 1995 showed that cropland cover was 38.5% in the Amhara Region, indicating that at least 38.5% of the original vegetation was converted to the cropland. Conversely, forest and woodland cover was low, 1.6% and 5.7%, respectively. Cropland cover was higher in the *weyna dega* (1,500-2,300 m), *dega* (2,300-3,200 m), and *wurch* (3,200-3,700 m) zones than in the other zones.

[1] Ethiopia is the federate state that consists of nine national regional states and two chartered cities. The Amhara National Regional State (ANRS) is commonly known as the Amhara Region.

Cropland cover was also higher in high rainfall areas than low rainfall areas. These results suggest that population pressure was higher in these areas than the other areas. However, forest cover was also higher in high rainfall areas, even though cropland cover was high. This may be due to favorable conditions for forest growth in high rainfall areas.

Analysis of four land cover maps in 1972-1978, 1995, 1999-2000, and 2003 indicated that forest cover in the Amhara Region fluctuated from 0.4% to 1.6% during this period. However, this may be due to variation in spatial resolution of satellite imagery rather than actual land cover changes. It can be inferred that areas of most forests were so small that they should be identified by high resolution satellite imagery only. Woodland, shrubland, grassland, and cropland covers also fluctuated greatly. This may be because of difference in the classification method of satellite imagery rather than actual land cover change.

Current land cover, slope gradient range, elevation range, and annual rainfall range were used as criteria for suitability analysis of six useful tree species. The suitable slope gradient ranges for agroforestry and forestry species were set at 0-50% and 30-50%, respectively. This had large influence on the results because the area percentages of the two slope gradient ranges were largely different. However, the criteria of suitability classification by slope gradient range was provisional, which needs to be reexamined based on reliable scientific methods and ground-truthing. The suitable elevation and annual rainfall ranges for each tree species were estimated by reference to information from several sources. The criteria of suitability classification by elevation and annual rainfall ranges also needs to be reexamined since the information varied by literature source.

Using slope gradient, elevation, and annual rainfall ranges for suitability assessment of tree species in the Amhara Region seemed practical because these factors significantly vary by location. The method was easy to understand and implement. Necessary maps can be obtained on the web for free. The same suitability analysis method is applicable at smaller units of administration for afforestation planning.

BIOGRAPHICAL SKETCH

Akira Shintani was born in Osaka, Japan in 1975. He received a Bachelor’s degree in bioresources in 1997 and Master of Science degree in bioresources in 2000 from Mie University, Japan.

He has worked for OYO Corporation, IC Net Limited, and Sanyu Consultants Inc. as a consultant in the field of nature conservation, natural resource management, and rural development. He has been involved in many official and private projects in Japan and official development assistance projects in developing countries such as Ethiopia, Kenya, and Zambia.

He entered the Master of Professional Study (MPS) program in College of Agriculture and Life Sciences, Cornell University in August 2010. However, he left the school due to personal reasons after he stayed in Ithaca from Fall 2010 semester to Summer 2011 having completed all required coursework. After that, he re-enrolled the school in Spring 2020 semester to complete this capstone project report based on work he completed while at Cornell University.

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LIST OF ABBREVIATIONS

ANRS	Amhara National Regional State
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BoA	Bureau of Agriculture
BoFED	Bureau of Finance and Economic Development
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization of the United Nations
FDRE	Federal Democratic Republic of Ethiopia
GCS	Geographic Coordinate System
GDEM	Global Digital Elevation Model
GIS	Geographic Information System
GLCNMO	Global Land Cover by National Mapping Organizations
MCDA	Multicriteria Decision Analysis
MEFCC	Ministry of Environment, Forest and Climate Change
METI	Ministry of Economy, Trade and Industry of Japan
MoA	Ministry of Agriculture
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NFPA	National Forest Priority Area
RFPA	Regional Forest Priority Area
UNDP	United Nations Development Programme

UTM	Universal Transverse Mercator
WBISPP	Woody Biomass Inventory and Strategic Planning Project
WGS	World Geodetic System

CHAPTER 1

INTRODUCTION

1.1 Forest Decrease in Ethiopia

In Ethiopia, degradation of natural vegetation is widespread (Ministry of Environment, Forest and Climate Change [MEFCC], 2018). This has been a serious concern for a long time, inducing several problems such as soil erosion and fuelwood shortage (Birhane et al., 2006; UNDP & FAO, 1984a). It is believed that the country was originally covered with large areas of forest, which drastically decreased throughout the 20th century (FAO, 1986a; Gore, 1993; Pohjonen & Pukkala, 1990; Sayer et al., 1992; UNDP & FAO, 1984a).

Forest decrease has been severe in northern highland area of the country (Belayneh et al., 2018; Berhanu & Fayera, 2005; Binggeli et al., 2003; Bishaw, 2001; Darbyshire et al., 2003; Desta et al., 2000; FAO, 1986a), especially in the eastern part (Egziabher, 2006). Most of the remaining forests are found in southwestern and southern parts of the country (Birhane et al., 2006; De Vletter, 1991; Sayer et al., 1992).

In Ethiopia, major reasons for the forest decrease have been the intensive use of forest resources by people and livestock (FAO, 1986a; Huffnagel, 1961; Nyssen et al., 2004; UNDP & FAO, 1984a). In general, forest decrease and land degradation are slow and complex and in most cases, lands are eventually converted to agricultural lands (Yirdaw, 1996a). There is urgent need to restore vegetation cover of the Ethiopian highland areas to put an end to soil erosion and woody biomass depletion (Wyk et al., 2006).

1.2 Causes of the Forest Decrease

Though forest decrease occurs through either deforestation or natural disasters, deforestation is much more important (FAO, 2010). In Ethiopia, deforestation is practiced for several reasons including cropland expansion, charcoal production, and construction material production (Selassie, 2017). These reasons vary considerably between areas (MEFCC, 2018).

It was reported that there has been no significant change in annual rainfall trends in the Ethiopian highlands in the latter half of 20th century (Cheung et al., 2008; Hurni et al., 2005). Therefore, it is inferred that the forest decrease during this period was not related to climate change.

Deforestation by people existed even before the pre-agricultural era, but dramatically increased after the beginning of agriculture; hence, humans have reduced forest cover over the past 10,000 years (Sands, 2005). In Africa, deforestation by humans has occurred for several thousand years, and forest cover has been converted into other land uses by agricultural and pastoral people (Yirdaw, 1996b).

In tropical countries, deforestation by people can be classified into two types, namely, deforestation for subsistence and deforestation for profit. Subsistence deforestation is caused by urgent need of households for agricultural land and fuelwood, while profit deforestation occurs by converting forests to agricultural land and utilizing forest resources for making money (Viitanen, 1996).

1.2.1 Direct Causes and Root Causes

In general, direct causes of forest decrease include agricultural activity, overgrazing, logging, fuelwood collecting, urbanization, and forest fire (Bewket, 2003; Geist & Lambin, 2002; Sands, 2005; Thomas & Middleton, 1994; Yirdaw, 1996b). In Africa, the most common direct cause is clearance of forests to provide land for agricultural activities and the other direct causes include fuelwood gathering and overgrazing (Harrison, 1987; Sands, 2005). The same things also apply to Ethiopia (Birhane et al., 2006; Teketay, 2001).

As for root causes, it is generally agreed that population growth is the most common factor of forest decrease in developing countries (Mather & Needle, 2000; Thomas & Middleton, 1994; Tole, 2004). As the population grows, forests are cleared to provide lands for agricultural activities (Sands, 2005; Viitanen, 1996; Yirdaw, 1996b). In developed countries, on the other hand, there is less need to clear forest for agriculture because of low population growth and high agricultural productivity (Sands, 2005).

However, Geist and Lambin (2002) pointed out that earlier studies put too much emphasis on population increases and agricultural activities as causes of forest decrease. They conclude that forest decreases in developing countries in general are caused by a combination of direct and root causes rather than a single factor, which vary by geographical and historical background.

1.2.2 Population Increase

Population increase is considered as the most important root cause of the forest decrease in Ethiopia. As a result of increasing population, forests have been cleared to provide land for agriculture and pasture and to harvest fuelwood (Bishaw, 2001; Darbyshire et al., 2003; De Vletter, 1991; Sayer et al., 1992; Wood, 1990; Yirdaw, 1996a, 2002; Yirdaw & Luukkanen, 2003). In highland areas of the country, population density has been high for a considerably long time, which induced high rates of forest depletion. In lowland areas, on the other hand, population density has been low and forest decrease has not been a serious concern until recently (Yirdaw, 1996a).

However, there is no reliable demographic data to characterize historical population change in the country (Kuru, 1986). It is estimated that the national population was 0.5 million in the first century, and then gradually increased to 1.0 million by 1000, reaching 2.0 million in 1500 and 3.2 million in 1820 (Maddison, 2006). During the last two centuries, the population grew more rapidly and increased to 39.9 million in 1984 and 73.8 million in 2007 (Population Census Commission, 2008).

The environment of the Ethiopian highland has been suitable to human inhabitation before deforestation and subsequent land degradation became a serious concern recently (Hurni, 1988). As a result, 88% of people live in the area over 1,500 m above sea level, although it accounts for only 44% of the country's land area (Eshetu & Högberg, 2000).

1.2.3 Agricultural and Grazing Lands Development

In Ethiopia, cropland expansion has been a major cause of extensive deforestation (Federal Democratic Republic of Ethiopia [FDRE], 2011). Natural forests and plantations have been cleared for agriculture or grazing by rural people (Teketay, 2001). Agricultural lands have expanded from mildly sloping areas to the steeper slopes due to a shortage of lands (Hurni, 1988).

Ethiopian highlands are more favored for both settlement and farming than lowlands because temperature and rainfall conditions are generally ideal for agricultural production, while lowlands are suitable for nomadic grazing due to hot and relatively dry environment (Wolde-Mariam, 1988). Agriculture with livestock husbandry is prevalent in highland areas between 1,500 m and 3,500 m above sea level (Ritler, 2003).

1.2.4 Fuelwood Consumption

In Ethiopia, overharvesting of fuelwood has also been a major cause of extensive deforestation (Bewket, 2003). Fuelwood and charcoal accounted for over 90% of woody biomass consumption in 2013 (MEFCC, 2017) because these are the primary sources of energy for most urban and rural populations (Ministry of Agriculture [MoA], 2004a). Fuelwood and other woody biomass account for over 90% of rural energy (FDRE, 2011).

1.3 Impact of the Forest Decrease

Forest decrease in the Ethiopian highlands has induced soil erosion, biodiversity degradation, and shortage of fuelwood and other forest products (Birhane, et al., 2006; Bishaw, 1988; Teketay, 2001; Wood, 1990; Yirdaw, 1996a, 1996b). Soil erosion has been the most serious environmental problems in northern highland areas (Bishaw, 2001). Precipitous topography and high rainfall in these areas have exacerbated the problem (Tekle, 2001; Wood, 1990; Yirdaw, 1996a). Land degradation, together with population increase, inadequate technology, and drought, poses a threat to food security in the country (Holden et al., 2003).

1.3.1 Shortage of Fuelwood

Fuelwood demand is estimated to increase by roughly 40% from 2013 to 2033 due to population increase (MEFCC, 2017). As a result of increased demand for fuelwood and decreased woody biomass resources, the gap between supply and demand for fuelwood is expanding (Lemenih & Kassa, 2014).

1.3.2 Land Degradation and Productivity Loss

In Ethiopian highland, natural forest clearance for agricultural land development gradually induced soil depletion and degradation over long periods of time (Hurni, 1988; Lemenih et al., 2005). Deforestation and subsequent soil erosion reduce agricultural productivity in two ways. First, soil erosion reduces capacity of land to hold water for plant growth (Yirdaw, 1996b). Second, rural people use more dung and crop residues as household energy sources when fuelwood availability becomes limited. Increased utilization of cow dung and crop residues not for natural fertilizers but for energy leads to soil fertility loss (Bishaw, 1988; Harrison, 1987; Teketay, 2001; Yirdaw, 1996a, 1996b). When crop yield decline, people need to clear more forests to produce more crops (Yirdaw, 1996b). Forest decrease and subsequent land degradation are regarded as one of the most important issues threatening the people's life and food security in the country (Bishaw, 2001; Holden et al., 2003).

1.4 Purposes of the Project

Considering the seriousness of land degradation in Ethiopia, especially in the northern highland areas, there is urgent need to restore the degraded lands and manage the remaining natural resources in a sustainable way. Therefore, this project (i) determines important factors influencing on current distribution pattern of forests and other land cover types by using a geographic information system (GIS) and several thematic maps, (ii) estimates the trajectory of forest cover change using a literature review and comparison of land cover maps in different years, and (iii) investigates practical modeling methods to identify suitable locations for common useful tree species in the Amhara Region, one of the National Regional States[1] located in the northern highland of Ethiopia.

1.5 Project Area

The Amhara Region of Ethiopia is selected as the target area of the project (Figure A1) (see Appendix.) The region is known as the most seriously degraded region in the northern highland. The total area of the region is 155,648 km^2 and population was 17.2 million in 2007 (Population Census Commission, 2008).

1.6 Outline of the Project

This project paper is comprised of five chapters. This first chapter provided an overview of the main subject of this study, namely forest decrease and its causes and impacts in Ethiopia. Chapter 2 reviews literature about the present status and management of forest resources in the Amhara Region. Chapter 3 analyzes current distribution of forest and other land covers in the region by using digital land cover maps and attempts to determine major factors influencing the current forest distribution, such as annual rainfall and elevation. Chapter 4 estimates forest cover change in the Amhara Region during the past millennia using a literature review and from 1972 to 2003 by comparing digital land cover maps. Chapter 5 attempts to identify suitable sites for major useful tree species in the region and to investigate practical methods for suitability modeling. Chapter 6 provides overall conclusions arising from this project.

CHAPTER 2

FOREST RESOURCES AND ITS MANAGEMENT IN THE AMHARA REGION

2.1 Definition of the Words for Forest Resources

Differences between the words forest, woodland, and shrubland are sometimes confusing. FAO (2018) defines forest as “Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ” and other wooded land as “Land not classified as “Forest”, spanning more than 0.5 hectares; with trees higher than 5 meters and a canopy cover of 5-10 percent, or trees able to reach these thresholds in situ; or with a combined cover of shrubs, bushes and trees above 10 percent”. In Ethiopia, MEFCC (2018) defines forest as “land occupied with trees (natural and planted, including bamboo) attaining a height of more than 2 meters at maturity, canopy cover of more than 20% and covering an area of more than 0.5 ha, with a minimum width of 20 meters or not more than two-thirds of its length”.

Sands (2005) pointed out that difference of the meaning between deforestation and degradation is ambiguous and it makes the precise reporting of forested and cleared areas difficult. He said that deforestation is the transformation of forest to another permanent land use such as farmland, grazing land, or urban area and forest degradation is the deterioration of the ecosystem functions without clearance of the forest over naturally recoverable level.

2.2 Current Status of Forest Resources

In Ethiopia, forests are under threat of deforestation and degradation today due to population growth and accompanying fuelwood consumption increase (Smith et al., 2016). However, consistent and reliable data on forest resource are limited (MEFCC, 2017, 2018; Smith et al., 2016). The work by the Woody Biomass Inventory and Strategic Planning Project (WBISPP) of Ministry of Agriculture is a commonly cited source of forest resource data including land cover (Smith et al., 2016).

According to the result of WBISPP, the cover of forest, plantation, woodland, and shrubland in the country were 3.6%, 0.4%, 25.9%, and 23.1%, respectively in 1986-2000 and in the Amhara Region were 0.6%, 1.3%, 6.6%, and 27.6%, respectively in 1995 (MoA, 2004b). According to the estimation by MEFCC (2018), forest cover in the country is 15.7%, which include natural forest, plantation, dense woodland, and bamboo. Mekonnen et al. (2016) also estimated that the cover of forest, plantation, woodland, and shrubland in the Amhara Region were 3.1%, 0.4%, 4.7%, and 5.7%, respectively in 2008.

2.3 Ownership of Forests

2.3.1 Ownership Change and Land Redistribution

Forest property rights have been one of the most important factors contributing to deforestation in Ethiopia (Bewket, 2003). From a standpoint of land tenure policy changes, there are three time periods, namely the pre-1975 land tenure system, the rule of *Derg* from 1975 to 1991, and the period since 1991 (Berhanu & Fayera, 2005).

(1) Before 1975

In Ethiopia, there were complex land tenure systems until the 1974 revolution. The most common form was a communal land called *rist* (Berhanu & Fayera, 2005; Teklu, 2005). The land reform conducted in the early 17th century had a large impact on the forest resources of the northern highland. All lands not cultivated were transformed to communal lands. As a result, deforestation was accelerated and afforestation was decelerated (Yirdaw, 1996b).

(2) Between 1975 and 1991

In 1975, after the end of imperial regime, the military government abolished private land ownership and made all lands the common property of Ethiopian people. Individual households could have only user rights that could not be transferred by sale, lease, or mortgage (Ali et al., 2011; Berhanu & Fayera, 2005; Bewket, 2003; Mekonnen, 2009; Teklu, 2005). The nationalization of land caused indifference among people toward responsibility for maintenance of forest resources (Bekele, 2003). During this period, on-farm tree harvesting was prohibited and there were frequent redistributions of farmland, so tree planting on farms was not common (MoA, 2004b).

(3) After 1991

Even after the fall of the military government in 1991, the new government kept land as public property and stipulated it in the constitution (Teklu, 2005). In the Amhara Region, land redistribution took place in 1997, which created fear among rural people that their land would be redistributed without compensation at any time and discouraged tree planting and improvement of their land (Berhanu & Fayera, 2005; Holden et al., 2003). However, land transactions such as sharecropping and lease were liberalized, while sales and mortgaging remained prohibited (Berhanu &

Fayera, 2005). After the land redistribution ended in 2000, on-farm tree planting, which was not common before 1991, considerably increased (MoA, 2004b).

2.3.2 Forest Ownership Types

In the Amhara Region, four forest ownership types are currently known: state, community, private, and church forests (Amhara National Regional State Bureau of Agriculture [ANRS BoA], 1999).

(1) State Forests

In Ethiopia, most of the remaining natural forests were designated as National Forest Priority Areas (NFPAs) for purpose of protection and conservation of biodiversity (Teketay et al., 2010). There are 58 NFPAs across the country (MEFCC, 2018). The responsibility of NFPAs was transferred to the regional governments and NFPAs are also called Regional Forest Priority Areas (RFPAs) since then (Teketay et al., 2010). In the Amhara Region, there are 13 RFPAs, which has an estimated area of 549,417 ha (ANRS BoA, 1999).

(2) Community Forests

In many places across the country, traditional community forests have been established to provide fuelwood and construction materials and to rehabilitate degraded areas (ANRS BoA, 1999). In addition to traditional management systems, area enclosures and participatory forest management projects have been carried out by government organizations, NGOs, and donor agencies (Teketay et al., 2010).

(3) Private Forests

In the Amhara Region, farmers have been involved in conservation and tree planting in homesteads, on agricultural lands, and in other areas to satisfy wood demand by households and to sell forest products for cash (Teketay et al., 2010).

(4) Church Forests

In Ethiopia, forest patches are conserved as sacred groves in and around churches. Local people call a church with forest *debr* or *geddam*, which means holy place (Wassie et al., 2010). There are about 35,000 church forests across the country (Abbott, 2019). These forests are found between 1,400 m and 3,000 m above sea level and mostly less than 2 ha in size (Binggeli et al., 2003). In the Amhara Region, since most natural forests have been converted to other land uses such as farmlands and grazing lands, forests are found only around churches (Aerts et al., 2006; Teketay et al., 2010).

Church forests are the last remnant of high indigenous biodiversity reflecting the original ecosystems of each area (Abbott, 2019; Bongers et al., 2006), so they can perform as seed sources for forest restoration (Muys et al., 2006). However, in most church forests natural regeneration is disturbed by overgrazing and unsustainable tree harvesting for timber and fuelwood (Binggeli et al., 2003).

CHAPTER 3

FOREST COVER DISTRIBUTION IN THE REGION

3.1 Factors Determining Forest Cover Distribution

In Ethiopia, several natural vegetation types, which range from desert to tropical forest and alpine grassland, are found due to diverse environmental conditions across the country, including climate, soil, and topography (FAO, 1986a). These vegetation types are divided into eight, namely afroalpine and sub-afroalpine vegetation, dry evergreen montane forest and grassland complex, moist evergreen montane forest, *Acacia-Comiphora* woodland, *Combretum-Terminalia* woodland, lowland semi-evergreen forest, desert and semi-desert scrubland, and inland waters (Asefa et al., 2020; Institute of Biodiversity Conservation [IBC], 2005).

3.1.1 Elevation and Rainfall

Elevation and rainfall ranges are the most important environmental factors to determine distribution of natural vegetation types in the country (De Vletter, 1991). Elevation is the most decisive factor of temperature distribution (Westphal & Stevels, 1975); the following regression formula is applied in most parts of the country (UNDP & FAO, 1984c).

$$\text{Mean temperature (degrees C)} = 30.2 - 0.0059 * \text{elevation (m)}$$

In dry lowland areas, steppe vegetation of low shrubs dominates. As the amount of rainfall increases, the natural vegetation changes to open woodland of small trees and shrubs and to deciduous woodlands (FAO, 1986a). The dominant trees in lowland areas include *Acacia* species, *Combretum collinum*, and *Terminalia Brownii*

(Bekele, 2003). At transitional areas between lowland and highland, evergreen woodlands dominate. In highland areas over 1,500 m above sea level, multistory forests are prevalent (FAO, 1986a). Common vegetation types here are *Juniperus*, *Arundinaria*, *Podocarpus*, *Aningeria*, *Olea*, and *Baphia* forests (UNDP & FAO, 1984d). As the elevation increases and the annual rainfall decreases, the natural vegetation changes to mountain woodland over 2,400 m, mountain savannah over 2,700 m, and sub-alpine and alpine vegetations of only short grasses over 3,400 m (FAO, 1986a).

In Ethiopia, traditional agro-climatic zone system classified by elevation and annual rainfall ranges has been used for agriculture production and natural resources management. The classification and range of elevation slightly vary in different studies (Table A1). In this project, the classification used by Bekele-Tesemma (2007a) and De Vletter (1991) is adopted. In the classification, agro-climatic zones are divided into *bereha* (< 500 m), *kolla* (500-1,500 m), *weyna dega* (1,500-2,300 m), *dega* (2,300-3,200 m), and *wurch* (> 3,200 m). These zones are subdivided by annual rainfall ranges into dry (< 900 mm), moist (900-1,400 mm), and wet (> 1,400 mm).

3.1.2 Soil and Topography

Soil is important for plant growth because it anchors plants and provides water and nutrients. Deep soil is better because it can store more water and nutrients than more shallow soils. In general, soil is deeper in valleys than mountain ridges and at flat areas than along steep slopes (Sands, 2005).

Topography of Ethiopia is characterized by a great difference between hot lowlands and cool highlands separated by the rift valley (Kuru, 1986; Westphal & Stevels, 1975). There are high and steep mountains, flat-topped tablelands, deep canyons, and rolling plains (Teketay, 2001). According to a study of two small watersheds in northern highland areas, remaining natural forests were found mostly on inaccessible steep slopes (Gebresamuel et al., 2010).

3.1.3 Population density

Highland areas of Africa are generally highly populated due to favorable climatic conditions, especially high amount of rainfall and population increase seems to be the main root cause of forest decrease (Yirdaw, 1996b). In Ethiopia, population density of highlands is much higher than lowlands (Eshetu & Högberg, 2000). The proportion of agricultural land also increases in highlands (Wolde-Mariam, 1988). The area from 1,500 m to 2,500 m is densely populated by sedentary subsistent farmers, so the landscape in this area dominates agricultural lands, while the area below 1,500 m is occupied by nomadic pastoralist (Teketay et al., 2010).

3.2 Methods

As the above mentioned, there are several factors that presumably have influence on the current distribution of forest and other land cover types in the country. However, relationships between these factors and land cover distribution have not been verified quantitatively. Accordingly, this chapter attempts to understand the influence of elevation and annual rainfall on forest and other land cover distributions in the Amhara Region.

3.2.1 Materials

Exiting digital thematic maps and GIS software, namely ESRI ArcGIS, were used for the analysis. The thematic maps include administrative boundaries, land cover types, annual rainfall, and elevation. For the administrative boundary map, GADM database version 2.5 (GADM, 2015) was used. The land cover map was obtained at the Amhara National Regional State (ANRS)[1] Bureau of Finance and Economic Development (BoFED) in Bahir Dar, Ethiopia, which is a product of Woody Biomass Inventory and Strategic Planning Project (WBISPP) of Ministry of Agriculture (MoA) that is based on Landsat TM satellite imagery acquired in 1995 at 30 m spatial resolution (MoA, 2004b). As for the annual rainfall map, WorldClim 1.4 (WorldClim, 2005) at 1 km spatial resolution was used, which was produced by Hijmans et al. (2005) based on historical data from 1960 to 1990. Concerning elevation, ASTER Global Digital Elevation Model (GDEM) at 30 m spatial resolution was used, which was produced by the Ministry of Economy, Trade and Industry of Japan and National Aeronautics and Space Administration (METI & NASA, 2009).

Original classification of the WBISPP land cover map consists of nine major classes, namely forest, woodland, shrubland, grassland, cropland, afro-alpine vegetation, water area, bareland, and urban areas. These are further sub-divided into 56 subclasses. Forest is subdivided into nine subclasses, namely montane broadleaf, montane mixed, montane coniferous, dry *Juniperus*, lowland semi-evergreen, riparian, highland bamboo, lowland bamboo, and plantation. Each of the subclasses is further divided into three subclasses by crown cover density, namely open, dense, and closed (MoA, 2004b).

3.2.2 Flow of the Spatial Analysis

Figure A2 shows the flow of the spatial analysis. Preprocessing of the digital maps included projections from geographic coordinate system (GCS) to Universal Transverse Mercator (UTM), datum transfer from Adindan to WGS84, extraction of maps of the Amhara Region, resampling of raster cell size, and reclassification of attribute. Additionally, areas of forest and other land cover types were tabulated. Subsequently, the distribution of forest and other land cover types were compared between different elevation classes and annual rainfall classes.

3.3 Results

3.3.1 Land Cover of the Amhara Region in 1995

Figure A3 is the land cover map of the Amhara Region in 1995 extracted from the WBISSP land cover map (MoA, 2004b). Though the original map consists of nine major classes and 56 subclasses, this rearranged map represents the nine major classes only: forest, woodland, shrubland, grassland, cropland, afro-alpine vegetation, water area, bareland, and urban areas.

Table A2 shows the area of each land cover type in the Amhara Region in 1995 based on the analysis of the WBISSP land cover map as described above. All the nine major classes and 30 of the 56 subclasses were identified. Regarding the major classes, cropland accounted for the largest area (38.5%), followed by shrubland (26.6%), grassland (17.9%), bareland (6.6%), woodland (5.7%), water (2.6%), forest (1.6%), afro-alpine (0.4%), and urban (0.01%). As for subclasses of the forest, plantation was the largest (48.0%), followed by riparian (25.7%), montane broadleaf (18.3%), and others.

3.3.2 Elevation, Rainfall, and Land Cover

(1) Elevation and Land Cover

Figure A4 is the elevation map of the Amhara Region extracted from ASTER GDEM (METI & NASA, 2009). The elevation ranged from 452 m to 4,532 m. As for traditional agro-climatic zones, the *kolla* zone (500-1,500 m), *weyna dega* zone (1,500-2,300 m), and *dega* zone (2,300-3,200 m) accounted for almost whole area of the region (96.9%).

Table 1 shows the percentage of area by land cover type in each elevation range based on the analysis of the land cover and elevation maps. The area of the *bereha* zone (< 500 m) is of too limited spatial extent to be considered in this analysis and was not included. The most dominant land cover type in each zone was shrubland in the *kolla* zone, cropland in the *weyna dega* and *dega* zones, grassland in the *wurch* zone (3,200-3,700 m), and afro-alpine in the *high wurch zone* (> 3,700 m).

Forest cover was generally low in all the five zones ranging from 0.2% to 2.6%. Woodland cover was also generally low, ranging from 0.1% to 1.8%, except 17.0% in the *kolla* zone. Shrubland cover was higher than forest and woodland covers in lower areas: 41.8% in the *kolla* zone, 26.1% in the *weyna dega* zone, and 12.6% in the *dega* zone. Cropland cover was generally high, ranging from 20.9% to 56.9%, except in the *high wurch* zone.

Table 1. Percentage of Area by Land Cover Type in Each Elevation Range in the Amhara Region in 1995

Land Cover	Elevation Ranges (Agro-climatic Zones)					
	500-1,500 m (*kolla*)	1,500 -2,300 m (*weyna dega*)	2,300 -3,200 m (*dega*)	3,200 -3,700 m (*wurch*)	> 3,700 m (*High wurch*)	Total
Afro-alpine	0.001	0.01	0.02	1.1	**87.0**	0.4
Forest	0.6	1.7	2.6	2.2	0.2	1.6
Woodland	17.0	1.8	0.4	1.3	0.1	5.7
Shrubland	**41.8**	26.1	12.6	0.0	1.6	26.7
Grassland	16.4	17.8	17.7	**48.4**	9.1	17.9
Cropland	20.9	**39.6**	**56.9**	43.8	1.8	38.5
Bareland	2.7	7.7	9.6	3.3	0.2	6.6
Water	0.5	5.2	0.3	0.0	0.0	2.6
Urban	0.0	0.01	0.01	0.0	0.0	0.01
Unknown	0.2	0.0	0.0	0.0	0.0	0.05

(2) Annual Rainfall and Land Cover

Figure A5 is the annual rainfall map of the Amhara Region during 1960-1990 extracted from WorldClim 1.4 (WorldClim, 2005). The annual rainfall ranged from 555 mm to 2,026 mm. As for traditional agro-climatic zones, the moist zone (900-1,400 mm) accounted for the largest area (60.9%), followed by the dry zone (< 900 mm) at 24.1% and the wet zone (> 1,400 mm) at 15.0%.

Table 2 shows the percentage of area by land cover type in each annual rainfall range based on the analysis of the land cover and annual rainfall maps above. The most dominant land cover type in each zone was shrubland in the dry zone (48.4%) and cropland in the moist (40.6%) and wet (60.3%) zones. Forest and cropland covers increased in proportion to the annual rainfall amount. Forest cover increased from 0.5% in the dry zone to 4.8% in the wet zone. Cropland cover increased from 19.4% to 60.3% in the same. Contrarily, shrubland cover decreased from 48.4% in the dry zone to 6.8% in the wet zone.

Table 2. Percentage of Area by Land Cover Type in Each Annual Rainfall Range in the Amhara Region in 1995

Land Cover	Annual Rainfall Ranges (Agro-climatic Zones)		
	< 900 mm (dry)	900-1,400 mm (moist)	> 1400 mm (wet)
Afro-alpine	0.02	0.5	0.6
Forest	0.5	1.3	4.8
Woodland	5.4	5.6	6.2
Shrubland	**48.4**	23.1	6.8
Grassland	21.3	16.2	18.9
Cropland	19.4	**40.6**	**60.3**
Bareland	4.7	8.9	0.7
Urban	0.0	0.01	0.003
Water	0.1	3.7	1.7
Unknown	0.2	0.1	0.0

(3) Rainfall, Elevation and Land Cover

Table A3 shows the percentage of area by elevation and annual rainfall ranges based on the analysis of the elevation and annual rainfall maps. The moist (900-1,400 mm) *weyna dega* (1,500-2,300 m) zone was the most dominant accounting for 25.7% of the total area, followed by the moist *dega* (2,300-3,200 m) zone for 17.5% and the moist *kolla* (500-1,500 m) zone for 15.3%.

Table A4 shows the percentage of area by land cover type in each elevation and annual rainfall range based on the analysis of the land cover, elevation, and annual rainfall maps. Forest cover generally increased according to the annual rainfall increase except in the *kolla* zone (Table A5). Woodland cover was generally higher in the *kolla* zone than the other zones: from 10.6% to 38.6% in the *kolla* zone and from 0.1% to 3.0% in the other zones (Table A6). Woodland cover increased in proportion to the rainfall amount in the *kolla* zone. Shrubland cover was generally higher in drier areas, ranging from 47.1% to 49.6% in dry zones (Table A7). Cropland cover was generally high in the moist and wet zones, especially in the *weyna dega*, *dega*, and *wurch* zones they ranged from 39.7% to 74.0% (Table A8).

3.4 Discussion

3.4.1 Land Cover of the Amhara Region in 1995

Forest, woodland, and shrubland covers of the Amhara Region in 1995 were 1.6%, 5.7%, and 26.6%, respectively (Table A2). These figures slightly differ from 1.9%, 6.6%, and 27.6%, respectively, as stated in the original WBISPP report (MoA, 2004b). This may be mainly because these studies used different administrative boundary maps. The country does not have an official administrative boundary map, so each study uses a different boundary map.

Cropland accounted for 38.5%, the largest area of the nine major land cover classes. This implies that at least 38.5% of the original vegetation was lost by 1995. Grassland accounted for 17.9%, some of which may be grazing land. The high percentages of cropland and grassland cover in the Amhara Region indicate that the main causes of forest decrease are the conversion of land for agriculture and grazing.

3.4.2 Elevation, Rainfall, and Land Cover

Cropland cover was high in the *weyna dega* (1,500-2,300 m), *dega* (2,300-3,200 m), and *wurch* (3,200-3,700 m) zones, ranging from 39.6% to 56.9% (Table 1). Grassland cover was also high in these zones, ranging from 17.7% to 48.4%. Conversely, forest and woodland covers were generally low in these zones, ranging from 1.7% to 2.6% and from 0.4% to 1.8%, respectively. This indicates that original woody vegetation was cleared and converted to cropland and grazing land due to high population pressure in these three zones. On the other hand, in the *kolla* zone (500-1,500 m), cropland and grassland covers were lower and woodland and shrubland cover was higher than the three zones above. In the *high wurch* zone (> 3,700 m), cropland cover was only 1.8% and afro-alpine vegetation dominated (87.0%). This suggests that population pressure was lower and conversion from original woody vegetation to cropland was less serious in the *kolla* and *high wurch* zones than in the other three zones.

Cropland cover increased with annual rainfall increases (Table 2): 19.4% in the dry zone (< 900 mm), 40.6% in the moist zone (900-1,400 mm), and 60.3% in the wet zone (> 1,400 mm). This suggests that population pressure was higher in high rainfall areas. However, forest cover also increased from 0.5% to 1.3% and 4.8% with annual rainfall increase. It may be because of relatively favorable conditions for forest growth in the high rainfall areas.

In terms of both elevation and annual rainfall ranges, cropland cover was higher in the moist and wet *weyna dega*, *dega*, and *wurch* zones than the other zones, ranging from 39.7% to 74.0% (Table A8). On the other hand, woodland and shrubland covers were lower in these zones (Table A6 and Table A7). This suggests that population pressure was higher in these six zones than the other zones. However, forest cover was higher in the wet *weyna dega*, *dega*, and *wurch* zones than other zones, even though cropland cover was higher. This may be because of relatively favorable conditions for forest growth in the wet zones.

This analysis does not include estimation of change from original vegetation to the current land cover, although it is important. In Ethiopia, however, information of original land cover is limited. At this moment, the potential natural vegetation map of eastern and southern Africa produced by van Breugel et al. (2015) and the potential ecosystem map of Africa produced by Sayre et al. (2013) may be possible choices.

3.5 Conclusion

In 1995, cropland accounted for 38.5% of the area in the Amhara Region. This means that at least 38.5% of the original vegetation was converted to cropland. On the other hand, forest and woodland covers were low, 1.6% and 5.7%, respectively.

Cropland cover was higher in the *weyna dega*, *dega*, and *wurch* zones (1,500-3,700 m) than in the other zones. Cropland cover was also higher in high rainfall areas than low rainfall areas. These results suggest that population pressure was higher in the *weyna dega*, *dega*, and *wurch* zones than in other zones and in the high rainfall areas than low rainfall areas. However, forest cover was also higher in high rainfall areas, even though cropland cover was high. This may be due to favorable conditions for forest growth in high rainfall areas.

CHAPTER 4

FOREST COVER CHANGES IN THE REGION

4.1 Discrepancy of Statistics on Forest Cover Changes

In tropical countries, existing data on past deforestation events are generally doubtful, since these data are not based on continuous forestry inventory (Palo & Lehto, 1996). Furthermore, the standard and nature of such reporting are not consistent (Sands, 2005). Even a single organization like FAO uses inconsistent statistics of country-level deforestation rates (Teketay et al., 2010).

In Ethiopia, it is difficult to ascertain exact information about the past deforestation rate, since reliable data are limited like some other developing countries (De Vletter, 1991; MEFCC, 2018; Teketay et al., 2010; Woien, 1995). Each report adopts a different classification systems and definitions of the words such as forest and deforestation. Data on annual deforestation and afforestation are based on very rough estimations (Bekele, 2003; De Vletter, 1991).

Estimation of original forest cover in Ethiopia differs according to report: 35% (Sayer et al., 1992), 42-48% (Huffnagel, 1961), 60% (Bishaw, 1988), and 87% (Wood, 1990). Until recently, it has been frequently referred that 40% of the country was covered with forest in middle or beginning of the 20th century and since then degraded severely (Bishaw, 2001; De Vletter, 1991; Harrison, 1987; Pohjonen & Pukkala, 1990). However, several authors (e.g., Bekele, 2003; McCann, 1997, 1999; Woien, 1995) pointed out that this figure is not based on field evidence.

It seems that the period and magnitude of deforestation events vary according to the locations in the country (Yirdaw, 1996a). Some authors tried to verify forest cover change by analyzing historical photographs, aerial photographs, satellite images, pollen records, or other sources (e.g., Darbyshire et al., 2003; Nyssen et al., 2009; Ritler, 2003). These results showed that the degradation of the forest was already severe at the beginning of the 20th century.

4.2 Case Studies of Forest Cover Change Estimation

4.2.1 Forest Cover Changes during the Last 3000 Years

It appears that human-induced forest decrease had already started 2,000-3,000 years ago in the highland areas of Ethiopia (Darbyshire et al., 2003; Yirday, 1996a). According to pollen and charcoal analyses of sediment cores from two lakes in the Amhara Region by Darbyshire et al. (2003), for example, people started to clear natural *Podocarpus-Juniperus* forest around 500 B.C. and these forests had disappeared by 1200. After that, grassland dominated from 1200 to 1400 and then secondary *Juniperus* forest dominated from 1400 to 1700. Forest degradation became serious again during the last 300 years, probably because of population increase and agricultural activities.

4.2.2 Forest Cover Changes during the Last 200 Years

Ritler (2003) examined 60 historical travel reports and 15 photographs dated between 1865 and 1930. He reported that highland areas of Ethiopia were already largely used for agricultural purposes and forest and other wooded vegetation were mostly found in thinly populated or inaccessible areas such as steep slopes and valleys. Nyssen et al. (2009) also examined historical photographs from 13 sites in northern

Ethiopia. They concluded that vegetation cover was already highly degraded in 1868 and generally improved after that.

4.2.3 Forest Cover Changes during the 1950s to 2010s

There are several studies that examined land cover change during the past decades in the Amhara Region by using aerial photographs and/or satellite imagery (Table A9). For example, forest cover of study areas decreased from 27.1% in 1957 to 2.2% in 1995 in the Dembecha District (Zeleke & Hurni, 2001), from 8.6% in 1958 to 5.9% in 1986 in the Kalu District (Tekle & Hedlund, 2000), and from 2.7% in 1995 to 2.3% in 2014 on the eastern border of the region (Ayele et al., 2018).

Contrarily, forest cover of study areas increased from 4.7% in 1957 to 9.2% in 1986 in the Debre Sina District (Woien, 1995), from 2.4% in 1957 to 3.6% in 1998 in the Guzamn District (Bewket, 2002), and from 20.6% in 1995 to 25.6% in 2015 in the Fagita Lekoma District (Wondie & Mekuria, 2018).

4.3 Methods

As noted above, several authors have already estimated historical land cover changes at some areas of the Amhara Region. However, these studies generally did not cover large areas to be associated with the overall trend of the Amhara Region. Therefore, the study described in this chapter estimates the general trend of land cover changes in the region by comparing several land cover maps in different years.

4.3.1 Materials

Digital land cover maps from different years and GIS software, namely ESRI ArcGIS, were used for analysis. All the maps are products of different projects based on satellite imagery analyses. The periods of satellite imagery are 1972-1978, 1995, 1999-2000, and 2003.

The land cover map in 1972-1978 is a national-level map of Ethiopia in vector format, which was created from Landsat MSS imagery at 80 m spatial resolution in the Assistance to Land Use Planning Project of UNDP & FAO (1984c). The legend consists of 12 major classes and 30 subclasses.

The land cover map in 1995 is a national-level map of Ethiopia in vector format, which was created from Landsat TM imagery at 30 m spatial resolution in the Woody Biomass Inventory and Strategic Planning Project (WBISPP) of the Ministry of Agriculture (MoA, 2004b). The legend consists of nine major classes and 56 subclasses.

The land cover map in 1999-2000 is a map of Africa in raster format, which was created from SPOT 4 VEGETATION imagery at 1 km spatial resolution in the Global Land Cover 2000 Project (GLC 2000) of European Commission (Mayaux et al., 2003). The legend consists of six major classes and 27 subclasses.

The land cover map in 2003 is a global map in raster format called Global Land Cover by National Mapping Organizations (GLCNMO) version 1, which was created from MODIS Terra imagery at 1 km spatial resolution by Geospatial Information Authority of Japan (GSI) and Chiba University (Tateishi et al., 2011). The legend consists of 20 classes.

4.3.2 Flow of the Spatial Analysis

Figure A6 is the flow of spatial analysis by GIS. As with Chapter 3, the preprocessing of the digital maps included projections from geographic coordinate system (GCS) to Universal Transverse Mercator (UTM), datum transfer from Adindan to WGS84, extraction of maps of the Amhara Region, and reclassification of attributes. Subsequently, areas of forests and other land cover types were tabulated and differences across the years were tabulated and compared.

4.4 Results

Table 3 shows the percentage of area by land cover type in the Amhara Region in 1972-78, 1995, 1999-2000, and 2003 based on the analysis of the land cover maps above. Forest cover was low in all the maps: 0.5% in 1972-1978, 1.6% in 1995, and 0.4% in 1999-2000 and 2003. Cropland cover was consistently high: ranging from 38.5% in 1995 to 71.9% in 1999-2000. However, cropland cover increased and decreased unnaturally. Woodland, shrubland, and grassland cover also fluctuated.

Table 3. Percentage of Area by Land Cover Type in the Amhara Region in Different Years

Year	1972-78	1995	1999-2000	2003
Spatial Resolution	80 m	30 m	1 km	1 km
Afro-alpine	0.8	0.4	n/a	n/a
Forest	0.5	1.6	0.4	0.4
Woodland	1.5	5.7	0.4	30.3
Shrubland	20.8	26.7	24.2	0.1
Grassland	16.2	17.9	0.9	11.8
Cropland	57.9	38.5	71.9	55.3
Bareland	0.1	6.6	0.1	0.1
Water	2.3	2.6	2.0	1.9
Developed	0.0	0.0	0.0	0.0

4.5 Discussion

Forest cover was consistently low during the last decades ranging from 0.4% to 1.6%. In 1995, forest cover was higher (1.6%) than the other years (0.1-0.5%). This may be due to differences in spatial resolution rather than actual land cover changes. Spatial resolution of the satellite imagery used for the map in 1995 was much higher (30 m) than the other maps (80 m and 1 km). Therefore, it can be inferred that areas of remaining forests were so small that they were identified by high resolution satellite imagery only. The area of woodland, shrubland, grassland, and cropland increased and decreased unnaturally. This may be due to the classification method of satellite imagery rather than change in actual land cover.

As described above, the four maps compared in this analysis were produced using different spatial resolution satellite imagery and different classification methods, which made it difficult to exactly know the change of land cover extent. Using maps made by consistent spatial resolution and classification method is important to obtaining better results. There are some possible choices of land cover maps for further analyses, such as the global land cover map during the period from 1992 to 2015 that was produced by European Space Agency (ESA) Climate Change Initiative Land Cover (CCI-LC) project (UCL-Geomatics, 2017) and the similar maps during the period from 2001 to 2018 called MODIS Land Cover Type Product (Friedl & Sulla-Menashe, 2019).

4.6 Conclusion

According to the analysis of the four land cover maps, forest cover in the Amhara Region fluctuated from 0.4% to 1.6% during 1972-2003. This may be due to variation in spatial resolution of satellite imagery rather than actual land cover changes.

It can be inferred that areas of most forests were of such limited spatial extent that they can be identified by only high-resolution satellite imagery. Woodland, shrubland, grassland, and cropland covers also fluctuated a lot. This may be because of differences in the classification method of satellite imagery rather than actual land cover changes. Better result would be obtained by using land cover maps created with spatial data having a consistent spatial resolution and analyzed with a more robust classification method.

CHAPTER 5

SUITABILITY ANALYSIS OF USEFUL TREE SPECIES IN THE REGION

5.1 Restoration of the Degraded Lands

There is urgent need to restore degraded lands of the Ethiopian highland. To recover from the present status, establishment of forests through agroforestry, forestry, and conservation of remnant natural forests is necessary (Bishaw, 2001).

Agroforestry is one of the most important solutions to both land degradation and livelihood improvement in the country. Multipurpose trees planted on farmland not only improve soil, but also provide fuelwood, fodder, and other basic goods for farmers (Bewket, 2003; Yirdaw, 1996b).

In recent years, plantation forestry has been receiving attention as an important tool to help recover natural ecosystems because planting of fast-growing tree species on heavily degraded areas facilitate recovery of soil fertility, flora, and fauna faster than natural recovery (Lemenih, 2006; Yirdaw, 2002). In Ethiopia, there are three types of tree plantations, namely commercial plantations, woodlots, and peri-urban plantations (MEFCC, 2018). Plantation forestry was introduced to Ethiopia around 1900, which not only provides fuelwood and timber for nearby communities, but also minimizes soil erosion (Yirdaw, 1996a). However, most plantations are managed without basic information such as growth rates and past planting record (MEFCC, 2018).

Natural recovery of vegetation is one of the best options in those areas where environmental conditions such as temperature and rainfall are favorable. Exclusion of people and animals from degraded lands contributes to initial growth and following succession of natural vegetation (Lemenih & Kassa, 2014; MEFCC, 2017; Tekle, 2001). In certain degraded areas of the northern highlands, communities restrict natural resources utilization by human and domestic animals to prevent further land degradation and promote vegetation recovery (Birhane et al., 2006). In these areas, however, absence of natural vegetation as a seed source limits the colonization of the native tree species (Yirdaw, 2002). Therefore, enrichment tree planting of indigenous and exotic species to assist natural regeneration process is recommended at enclosures (Mengistu et al., 2005). Locating enclosures near remnant natural forest is also recommended. This can promote invasion of indigenous and pioneer tree species and they work as nurse trees for growth of climax tree species (Muys et al., 2006).

5.2 Tree Species for Afforestation

In most cases, pioneer tree species are chosen for afforestation because they can grow well and outcompete weeds under strong sunlight. Required properties for plantation trees include fast growth, high wood quality, and strong disease resistance. However, tree species having these properties are limited to some exotics such as eucalyptus (Sands, 2005).

In Ethiopia, plantation forests are predominantly comprised of exotic tree species (MEFCC, 2018). Several factors such as fast growth, environmental tolerance, lack of basic data, and limited seed availability have resulted in excessive dependence on monoculture plantation of eucalyptus (Bewket, 2003). *Eucalyptus globules* and *E. camaldulensis* are the most common fuelwood and timber trees (FAO, 1986a; Wassie, 2017). However, there are several potential useful species including not only exotics but also indigenous species (Bekele-Tesemma, 2007b; FAO, 1986b; MoA, 2004b; UNDP & FAO, 1984a; Yirdaw, 1996a).

5.2.1 Pros and Cons of Exotic Tree Species

Exotic tree species play an important role in rehabilitation of degraded lands as well as producing socio-economic and environmental benefits for communities (Wyk et al., 2006). Afforestation of exotic species compensates for decreasing supplies of woody products from declining natural forests and maintains soil fertility (Michelsen et al., 1996). The advantages of exotic species over native species for tree plantation include: (i) adequate information on silvicultural techniques and management practices, (ii) relatively fast growth, and (iii) property of woody material that can be used for various purposes (Feyera et al., 2002; Wyk et al., 2006).

A plantation of exotic species has several positive impacts on the environment, especially when planted on hillsides or degraded lands. These impacts include biomass increase, soil improvement, run-off reduction, and decrease of harvesting pressure on natural forests (Jagger & Pender, 2003). With appropriate management practices, a plantation of exotic trees can facilitate the process of forest succession by providing a nursery effect for native tree colonization (Feyera et al., 2002; Quine & Humphrey, 2010; Yirdaw, 1996b).

Conversely, exotic tree species have several disadvantages. For example, they are generally more competitive than indigenous species for water, nutrients, and light. They have been alleged to cause negative environmental changes in and around plantations (Feyera et al., 2002; Nyssen et al., 2004; Pohjonen & Pukkala, 1990; Yirdaw, 2002). In the case of eucalyptus, for example, they use less water than deciduous trees during rainy seasons but continue to grow and use more water during dry seasons (Gindaba, 2006; Muys et al., 2006). Furthermore, it has been said that eucalyptus plantations may result in soil erosion because they inhibit growth of ground surface vegetation (Yirdaw, 2002). In moisture-stressed environments, the negative impacts of eucalyptus on water sources may be more serious (Jagger & Pender, 2003).

Negative impacts of exotic species on site condition and understory vegetation vary according to several factors, such as planted species, site history, and management practices (Feyera et al., 2002; Lemenih et al., 2004). Change from natural forests to plantations of exotic species is generally harmful. However, in the case of degraded areas of Ethiopian highland, positive impacts on environment would generally outweigh the negative ones (Pohjonen & Pukkala, 1990; Yirdaw, 1996a, 1996b). In degraded areas, there is also urgent need to meet increasing demands for forest products such as fuelwood and timber (Feyera et al., 2002).

5.2.2 Indigenous Species for Afforestation

In Ethiopia, dominant tree species in natural vegetation include *Juniperus procera*, *Podocarpus jalcatus*, *Olea welwitschii*, and *Cordia africana* in the highland areas and *Acacia* species, *Combretum collinum*, and *Terminalia brownii* in the lowland areas (Bekele, 2003). *Faidherbia albida* is one of the most common indigenous species for agroforestry (FAO, 1986a). There are also a variety of valuable native tree species. However, most of them are climax species, which are difficult to cultivate, and pioneer species such as *Cordia africana* grow very slowly. Some native species such as *Juniperus procera* and *Podocarpus gracilior* can grow easily under *Eucalyptus globulus*. Therefore, transformation of plantation forests of exotic species to those of indigenous species may be one of the desirable ways to restore natural vegetation (Pohjonen & Pukkala, 1990).

5.2.3 Exotic Species for Afforestation

In Ethiopia, species from four genera, namely *Eucalyptus*, *Cupressus*, *Pinus*, and *Acacia*, are commonly planted (Lemenih & Kassa, 2014). Eucalyptus was introduced to the country around 1895 to relieve fuelwood and timber shortages in Addis Ababa, and then expanded to other parts within a few decades (Ritler, 2003). It is estimated that over 120 eucalyptus species have been introduced to the country (Wassie, 2017). They are preferred mainly because of fast growth and suitability to a wide range of environments (Bewket, 2003). More than 90% of plantation forests are comprised of eucalyptus today (MEFCC, 2018).

Eucalyptus globulus and *E. camaldulensis* are the most common exotic species in the Amhara Region (Wassie, 2017). People use these wood and foliage as fuel and small timbers as poles for construction (Pohjonen & Pukkala, 1990). These species grow well even in dry and nutrient deficit soils of the highland areas (Gindaba, 2006). *Acacia saligna*, *Leucaena leucocephala*, and *Sesbania grandiflora* are common exotic species for agroforestry (FAO, 1986a). Since early 2000s, *Acacia decurrens* has been the most preferred exotic species in the Fagita Lekoma District in the Amhara Region due to high survival rate, fast growth, and suitability for charcoal (Belayneh et al., 2018)

5.3 Land Suitability Models by GIS

In general, land suitability analyses by geographic information system (GIS) consist of three steps: (i) preprocessing of spatial data, (ii) developing a spatial analysis flowchart illustrating the modeling process, and (iii) executing and evaluating the model (Malczewski, 2004). In the field of forestry, ecology, and agriculture, the multicriteria decision analysis (MCDA) approach, including weighted summation, analytical hierarchy process (AHP), and ordered weighed averaging (OWA), is commonly used (Malczewski, 2006). For suitability analyses of plant species, a decision tree analysis is also commonly used (e.g. Bydekerke et al., 1998; Rahim et al., 2010; Wandahwa & van Ranst, 1996).

The land evaluation framework of FAO (1976) categorizes land suitability into five classes: S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable), N1 (currently not suitable), and N2 (permanently not suitable). This classification has been used commonly for suitability analysis of plant species and various land use practices (e.g. UNDP & FAO, 1984b; Tadesse & Negese, 2020; Teka & Welday, 2017; Yalew, 2018; Yalew et al., 2016; Yohannes & Soromessa, 2018).

Each study employs a different set of factors in suitability modeling. For example, Dengiz et al. (2010), Rahim et al. (2010), and Teka and Welday (2017) used only soil attributes, while Moriondo et al. (2008) used rainfall and temperature. Other studies used several other sets of factors (e.g. Mezquida et al., 2010; Rubio & Sánchez-Palomares, 2006; Tadesse & Negese, 2020; Yalew, 2018; Yohannes & Soromessa, 2018). In Ethiopia, natural vegetation types are determined mainly by elevation and rainfall (De Vletter, 1991), which is the approach used here.

5.4 Methods

Selection of tree species based on land suitability is important for afforestation. However, in Ethiopia, information about suitable areas for forestry and agroforestry species seems generally unknown. Therefore, this chapter (i) identifies suitable areas for six common useful tree species in the Amhara Region and (ii) investigates practical methods for suitability modeling applicable to tree species for afforestation practices in Ethiopia.

5.4.1 Tree Species

In this suitability analysis, six common species in Ethiopian highland were chosen. *Eucalyptus globulus* and *E. camaldulensis* are the most common tree species for fuelwood and timber. *Faidherbia albida*, *Acacia saligna*, *Leucaena leucocephala*, and *Sesbania grandiflora* are the common multipurpose tree species for agroforestry (FAO, 1986a). All species except *F. albida* are exotics.

5.4.2 Criteria and Classification

The decision tree methodology was used in the suitability modeling. Current land cover, slope gradient, elevation, and annual rainfall were used as criteria. Suitability was classified into four levels according to the classification in the FAO's land evaluation framework (FAO, 1976), namely S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable), and N (not suitable). Although the original FAO's framework has N1 (currently not suitable) and N2 (permanently not suitable), these classes were merged into one class, N (not suitable), in this study.

Figure 1 is the decision tree used in this analysis. First, water areas were classified as not suitable and land areas were classified as suitable. After that, suitability levels based on slope gradient, elevation, and annual rainfall ranges were analyzed for each tree species by using the criteria described in Table A10. Suitable slope gradient ranges for each species were determined with reference to information in FAO (1986b). In this study, suitable slope gradient ranges for forestry and agroforestry species were set at 0-30% and 0-50%, respectively. Suitable elevation and rainfall ranges for each species were determined with reference to information from several sources, namely Bekele-Tesemma (2007b), Desta et al., (2005), and Orwa et al., (2009). Suitable elevation ranges were estimated from suitable temperature ranges using the following regression formula (UNDP & FAO, 1984c).

Mean temperature (degrees C) = 30.2 - 0.0059 * elevation (m)

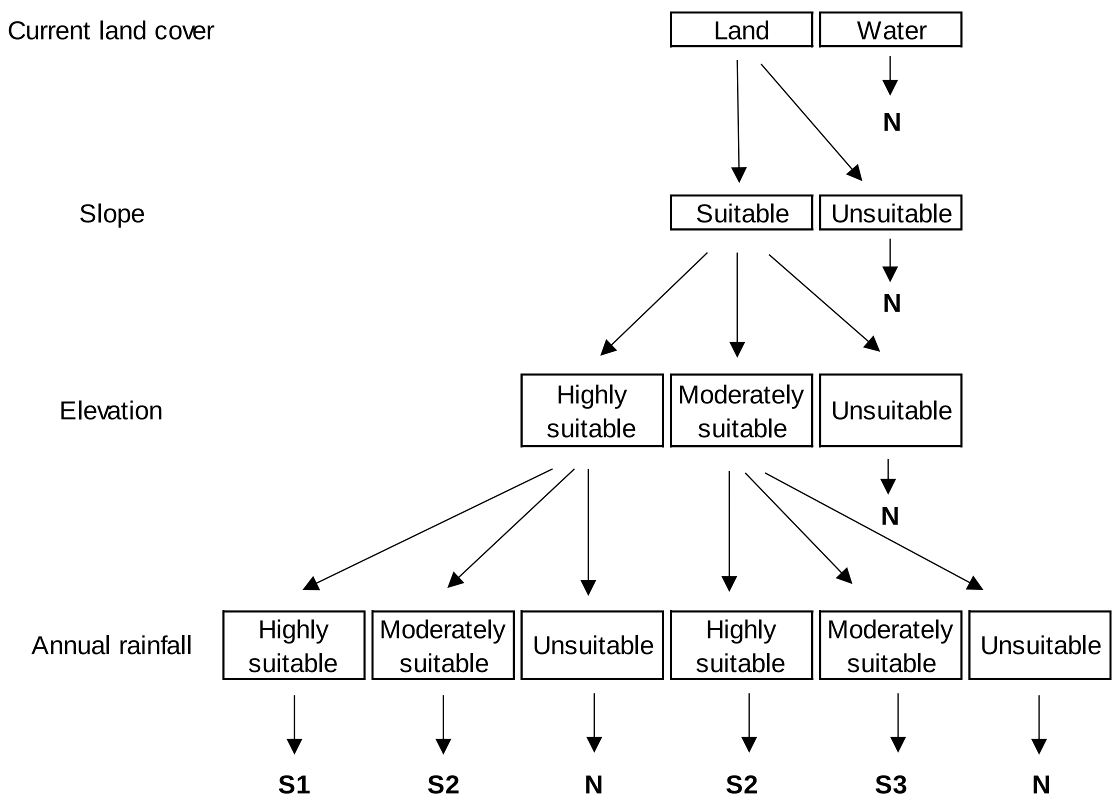

Figure 1. Decision Tree for the Suitability Analysis

S1 = Highly Suitable; S2 = Moderately Suitable; S3 = Marginally Suitable; N = Not Suitable.

5.4.3 Materials

Several digital thematic maps and GIS software, ESRI ArcGIS, were used. As for administrative boundary, land cover, annual rainfall, and elevation maps, the same maps were used as those described in the Chapter 3.

5.4.4 Flow of the Spatial Analysis

Figure A7 is the flow of spatial analysis by GIS. As described in Chapters 3 and 4, the preprocessing of the digital maps included projections from geographic coordinate system (GCS) to Universal Transverse Mercator (UTM), datum transfer from Adindan to WGS84, extraction of maps of the Amhara Region, and reclassification of attributes. Subsequently, suitability maps were generated based on the decision tree output (Figure 1). Lastly, percentages of areas by suitability level were tabulated for each of the six tree species.

5.5 Results

Water area, which was classified as not suitable for afforestation, was 2.6% of the Amhara Region as described in Chapter 3 (Table A2). Figure A8 is the slope gradient map of the region. Table A11 shows percentage of area by slope gradient ranges. Slope gradients from 0-50%, which were classified as suitable for agroforestry species, was 72.3%. Slope gradients from 30-50%, which were classified as suitable for forestry species, was 16.9%. Annual rainfall ranged from 555 mm to 2,026 mm (Figure A5) and elevation ranged from 442 m to 4,532 m (Figure A4) as described in Chapter 3.

Figure A9 to Figure A14 are the suitability maps for the six species. Table 4 shows the percentage of suitable area by species made from these maps. Suitable area (total of S1, S2, and S3) significantly varied by species, ranging from 7.1% for *Acacia saligna* to 52.5% for *Faidherbia albida*. Suitable areas for the other species were 12.0% for *Eucalyptus globlus*, 15.1% for *E. camaldulensis*, 26.3% for *Leucaena leucocephala*, and 33.9% for *Sesbania grandiflora*.

Table 4. Percentage of Area by Suitability Level for the Six Tree Species in the Amhara Region

Species	S1	S2	S3	N
Eucalyptus globlus	3.8	7.1	1.1	88.0
Eucalyptus camaldulensis	9.3	5.5	0.3	84.9
Faidherbia albida	2.1	21.1	29.2	47.5
Acacia saligna	0.1	1.9	5.1	92.9
Leucaena leucocephala	6.7	19.1	0.5	73.7
Sesbania grandiflora	7.0	15.7	11.2	66.1

Note. S1 = Highly Suitable; S2 = Moderately Suitable; S3 = Marginally Suitable; N = Not Suitable.

5.6 Discussion

In the spatial analysis, slope gradient range was a significant determinative factor. The suitable slope gradient range for agroforestry species was set at 0-50% (Table A10) and accounted for 89.2% of the study area (Table A11). Conversely, the suitable slope gradient range for forestry species was set at 30-50% (Table A10) and accounted for only 16.9% (Table A11). As a result, the suitable areas (total of S1, S2, and S3) for the forestry species, *Eucalyptus globulus* and *E. camaldulensis*, were only 12.0% and 15.1%, respectively (Table 4). The suitable areas for agroforestry species, *Faidherbia albida*, *Leucaena leucocephala*, and *Sesbania grandiflora*, were generally high, 52.5%, 26.3%, and 33.9%, respectively, except *Acacia saligna* (Table 4). The suitable area of *Acacia saligna* was of small areal extent due to preference for drier areas.

However, the criteria of suitability classification by slope gradient range was provisional, so these need to be reexamined based on reliable scientific methods and ground-truthing. The criteria of suitability classification by elevation and annual rainfall ranges were estimated by reference to the information from several sources.

However, some of figures significantly differed by source, so the reliability of these information also needs to be reexamined.

For this analysis, suitable elevation ranges were calculated from suitable mean temperature by using regression formula of UNDP & FAO (1984c). However, this process is not necessary if a mean temperature map is available. For example, the annual mean temperature map produced by Fick and Hijmans (2017) is available on the WorldClim website for free.

Using slope gradient, elevation, and annual rainfall ranges for the suitability assessment seems practical because these factors significantly differ by location in the Amhara Region. The method was so simple and it was easy to understand and implement. Furthermore, the digital elevation model (DEM) and annual rainfall maps can be obtained on the web for free. Slope gradient maps can be made from DEM by using GIS software.

In the analysis, mapping and tabulation were made at the regional level only. However, the same method is applicable for areas of smaller spatial extent. In the Amhara Region, Bureau of Agriculture (BoA) has branches at Zones, Districts, and Wards. This kind of suitability method can be applied also at these levels of administration for afforestation planning.

5.7 Conclusions

The suitable slope gradient ranges for agroforestry and forestry species were set at 0-50% and 30-50%, respectively. This had considerable influence on the results because the area percentages of these two slope gradient ranges were largely different. However, the criteria of suitability classification by slope gradient range was provisional, which needs to be reexamined based on reliable scientific methods and ground-truthing. The suitable elevation and annual rainfall ranges for each tree species were estimated by reference to information from several sources. The criteria of suitability classification by elevation and annual rainfall ranges also needs to be reexamined since the information varied among different studies.

Using slope gradient, elevation, and annual rainfall ranges for suitability assessment of tree species in the Amhara Region seemed practical because these factors significantly vary by location. The method was easy to understand and implement. Necessary maps can be obtained on the web for free. The same suitability analysis method is applicable at smaller units of administration for afforestation planning.

CHAPTER 6

CONCLUSIONS

Degradation of natural vegetation has been a serious concern in northern highland areas of Ethiopia for a long time. There is urgent need to restore the degraded lands and manage the remaining natural resources in a sustainable way. Against this background, this project (i) determined important factors influencing on current distribution pattern of forests and other land cover types by using a Geographic Information System (GIS) and several thematic maps, (ii) estimated the trajectory of forest cover change through literature review and comparison of land cover maps in different years, and (iii) found practical modeling methods to identify suitable locations for common useful tree species in the Amhara Region located in the northern highland of Ethiopia.

Analysis of a land cover map in 1995 showed that forest and woodland cover in the Amhara Region was low, 1.6% and 5.7%, respectively. Cropland cover was higher in the *weyna dega* (1,500-2,300 m), *dega* (2,300-3,200 m), and *wurch* (3,200-3,700 m) zones than the other zones and in higher rainfall areas than lower rainfall areas. These results suggest that population pressure was higher in these areas.

Several authors (e.g. Darbyshire et al., 2003; Nyssen et al., 2009; Ritler, 2003) analyzed historical photographs, aerial photographs, satellite images, pollen records, or other sources. These results showed that the degradation of the forest was already severe at the beginning of the 20th century.

Analysis of four land cover maps indicated that forest cover in the Amhara Region fluctuated from 0.4% to 1.6% during 1972-2003. However, this may be due to variation in spatial resolution of satellite imagery rather than actual land cover changes.

Woodland, shrubland, grassland, and cropland covers also fluctuated greatly. This may be because of difference in the classification method of satellite imagery rather than actual land cover change. Better result would be obtained by using land cover maps created with spatial data having a consistent spatial resolution and analyzed with a more robust classification method.

Using slope gradient, elevation, and annual rainfall ranges for suitability assessment of tree species in the Amhara Region seemed practical because these factors significantly vary by location. The same suitability analysis method is applicable at smaller units of administration for afforestation planning. However, the criteria of suitability classification by slope gradient, elevation, and rainfall range used in this project were provisional, which need to be reexamined.

APPENDIX

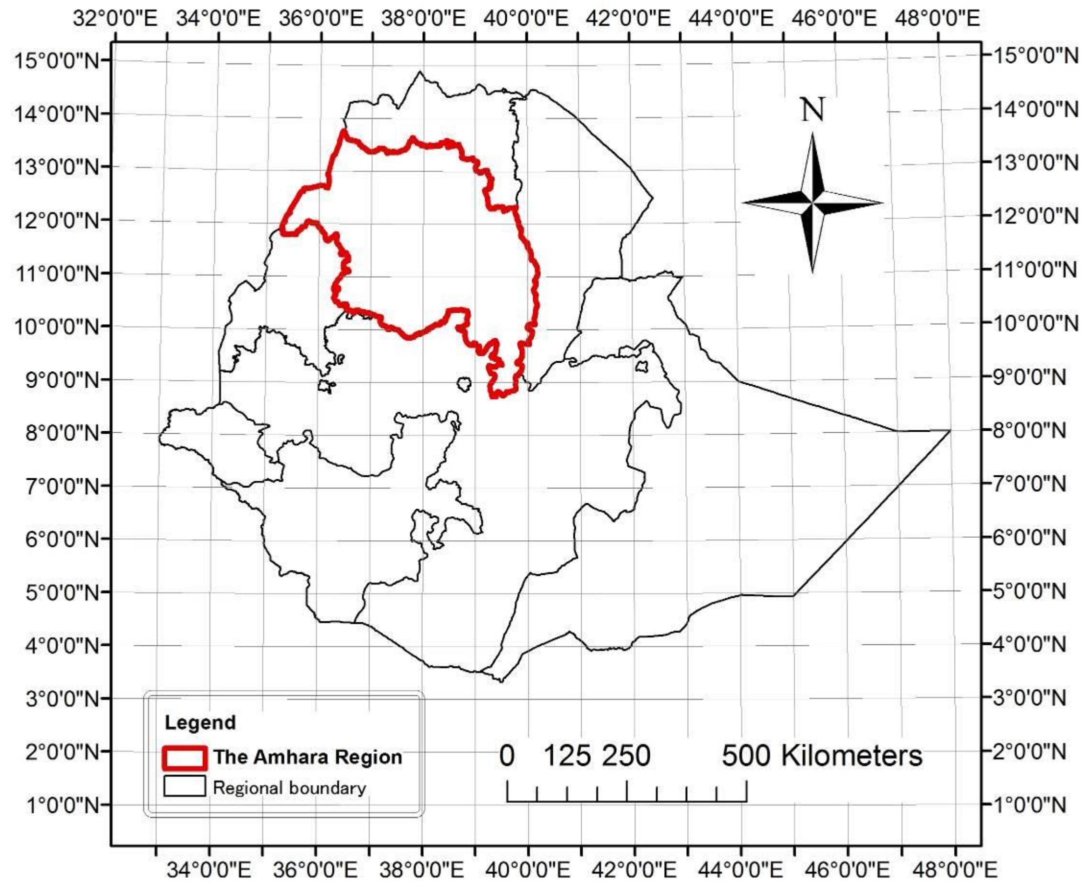

Figure A1. Map of the Amhara Region.

Data for the Administrative Boundary was Adapted from GADM (2015).

Table A1. Different Elevation Ranges of Traditional Agro-climatic Zones

Agro-climatic Zones	Gamachu (1977)	Getahun (1984)	Kuru (1986)	Bekele-Tesemma, (2007a), De Vletter (1991)	Araya, Keesstra, & Stroosnijder (2010)
Wurch	>3,000 m	3,500-4,600 m	>3,300 m	> 3,200 m	>3,000 m
Dega	2,300-3,000 m	2,400-3,500 m	2,400-3,300 m	2,300-3,200 m	2,500-3,000 m
Weyna Dega	1,500-2,300 m	1,800-2,400 m	1,800-2,400 m	1,500-2,300 m	2,000-2,500 m
Weyna Kolla	n/a	n/a	n/a	n/a	1,500-2,000 m
Kolla	800-1,500 m	1,500-1,800 m	500-1,800 m	500-1,500 m	1,000-1,500 m
Bereha	<800 m	n/a	<500 m	< 500 m	n/a

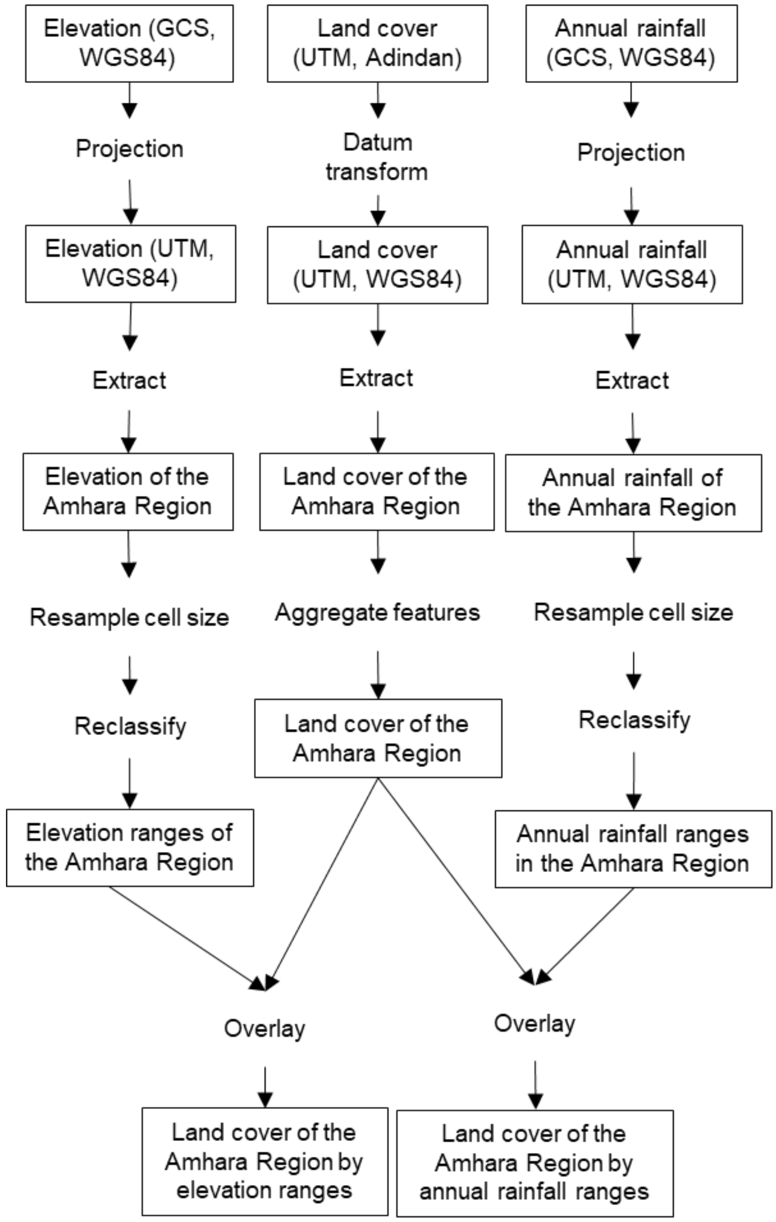

Figure A2. Flowchart of the GIS Spatial Analysis for Land Cover Distribution in the Amhara Region in 1995

GSC = geographic coordinate system; UTM = Universal Transverse Mercator; WGS = World Geodetic System.

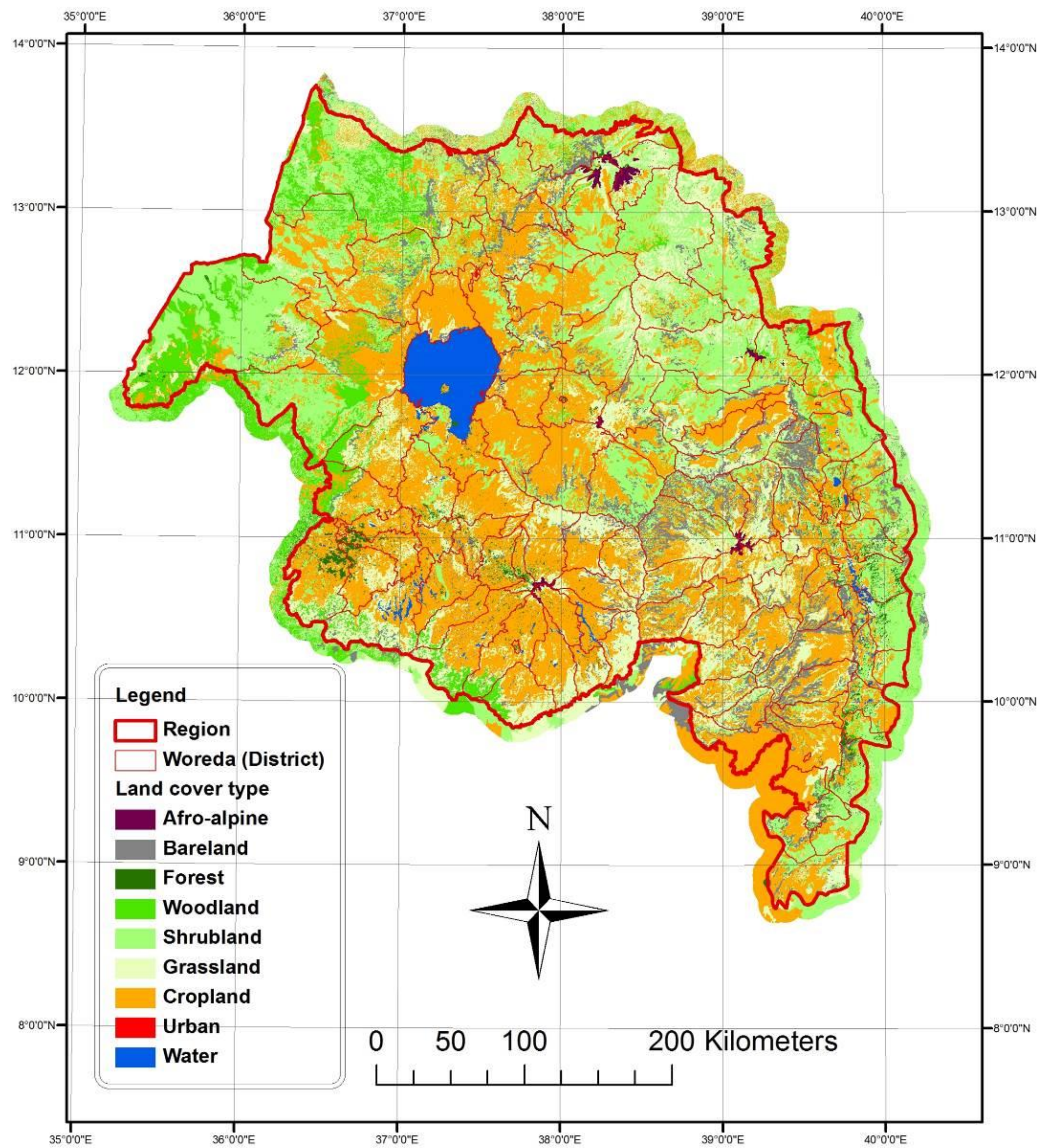

Figure A3. Land Cover Map of the Amhara Region in 1995

Data for the Land Cover Type was Adapted from Ministry of Agriculture (MoA, 2004b) and Data for the Administrative Boundary was Adapted from GADM (2015).

Table A2. Area of Each Land Cover Type in the Amhara Region in 1995

<table>
<tr><th colspan="5" rowspan="2">Land cover type</th><th colspan="2">Area</th></tr>
<tr><th>(km^2)</th><th>(%)</th></tr>
<tr><td rowspan="2">Afro-alpine</td><td colspan="4">Erica / Hypericum</td><td>32.6</td><td>0.02</td></tr>
<tr><td colspan="4">Grassland / Moorland</td><td>602.1</td><td>0.4</td></tr>
<tr><td rowspan="9">Forest</td><td colspan="2">Montane broadleaf</td><td colspan="2">Open (20-50% crown cover)</td><td>456.7</td><td>0.3</td></tr>
<tr><td colspan="2">Montane coniferous</td><td colspan="2">Open (20-50% crown cover)</td><td>163.4</td><td>0.1</td></tr>
<tr><td colspan="2">Montane mixed</td><td colspan="2">Open (20-50% crown cover)</td><td>33.0</td><td>0.02</td></tr>
<tr><td colspan="2" rowspan="3">Plantation</td><td colspan="2">Closed (>80% crown cover)</td><td>2.7</td><td>0.002</td></tr>
<tr><td colspan="2">Dense (50-80% crown cover)</td><td>13.8</td><td>0.01</td></tr>
<tr><td colspan="2">Open (20-50% crown cover)</td><td>1,179.7</td><td>0.8</td></tr>
<tr><td colspan="2" rowspan="2">Bamboo</td><td colspan="2">Dense (50-80% crown cover)</td><td>0.1</td><td>0.0001</td></tr>
<tr><td colspan="2">Open (20-50% crown cover)</td><td>3.7</td><td>0.002</td></tr>
<tr><td colspan="2">Riparian</td><td colspan="2">Open (20-50% crown cover)</td><td>641.0</td><td>0.4</td></tr>
<tr><td rowspan="2">Woodland</td><td colspan="4">Dense (>50% tree crown cover)</td><td>2,416.0</td><td>1.6</td></tr>
<tr><td colspan="4">Open (20-50% tree crown cover)</td><td>6,389.4</td><td>4.1</td></tr>
<tr><td rowspan="2">Shrubland</td><td colspan="4">Dense (>50% woody plant crown cover)</td><td>8,831.2</td><td>5.7</td></tr>
<tr><td colspan="4">Open (20-50% woody plant crown cover)</td><td>32,778.7</td><td>21.1</td></tr>
<tr><td rowspan="3">Grassland</td><td colspan="4">with moderate stock of woody biomass</td><td>1,881.5</td><td>1.2</td></tr>
<tr><td colspan="4">with light stock of woody biomass</td><td>2,327.2</td><td>1.5</td></tr>
<tr><td colspan="4">with few stocks of woody biomass</td><td>23,590.5</td><td>15.2</td></tr>
<tr><td rowspan="6">Cultivated land</td><td colspan="4">Irrigated</td><td>452.7</td><td>0.3</td></tr>
<tr><td rowspan="3">Rainfed</td><td colspan="2" rowspan="3">Cereal Land Cover System</td><td>with few stocks of woody biomass</td><td>26,882.2</td><td>17.3</td></tr>
<tr><td>with light stock of woody biomass</td><td>18,066.9</td><td>11.6</td></tr>
<tr><td>with moderate stock of woody biomass</td><td>7,952.1</td><td>5.1</td></tr>
<tr><td rowspan="2">Shifting cultivation</td><td colspan="3">with light stock of woody biomass</td><td>304.6</td><td>0.2</td></tr>
<tr><td colspan="3">with moderate stock of woody biomass</td><td>6,270.5</td><td>4.0</td></tr>
<tr><td rowspan="3">Wetland</td><td colspan="4">Open water</td><td>3,107.7</td><td>2.0</td></tr>
<tr><td colspan="4">Perennial Swamp / Marsh</td><td>305.8</td><td>0.2</td></tr>
<tr><td colspan="4">Seasonal Swamp / Marsh</td><td>563.4</td><td>0.4</td></tr>
<tr><td rowspan="2">Bareland</td><td colspan="4">Exposed rock</td><td>8,612.0</td><td>5.5</td></tr>
<tr><td colspan="4">Exposed sand / soil</td><td>1,702.7</td><td>1.1</td></tr>
<tr><td colspan="5">Urban</td><td>9.4</td><td>0.01</td></tr>
<tr><td colspan="5">TOTAL</td><td>155,648.1</td><td>100.0</td></tr>
</table>

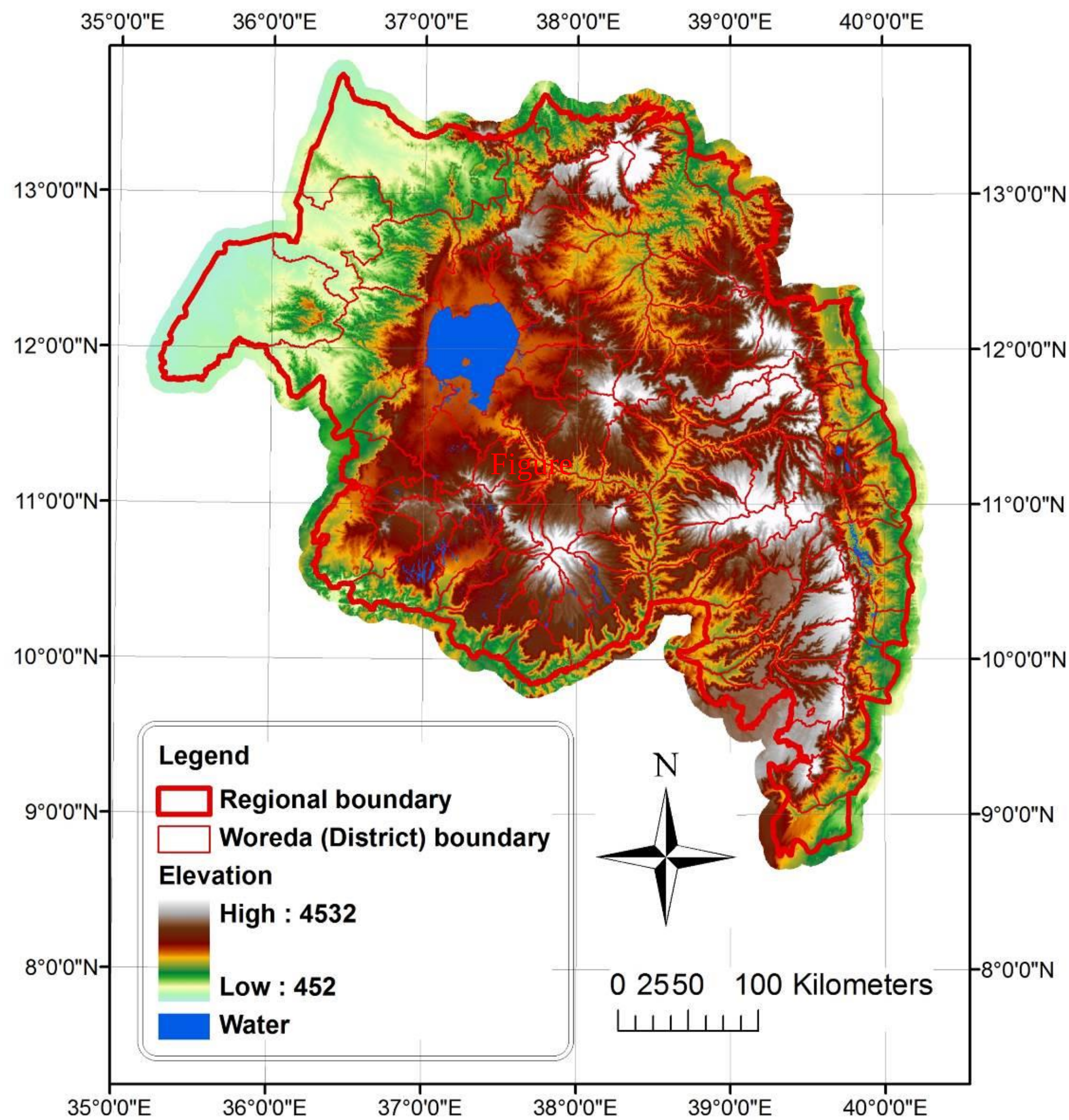

Figure A4. Elevation Map of the Amhara Region.

Data for the Elevation was Adapted from Ministry of Economy, Trade and Industry of Japan and National Aeronautics and Space Administration (METI & NASA, 2009) and Data for the Administrative Boundary was Adapted from GADM (2015).

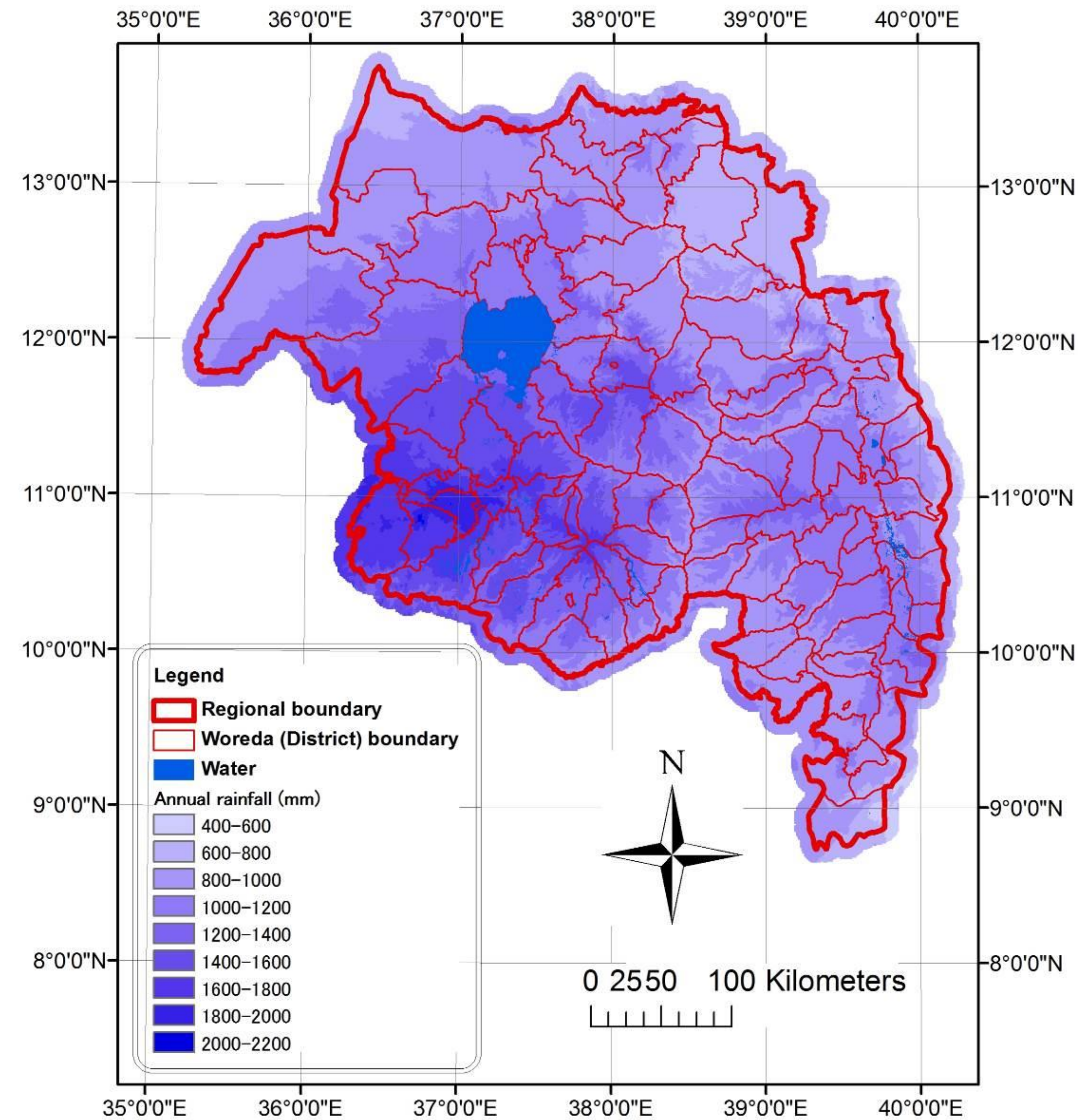

Figure A5. Annual Rainfall Map of the Amhara Region.

Data for the Annual Rainfall was Adapted from WorldClim (2005) and Data for the Administrative Boundary was Adapted from GADM (2015).

Table A3. Percentage of Area by Annual Rainfall and Elevation Ranges

Elevation (Agro-climatic Zones)	Annual Rainfall			
	< 900 mm (dry)	900-1,400 mm (moist)	> 1,400 mm (wet)	Total
> 3,700 m (*Alpine Wurch*)	0.001%	0.3%	0.1%	0.4%
3,200-3,700 m (*Wurch*)	0.02%	2.2%	0.4%	2.6%
2,300-3,200 m (*Dega*)	2.0%	17.5%	4.5%	24.0%
1,500-2,300 m (*Weyna Dega*)	11.2%	25.7%	8.3%	45.2%
500-1500 m (*Kolla*)	10.7%	15.3%	1.7%	27.7%
< 500 m (*Bereha*)	0.001%	0.0001%	-	0.001%
Total	24.1%	60.9%	15.0%	100%

Table A4. Percentage of Area by Land Cover Type in Each Elevation and Annual Rainfall Ranges in the Amhara Region in 1995

Elevation (Agro-climatic Zone)	Annual Rainfall (Agro-climatic Zone)		
	< 900 mm (Dry)	900-1,400 mm (Moist)	> 1,400 mm (Wet)
> 3,700 m (Alpine Wurch)	Afro-alpine 72.7 Forest 0.3 Woodland 0.02 Shrubland 3.6 Grassland 23.4 (1.0 km^2)	Afro-alpine 86.9 Forest 0.1 Woodland 0.1 Shrubland 1.9 Grassland 8.9 Cropland 1.9 Bareland 0.3 (521.7 km^2)	Afro-alpine 87.7 Forest 0.5 Shrubland 0.7 Cropland 1.4 Grassland 9.7 (145.4 km^2)
3,200-3,700 m (Wurch)	Afro-alpine 0.1 Forest 1.9 Woodland 2.4 Shrubland 24.7 Grassland 43.3 Cropland 21.5 Bareland 6.2 (28.6 km^2)	Afro-alpine 1.2 Forest 1.0 Woodland 1.5 Shrubland 12.5 Grassland 35.2 Cropland 44.7 Bareland 3.8 (3,437.7 km^2)	Afro-alpine 0.6 Forest 8.8 Shrubland 6.7 Grassland 44.2 Cropland 39.7 (619.5 km^2)
2,300-3,200 m (Dega)	Forest 1.4 Woodland 1.1 Shrubland 49.6 Grassland 18.2 Cropland 19.3 Bareland 10.4 (3,157.1 km^2)	Afro-alpine 0.002 Forest 1.8 Woodland 0.3 Shrubland 10.7 Grassland 18.2 Cropland 56.8 Urban 0.0 Bareland 11.9 Water 0.4 (27,213.3 km^2)	Forest 6.7 Woodland 0.3 Shrubland 3.1 Grassland 15.4 Cropland 74.0 Urban 0.0 Bareland 0.2 Water 0.3 (6,946.6 km^2)
1,500-2,300 m (Weyna Dega)	Afro-alpine 0.04 Forest 0.2 Woodland 1.3 Shrubland 49.5 Grassland 23.6 Cropland 20.3 Bareland 5.1 Water 0.0 (17,486.6 km^2)	Forest 1.3 Woodland 1.6 Shrubland 22.2 Grassland 15.2 Cropland 40.3 Urban 0.0 Bareland 11.2 Water 8.2 (39,944.5 km^2)	Forest 4.6 Woodland 3.0 Shrubland 6.8 Grassland 18.2 Cropland 63.7 Bareland 0.7 Water 3.0 (12,974.1 km^2)
500-1,500 m (Kolla)	Afro-alpine 0.004 Forest 0.6 Woodland 10.6 Shrubland 47.1 Grassland 19.6 Cropland 18.4 Bareland 3.2 Water 0.2 n/a 0.3 (16,638.6 km^2)	Forest 0.6 Woodland 19.1 Shrubland 41.0 Grassland 13.2 Cropland 23.0 Bareland 2.5 Water 0.7 n/a 0.1 (23,815.3 km^2)	Forest 0.5 Woodland 38.6 Shrubland 16.3 Grassland 25.7 Cropland 17.2 Bareland 1.7 Water 0.02 (2,719.1 km^2)
< 500 m (Bereha)	Forest 0.9 Woodland 32.0 Shrubland 55.9 n/a 11.2 (0.9 km^2)	Forest 0.9 Shrubland 99.1 (0.1 km^2)	

Table A5. Percentage of Forest Area by Elevation and Rainfall Ranges in the Amhara Region in 1995

Elevation (Agro-climatic Zone)	Annual Rainfall (Agro-climatic Zone)		
	< 900 mm (Dry)	900-1,400 mm (Moist)	> 1,400 mm (Wet)
> 3,700 m (Alpine Wurch)		0.1	0.5
3,200-3,700 m (Wurch)		1.0	8.8
2,300-3,200 m (Dega)	1.4	1.8	6.7
1,500-2,300 m (Weyna Dega)	0.2	1.3	4.6
500-1,500 m (Kolla)	0.6	0.6	0.5

Table A6. Percentage of Woodland Area by Elevation and Rainfall Ranges in the Amhara Region in 1995

Elevation (Agro-climatic Zone)	Annual Rainfall (Agro-climatic Zone)		
	< 900 mm (Dry)	900-1,400 mm (Moist)	> 1,400 mm (Wet)
> 3,700 m (Alpine Wurch)	n/a	0.1	0.0
3,200-3,700 m (Wurch)	n/a	1.5	0.0
2,300-3,200 m (Dega)	1.1	0.3	0.3
1,500-2,300 m (Weyna Dega)	1.3	1.6	3.0
500-1,500 m (Kolla)	10.6	19.1	38.6

Table A7. Percentage of Shrubland Area by Elevation and Rainfall Ranges in the Amhara Region in 1995

Elevation (Agro-climatic Zone)	Annual Rainfall (Agro-climatic Zone)		
	< 900 mm (Dry)	900-1,400 mm (Moist)	> 1,400 mm (Wet)
> 3,700 m (Alpine Wurch)	n/a	1.9	0.7
3,200-3,700 m (Wurch)	n/a	12.5	6.7
2,300-3,200 m (Dega)	49.6	10.7	3.1
1,500-2,300 m (Weyna Dega)	49.5	22.2	6.8
500-1,500 m (Kolla)	47.1	41.0	16.3

Table A8. Percentage of Cropland Area by Elevation and Rainfall Ranges in the Amhara Region in 1995

Elevation (Agro-climatic Zone)	Annual Rainfall (Agro-climatic Zone)		
	< 900 mm (Dry)	900-1,400 mm (Moist)	> 1,400 mm (Wet)
> 3,700 m (Alpine Wurch)	n/a	1.9	1.4
3,200-3,700 m (Wurch)	n/a	44.7	39.7
2,300-3,200 m (Dega)	19.3	56.8	74.0
1,500-2,300 m (Weyna Dega)	20.3	40.3	63.7
500-1,500 m (Kolla)	18.4	23.0	17.2

Table A9. Examples of Forest Area Change Estimation in the Amhara Region

Source	Zeleke and Hurni (2001)	Tekle and Hedlund (2000)	McHugh et al. (2007)	Ayele et al. (2018)	Woien (1995)	Bewket (2002)	Wondie and Mekuria (2018)	Belayneh et al. (2018)
Result	Decreased	Decreased	Decreased	Decreased	Increased	Increased	Increased	Increased
Before	27.1% (1957)	8.6% (1958)	n/a (1964)	2.7% (1995)	4.7% (1957)	2.4% (1957)	20.6% (1995)	5.8% (2003)
After	2.2% (1995)	5.9% (1986)	n/a (2001)	2.3% (2014)	9.2% (1986)	3.6% (1998)	25.6% (2015)	20.5% (2017)
Zone	West Gojam	South Wello	North Wello	n/a	North Shewa	East Gojam	Awi	Awi
District	Dembecha	Kalu	Kobo	n/a	Debre Sina	Guzamn	Fagita Lekoma	Fagita Lekoma
Area (ha)	27,103	11,000	n/a	1,877,278	15,000	36,400	67,750	n/a
Elevation (m)	1,800-2,800	1,705-3,000	1,460-1,730	580-3,960	1,700-3,500	2,420-4,000	1,888-2,915	1,887-2,902
Annual Rainfall (mm)	1,600	800-1,200	830	476-1,930	n/a	1,300	1,700	2,360-2,431
Data source	Aerial photo & satellite imagery	Aerial photo	Aerial photo & satellite imagery	Satellite imagery	Aerial photo	Aerial photo & satellite imagery	Satellite imagery	Satellite imagery

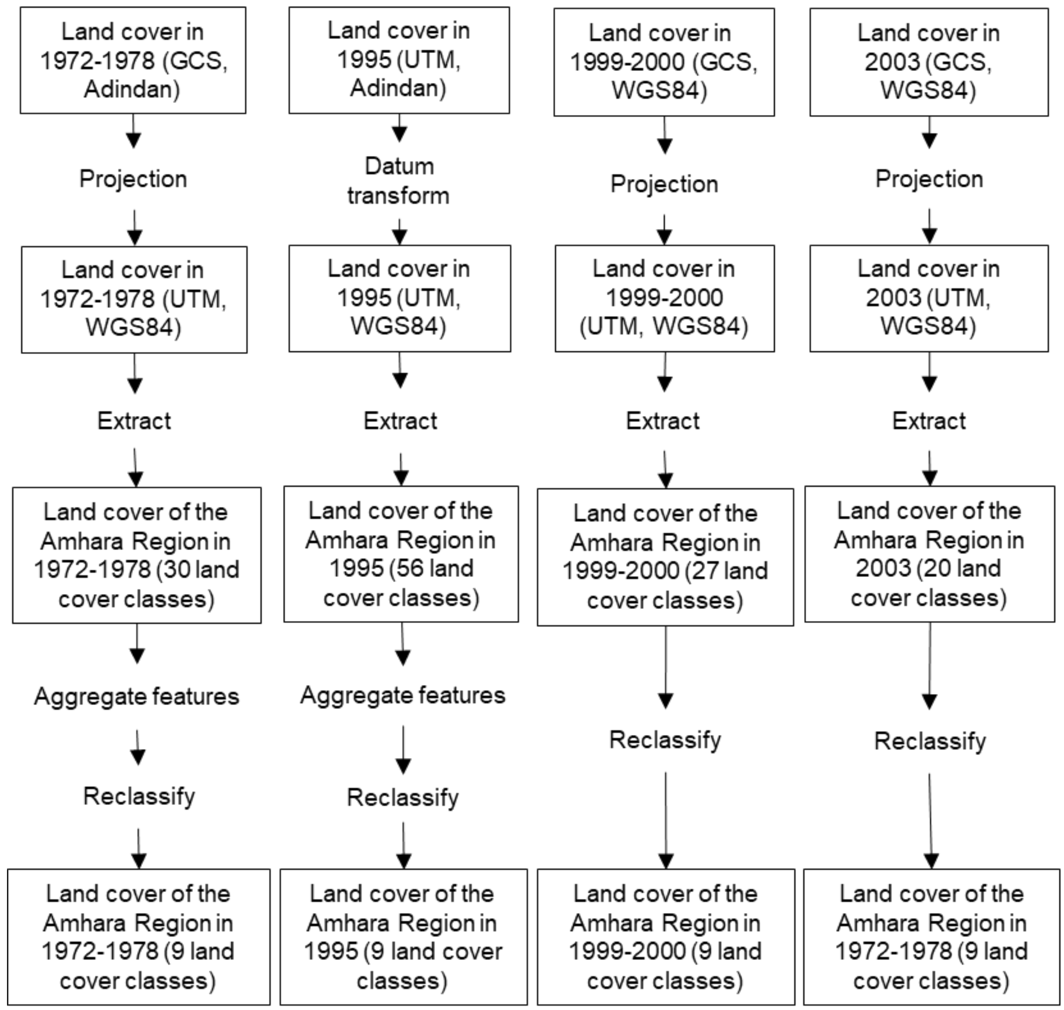

Figure A6. Flowchart of the GIS Spatial Analysis for Forest Cover Change

GSC = geographic coordinate system; WGS = World Geodetic System; UTM = Universal Transverse Mercator.

Table A10. Criteria of Suitability Classification by Slope Gradient, Elevation, and Annual Rainfall Ranges

Species	Suitability							
	Slope (%)		Elevation (m)			Annual rainfall (mm)		
	Suitable	Unsuitable	Highly suitable	Moderately suitable	Unsuitable	Highly suitable	Moderately suitable	Unsuitable
Eucalyptus globulus	30-50%	0-30% > 50%	2,100-2,800	1,500-2,100 2,800-3,200	< 1,500 > 3,200	750-1,250	500-750 1,250-1,500	< 500 > 1,500
Eucalyptus camaldulensis	30-50%	0-30% > 50%	1,200-2,300	500-1,200 2,300-2,800	< 500 > 2,800	800-1,950	250-800 1,950-2,500	< 250 > 2,500
Faidherbia albida (Acacia albida)	0-50%	> 50%	1,500-2,000	100-1,500 2,000-2,600	< 100 > 2,600	450-800	250-450 800-1,200	< 250 > 1,200
Acacia saligna	0-50%	> 50%	500-1,200	< 500 1,200-2,300	> 2,300	450-600	350-450 600-800	< 350 > 800
Leucaena leucocephala	0-50%	> 50%	100-800	< 100 800-1,500	> 1,500	650-2,000	500-650 2,000-3,000	< 500 > 3,000
Sesbania grandiflora	0-50%	> 50%	100-1,300	< 100 1,300-1,800	> 1,800	1,000-1,500	800-1,000 1,500-4,000	< 800 > 4,000

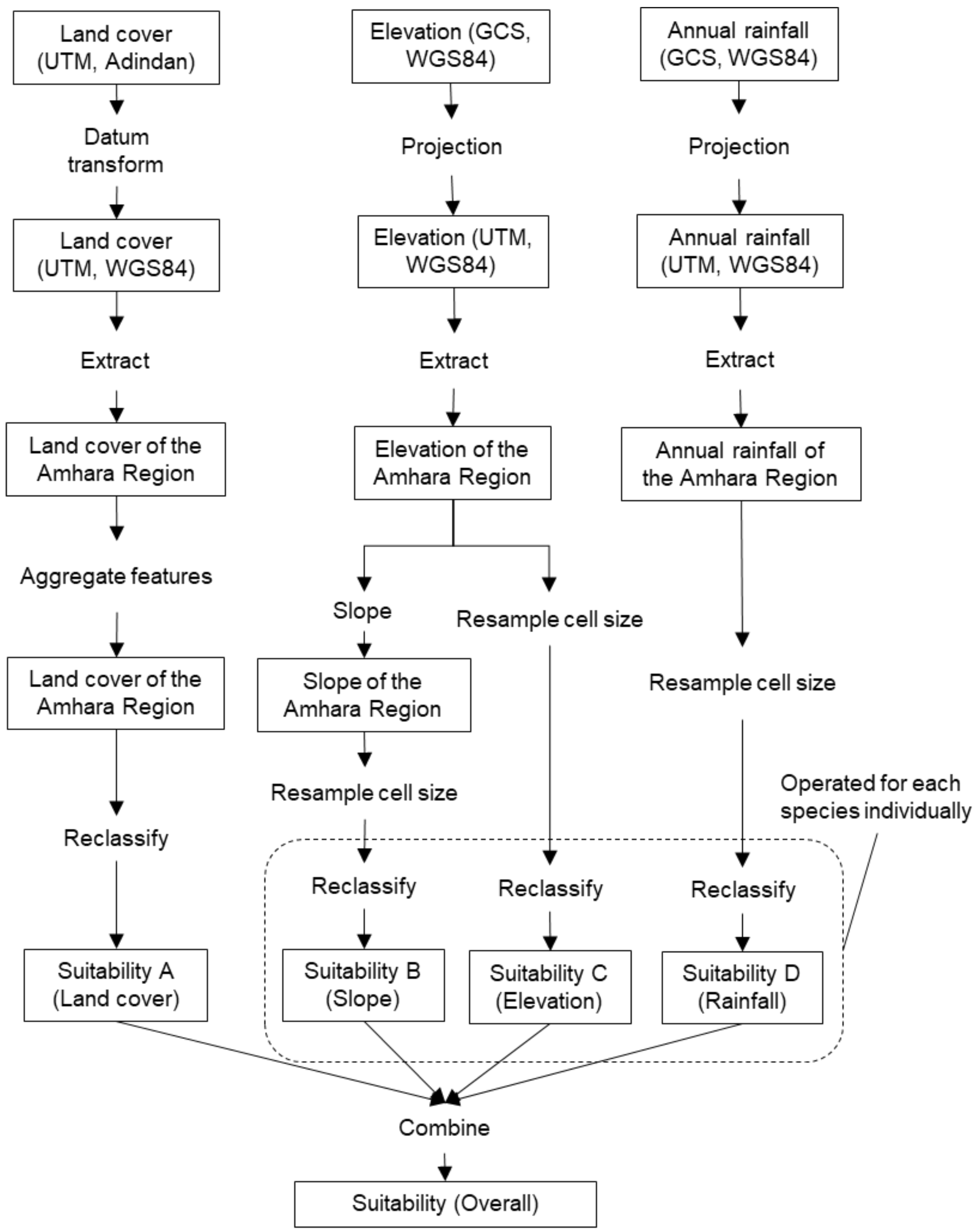

Figure A7. Flowchart of the GIS Spatial Analysis for Suitability

GSC = geographic coordinate system; WGS = World Geodetic System; UTM = Universal Transverse Mercator.

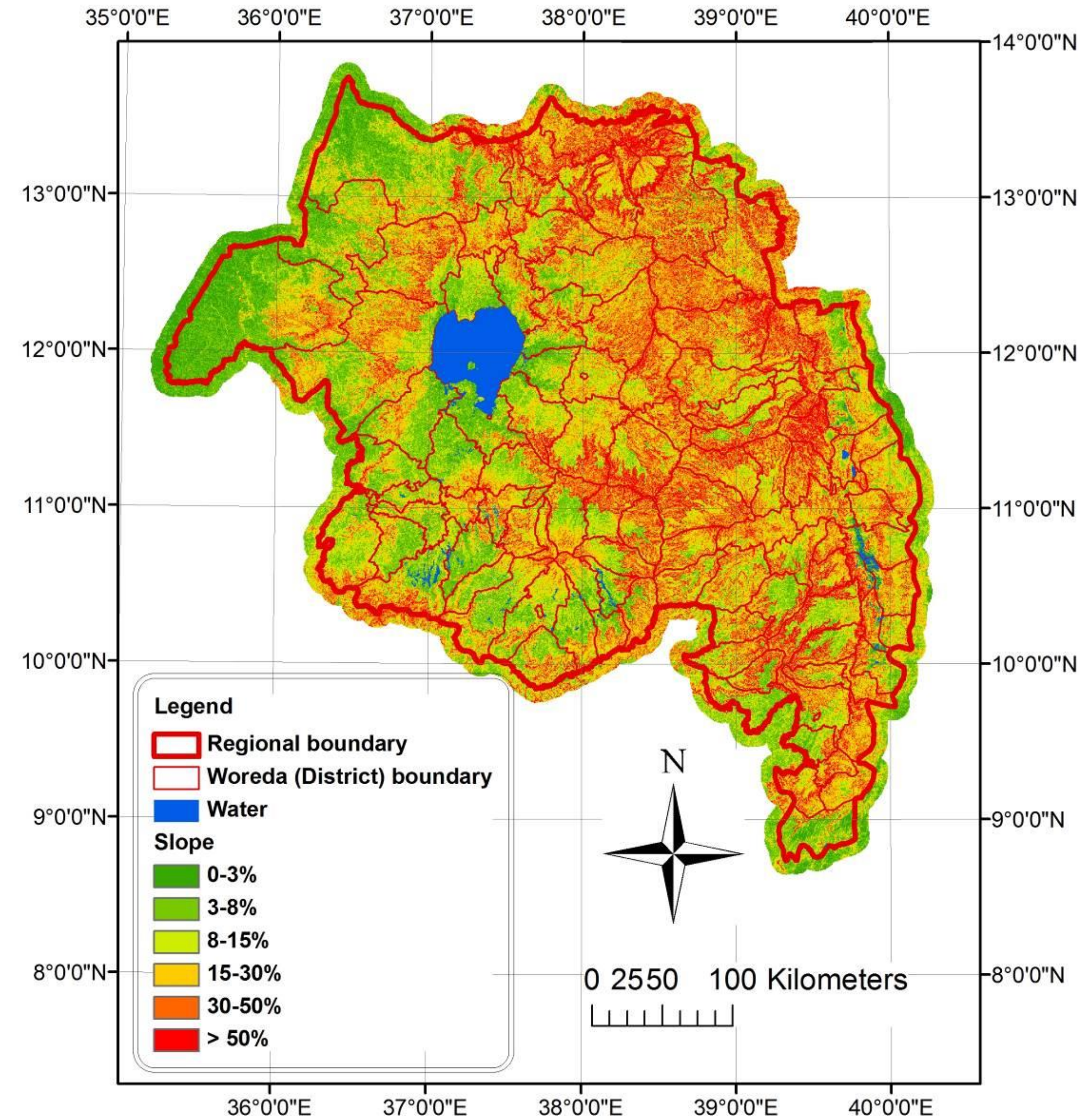

Figure A8. Slope Gradient Map of the Amhara Region

Data for the Administrative Boundary was Adapted from GADM (2015).

Table A11. Percentage of Each Slope Gradient Class in the Amhara Region

Slope class	Percentage (%)
Flat of almost flat (0-3%)	10.1
Gently sloping (3-8%)	19.7
Sloping (8-15%)	18.8
Moderately steep (15-30%)	23.7
Steep (30-50%)	16.9
Very steep (> 50%)	10.8
Total	100.0

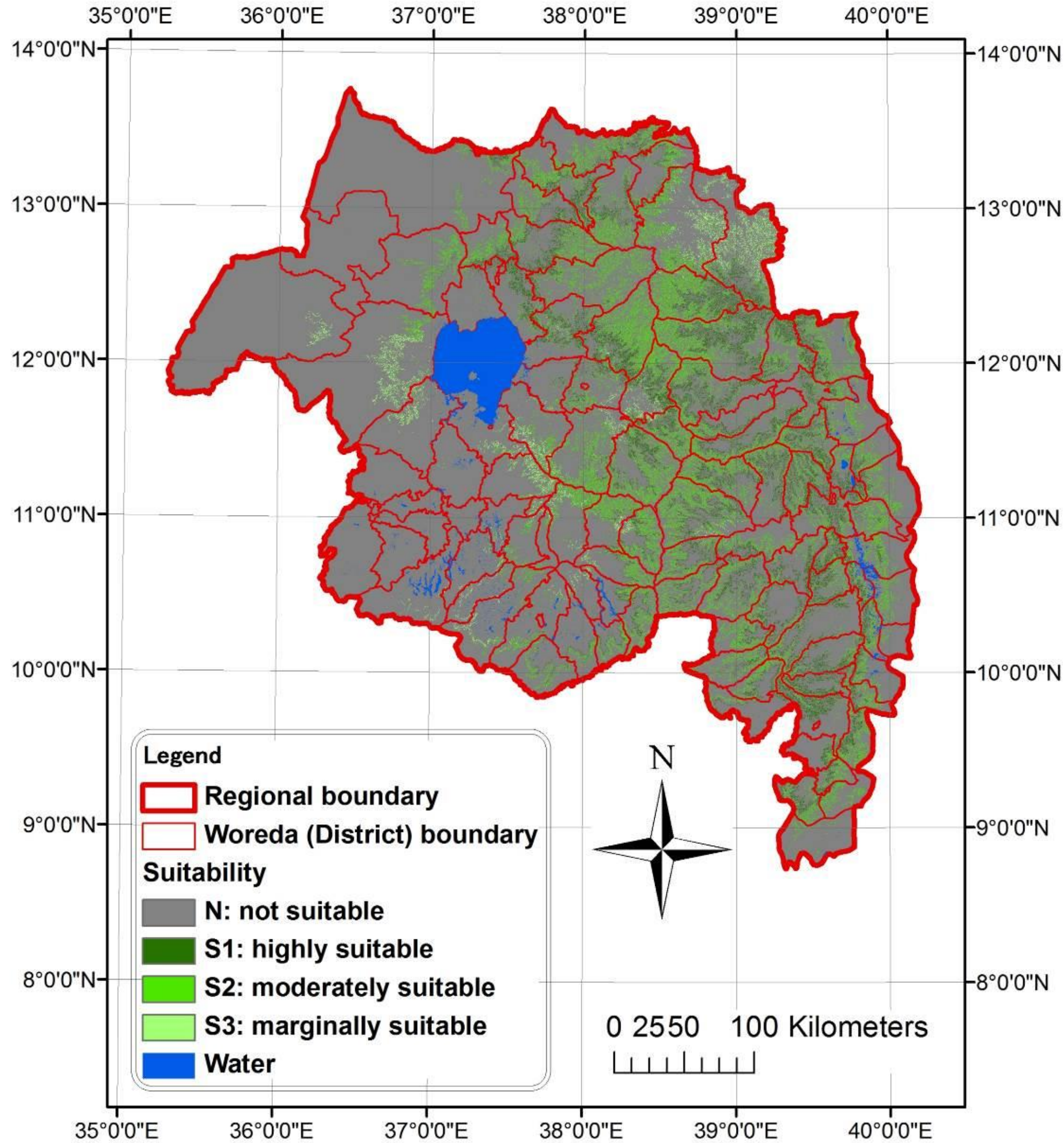

Figure A9. Suitability Map of *Eucalyptus globulus* in the Amhara Region

S1 = Highly Suitable; S2 = Moderately Suitable; S3 = Marginally Suitable; N = Not Suitable. Data for the Administrative Boundary was Adapted from GADM (2015).

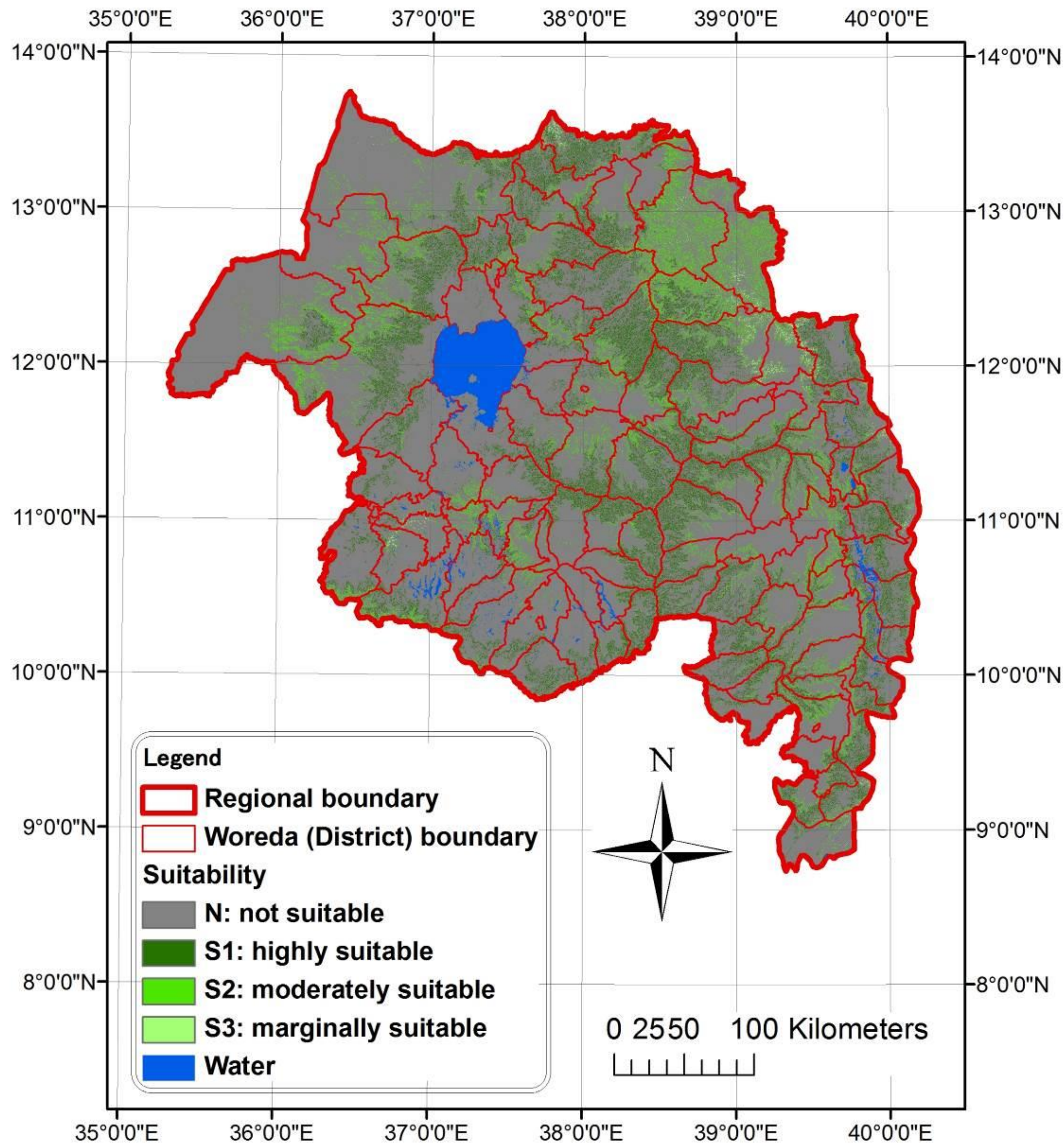

Figure A10. Suitability Map of *Eucalyptus camaldulensis* in the Amhara Region

S1 = Highly Suitable; S2 = Moderately Suitable; S3 = Marginally Suitable; N = Not Suitable. Data for the Administrative Boundary was Adapted from GADM (2015).

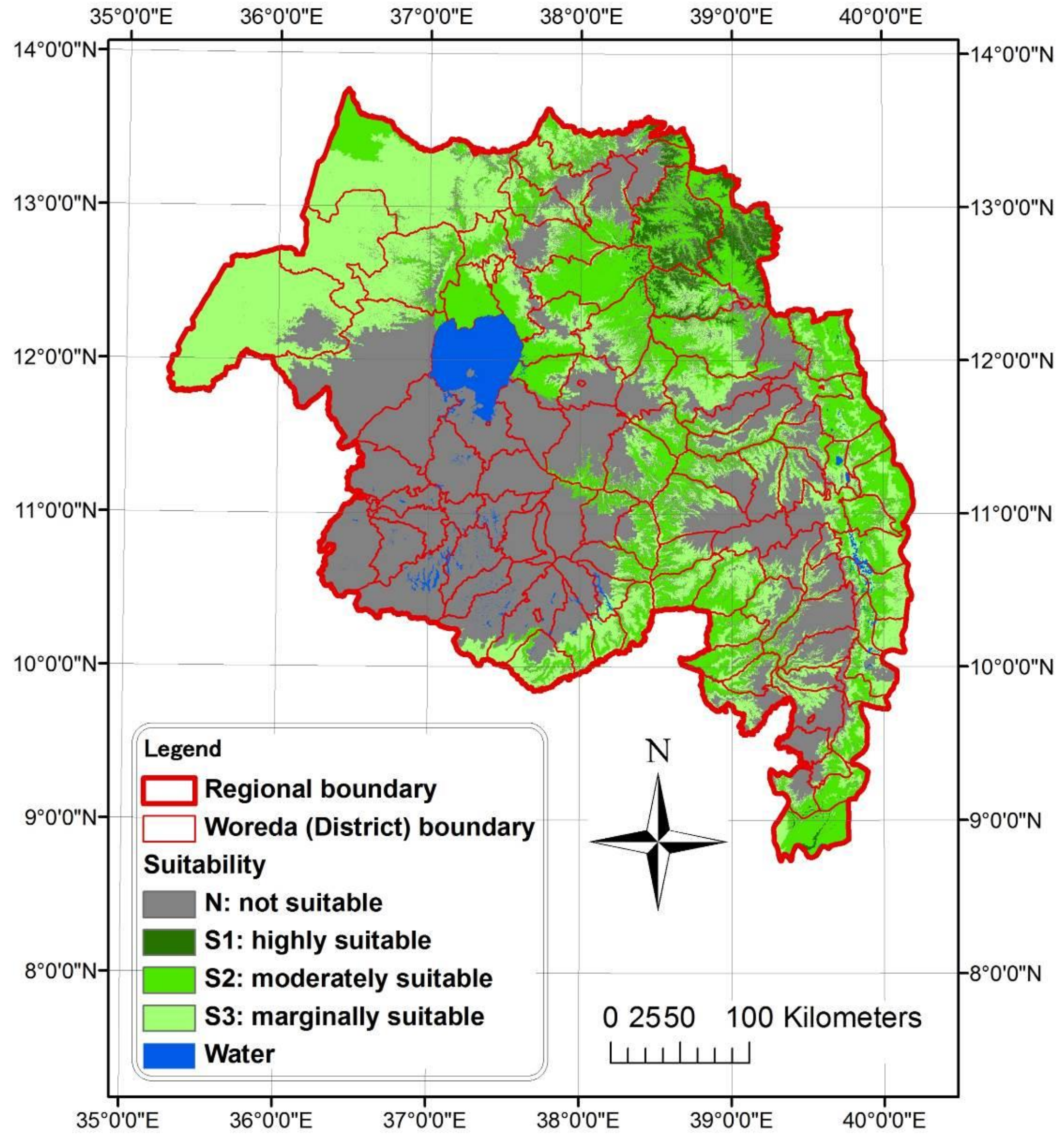

Figure A11. Suitability Map of *Faidherbia albida* in the Amhara Region

S1 = Highly Suitable; S2 = Moderately Suitable; S3 = Marginally Suitable; N = Not Suitable. Data for the Administrative Boundary was Adapted from GADM (2015).

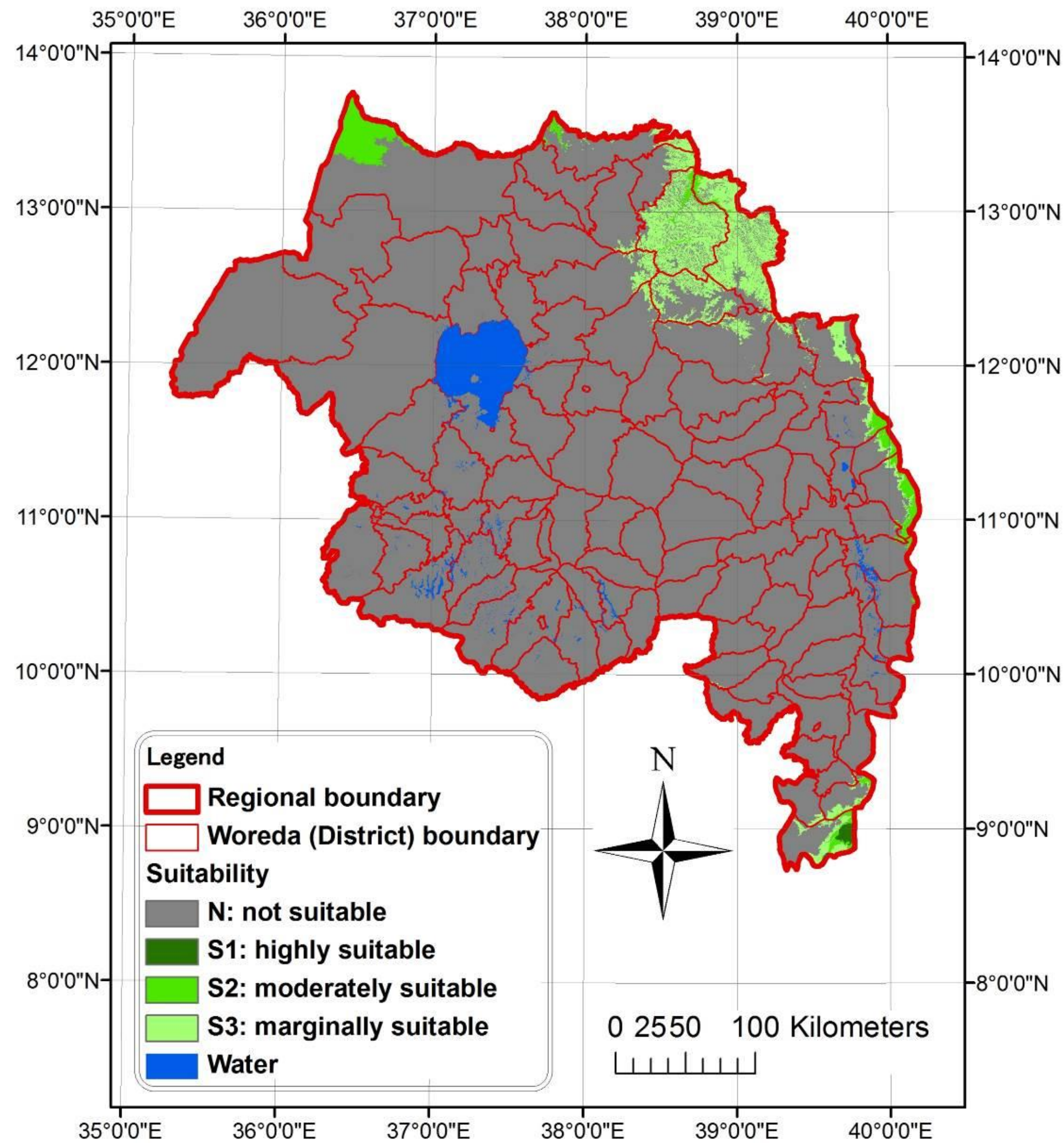

Figure A12. Suitability map of *Acacia saligna* in the Amhara Region

S1 = Highly Suitable; S2 = Moderately Suitable; S3 = Marginally Suitable; N = Not Suitable. Data for the Administrative Boundary was Adapted from GADM (2015).

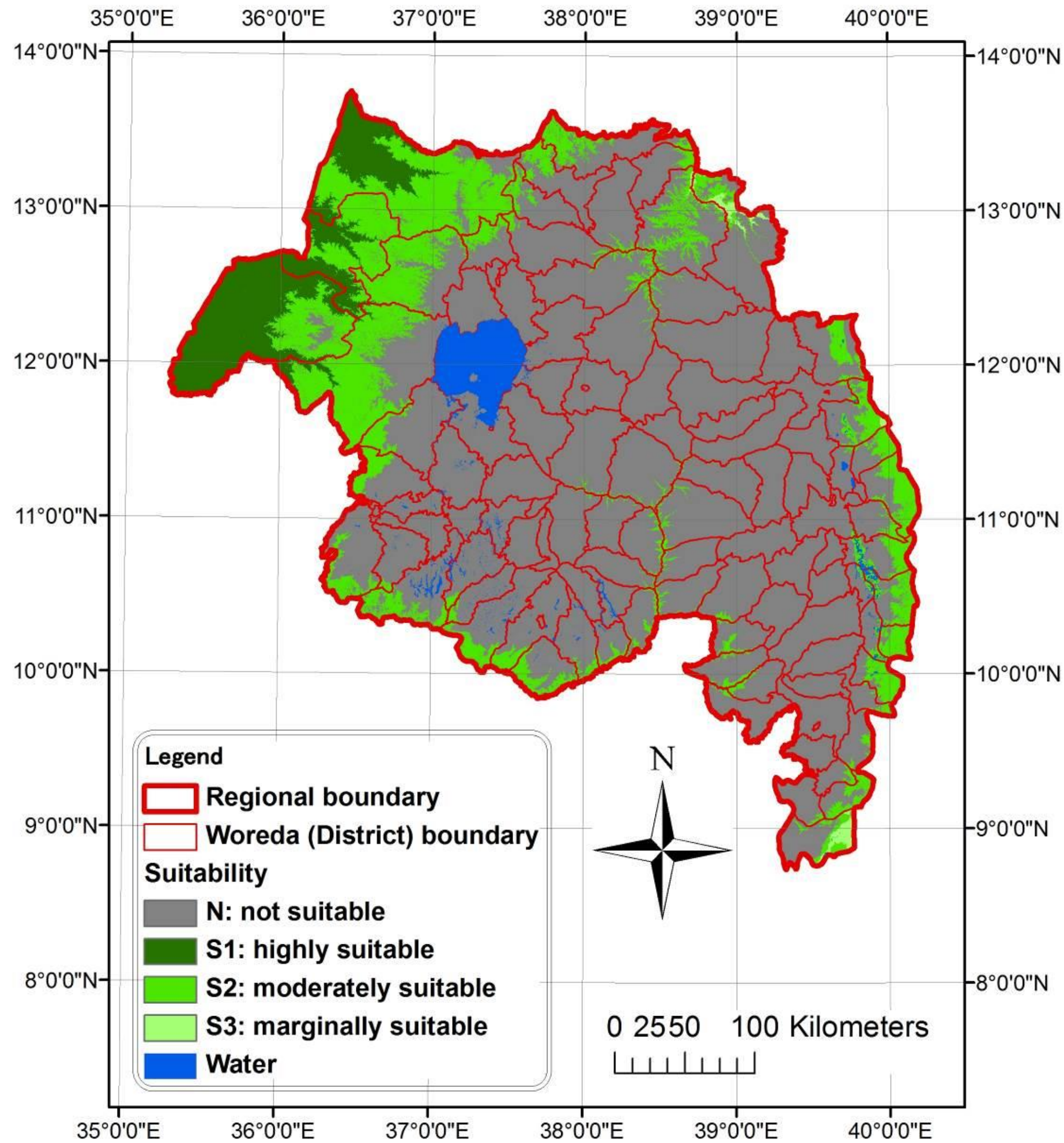

Figure A13. Suitability Map of *Leucaena leucocephala* in the Amhara Region

S1 = Highly Suitable; S2 = Moderately Suitable; S3 = Marginally Suitable; N = Not Suitable. Data for the Administrative Boundary was Adapted from GADM (2015).

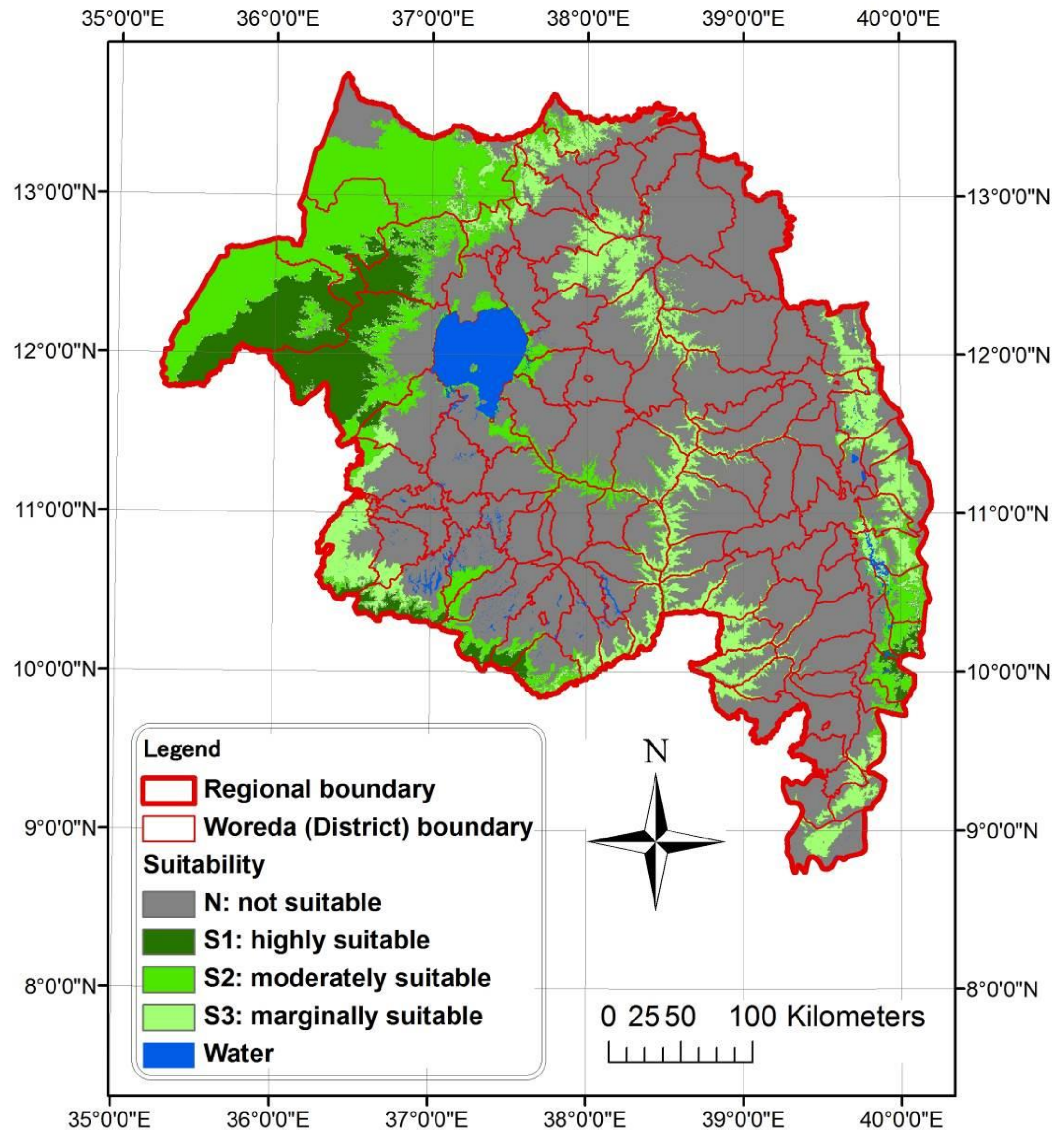

Figure A14. Suitability Map of *Sesbania grandiflora* in the Amhara Region

S1 = Highly Suitable; S2 = Moderately Suitable; S3 = Marginally Suitable; N = Not Suitable. Data for the Administrative Boundary was Adapted from GADM (2015).

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