Universität für Bodenkultur Wien
University of Natural Resources
and Life Sciences, Vienna

Modeling Soil and Aboveground Carbon Dynamics of Afromontane Forest Ecosystem, Northern Ethiopia

Dissertation
Submitted to obtain the degree of Doctor of Philosophy (*Dr. nat. techn.)*
at University of Natural Resources and Life Sciences, Vienna

Submitted by:

Beyene Belay

Supervisor: Rector Univ.Prof. Dipl.-Ing. Dr. Hubert Hasenauer
Co-supervisor: Dipl.-Ing. Dr. Elisabeth Pötzelsberger

August 2018

Vienna, Austria

Acknowledgement

ምንትኑ አዐሥዮ ለእግዚአብሔር በእንተ ኵሉ ዘገብረ ሊተ

I am very grateful to the Austrian government and people, as this study is part of the “Carbo-part” project, funded by the Austrian Ministry of Agriculture, Forestry, Environment, and Water Management. I also obliged to thank the Amhara Region Agricultural Research Institute (ARARI) of Ethiopia in providing the opportunity to pursue my PhD study here in Vienna.

My supervisor, Rector Univ.Prof. Dipl.-Ing. Dr. Hubert Hasenauer, who offered me the opportunity to study here at BOKU, deserves my deepest and greatest thanks. He went through the whole ups and downs of my study, from the very beginning of the field data collection to the final PhD thesis. I was always surprised how he managed his busy and tight schedule. Despite a number of leadership responsibilities, he was always available to me whenever I needed his help. He is very skilled at managing, supervising, motivating and teaching his students. His daily supervision and advice was not only given to accomplish my PhD, but also to shape my future and make me a better researcher. His care and treatment of my private issues made my stay in Vienna very lovely and enjoyable.

My special thanks go to my co-supervisor, Dipl.-Ing. Dr. Elisabeth Pötzelsberger, who always guided and helped me, politely and patiently. Her special skill in tracing and solving whatever technical problems faced me, kept me moving forward to reach this final level. Had it not been for her unreserved and keen help, it would have hardly been possible to accomplish my PhD study within this time period. It was a pleasure to work with her. I am also very grateful to Dr. Christopher Thurnher, who helped me unreservedly till he left the Institute.

My office mate Dipl.-Ing. Patrick Huber deserves my deepest thanks. He was always on my side, even in my private issues. He has a very kind and polite heart, open to listen and help people. I am also respectful of Dr.rer.nat.Charalambos Neophytou, Dipl.-Ing. Dr.Neumann Mathias, my office mates Dr.Brady Mattsson, B.Sc.Gergö Dioszegi, and Dipl.-Ing.Mortimer Müller for the enjoyable time I had and valuable ideas shared with you. I am very happy to express my thanks to all colleagues at the

Silviculture Institute and staff Monika Lex, Eugen Zimm, Eva Motsch, Eva Lanz and Marion Hummer.

I am in debt to the Ethiopian Orthodox Tewohido church fathers, who kept such old-aged remnant natural forests and gave me the permission to work in these holy gardens of the churches. I also express my respect for all who were with me during the data collection for their keen support. Especially the Monastery fathers and forest guards of the Mahiberse Selassie, who spent all day and night with me in such a remote area. I will never forget your care and generosity in preparing the food and drink I needed.

I am grateful to all my Ethiopian friends and Kidane Mihiret Church members of the Ethiopian Orthodox in Vienna, who made me feel at home during my stay.

My wife's brothers, Zelek and Yosefe, my wife's mother, Alganesh, my mother's sister, Almtsehay and her husband, Agegnehu, and my brother, Workineh are unforgettable and cared for my family on behalf of me. I would like to thank my father, Belay and mother, Haimanot, who have been always with me in their prayers and good wishes.

My lovely wife, Kidist Belay, she has a special and irreplaceable place in my life. Words cannot express my feelings for her. Bearing my absence and carrying all my family responsibilities, she was always by my side, motivating and encouraging me. This kept me going forward and stopped me from losing focus. My baby boy, Leul, was born during my study time. Seeing him grow up so fast relaxed and energized me when I got fed up.

Beyene Belay August, 2018

Preface

The study was carried out under the main project “***Carbon Storage and Soil Biodiversity in Forest Landscapes in Ethiopia: Knowledge Base and Participatory Management”***, funded by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management.

This cumulative dissertation contains the extended summary of the whole study and two peer-reviewed scientific papers. The extended summary (section 1 to 8) shows the linkage between two peer-reviewed scientific papers, found in the Appendix part (section 9.1 to 9.2), started from plot level inventory data to landscape level sustainable forest management estimation using ecosystem process model.

To cite this PhD study: Belay, B., 2018. Modeling Soil and Aboveground Carbon Dynamics of Afromontane Forest Ecosystem, Northern Ethiopia. PhD Dissertation. University of Natural Resources and Life Sciences, Vienna, Austria. Or by reference of the individual papers.

List of papers

1. Belay, B., Pötzelsberger, E., Sisay, K., Assefa, D., Hasenauer, H., 2018. The Carbon Dynamics of Dry Tropical Afromontane Forest Ecosystems in the Amhara Region of Ethiopia. Forests 9(1), 18, 1–16. doi:10.3390/f9010018
2. Belay, B., Pötzelsberger, E., Hasenauer, H., 2018. The Carbon Sequestration Potential of Degraded Agricultural Land in the Amhara Region of Ethiopia. Forests 9(8), 470, 1–24. doi:10.3390/f9080470

Abstract

The Ethiopian government is working on restoring degraded areas and set the forest sector as one pillar in the country´s green economy strategy. Our study aims to (i) assess the impact of land use change on soil carbon stock, (ii) evaluate the biogeochemical ecosystem model Biome-BGC applicability in the Ethiopian Afromontane forest, (iii) identify potentially suitable reforestation areas in Amhara region, and (iv) predict the carbon sequestration potential and forest management impacts. We collected forest and soil data in four study areas located across the region. Biome-BGC outputs, including aboveground and soil carbon, and net primary productivity (NPP) were compared with field inventory results. Potentially suitable reforestation areas in the Amhara region were identified based on land use suitability, potential vegetation/elevation belt and aridity index. The carbon sequestration potential of identified area was predicted using Biome-BGC under different forest management scenarios: (i) unmanaged (ii) light thinning (thinning 1, 5%, 20yr intervals) and (iii) heavy thinning (thinning 2, 10%, 20yr intervals) and with different rotation periods (10, 30, 50, 100 and 150 years). The inventory results of soil carbon ranged from 61 to 206 t C ha^{-1}, whereas the aboveground carbon ranged from 13 to 60 t C ha^{-1}. About 3.4 Mha (Mha = Million hectare) of land, including bare land (0.7 Mha), grass land (1.2 Mha) and shrub land (1.5 Mha) is suitable for reforestation in the Amhara region. Assuming all identified areas are reforested in a 100 year rotation period, net carbon sequestration (soil and aboveground) could be 178 Tg C (Teragram =10^{12} gram) in unmanaged, 168 Tg C in light thinned and 159 Tg C in heavy thinned forests.

Key Words: Ethiopia, Biome-BGC, reforestation, forest management, carbon sequestration

Zusammenfassung

Die äthiopische Regierung hat sich zum Ziel gesetzt, den Verlust wertvollen Bodens anzuhalten und umzukehren. Der Forstsektor soll dabei eine Säule der grünen Wirtschaft des Landes darstellen. In dieser Studie war das Ziel für die Region Amhara (i) die Auswirkungen der veränderten Landnutzung auf die Bodenkohlenstoffspeicher zu untersuchen, (ii) die Anwendbarkeit des biogeochemischen Ökosystemmodells Biome-BGC zu testen, (ii) potenzielle Wiederaufforstungsgebiete zu bewerten und (iv) das Kohlenstoffsequestrierungspotenzial und die Auswirkungen von forstlicher Bewirtschaftung auf dieses Potential vorherzusagen. Wir erhoben Wald- und Bodendaten in vier Untersuchungsgebieten. Die Modellvorhersagen zu oberirdischem pflanzlichen Kohlenstoff, Bodenkohlenstoff und Nettoprimärproduktivität (NPP) wurden mit den erhobenen Daten verglichen. Potentiell geeignete Wiederaufforstungsgebiete wurden anhand Landnutzung, der Höhen- bzw. Vegetationsgürtel und des Trockenheitsindex identifiziert. Das Potential der Kohlenstoffsspeicherung wurde unter Verwendung von Biome-BGC unter verschiedenen Waldbewirtschaftungsszenarien, (i) unbewirtschaftet (ii) leichte Durchforstung (5%, 20-JahrIntervalle) und (iii) starke Durchforstung (10%, 20-Jahr Intervalle) und mit unterschiedlichen Rotationsperioden (10, 30, 50, 100 und 150 Jahre) vorhergesagt. Die Messungen zeigten einen höheren Kohlenstoffgehalt des Bodens von 61 t C ha^{-1} bis 206 t C ha^{-1}. Der entsprechende oberirdische Kohlenstoffspeicher reichte von 13 bis 60 t C ha^{-1}. Etwa 3,4 Mha (= Million Hektar), einschließlich Brachland (0,7 Mha), Grasland (1,2 Mha) und Buschland (1,5 Mha) sind für die Wiederaufforstung in Amhara geeignet. Unter Annahme einer 100-Jahre Rotationsperiode und Aufforestung aller potentiellen Gebiete liegt das Potential der netto Kohlenstoffbindung (Boden und oberirdisch) bei ca. 178 Tg C (Teragram = 10^{12} Gramm) in unbewirtschafteten, 168 Tg C in leicht durchforsteten und 159 Tg C in stark durchforsteten Wäldern.

Schlüsselwörter: Äthiopien, Biome-BGC, Wiederaufforstung, Forstwirtschaft, Kohlenstoffsequestrierung

Contents

1. INTRODUCTION ... 1

1.1 BACKGROUND ... 1
1.2 FOREST ECOSYSTEM AND CARBON STOCK ... 2
1.3 FOREST LOSS AND CLIMATE CHANGE ... 3
1.4 REFORESTATION AND INTERNATIONAL AGREEMENTS ... 3

2. FOREST IN ETHIOPIA ... 4

2.1 FOREST RESOURCE ... 4
2.2 DEFORESTATION, DRIVERS AND CONSEQUENCES ... 5
2.3 REFORESTATION INITIATIVES ... 6

3. STUDY OBJECTIVES AND FRAMEWORK ... 7

4. MATERIALS AND METHODS ... 9

4.1 STUDY AREA ... 9
4.2 DATA ... 10
4.2.1 Forest data ... 10
4.2.2 Soil data ... 12
4.2.3 Climate data ... 12
4.3 BIOME-BGC MODEL ... 14
4.4 MODEL SIMULATION PROCEDURE ... 17
4.5 CARBON SEQUESTRATION POTENTIAL OF REFORESTATION AT LANDSCAPE LEVEL ... 17

5. RESULTS ... 18

5.1 BIOME-BGC MODEL EVALUATION AND FOREST CARBON FLUX ... 18
5.2 POTENTIALLY SUITABLE REFORESTATION AREAS ... 21
5.3 CARBON SEQUESTRATION AND DISTRIBUTION IN THE STUDY AREA ... 23
5.3.1 Thinning management and carbon stock ... 23
5.3.2 Normal-forest system and carbon stock ... 26

6. DISCUSSION ... 29

7. CONCLUSION ... 32

8. REFERENCES ... 35

9. APPENDIX ... 46

9.1 PAPER I ... 46
9.2 PAPER II ... 63

1. Introduction

1.1 Background

Forests are the main important components of the terrestrial ecosystem. Forests, which have 10% tree cover, account for 30-31% (about 4 billion hectare) of the world's terrestrial ecosystem (Keenan et al., 2015; MacDicken, 2015). The highest world's total forest proportion (31%) is found in Asian countries, including Russia, followed by South America (21 %) and Africa 17% (FAO, 2010). Tropical and sub-tropical countries together account for roughly 52% of global forest cover, followed by temperate and boreal countries with 26% and 22%, respectively (Keenan et al., 2015). From total global natural forest (4 billion hectare), only 26% is reported to be primary natural, while 5% is a commercial plantation.

Forests are also an integral part of people´s livelihood in many parts of the world, either directly as a source of wild fruit, timber, fodder and fibre, fuelwood, medicine, food, and income and employment or indirectly through ecological and environmental protection and stabilization (Köhl et al., 2015; Price et al., 2011; Rasmussen et al., 2017). Approximately 1-2 billion people in the world depend on forests to a varying degree, but about 200 million indigenous communities are almost fully dependent on forests (Chao, 2012). Particularly people who live near the forest have a greater opportunity to access food, including wild fruits, edible green leaves and herbs, root tubers, mushrooms and wild meats (Pingali, 2015; Powell et al., 2015). In addition, forest-based activities provide about 30 million jobs in the informal sector, as well as up to one-third of all rural, non-farm employment in developing countries. According to the Food and Agriculture Organization of the United Nations report (FAO, 2010), globally, about 10 million people are employed in forest conservation and management activities.

Along with income maximizing through wood and non-wood products, forests and trees are increasingly demanding for environment protection and regulation services, public recreation and other spiritual/cultural values (Reed et al., 2017). Though all forests and woodlands provide protection or play a protective role, a report in 2015 shows that about 1 billion hectare of forest areas are particularly allocated for the protection of soil and water resources across the world (Miura et al., (2015).

Similarly, about 4% of world´s forest is designated for the provision of social services (FAO, 2010).

Following global warming, mainly due to human-driven activities, forests have got the world´s attention as a mitigation mechanism of climate change. Forests store a large amount of carbon as aboveground live biomass or in the soil and can thus potentially determine carbon cycle/exchange between the terrestrial ecosystem and the atmosphere (Baccini et al., 2012; Houghton, 2005; Pan et al., 2011). In this regard, apart from understanding and protecting current forests' carbon stock, increasing carbon sink through reforestation of degraded or marginalized areas and improving forest management techniques have got national and international attention.

1.2 Forest ecosystem and carbon stock

According to Pan et al., (2011) the world´s forest stored about 861 Pg (pentagrams = 10^{15} g C) of carbon stock with 383 Pg C in the soil, 363 Pg C in live biomass (above and below ground) and 116 Pg C in deadwood and litter. Given the estimation difference within the literature, forests store about 77-80% vegetation carbon as live/tree biomass and 42-80% of the global soil carbon (Jandl et al., 2007; Jobbagy et al., 2000; Six et al., 2002), and also share 75% of the terrestrial gross primary production (Beer et al., 2010).

With a terrestrial biomass share (~92%), forests control the geographical distribution of global biomass (Pan et al., 2013) thus, the highest total carbon storage is found in tropical forests with 471 Pg C (55%) followed by boreal forest 272 Pg C (32%) and temperate forest 119 Pg C (14%) (Pan, 2011). The carbon stock also follows the same pattern, i.e. tropical, boreal and temperate forest with 242 t C ha^{-1}, 239 t C ha^{-1}, 155 t C ha^{-1}, respectively. Mostly, tropical forests store the highest proportion of total carbon on aboveground biomass (~56%) whereas boreal forests contain in the soil (~60%). Global annual carbon sink rate, between the year 2000-2007, varies from 0.5 Pg C $year^{-1}$ in boreal forest and is proceeded by 0.78 Pg C $year^{-1}$ and 1.02 Pg C $year^{-1}$ in temperate and tropical, respectively (Pan, 2011). The total global forest carbon sinks are estimated to have been about 2.4 Pg C yr^{-1} between the years 1990 to 2007 (see Pan et al., 2011).

1.3 Forest loss and climate change

Land use change, e.g. changing forest to agricultural land is an important anthropogenic carbon emission. Due to population growth followed by a growing demand for agricultural land and fuelwood, forest land is increasingly declining across the world (Laurance et al., 2014). The satellite imagery-based study by Hansen et al. (2013), showed a total of 230 Mha of forest lost between the years 2000-2012. According to FAO global forest resources assessment, total forest area coverage in the world has declined by 129 Mha (3%), from 4128 Mha in 1990 to 3999 Mha in 2015 (Keenan et al., 2015). In the same time interval, plantation forests increased from 168 Mha to 278 Mha, but natural forest dropped from 3961 Mha to 3721 Mha (see Keenan et al., 2015). The FAO (2010) also reported that 13 Mha year^{-1} of the forest was converted to other land use forms during the period 2000–2010. Tropical forest conversion to other land use, particularly to crop and pasture is the main reason for the forest loss worldwide. For instance, between 1980 and 1990, more than 28% of new agricultural land came from the expansion of intact tropical forests (Gibbs et al., 2010).

The decrease in forest area coverage or density/per hectare biomass tremendously affects the flux of carbon between the earth and atmosphere (Houghton, 2005), because forests are the largest carbon sinks of terrestrial ecosystems. Different land use change and management accounted for 33% of the total anthropogenic carbon emission between the years 1850 and 2000 (Houghton et al., 2004). The majority (~60%) of these emissions is attributed to tropical and subtropical deforestation (Houghton et al., 2004; Ross et al., 2016). Similarly, a study in Ethiopia showed that the change of forest to crop- or grass land has led to a loss of 40–85% of the soil C stocks (Belay et al., 2018a).

1.4 Reforestation and international agreements

Reducing emissions and/or removing of CO_2 from the atmosphere is important to achieve international climate change mitigation targets, such as keeping the increase of global temperatures to less than 2 °C, compared to the preindustrial level (Clarke et al., 2014). Thus, reforestation has been believed to be one of such cost-effective mitigation options (Bolin, 1995), because it offers a high carbon sequestration potential at a moderate cost (Kreidenweis et al., 2016;IPCC, 2014; Smith et al., 2015). This made the forest sector to be considered as one of the main options in many climate change mitigation policies to combat human-induced carbon emission (Reyer et al., 2009).

Large-scale reforestation for more carbon sequestration might compete with other land use forms, such as agricultural and grazing land and increase food prices (Kreidenweis et al., 2016). Hence, legally bound compensations have to be developed to balance such competitive relations. This should also increase the willingness of farmers and developing nations to practice reforestation and avoid further deforestation. As a result, the Kyoto protocol accord has established and set different mechanisms to enhance reforestation, including subsidizing or funding such activities for less developed countries (Babiker et al., 2000). In the Kyoto protocol of the United Nations framework convention to combat climate change (UNFCCC, 1997), especially reforestation activities were legally set to be done under clean development mechanism to enhance the CO_2 sink.

Thus the impact of land use change on global climate change, including deforestation and forest degradation and reducing emissions from land use change were also included in the climate mitigation objectives. Especially in the UNFCCC 2005 meeting, reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+) was negotiated as an emission reduction option for the first time. The main aim of REDD+ is to produce sustainable development in developing countries and implement cost-effective emissions reductions by avoiding further afforestation (Zomer et al., 2008).

2. Forest in Ethiopia

2.1 Forest resource

The Ethiopian vegetation is classified into 8 main types (Friis et al., 2010) where montane forest types constitute the main part of the natural vegetation, with dry Afromontane forests being the largest part (Demessie et al., 2017). Though available, scientific evidence is very limited (McCann, 1997); it is believed that about 30-40% of Ethiopia was covered with forest in the late nineteenth century (Bishaw, 2001). Remnant patch forests composed of old-aged indigenous tree species on religious or cultural places and inaccessible areas of the country are living witnesses that Ethiopia had a very good forest cover. According to the forest resource assessment of the Woody Biomass Inventory and Strategic Planning Project (WBISPP, 2005), the current Ethiopian forest is estimated to cover 4.1 Mha, or 3.6% of the whole land area of the country. Wood and shrub land, however, cover a greater portion of the country, i.e. 56.0 Mha (48.9%), followed by plantation with 0.5 Mha (0.4%) and low and high land bamboo with 1.1 Mha (1%), and Afro-alpine land with 0.2 Mha (0.2%).

Based on definitions and classifications of the global forest resource assessment (FRA, 2010), the total woody vegetation cover of Ethiopia reached about 60.0 Mha (FAO, 2010), accounting for about 55.8% of the country. This includes about 12.3 Mha (11%) of forest and about 44.7 (41%) of other wooded lands. Currently, except for a few patch forests in the northern and central parts of Ethiopia, the majority of remnant dense forests have retreated to the southern and western edges of the country (Lemenih and Kassa, 2014).

2.2 Deforestation, drivers and consequences

Forest cover in Ethiopia is steadily decreasing from 15.1 Mha in 1990 to 12.3 Mha in 2010 (FAO, 2010), which implies about 140,000 ha of natural forest is lost every year. The increasing demand for arable land is the main driver of deforestation in Ethiopia as agriculture is the nation’s dominant economic sector, on which 85% of the population’s livelihood depends. In addition, most of the agriculture-related big investment programs currently running in the country are mostly implemented at the cost of remnant forests found on the periphery of the country (Degife, 2017; Palm et al., 2009). People who settled around or within the investment target areas are also moved to other areas, including forests, woodlands or grazing lands.

Forest fuel wood harvesting (Amare et al., 2017; Belay et al., 2012; Dresen et al., 2014) and livestock grazing and trampling (Mamo et al., 2016) have also greatly contributed to the decline of forest coverage and quality in Ethiopia. Since over 80% of the population live in rural areas and have less electric power access, more than 88% of the total energy consumed in the country comes from biomass fuels (mainly woody biomass) (FDRE, 2012). The traditional energy-insufficient stoves, commonly used in many rural areas of Ethiopia are the other indirect deforestation drivers

(Beyene and Koch, 2013; Gebreegziabher et al., 2012). However, the government and non-governmental organizations are intensively working to change this with improved stoves (Mamuye et al., 2018).

Permanent change of forest land into other land use systems is not only impairing the direct forest benefits, but has a multitude of impacts on food security and sustainability, and other environmental and ecological services. Due to forest cover change and agricultural practices in Ethiopia, soil erosion and land degradation have become a serious environmental problem. This results in a loss of fertile and productive soil, deterioration of water availability and quality (Miheretu and Yimer, 2018, 2017) and sediment loads on dams and lakes (Bewket and Tefer, 2009; Haregeweyn et al., 2017). For instance, a study in Ethiopia shows annual soil losses ranging from 4.8 to 7.7 t ha^{-1} yr^{-1} in different years (Tadesse et al., 2017).

2.3 Reforestation initiatives

Ethiopia has been taking actions through degraded area rehabilitation and reforestation to avoid further forest loss and subsequent economic, as well as environmental problems. According to Lemenih and Kassa, (2014), 3.1 Mha of degraded land was rehabilitated as exclosure in the Amhara and Tigray region. Small and large-scale plantations are also increasing in many parts of the country. Bekele (2011) reported that 972,000 ha (including industrial and non-industrial) are growing as forest plantations in Ethiopia. Especially small-scale private plantations are of high interest following a decline of fuelwood source and growing market for construction poles and charcoal. This considerably contributed to the energy demand and thus minimizes the human pressures on remnant natural forests.

Currently, the Ethiopian government has joined the international reforestation programs (FDRE, 2011; MEFC, 2017). Thus, recently the forest sector is being held to be one of the green economy development pillars of the country and REDD+ secretariats and implementation strategies were established (Arbonaut, 2016; FDRE, 2011; MEFC, 2017). In the REDD+ implementation strategic plan, the main targets of Ethiopia are avoiding deforestation, improving management and protection of existing forests, as well as increasing carbon sequestration through reforestation. The Amhara region, our specific study area, has made progress in the rehabilitation of degraded forest areas through area exclosure and expanding plantation (Lemenih and Kassa, 2014). The Amhara region in Ethiopia has the largest share of the country´s potential future reforestation areas (Arbonaut, 2016; FDRE, 2011; MEFC, 2017).

3. Study objectives and framework

The main mission of this PhD work is to model the carbon flux under reforestation on different land use forms and forest management activities and develop a regional and/or landscape level sustainable forest management framework for the Amhara region. The study combines plot level inventory forest and soil data with process-based ecosystem modeling techniques based on the following objectives:

i. Evaluate the process-based ecosystem model Biome-BGC in explaining forest carbon flux under changing land use system
ii. Identify suitable reforestation areas and estimate carbon sequestration potential of those areas
iii. Predict the dynamics of forest carbon stock under different management scenarios

Figure 1 depicts the study procedure for this PhD study. The first section deals with the evaluation of the ecosystem model Biome-BGC applicability for the Ethiopian Afromontane forest ecosystem (Paper 1). In this section, field inventory data (including vegetation/aboveground carbon, NPP and forest soil carbon) were used to compare Biome-BGC model outputs. Data collected from grazing land was used as soil initial values of the model for degraded land recovery estimations (see Belay et al., 2018a). Model input parameters, including eco-physiological parameters, daily climate data, and site physical variables are used to run the model simulation. In the second section (Paper II), we selected potentially suitable future reforestation areas and estimated the sequestration potential of the aboveground and soil carbon stock and NPP with varying forest management scenarios and rotation periods, using Biome-BGC (see Belay et al., 2018b).

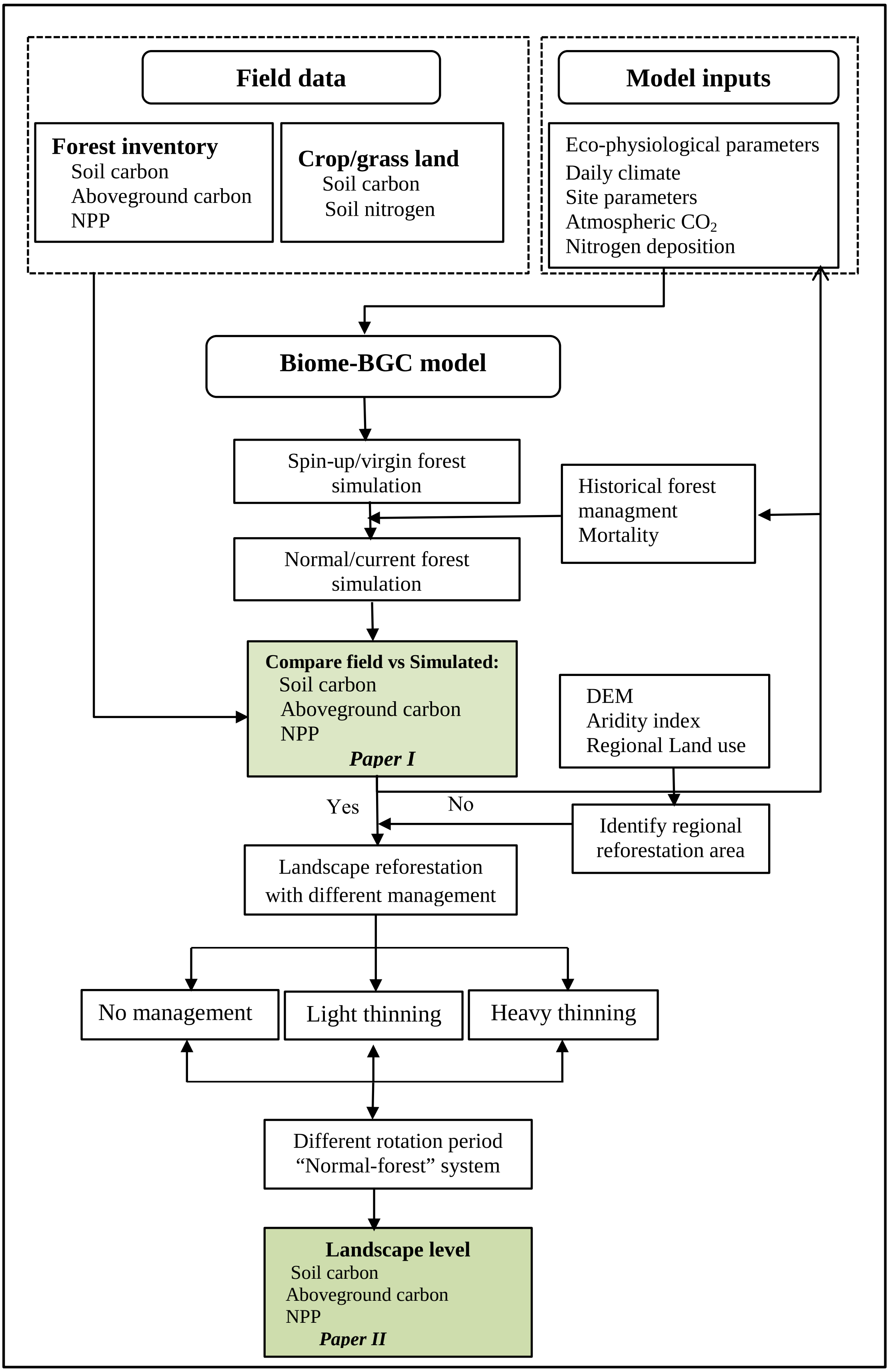
Field data
Model inputs
Forest inventory
Soil carbon
Aboveground carbon
NPP
Crop/grass land
Soil carbon
Soil nitrogen
Eco-physiological parameters
Daily climate
Site parameters
Atmospheric CO_2
Nitrogen deposition
Biome-BGC model
Spin-up/virgin forest simulation
Historical forest managment
Mortality
Normal/current forest simulation
Compare field vs Simulated:
Soil carbon
Aboveground carbon
NPP
Paper I
DEM
Aridity index
Regional Land use
Yes
No
Identify regional reforestation area
Landscape reforestation with different management
No management
Light thinning
Heavy thinning
Different rotation period
"Normal-forest" system
Landscape level
Soil carbon
Aboveground carbon
NPP
Paper II

Figure 1. The study framework

4. Materials and methods

4.1 Study area

Our study area, the Amhara region in Northern Ethiopia, extends 9° 20' - 14° 20' N and 36° 20' - 40° 20' E, and covers 15.7 Mha. The region has high altitudinal gradients, ranging from the lowland area (500 m) to the highest peak, the Ras Dejen (4600 m) (Figure 2). The mean monthly minimum and maximum temperature range from 7.8 to 26.1 °C, respectively (Figure 3). The mean annual precipitation is 1270 mm with a pronounced rainy season, about 80% of the annual rainfall, between June and September.

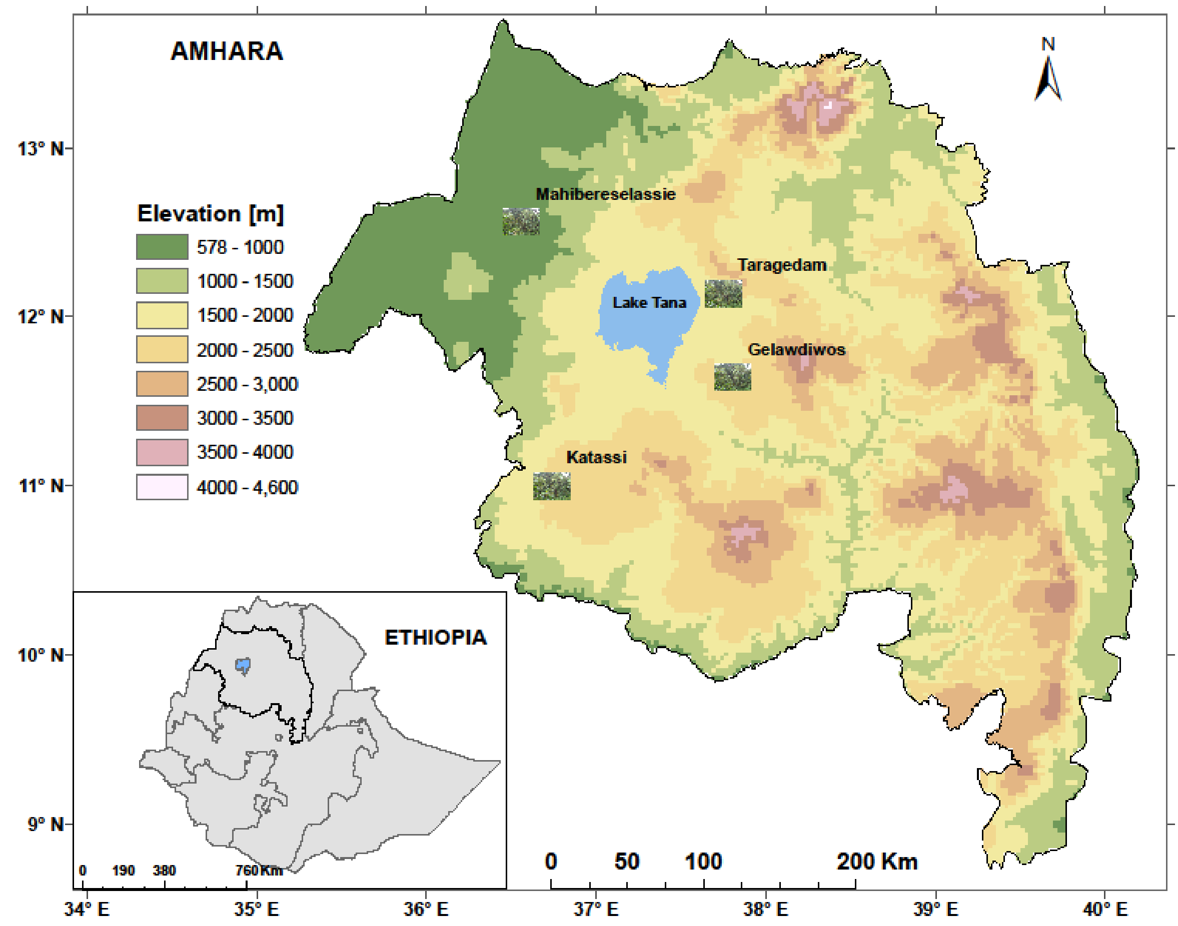

Figure 2. The study region and location of the inventory sites.

Similar to the other part of the Ethiopian vegetation distribution, crop production and other farming activities, and even the population settlement in the Amhara region follows the topographic condition and climatic pattern of the region (Friis, 2010; Friis et al., 2016; Headey et al., 2014). Midland and highland areas are more productive and highly populated compared to the lowland and alpine highland areas.

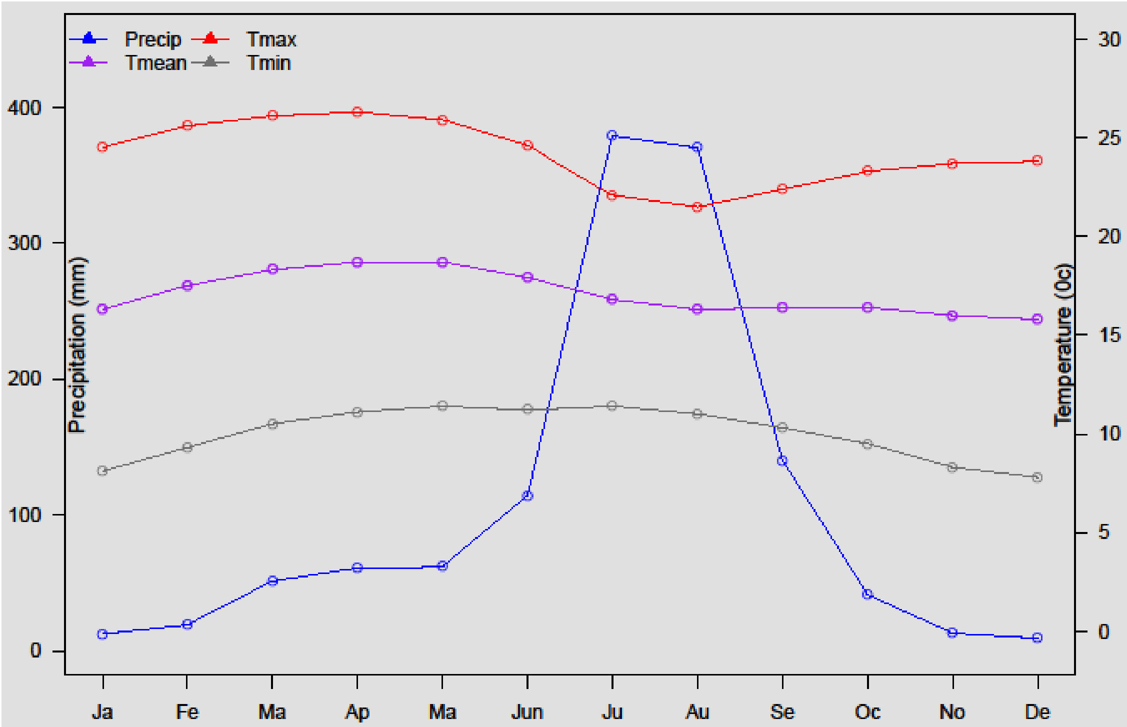

Figure 3. The mean monthly precipitation, mean daily maximum and minimum temperature between the years 1979-2010 of the study region.

Thus, average landholding size per household in the region varies from 0.4 ha (Headey et al., 2014) to 1.8 ha (ERSS, 2013), depending on the population density.

4.2 Data

Four study areas were selected in different agro-ecological zones of the Amhara region in Northern Ethiopia, for soil and vegetation data collection (Figure 2 & 4). These include Gelawdiwos, representing the highland area, Injibara/Katassi and Taragedam in midland and Mahibereselassie in the lowland area (Belay et al., 2018a). Each study area encompassed natural forest and crop/grazing sites located next to each other, for pairwise comparison of the impact of land use change on soil carbon stock. The three forests sites are maintained and managed by the Ethiopian Orthodox Tewahedo Church, but Katassi is owned by the local government.

4.2.1 Forest data

Circular sample plots were systematically laid out in the four selected forest sites for forest data collection. The sample sizes were a 10/15 m radius, depending on forest area coverage and forest stand density (Belay et al., 2018a). Each tree with a DBH (diameter at breast height) >10 cm in every sample plot was recorded for species name, location in the plot, DBH, crown width in the four cardinal directions and height to live crown base. Height and core increment from one median/central stem DBH of each species was measured for each species in each sample plot. The other missing heights were derived from the Petterson height-diameter curve (Schmidt, 1976). The core increment data was used to calculate radial increment/growth of each tree. Similarly, trees with DBH <10 cm and a height >1.5 m were collected in a smaller, circular (4 m radius) for the same tree variables.

Figure 4. Photo of the four study forest sites taken during preliminary survey and data collection.

The aboveground biomass of each tree was measured using the allometric equation of Chave et al. (2005). The corresponding aboveground carbon was derived from the biomass, as the carbon content was assumed to be 50% of the biomass. Similarly, the annual NPP (g C m^{-2} $year^{-1}$) of the woody part of each tree was calculated as the mean annual woody carbon increment for the 10 year period between 2005 and 2014. The total annual terrestrial NPP for each inventory plot is the sum of woody carbon increment, the litterfall and the root increment (fine root production and coarse root increment) (Van Do et al., 2015). For the detailed forest inventory data collection and methodology refer to (Sisay et al., 2017).

4.2.2 Soil data

In each of the four study sites, soil data was collected both in the forest and nearby agricultural/grazing sites. In the forest, soil samples were taken from about one-fourth of the forest sampling grid points. Similarly, for neighboring crop/grazing sites, we sampled a total of 40 plots, 10 plots for each study site, on transects at 50 m/100 m intervals. The soil samples on each point were taken in 0–10 cm, 10–20 cm, 20–30 cm, and 30–50 cm soil depth with a soil corer (Pürckhauer type, inner diameter 30 mm).

The samples were sieved to 2 mm and analyzed in a laboratory for soil organic carbon, nitrogen and texture. The soil organic matter was calculated as the loss of ignition when heating the soil samples in a muffle furnace (Heiri et al., 2001). The organic matter was combusted to ash at a temperature of 450 °C and the weight loss is proportional to the amount of organic carbon contained in the sample. The carbon concentration was corrected for bulk density and soil volume (see Belay et al., 2018a).

4.2.3 Climate data

For the whole Amhara region, the daily climate data was downscaled with 1km * 1km resolution from global datasets (WorldClim and NCEP) and corrected using observed climate data from weather stations (Sisay et al., 2016). However, the correction was done using a single correction equation for the whole Amhara region, which resulted in over/under estimation of climate values in some areas compared to observed data, especially daily precipitation. Using single correction equation for the whole Amhara region might create some bias because (i) the study region is very large and is highly mountainous, ranging from 500 m to peak Ethiopian mountain 4300 m and (ii) precipitation is highly affected by topography and orography. Hence, another correction method was employed specifically for daily precipitation, because it significantly dictates forest productivity. The daily minimum and maximum temperature were directly used from Sisay et al., (2016), because his corrected values well fit with observed values.

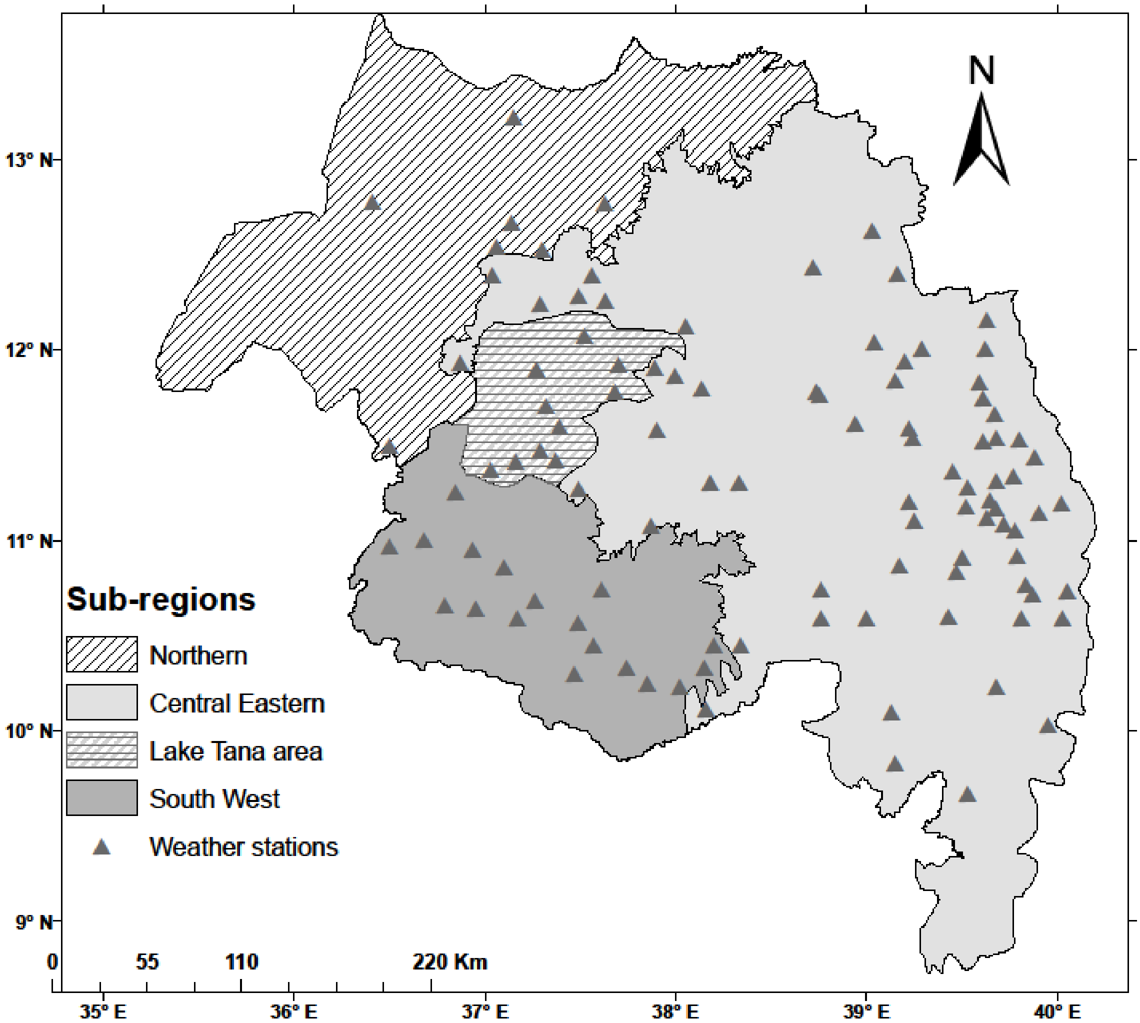

Figure 5. Weather stations and the four sub-regions of Amhara region.

For the new correction method, the whole region was classified into four sub-regions (Figure 5), based on the correlation of mean annual precipitation difference between downscaled and observed climate data (Figure 6). Note that the downscaled values were taken at the same coordinate point with the corresponding observed stations. Once we classified the sub-regions, the daily mean precipitation difference between downscaled and observed data was calculated in a 10 day interval, implying a year has 37 groups each, with 10 days, except the 37th. Hence, a total of 37 correction equations were developed for each sub-region, based on the regression correlation between each daily interval precipitation difference and corresponding pixel elevation. The developed correction equations were applied for each corresponding sub-region to calculate the final corrected precipitation data of 1 km* 1 km resolution. Generally, the procedure followed is similar to Sisay et al., (2016) but the correction was done separately for each sub-region (Figure 6).

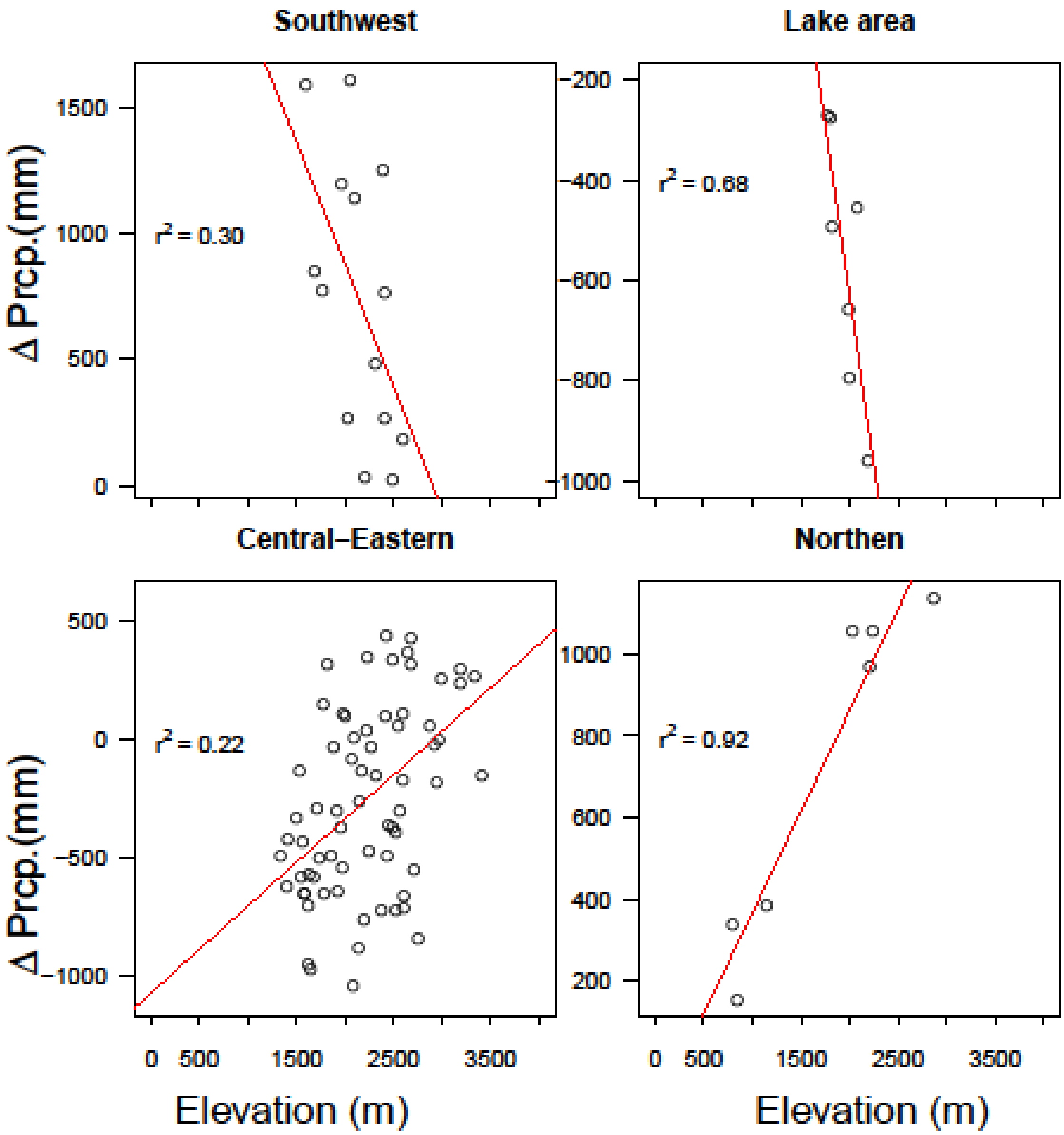

Figure 6. Correlation between the annual mean precipitation difference (ΔPrcp) and elevation of a pixel in each of the sub-regions. ΔPrcp is a difference between downscaled and observed precipitation of each pixel.

4.3 Biome-BGC model

Predicting the future is difficult under the changing climate and interaction with different biophysical conditions. Therefore, models are better options for estimating process responses. The biogeochemical-mechanistic ecosystem model Biome-BGC version 4.1.2 (Running and Coughlan, 1988; Running and Gower, 1991) was used for this study. The current improved Biome-BGC version was developed for the self-initialization algorithm to mimic undisturbed ecosystems (Hasenauer et al., 2005; Pietsch and Hasenauer, 2006) and forest management interventions e.g., historic land use changes, thinning, clear-cut and planting (Petritsch et al., 2007; Thurnher et al., 2014). Biome-BGC is fully prognostic, which does not require detailed input data for self-initialization simulation. The Biome-BGC model needs three main input variables for a simulation run (Chiesi et al., 2016; Hidy et al., 2012; Mao et al., 2016; Pietsch et al., 2005): (1) eco-physiological parameters (2) site physical variables (3) climate/ atmospheric data.

Eco-physiological parameters: Characterize the physiology of the given forest ecosystem. Originally, seven biome level parameter sets were developed, including evergreen broadleaf, deciduous broadleaf, evergreen needle, deciduous needle, shrubs, and C3 grass and C4 grass (White et al., 2000), but today, there exist several regional or species-specific parameters, mostly for European species (Ichii et al., 2005; Pietsch et al., 2005). Each Biome or species level set can be defined by about 39 main eco-physiological parameters containing a canopy water interception coefficient, maximum stomatal conductance, leaf water potential, and carbon allocation in plant parts (Table 2). For this study, we used evergreen tropical broadleaved forest (EBF) parameters set by Ichii et al. (2005).

Table 1.The ecophysiological parameters used for the simulation of forests in four of the study sites (Ichii et al., 2005)

Parameter description	unit	EBF
true = EVERGREEN, false= DECIDUOUS	-	true
true= MODEL PHENOLOGY, false = USER- SPECIFIED PHENOLOGY		true
Year day to start new growth (when phenology flag = false)	yday	-
Year day to end litterfall (when phenology flag = false)	yday	-
Transfer growth period as fraction of growing season	prop.	0.2
Litter fall as fraction of growing season	prop.	0.2
annual leaf and fine root turnover fraction	yr^{-1}	0.5
annual live wood turnover fraction	yr^{-1}	0.7
Annual whole-plant mortality fraction	yr^{-1}	0.03
Annual fire mortality fraction	yr^{-1}	0
Allocation new fine root c : new leaf	ratio	1.2
Allocation new stem c : new leaf	ratio	2.2
Allocation new live wood c : new total wood	ratio	0.16
Allocation new coarse root c : new stem	ratio	0.22
Allocation current growth proportion : Storage growth	ratio	0.5
C : N of leaves	kg C/kg N	25
C : N of leaf litter, after retranslocation	kg C/kg N	55
C : N of fine roots	kg C/kg N	48
C : N of live wood	kg C/kg N	50
C : N of dead wood	kg C/kg N	550
Leaf litter labile proportion	DIM	0.38
Leaf litter cellulose proportion	DIM	0.44
Leaf litter lignin proportion	DIM	0.18
Fine root labile proportion	DIM	0.34
Fine root cellulose proportion	DIM	0.44
Fine root lignin proportion	DIM	0.22
Dead wood cellulose proportion	DIM	0.77
Dead wood lignin proportion	DIM	0.23
Canopy water interception coefficient	1/LAI/d	0.01
Canopy light extinction coefficient	DIM	0.54
All-sided to projected leaf area ratio	DIM	2.0
Canopy average specific leaf area (projected area basis)	m2/ kg C	18
Shaded SLA : sunlit SLA	DIM	2.0
Fraction of leaf N in Rubisco	DIM	0.062
Maximum stomatal conductance (projected area basis)	$m\ s^{-1}$	0.006
Cuticular conductance (projected area basis)	$m\ s^{-1}$	0.00001
Boundary layer conductance (projected area basis)	$m\ s^{-1}$	0.01
Leaf water potential :start of conductance reduction	MPa	-0.34
Leaf water potential : complete conductance reduction	MPa	-2.2
Vapour pressure deficit : start of conductance reduction	Pa	1100
Vapour pressure deficit : complete conductance reduction	Pa	3600

***Site physical variables*:** describes the study site condition, which includes location, elevation, soil texture and effective soil depth, slope,and aspect. For the first section of this study/model evaluation (Appendix 9.1), soil texture was determined from soil samples collected in the four study sites but for the second section/landscape level study (Appendix 9.2), we extracted soil texture from the soil texture map of the Amhara Design and Supervision Works Enterprise (ADSWE, 2012). Similarly, soil depth was obtained from the regional soil depth map provided by ADSWE (2012).

Climate variables: Climatic variables are one of the main Biome-BGC model input variables, and are important for forest productivity. Biome-BGC requires daily metrological data, including minimum and maximum temperature and precipitation (see section 4.2.3), pre-industrial and current atmospheric CO_2 and nitrogen deposition.

4.4 Model simulation procedure

Modeling with Biome-BGC requires two steps:

Spin-up simulation: It is an adjustment process of the model internal state to an equilibrium level, starting from few initial input variables and pre-industrial atmospheric CO_2 and nitrogen deposition. Accordingly, BGC spin-up runs to mimic a fully grown forest ecosystem or accumulation of soil carbon at a “steady state”, which might take hundreds to thousands of years to achieve, depending on climate and site condition of the study area. In our spin-up run, the constant preindustrial atmospheric CO_2 concentration was set to 278 ppm (Enting et al., 1994; IPCC, 1992) and 0.129 g N m^{-2} $year^{-1}$ for Nitrogen deposition (Dentener et al., 2006).

Current forest simulation: The spin-up run is followed by current forest simulation, which explains the current forest ecosystem under the changing climatic condition and forest management interventions (eg. thinning, clear-cut and replanting). The soil carbon and nitrogen stock final value from the spin-up run are adjusted to the current degraded site level and used as initial values to run current forest simulation or future reforestation prediction (see Appendix 9.1 and 9.2).

4.5 Carbon sequestration potential of reforestation at landscape level

There is a considerable amount of degraded land in Ethiopia, which needs restoration either through plantation or natural regeneration. Suitable environmental or biophysical variables are crucial for successful forest growth and productivity in those areas. Moreover, the policy of the government and competition between other land uses also determine the available suitable reforestation area. Most midland and highland parts of Ethiopia are relatively productive and can support forest plantations, but are highly populated and intensively used for crop production compared to lowland and highland alpine areas (Friis, 2010; Friis et al., 2016; Headey et al., 2014; Taffesse et al., 2011).

Despite the existing intensive land competition, current plantation activities are dominantly found within these areas (Mekonnen et al., 2016; Zeleke and Hurni, 2001) on former crop or grass lands. Hence, for a cost-effective and successful reforestation plan, we identified suitable reforestation areas based on: (i) land use suitability, the (ii) potential elevation/vegetation belts and (iii) aridity index and (see Appendix 9.2).

Once the potential area is identified, we set simulation points with 9 km* 9 km resolution in each land use (bare land = 81, grass land = 135 and shrub land = 160). In each point, we modeled the carbon sequestration potential of reforestation under different management intervention using site condition, climate variables and eco-physiological parameters. Since there is no documented evidence of forest management practices in Ethiopia, we set different management scenarios considering continuous timber harvest and carbon sequestration. Accordingly, three forest management options are applied, including: (i) no management (control scenario), (ii) light thinning (thinning 1) with tree removal of 5% of the standing stock every 20 years and (iii) heavy thinning (thinning 2) with a removal of 10% of the standing stock every 20 years.

Based on the above thinning management scenario, the system does not allow yearly harvest for 100 years except thinning and this is against sustainable management principle. Because maintaining forest stand util full maturation might increase carbon sequestration potential but no chance of timber harvest for the local people or forest owners. To balance such environmental and economic benefits we propose the implementation of the Normal-forest approach, which provides a simple framework for ensuring sustainability based on an equal distribution of the land area by age and a defined rotation length. In this study, five different rotation lengths (10, 30, 50,100 and 150 years) were implemented together with management scenarios to show regional carbon sequestration potential in a Normal-forest system.

5. Results

5.1 Biome-BGC model evaluation and forest carbon flux

For the Biome-BGC model evaluation, we first analyzed the field inventory results of selected forests and nearby crop/grazing sites in four areas (Gelawdiwos, Katassi, Mahibereselassie and Taragedam). The inventory results recorded a significant difference between the study sites in their aboveground carbon stock ranging from 13.0 t C ha^{-1} to 60.4 t C ha^{-1} and soil carbon from 61 t C ha^{-1} 206 t C ha^{-1} (Table 2). A similar variation is observed in NPP between sites. Despite the assumption that all study sites except Katassi are "protected" church forests, the aboveground carbon recorded is very low. However, the soil carbon stock is relatively high in all study sites except Mahibereselassie (see Belay et al., 2018a). In general, study sites at higher elevations show the highest productivity and carbon storage compared to lowland sites (see Table 2).

We did a pairwise comparison of the soil carbon and nitrogen content between the forest and the neighboring crop/grazing sites (Belay et al., 2018a). Crop/grazing sites depict a significantly lower soil carbon and nitrogen content (about 40-85% reduction) compared to corresponding forest sites but not in Mahibereselassie forest site showed lower soil carbon than nearby crop study site.

Table 2. The four study forest sites: Gelawdiwos, Katassi, Mehabereselessie and Taragedam. Site elevation; the number of sample plots, plot number; aboveground carbon, Vegetation C; soil carbon, Soil C; and NPP of each study site plus the corresponding standard deviation.

Parameters	Gelawdiwos	Katassi	Mahibereselassie	Taragedam
Elevation (m)	2487	2150	863	2325
Plot number	33	56	19	36
Vegetation C (t C ha-1)	60.4 ± 46.5	41.2 ± 34.3	13.0 ± 5.5	19.9 ± 19.5
Soil C (t C ha-1)	206 ± 24.0	205 ± 31.8	61 ± 38.5	173 ± 28.4
NPP (g C m^{-2} yr-1)	640 ± 425	490 ± 327	150 ± 63	431 ± 333

For the same set of variables as analyzed in forest inventory data, we run the Biome-BGC model for each study area using the available climate data, soil physical conditions and eco-physiological parameters (see Table 1). The predicted result shows a well-fitted pattern of carbon (aboveground or soil) and NPP with the corresponding inventory results of four study areas. Figure 7 compares observed versus Biome-BGC predicted aboveground and soil carbon stock and NPP.

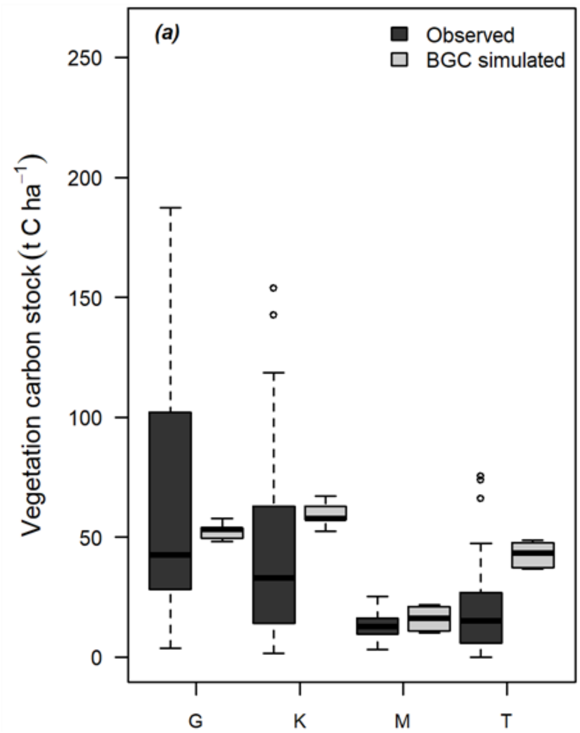

Figure 7a. Observed versus Biome-BGC predicted vegetation carbon of study sites (G=Gelawdiwos, K=Katassi, M=Mehabereselassie, T=Taragedam). The boxplots depict the median (black central line) and the 25th and 75th quartile of the samples.

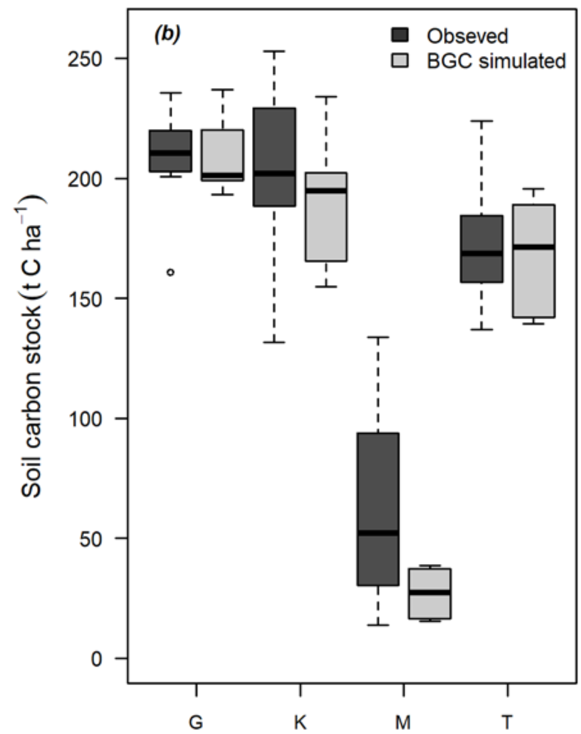

Figure 7b. Observed versus Biome-BGC predicted soil carbon of study sites (G=Gelawdiwos, K=Katassi, M=Mehabereselassie, T=Taragedam). The boxplots depict the median (black central line) and the 25th and 75th quartile of the samples.

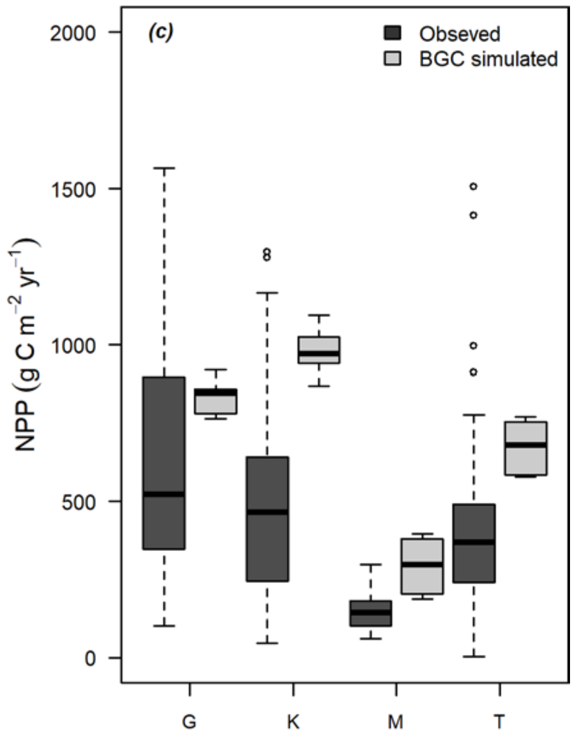

Figure 7c. Observed versus Biome-BGC predicted NPP of study sites (G=Gelawdiwos, K=Katassi, M=Mehabereselassie, T=Taragedam). The boxplots depict the median (black central line) and the 25th and 75th quartile of the samples.

Next, we evaluated the recovery potential of degraded crop/grazing sites through reforestation, using Biome-BGC. The model predicted results show that from a few decades to thousands of years are needed to restore the carbon and nitrogen stock of degraded areas to the current forest level or new steady state (Appendix 9.1). As management intensity increases, carbon accumulation velocity is getting very slow and increases the years required to attain a steady state.

5.2 Potentially suitable reforestation areas

Degraded area restoration has been given great attention by the Ethiopian government as one important option to meet Climate Resilient and Green Economy strategy (CRGE) which aim to transform the economy by 2025. For the successful implementation of such forest-related strategies, however, need to consider many ecological and economic and social factors. Accordingly, in this study, we estimated the available suitable reforestation area in the Amhara region based on: (i) land use suitability, (ii) potential elevation/vegetation belt and (iii) aridity index.

Land use suitability: In accordance with the government forest restoration strategic plan, we identified three potential land use types in the Amhara region using the regional land use map (BoA, 2012), which includes: (i) bare land, (ii) grass land and (iii) shrub land. ***Potential elevation/vegetation belt***: Once we selected the land use types, we additionally limited the reforestation areas within the vegetation belt classified as 'Dry evergreen Afromontane forest and grassland', found between 1800 m and 3200 m. In addition, we divided this vegetation belt into two elevation classes: (i) midlands (< 2300 m) and (ii) highlands (> 2300 m) highland. Depending on elevation and the corresponding annual precipitation in the area, each elevation class was re-classified into six agro-ecological zones (Hurni (1998) (see Table 3). ***Aridity index***: in dryland areas where annual evaporation is higher than precipitation, it is hard to have dense plantation forest without supplementary water, and thus we still used an aridity index (AI) for further decision in potential reforestation areas. Hence, areas with an aridity index AI < 0.65 are excluded from reforestation. For detailed methods and results (See Appendix 9.2).

With these aforementioned selection criteria, from the total Amhara region land size (15.7 Mha), about 3.4 Mha area of land (including shrub land, grass land and bare land) is suitable for reforestation. Among the identified land uses, shrub land covers a relatively large area (1.5 Mha), followed by grass land (1.2 Mha) and bare land (0.7 Mha). The identified reforestation areas are distributed as mosaic/patchy throughout the landscape of Amhara region, though most of the bare land and shrub land are concentrated in the central eastern and north-eastern part of the Amhara region. Figure 8 shows the distribution of identified potential reforestation areas across the Amhara region.

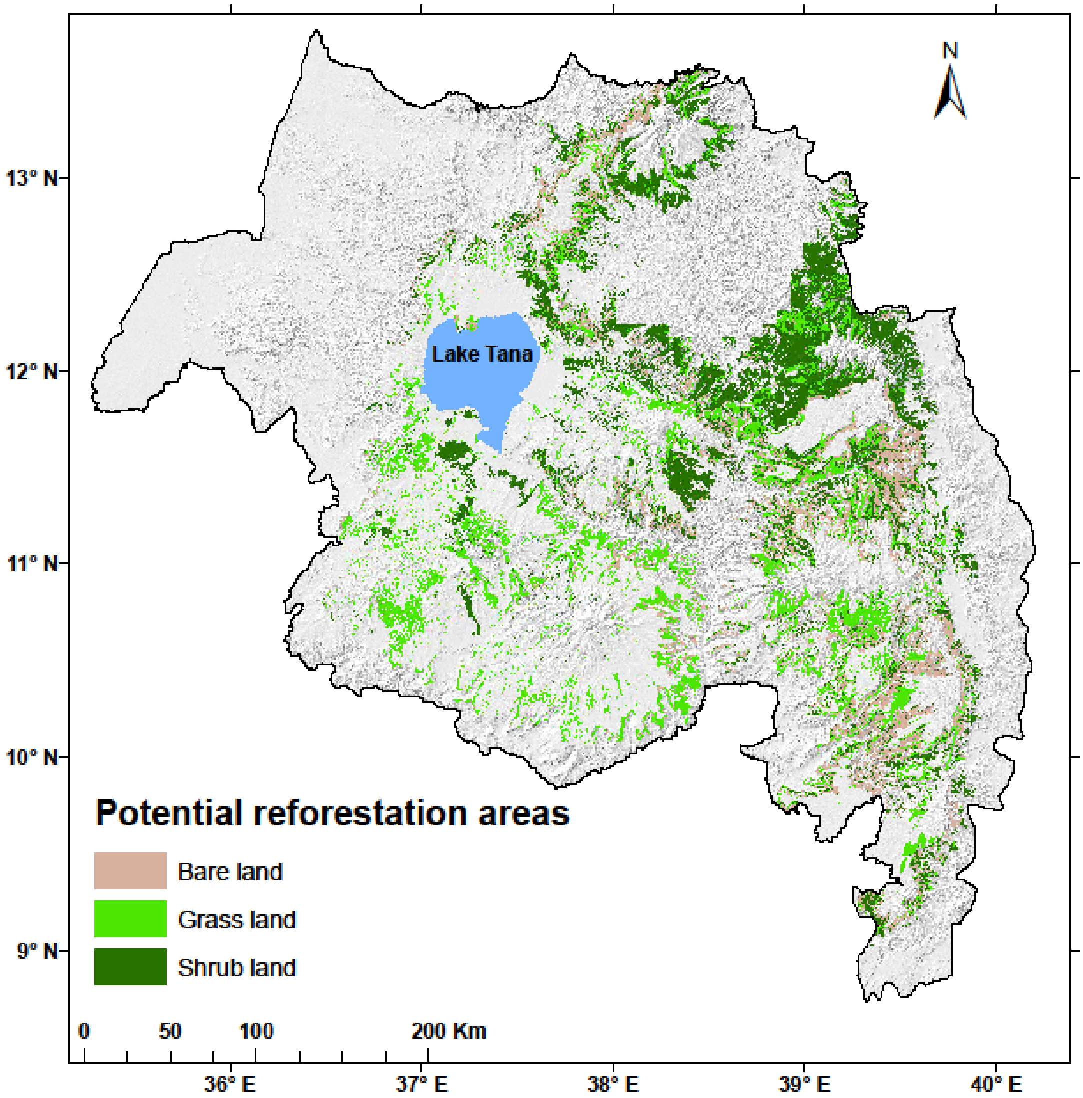

Figure 8. The spatial distribution of identified potentially suitable reforestation areas of different land uses (bare land, grass land and shrub land) across the Amhara region.

5.3 Carbon sequestration and distribution in the study area

5.3.1 Thinning management and carbon stock

Reforestation under different management interventions (no management, light thinning and heavy thinning) was simulated using the Biome-BGC to predict above and below ground carbon accumulation across the identified area. The gross accumulated carbon stock, including aboveground and soil carbon after 100 year reforestation varied from 156 t C ha^{-1} in the unmanaged forest to 145 t C ha^{-1} C ha^{-1} in light thinning and 135 t C ha^{-1} heavy thinning (Figure 9). The impact of management intensity is clearly seen in aboveground carbon stock rather than in other carbon pools (see Figure 9). Among model predicted carbon pools (aboveground, soil, root and litter), aboveground contributed the highest share (about 50%) of the whole forest ecosystem carbon stock.

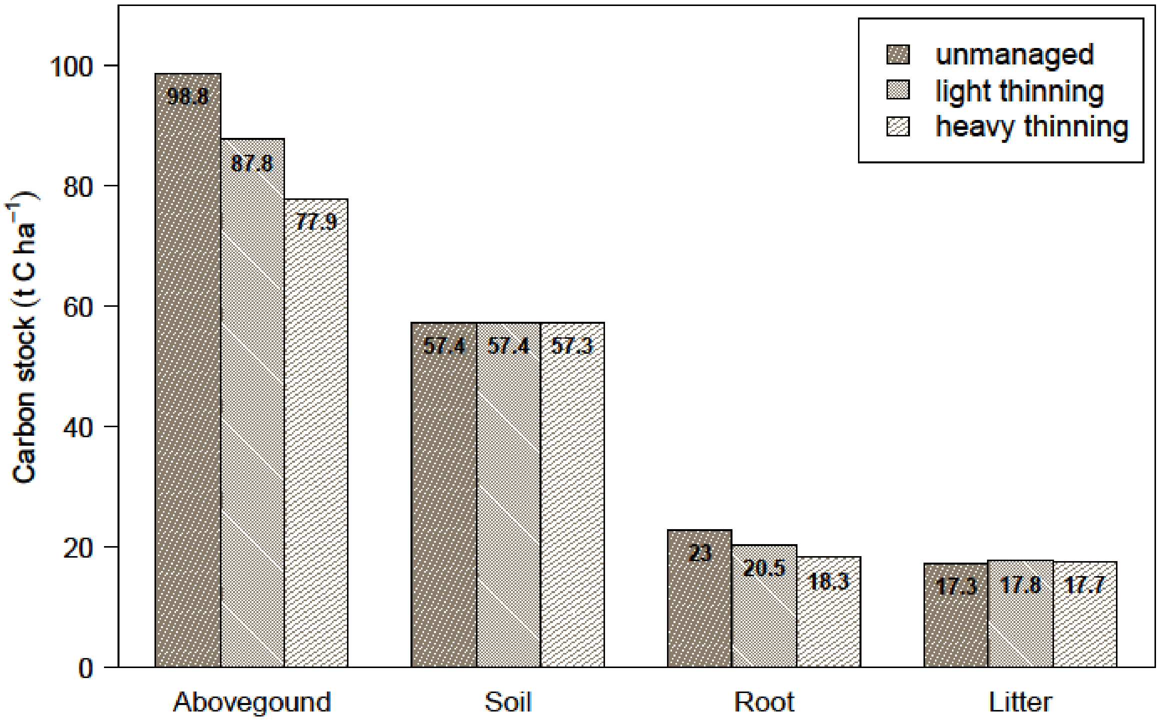

Figure 9. Predicted mean carbon stock in different pools of 100 years reforestation with different management scenarios.

The mean soil and aboveground carbon and annual NPP after 100 years reforestation with different management scenarios are shown in Table 3. Under no management, the highest accumulated soil carbon stocks are evident in the highland-wet grass land zone (91.0 t C ha^{-1}), while the lowest sequestration potential can be expected in the midland-dry bare land zone (26.2 t C ha^{-1}). Similarly, the highest NPP is found in highland-wet grass land zone. Both in highland and midland, dry locations have lower sequestration potential than moist and wet locations (see Table 3). The spatial distribution of the soil and aboveground carbon as well as NPP sequestered during a 100 year afforestation period (unmanaged condition) is mapped (Figure 10).

Table 3. Model predicted carbon sequestered through reforestation after 100 years for different current land uses, in different agro-ecological zones and management scenarios. Number of simulation points (Points), initial soil carbon ($SoilC_I$) and aboveground carbon ($AboveC_L$) are obtained from spin-up simulation and literature (see Appendix 9.2). Net carbon stock ($SoilC_N$, $AboveC_N$) is the difference between gross carbon stock ($SoilC_G$, $AboveC_G$) and the corresponding initial carbon stock ($SoilC_I$ and $AboveC_L$).

Land use	Agro-ecology	points	$SoilC_I$ (t C/ha)	$AboveC_L$ (t C/ha)	Gross carbon stock (t C/ha)						Net carbon stock (t C/ha)					
					Unmanaged		Light thinning		Heavy thinning		Unmanaged		Light thinning		Heavy thinning	
					$SoilC_G$	$AboveC_G$	$SoilC_G$	$AboveC_G$	$SoilC_G$	$AboveC_G$	$SoilC_N$	$AboveC_N$	$SoilC_N$	$AboveC_N$	$SoilC_N$	$Above_{-N}$
Bare land	Highland-dry	11	23.9	0	32.8	52.7	32.9	47.1	32.9	42.1	8.9	52.7	9.0	47.1	9.0	42.1
	Highland-moist	22	31.3	0	41.1	69.1	41.2	61.8	41.1	55.2	9.8	69.1	9.9	61.8	9.8	55.2
	Highland-wet	11	41.2	0	51.3	90.1	51.3	80.6	51.2	72.0	10.1	90.1	10.1	80.6	10.0	72.0
	Midland-dry	12	18.1	0	26.2	51.4	26.3	45.9	26.2	41.0	8.1	51.4	8.2	45.9	8.1	41.0
	Midland-moist	16	19.5	0	28.3	61.4	28.3	54.9	28.3	48.9	8.8	61.4	8.8	54.9	8.8	48.9
	Midland-wet	9	21.5	0	31.3	75.4	31.3	67.2	31.2	60.0	9.8	75.4	9.8	67.2	9.7	60.0
Grass land	Highland-dry	7	44.9	2.4	50.5	70.0	50.5	62.2	50.4	55.1	5.6	67.6	5.6	59.8	5.5	52.7
	Highland-moist	31	71.4	2.4	77.8	106.9	77.9	94.9	77.8	84.3	6.4	104.5	6.5	92.5	6.4	81.9
	Highland-wet	26	83.3	2.4	91.0	149.7	91.0	132.7	90.9	117.7	7.7	147.3	7.7	130.3	7.6	115.3
	Midland-dry	10	30.4	2.4	35.1	64.2	35.1	57.0	35.0	50.5	4.7	61.8	4.7	54.6	4.6	48.1
	Midland-moist	25	44.6	2.4	50.4	93.6	50.4	83.2	50.4	73.8	5.8	91.2	5.8	80.8	5.8	71.4
	Midland-wet	36	51.2	2.4	58.3	135.3	58.3	119.9	58.2	106.4	7.1	132.9	7.1	117.5	7.0	104.0
Shrub land	Highland-dry	8	69.9	7.1	73.9	92.9	73.9	82.5	73.9	73.1	4.0	85.8	4.0	75.4	4.0	66.0
	Highland-moist	27	82.2	7.1	86.2	115.0	86.3	102.2	86.3	90.7	4.0	107.9	4.1	95.1	4.1	83.6
	Highland-wet	7	76.1	7.1	80.7	143.1	80.8	126.8	80.8	112.5	4.6	136.0	4.7	119.7	4.7	105.4
	Midland-dry	30	43.7	7.1	46.3	73.3	46.4	65.0	46.2	57.4	2.6	66.2	2.7	57.9	2.5	50.3
	Midland-moist	65	53.3	7.1	56.5	98.9	56.6	87.9	56.5	77.8	3.2	91.8	3.3	80.8	3.2	70.7
	Midland-wet	23	52.7	7.1	56.8	119.2	56.9	105.9	56.8	93.8	4.1	112.1	4.2	98.8	4.1	86.7

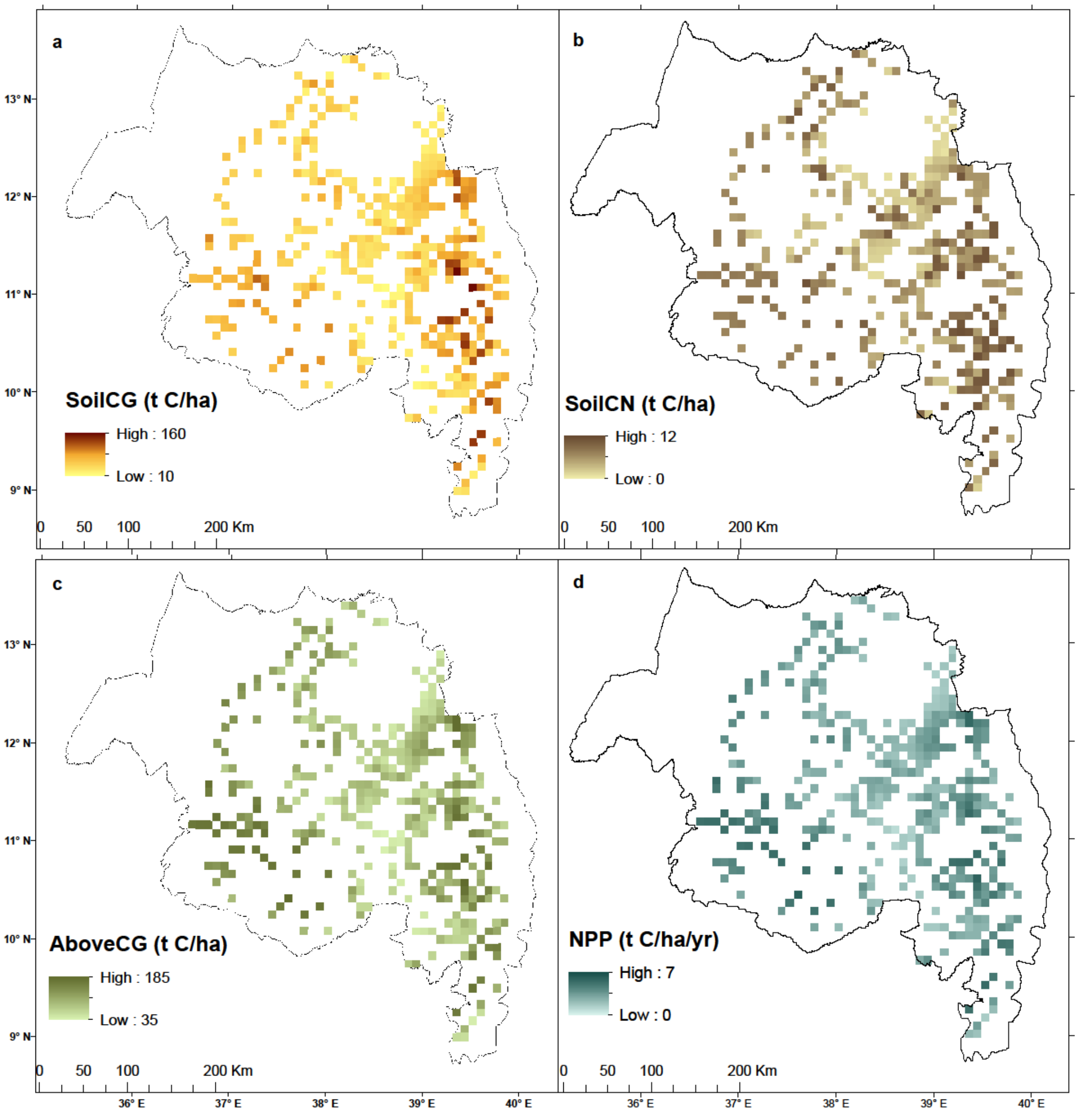

Figure 10. Spatial distributions of predicted soil and aboveground carbon and annual NPP after 100 years of reforestation (unmanaged) for the selected areas on the 9 km by 9 km resolution. (a) SoilCG – Gross soil carbon stock; (b) SoilCN – Net soil carbon stock calculated as the difference between SoilCG and the initial soil carbon stock SoilCI; (c) AboveCG – Gross aboveground carbon stock; (d) annual net primary production (NPP, 10 year mean, years 91-100 after reforestation).

5.3.2 Normal-forest system and carbon stock

In section 5.3.1 we presented the carbon accumulation potential of identified degraded areas after 100 years of reforestation with different thinning scenarios. This idea does not consider age variation and rotation periods of a given forest stand, which highly affect carbon sequestration potential and limit a continuous timber harvest. Hence, in addition to thinning scenarios, we applied the Normal-forest approach, which supports the idea of continuous and maximum production in perpetuity with an equal distribution of the land area by age classes and a defined rotation period. In the Normal-forest system, equal area stands are distributed by equal area class in equally productive areas. For example, we need to reforest 100 ha of land with a defined rotation length/period of 20 years. This means we reforest 5 ha of land every year for 20 years so that we have an equal area distribution of plantation by age class (5 ha/yr). Once, the whole area (100 ha) is fully reforested, we will have a continuous or yearly harvest of 5 ha timber, in addition to thinning (if thinning scenarios considered).

With this Normal-forest principle, we again predicted the carbon stock potential of reforestation in all identified degraded areas (3.4 Mha) with five different rotation periods and different management interventions (no management, light thinning and heavy thinning). The detailed methods and results of the gross and net total carbon stock (both soil and aboveground) under a Normal-forest system and five rotation length (10, 30, 50, 100, and 150 years) are presented (see Appendix 9.2).

There is a great amount of potential reforestation area in the Amhara region, however, this area is found distributed in the landscape as small patches intermingled with other different land uses (see Figure 8). As a result, most current and future reforestation activities in the region are small and mosaic in the landscape. Thus, here we are interested to show an example of Normal-forest system application on a small area of land (600 ha) under the identified different land uses (bare land = 200 ha, grass land = 200 ha, and shrub land = 200 ha) without management intervention in medium rotation length (20 years). In each year, 10 ha of land has to be reforested in each land use type for 20 years to cover the whole area (200 ha), because Normal-forest system approach considers an equal share of the area in each age class depending on the rotation length. Table 4 shows the gross and net soil and aboveground carbon sequestration of the Normal-forest system reforestation practice without management in a 20 year rotation length in different agro-ecologies. The carbon stock recorded in a short rotation period is lower (see Table 4) than the long rotation period (100 years) (see Table 4 in Appendix 9.2). The net aboveground carbon stock considerably increased with rotation length, whereas net soil carbon stock shows very little difference.

Table 4. Model predicted carbon sequestration potential through reforestation in a Normal-forest system without management in a 20 year rotation period in different land uses and agro-ecological zones. Initial soil carbon (SoilCI) and aboveground carbon (AboveCL) are as described in Table 3. Normal-forest gross carbon stock ($SoilC_{NF-G}$, $AboveC_{NF-G}$) is derived by summing model predicted carbon stock from year 0 to 20 and divided by the rotation period (20 years). Net carbon stock ($SoilC_{NF-N,}$ $AboveC_{NF-N)}$ is the difference between gross carbon stock and the corresponding initial carbon stock (SoilCI and AboveCL).

Land use	Agro-ecology	Points	$SoilC_I$ (t C/ha)	$AboveC_L$ (t C/ha)	Normal-forest gross carbon stock (t /ha)		Normal-forest net carbon stock (t /ha)	
					$SoilC_{NF-G}$	$AboveC_{NF-G}$	$SoilC_{NF-N}$	$AboveC_{NF-N}$
Bare land	Highland-dry	11	23.9	0	26.5	0.6	2.6	0.6
	Highland-moist	22	31.3	0	34.3	0.5	3.0	0.5
	Highland-wet	11	41.2	0	44.8	0.5	3.6	0.5
	Midland-dry	12	18.1	0	20.5	1.0	2.4	1.0
	Midland-moist	16	19.5	0	22.1	0.9	2.6	0.9
	Midland-wet	9	21.5	0	24.4	1.0	2.9	1.0
Grass land	Highland-dry	7	44.9	2.4	46.9	4.3	2.0	1.9
	Highland-moist	31	71.4	2.4	74.0	5.1	2.6	2.7
	Highland-wet	26	83.3	2.4	86.4	6.6	3.1	4.2
	Midland-dry	10	30.4	2.4	32.2	4.8	1.8	2.4
	Midland-moist	25	44.6	2.4	46.8	5.9	2.2	3.5
	Midland-wet	36	51.2	2.4	53.5	8.2	2.3	5.8
Shrub land	Highland-dry	8	69.9	7.1	71.9	7.9	2.0	0.8
	Highland-moist	27	82.2	7.1	84.3	8.0	2.1	0.9
	Highland-wet	7	76.1	7.1	78.1	10.1	2.0	3.0
	Midland-dry	30	43.7	7.1	45.3	7.6	1.6	0.4
	Midland-moist	65	53.3	7.1	55.1	8.1	1.8	1.0
	Midland-wet	23	52.7	7.1	54.4	9.5	1.7	2.4

Reforesting bare land recorded higher total net soil carbon storage than grass and shrub land within the same unit of land in a 20 year rotation period (Table 5). However, the net aboveground carbon stock is higher in grass land than the other land uses. Generally, in a short rotation period, higher total net carbon was stored in the soil than aboveground (see Appendix 9.2).

Table 5. Total carbon storage over the corresponding area coverage of different land uses. Initial soil carbon (SoilCI-T) and aboveground carbon (AboveCI-T) are as described in Table 3, model predicted gross and net soil and aboveground carbon sequestration potential in a 20 year rotation period under the Normal-forest system without management. All carbon values are in Gigagram (Gg C= 10^9 g C).

Land use	Area (ha)	$SoilC_{I-T}$ (Gg C)	$AboveC_{I-T}$ (Gg C)	Total Normal-forest gross carbon stock (Gg C)		Total Normal-forest net carbon stock (Gg C)	
				$SoilC_{NF-GT}$	$AboveC_{NF-GT}$	$SoilC_{NF-GT}$	$AboveC_{NF-GT}$
Bare land	200	5.3	0.0	5.8	0.1	0.6	0.1
Grass land	200	11.7	0.5	12.3	1.3	0.5	0.8
Shrub land	200	11.6	1.4	12.0	1.7	0.4	0.2
Sum	600	28.6	1.9	30.1	3.1	1.5	1.2

6. Discussion

The forest cover in Ethiopia is continuously declining, following a steadily increasing population growth. As a result, especially in the northern part of the country, many of the remnant forests are limited in some remote/non-accessible and cultural/religious areas. This does not only bring fuel/construction wood shortage but a huge amount of soil loss all over the country (Belay et al., 2018a; Bewket and Tefer, 2009; Tadesse et al., 2017), which in turn imposes agricultural productivity. In response to environmental and economic problems and international attention to avert climate change, Ethiopia is working on reforestation and forest conservation (MEFC, 2017).

In this study, we assessed the current forest condition, predicted the dynamics of aboveground and soil carbon under different management intervention and rotation periods using Biome-BGC in the Amhara region. The inventory results reveal a significant difference between the study forests in their aboveground and soil carbon stock, and NPP (Table 1), which might be the result from the difference in environmental condition and disturbance intensity. Despite the assumption that all study sites except Katassi are “protected” church forests, the aboveground carbon was very low, which indicates the existing disturbance pressure; this fits with other studies (Assefa et al., 2017; Wondie et al., 2016). There are also areas where church forests are the only remnant natural forest and source of many economic and medicinal valuable indigenous trees/shrubs species, which worsen the human disturbance pressure. Unlike aboveground carbon, all study sites except Mahibereselassie recorded considerably higher soil carbon stock, which might be the legacy of previously existing dense forest cover (Belay et al., 2018a). The forest in Mahiberseselassie, however, is found in a dry lowland part of the study region experiencing low precipitation and intensive grazing, and regular grass burning impacts.

The model predicted aboveground and soil carbon, as well as NPP were comparable with field inventory results (Belay et al., 2018a), implying the model can express the Ethiopian Afromontane forest ecosystem. Using the study forest eco-physiological parameters and documented historical management/human interventions, which we lacked in this study, could further improve the prediction accuracy of Biome-BGC. As all models are an abstraction or simplification of a real condition, the Biome-BGC model is also limited in showing the difference recorded between inventory plots, which could be due to age or disturbance variation within each forest.

In the Amhara region, a total of about 3.4 Mha of land (0.7 Mha bare land, 1.2 Mha grass land, and 1.5 Mha shrub land) is suitable for future reforestation (Belay et al.,2018b). The result only includes areas within the dry evergreen Afromontane forest vegetation belt (1800 m – 3200 m). As the main aim of this study is to identify potentially suitable plantation areas, moisture-stressed lowland and highland afro-alpine areas were excluded based on our selection criteria (land use suitability, potential elevation/vegetation belt and aridity index). However, these marginalized areas are still ecologically and economically important and have been rehabilitated through area exclosure (Lemenih and Kassa, 2014).

We also examined aboveground and soil carbon sequestration potential of identified degraded areas (bare land, grass land or shrub land) through reforestation with different management intervention and rotation periods (See Belay et al., 2018b). The model predicted reforestation shows a considerable increase in both soil and aboveground carbon. However, the reforestation site condition, applied management intervention and rotation length determine the carbon accumulation rate. Moreover, the initial land use, site elevation and the corresponding climatic conditions are also important factors in determining forest productivity and carbon sequestration potential (Barnes et al., 2016; Berthrong et al., 2012; Josephson et al., 2014; Toledo et al., 2011).

Reforestation on grass land and shrub land result in higher NPP and aboveground carbon stocks after 100 years compared with the bare land (See Belay et al., 2018b). Better current soil carbon and nitrogen stock in the grass and shrub land than in bare land might enhance forest productivity. In comparing agro-ecological zones, NPP and aboveground and soil carbon stocks, in general, are higher in the highland zones (with higher precipitation or wet areas) than the midlands (with low precipitation or dry areas). Specifically, the highest productivity in both in aboveground and soil carbon was recorded in highland-wet grass land, whereas the lowest in midland-dry bare land. The climatic conditions in highland-wet zones that induce less drought stress could be shown to be favorable for growth processes (Rahman et al., 2015).

Reforestation of degraded areas by itself is no guarantee for climate change mitigation and continuous timber harvest unless sustainably managed. Sustainable forest management increases direct economic benefits and environmental services while protecting deforestation and forest degradation. Many forests in the tropics and subtropics are still not managed sustainably. For instance, degraded areas have been rehabilitated in many parts of Ethiopia through closing from human and livestock intervention to promote natural regeneration (Mekuria et al., 2017, 2011; Yimer et al., 2015) but no management plan designed for how long the areas will be closed and how they will be managed for better economic and ecological outcomes (Lemenih and Kassa, 2014). This threatens the sustainability of reforested areas because local people will not get economic benefit from it (Balana et al., 2010). In implementing sustainable forest management, a range of ecological and economic and social factors need to be considered (Skovsgaard and Vanclay, 2008).

In this study, we first identified the available potential area in the Amhara region and estimated the carbon sequestration potential after 100 years reforestation under different management intervention (no management, light thinning and heavy thinning). Reforesting such a huge area of land in the same year and maintaining it for 100 years with only thinning management is far from a realistic situation because: (i) Resource and time is always limited to reforesting in one year, and (iii) It over-estimates the expected carbon sequestration potential of reforestation because the assumption does not consider different age class and rotation length. Hence, we again applied the Normal-forest principle with different rotation lengths to estimate the study area carbon sequestration potential. For instance, the maximum net soil carbon stock recorded after a 100 year reforestation without management was 10.1 t ha^{-1} in the highland-wet bare land zone, whereas the maximum net aboveground carbon stock was 147.3 t ha^{-1} in highland-wet grass land (See Table 3). However, the corresponding net soil and aboveground carbon stocks in Normal-forest system with 100 years rotation were 5.9 ha^{-1} and 77.3 ha^{-1}, respectively (See Table 4 in Appendix 9.2).

Though the optimal rotation period of a forest depends on the aim of the plantation, species type and climatic condition (Nyakundi et al., 2018), we investigated carbon sequestration potential based on Normal-forest system under different rotation lengths from short (10 years) to long (150 years) (see Table 3 and Appendix 9.2). In general, the aboveground carbon stock increased with rotation length, but very little difference is observed in soil carbon with rotation length. The Normal-forest practice assumes an equal share of age classes with annual normal-increment, which implies a continuous and maximum production in perpetuity (Leslie, 1966). Hence, Normal-forest can be described as pure, even-aged, densely stocked stands, and each age class represents in an equally productive area (Knuchel, 1953). In practice, the current plantation trend is focusing more towards mixed forests, less regular in composition, structure and arrangement which are different from the ideal Normal-forest principle. However, as the model is a simplified representation of reality, it is not intended to be an exact description of reality but it can show the patchy or mosaic type plantation practiced in the Amhara region and attempts to show the relationship between rotation length and carbon stock.

7. Conclusion

The dry Afromontane forest ecosystem in the Ethiopian highlands, covering about 50% of the African Afromontane forests, are known for their floral and faunal species richness and a high number of endemic species. Despite their ecological and economic significance, most of the Afromontane forests are being fragmented and modified or changed into other land use, driven by extensive farming and intensive grazing and fuelwood harvest. Designing viable forest management mechanisms, which the Ethiopian forest sector lacks, is very crucial for the sustainability of current forest and future reforestation. Sustainable forest management at a landscape level is crucial for alleviating forest degradation and deforestation, while increasing social benefits, including livelihood, income generation and employment and environmental services, like carbon sequestration, soil productivity and biodiversity conservation. This study is aimed at understanding the existing forest conditions and predicting future reforestation potentials, with possible management intervention in the Amhara region.

The inventory result on the existing remnant natural forest explained higher soil carbon sequestration stock but very low aboveground carbon stock. Changing these forests into crop/grazing or other non-forest lands, costs a considerable amount of forest carbon stock, which could require many centuries to restore. The study also shows that the terrestrial ecosystem model Biome-BGC did well in expressing/estimating the carbon stock compared to the inventory results. Thus, the model could be used in showing the dynamics of carbon, either during deforestation or reforestation, especially at a landscape level.

This study also identifies the potentially suitable reforestation areas in the Amhara region, which helps to set the future forest development plan. In the region, a total of about 3.4 Mha of land is potentially suitable for reforestation, including bare land (0.7 Mha), grass land (1.2 Mha), and shrub land (1.5 Mha). Moisture-stressed lowland areas and highland afro-alpines are excluded in the identified potential reforestation area based on the selection criteria. The study also shows the recovery potential of degraded, identified potential areas through reforestation, especially in restoring vegetation and soil carbon stock. This also fits with the current national and regional government strategic plans, aiming to improve carbon sequestration under the REDD+ strategic plan through forest management and reforestation of new areas.

Moreover, the study investigated carbon sequestration potential of the Amhara region with different management interventions, both with and without rotation period under different land uses and agro-ecologies. The management intervention shows a significance difference on aboveground carbon sequestration but negligible on soil carbon. In comparing agro-ecological zones, the highest total net carbon sequestration (soil and aboveground) was recorded in the highland-wet agro-ecological zone and the lowest values in the midland-dry zone. Reforestation of current grass and shrub land shows the highest net aboveground carbon sequestration than bare land, whereas the highest net soil carbon sequestration was observed in the current bare land.

Reforestation prediction without a rotation period shows higher carbon sequestration than Normal-forest with rotation period. However, Normal-forest system is more reliable in explaining the Amhara region reforestation practice because it can represent the patchy or mosaic forest practice in the landscape and also considers age and harvesting/rotation period variation of plantations. Generally, this study gives insight into combining plot level inventory data with ecosystem models for landscape-level forest carbon dynamics estimation and designing sustainable forest management strategies in the Amhara region, which has not been done before.

8. References

Amare, D., Mekuria, W., Wondie, M., Teketay, D., Eshete, A., Darr, D., 2017. Wood Extraction Among the Households of Zege Peninsula , Northern Ethiopia. Ecological Economics 142, 177–184. doi:10.1016/j.ecolecon.2017.06.002

Arbonaut, 2016. Study of causes of deforestation and forest degradation in Ethiopia and the identification and prioritization of strategic options to address those. Final report, Addis Ababa.

Assefa, D., Rewald, B., Sandén, H., Rosinger, C., Abiyu, A., Yitaferu, B., Godbold, D.L., 2017. Deforestation and land use strongly effect soil organic carbon and nitrogen stock in Northwest Ethiopia. Catena 153, 89–99. doi:10.1016/j.catena.2017.02.003

Babiker, M., Reilly, J.M., Jacoby, H.D., 2000. The Kyoto Protocol and developing countries. Energy Policy 28, 525–536. doi:10.1016/S0301-4215(00)00033-1

Baccini, a., Goetz, S.J., Walker, W.S., Laporte, N.T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P.S. a., Dubayah, R., Friedl, M. a., Samanta, S., Houghton, R. a., 2012. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. Nature Climate Change 2, 182–185. doi:10.1038/nclimate1354

Balana, B.B., Mathijs, E., Muys, B., 2010. Assessing the sustainability of forest management: An application of multi-criteria decision analysis to community forests in northern Ethiopia. Journal of Environmental Management 91, 1294–1304. doi:10.1016/j.jenvman.2010.02.005

Barnes, M.L., Moran, M.S., Scott, R.L., Kolb, T.E., Ponce-campos, G.E., Moore, D.J.P., Ross, M.A., Mitra, B., Dore, S., 2016. Vegetation productivity responds to sub- - annual climate conditions across semiarid biomes 7, 1–20.

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rödenbeck, C., Arain, M.A., Baldocchi, D., Bonan, G.B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H., Oleson, K.W., Roupsard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F.I., Papale, D., 2010. Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate. Science 329, 834–838. doi:10.1126/science.1184984

Bekele, M., 2011. Forest plantations and woodlots in Ethiopia. African forest forum working paper series. Nairobi, Kenya.

Belay, B., Pötzelsberger, E., Sisay, K., Assefa, D., Hasenauer, H., 2018. The Carbon Dynamics of Dry Tropical Afromontane Forest Ecosystems in the Amhara Region of Ethiopia. Forests 9(1), 18, 1–16. doi:10.3390/f9010018

Belay, B., Pötzelsberger, E., Hasenauer, H., 2018. The Carbon Sequestration Potential of Degraded Agricultural Land in the Amhara Region of Ethiopia. Forests 9(8), 470, 1–24. doi:10.3390/f9080470

Belay, B., Zewudie, S., Woldmariam, T., 2012. A Remnant coffee based natural forests: Floristic diversity and indigenous management of Zege Peninsula coffee forest,Ethiopia. LAP Lambert Academic.

Berthrong, S.T., Pineiro, G., Jobbagy, E.G., Jackson, R.B., 2012. Soil C and N changes with afforestation of grasslands across gradients of precipitation and plantation age 22, 76–86.

Bewket, W., Tefer, E., 2009. Assessment of Soil Erosion Hazard and Prioritization for Treatment at the Watershed Level: Case Study in the Chemoga watershed, Blue Nile Basin, Ethiopia. Land Degradation and Development 20, 587–588. doi:10.1002/ldr

Beyene, A.D., Koch, S.F., 2013. Clean fuel-saving technology adoption in urban Ethiopia. Energy Economics 36, 605–613. doi:10.1016/j.eneco.2012.11.003

Bishaw, B., 2001. Deforestation and Land Degradation on the Ethiopian Highlands : A Strategy for Physical Recovery, in: International Conference on Contemporary Development Issues in Ethiopia. Kalamazoo, Michigan.

BoA, 2012. GIS Based forest resources assessment, quantification and mapping in Amhara Region. Bureau of Agriculture, Bahir Dar, Ethiopia.

Bolin, B., 1995. Climate change 1995: IPCC SECOND ASSESSMENT REPORT 1–63.

Chao, S., 2012. Forest peoples: Numbers across the world. Forest Peoples Programme 27.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145, 87–99. doi:10.1007/s00442-005-0100-x

Chiesi, M., Chirici, G., Marchetti, M., Hasenauer, H., Moreno, A., Knohl, A., Matteucci, G., Pilegaard, K., Granier, A., Longdoz, B., Maselli, F., 2016. Testing the applicability of BIOME-BGC to simulate beech gross primary production in Europe using a new continental weather dataset. Annals of Forest Science 713–727. doi:10.1007/s13595-016-0560-7

Clarke, L.E., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P.R., Tavoni, M., van der Zwaan, B.C.C., van Vuuren, D.P., 2014. Assessing transformation pathways: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 413–510.

Degife, A.W., 2017. The intricacies of large scale agricultural investment in Gambella, in: Responsible Land Governance: Towards an Evidence Based Approach. Washington,DC, pp. 1–17.

Demessie, A., Singh, B.R., Lal, R., 2017. Soil Carbon Sequestration : Ethiopia. Encyclopedia of Soil Science. doi:10.1081/E-ESS3-120053587

Dentener, F., Drevet, J., Lamarque, J.F., Bey, I., Eickhout, B., Fiore, A.M., Hauglustaine, D., Horowitz, L.W., Krol, M., Kulshrestha, U.C., Lawrence, M., Galy-Lacaux, C., Rast, S., Shindell, D., Stevenson, D., Van Noije, T., Atherton, C., Bell, N., Bergman, D., Butler, T., Cofala, J., Collins, B., Doherty, R., Ellingsen, K., Galloway, J., Gauss, M., Montanaro, V., Müller, J.F., Pitari, G., Rodriguez, J., Sanderson, M., Solmon, F., Strahan, S., Schultz, M., Sudo, K., Szopa, S., Wild, O., 2006. Nitrogen and sulfur deposition on regional and global scales: A multimodel evaluation. Global Biogeochemical Cycles 20. doi:10.1029/2005GB002672

Dresen, E., DeVries, B., Herold, M., Verchot, L., Müller, R., 2014. Fuelwood Savings and Carbon Emission Reductions by the Use of Improved Cooking Stoves in an Afromontane Forest, Ethiopia. Land 3, 1137–1157. doi:10.3390/land3031137

Enting, I.G., Wigley, T.M.L., Heimann, M., 1994. Future Emissions and Concentrations of Carbon Dioxide : Key Ocean / Atmosphere / Land Analyses, CSIRO Division of Reserch Technical Paper. Australia.

ERSS, 2013. Ethiopia Rural Socioeconomic Survey (ERSS) Survey Report. Addis Ababa;Ethiopia.

FAO, 2010. Global Forest Resources Assessment 2010,Main report. Rome, Italy.

FDRE, 2012. Ministry of Water and Energy.Scaling - Up Renewable Energy Program Ethiopia Investment Plan (Draft Final). Addis Ababa;Ethiopia.

FDRE, 2011. Ethiopia's Climate-Resilient Green Economy. Green economy strategy. Addis Ababa, Ethiopia.

FRA, 2010. Global Forest Resources Assessment2010.Terms and definitions. Rome, Italy.

Friis, I., 2010. Atlas of the Potential Vegetation of Ethiopia Atlas of the Potential Vegetation of Ethiopia.

Friis, I., Demissew, S., Breugel, P. van, 2010. Atlas of the Potential Vegetation of Ethiopia Atlas of the Potential Vegetation of Ethiopia. The Royal Danish Academy of Sciences and Letters, Copenhagen, Denmark.

Friis, I., Gilbert, M.G., Weber, O., Demissew, S., 2016. Two distinctive new species of Commicarpus (Nyctaginaceae) from gypsum outcrops in eastern Ethiopia. Kew Bulletin 71, 1–19. doi:10.1007/s12225-016-9648-3

Gebreegziabher, Z., Mekonnen, A., Kassie, M., Köhlin, G., 2012. Urban energy transition and technology adoption: The case of Tigrai, northern Ethiopia. Energy Economics 34, 410–418. doi:10.1016/j.eneco.2011.07.017

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N., Foley, J.A., 2010. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proceedings of the National Academy of Sciences 107, 16732–16737. doi:10.1073/pnas.0910275107

Hansen, M.C., Potapov, P. V, Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. Science 134, 850–854.

Haregeweyn, N., Tsunekawa, A., Poesen, J., Tsubo, M., Meshesha, D.T., Fenta, A.A., Nyssen, J., Adgo, E., 2017. Comprehensive assessment of soil erosion risk for better land use planning in river basins: Case study of the Upper Blue Nile River. Science of the Total Environment 574, 95–108. doi:10.1016/j.scitotenv.2016.09.019

Hasenauer, H., Merganicová, K., Pietsch, S.A., 2005. Modeling biogeochemical cycles within old-growth forest ecosystems. Forest Snow and Landscape Research 90, 81–90.

Headey, D., Dereje, M., Taffesse, A.S., 2014. Land constraints and agricultural intensification in Ethiopia: A village-level analysis of high-potential areas. Food

Policy 48, 129–141. doi:10.1016/j.foodpol.2014.01.008

Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology 25, 101–110. doi:10.1023/A:1008119611481

Hidy, D., Barcza, Z., Haszpra, L., Churkina, G., Pintér, K., Nagy, Z., 2012. Development of the Biome-BGC model for simulation of managed herbaceous ecosystems. Ecological Modelling 226, 99–119. doi:10.1016/j.ecolmodel.2011.11.008

Houghton, R.A., 2005. Aboveground forest biomass and the global carbon balance. Global Change Biology 11, 945–958. doi:10.1111/j.1365-2486.2005.00955.x

Houghton, R., Houghton, B.R. a, Woods, T., Box, P.O., Hole, W., 2004. The annual net flux of carbon to the atmosphere from changes in land use 1850 – 1990 *. Tellus 51B, 378–390. doi:10.1034/j.1600-0889.1999.00013.x

Hurni, H., 1998. Agroecological Belts of Ethiopia.Explanatory notes on three maps at a scale of 1:1,000,000. Addis Ababa;Ethiopia.

Ichii, K., Hashimoto, H., Nemani, R., White, M., 2005. Modeling the interannual variability and trends in gross and net primary productivity of tropical forests from 1982 to 1999. Global and Planetary Change 48, 274–286. doi:10.1016/j.gloplacha.2005.02.005

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, United Kingdom and New York. doi:10.1017/CBO9781107415416

IPCC, 1992. Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment. Cambridge University Press.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137, 253–268. doi:10.1016/j.geoderma.2006.09.003

Jobbagy, E.G., Jackson, R.B., Applications, S.E., Apr, N., 2000. The Vertical Distribution of Soil Organic Carbon and Its Relation to Climate and Vegetation THE VERTICAL DISTRIBUTION OF SOIL ORGANIC CARBON AND ITS. Ecologico/ Applicaotius. 10, 423–436.

Josephson, A.L., Ricker-Gilbert, J., Florax, R.J.G.M., 2014. How does population density influence agricultural intensification and productivity ? Evidence from Ethiopia. Food Policy 48, 142–152. doi:10.1016/j.foodpol.2014.03.004

Keenan, R.J., Reams, G.A., Achard, F., de Freitas, J. V., Grainger, A., Lindquist, E., 2015. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. Forest Ecology and Management 352, 9–20. doi:10.1016/j.foreco.2015.06.014

Knuchel, H. H. 1953. Planning and Control in the Managed Forest (Trans. by M.L. Anderson). Oliver & Boyd, Edinburgh.

Köhl, M., Lasco, R., Cifuentes, M., Jonsson, Ö., Korhonen, K.T., Mundhenk, P., de Jesus Navar, J., Stinson, G., 2015. Changes in forest production, biomass and carbon: Results from the 2015 UN FAO Global Forest Resource Assessment. Forest Ecology and Management 352, 21–34. doi:10.1016/j.foreco.2015.05.036

Kreidenweis, U., Humpenöder, F., Popp, A., Dietrich, P., Humpenöder, F., Stevanovi, M., Bodirsky, B.L., 2016. Afforestation to mitigate climate change : impacts on food prices under consideration of albedo effects. doi:10.1088/1748-9326/11/8/085001

Laurance, W.F., Sayer, J., Cassman, K.G., 2014. Agricultural expansion and its impacts on tropical nature. Trends in Ecology & Evolution 29, 107–116. doi:10.1016/j.tree.2013.12.001

Lemenih, M., Kassa, H., 2014. Re-greening Ethiopia: History, challenges and lessons. Forests 5, 1896–1909. doi:10.3390/f5081896

Leslie, A.J., 1966. A review of the concept of the normal forest. Australian Forestry 30, 139–147. doi:10.1080/00049158.1966.10675407

MacDicken, K.G., 2015. Global Forest Resources Assessment 2015: What, why and how? Forest Ecology and Management 352, 3–8. doi:10.1016/j.foreco.2015.02.006

Mamo, Y., Asefa, A., Mengesha, G., 2016. Effects of livestock grazing on an Afromontane grassland bird community in the Bale Mountains of Ethiopia. African Journal of Ecology 54, 328–335. doi:10.1111/aje.12295

Mamuye, F., Lemma, B., Woldeamanuel, T., 2018. Emissions and fuel use performance of two improved stoves and determinants of their adoption in Dodola, southeastern Ethiopia. Sustainable Environment Research 28, 32–38. doi:10.1016/j.serj.2017.09.003

Mao, F., Li, P., Zhou, G., Du, H., Xu, X., Shi, Y., Mo, L., Zhou, Y., Tu, G., 2016.

Development of the BIOME-BGC model for the simulation of managed Moso bamboo forest ecosystems. Journal of Environmental Management 172, 29–39. doi:10.1016/j.jenvman.2015.12.013

McCann, J.C., 1997. The Plow and the Forest in Ethiopia , of Deforestation Narratives. Environmental History 2, 138–159.

MEFC, 2017. Strategic Environmental and Social Assessment (SESA) for the Implementation of REDD+ in Ethiopia,Final Report,Addis Ababa.

Mekonnen, M., Sewunet, T., Gebeyehu, M., Azene, B., Melesse, A.M., 2016. GIS and Remote Sensing-Based Forest Resource Assessment , Quantification , and Mapping in Amhara Region , Ethiopia, in: Landscape Dynamics, Soil and Hydrological Processes in Varied Climates. pp. 9–30. doi:10.1007/978-3-319-18787-7

Mekuria, W., Barron, J., Dessalegn, M., Adimassu, Z., 2017. Exclosures for Ecosystem Restoration and Economic Benefits in Ethiopia : A Catalogue of Management Options.

Mekuria, W., Veldkamp, E., Corre, M.D., 2011. Restoration of Ecosystem Carbon Stocks Following Exclosure Establishment in Communal. Forest, range, and Wildland Soils 75. doi:10.2136/sssaj2010.0176

Miheretu, B.A., Yimer, A.A., 2018. Land use/land cover changes and their environmental implications in the Gelana sub-watershed of Northern highlands of Ethiopia. Environmental Systems Research 6, 7. doi:10.1186/s40068-017-0084-7

Miheretu, B.A., Yimer, A.A., 2017. Estimating soil loss for sustainable land management planning at the Gelana sub-watershed, northern highlands of Ethiopia. International Journal of River Basin Management 5124, 1–10. doi:10.1080/15715124.2017.1351978

Miura, S., Amacher, M., Hofer, T., San-Miguel-Ayanz, J., Ernawati, Thackway, R., 2015. Protective functions and ecosystem services of global forests in the past quarter-century. Forest Ecology and Management 352, 35–46. doi:10.1016/j.foreco.2015.03.039

Nyakundi, F., Mulwa, R., Kabubo-Mariara, J., 2018. Determination of optimal rotation period for management of lumbering forests in Kenya. Journal of Sustainable Forestry 0, 1–16. doi:10.1080/10549811.2018.1447488

Palm, M., Ostwald, M., Berndes, G., Ravindranath, N.H., 2009. Application of Clean

Development Mechanism to forest plantation projects and rural development in India. Applied Geography 29, 2–11. doi:10.1016/j.apgeog.2008.05.002

Pan, Y., 2011. A Large and Persistent Carbon Sink in the World's Forests. Science 988. doi:10.1126/science.1201609

Pan, Y., Birdsey, R.A., Phillips, O.L., Jackson, R.B., 2013. The Structure, Distribution, and Biomass of the World's Forests. Annual Review of Ecology, Evolution, and Systematics 44, 593–622. doi:10.1146/annurev-ecolsys-110512-135914

Pan, Y., Birdsey, R. a, Fang, J., Houghton, R., Kauppi, P.E., Kurz, W. a, Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, a D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science (New York, N.Y.) 333, 988–993. doi:10.1126/science.1201609

Petritsch, R., Hasenauer, H., Pietsch, S.A., 2007. Incorporating forest growth response to thinning within biome-BGC. Forest Ecology and Management 242, 324–336. doi:10.1016/j.foreco.2007.01.050

Pietsch, S.A., Hasenauer, H., 2006. Evaluating the self-initialization procedure for large-scale ecosystem models. Global Change Biology 12, 1658–1669. doi:10.1111/j.1365-2486.2006.01211.x

Pietsch, S.A., Hasenauer, H., Thornton, P.E., 2005. BGC-model parameters for tree species growing in central European forests. Forest Ecology and Management 211, 264–295. doi:10.1016/j.foreco.2005.02.046

Pingali, P., 2015. Agricultural policy and nutrition outcomes – getting beyond the preoccupation with staple grains. Food Security 7, 583–591. doi:10.1007/s12571-015-0461-x

Powell, B., Thilsted, S.H., Ickowitz, A., Termote, C., Sunderland, T., Herforth, A., 2015. Improving diets with wild and cultivated biodiversity from across the landscape. Food Security 7, 535–554. doi:10.1007/s12571-015-0466-5

Price, M.F., Gratzer, G., Duguma, L.A., Kohler, T., Maselli, D., Romeo, R., 2011. Mountain Forests in a Changing World Mountain Forests in a Changing World Realizing values, addressing challenges, FAO/MPS and SDC, Rome. doi:10.13140/2.1.2386.5283

Rahman, M.S., Akter, S., Al-Amin, M., 2015. Forest and agro-ecosystem productivity in Bangladesh: a climate vegetation productivity approach. Forest Science and

Technology 11, 126–132. doi:10.1080/21580103.2014.957358

Rasmussen, L.V., Watkins, C., Agrawal, A., 2017. Forest contributions to livelihoods in changing agriculture-forest landscapes. Forest Policy and Economics 84, 1–8. doi:10.1016/j.forpol.2017.04.010

Reed, J., van Vianen, J., Foli, S., Clendenning, J., Yang, K., MacDonald, M., Petrokofsky, G., Padoch, C., Sunderland, T., 2017. Trees for life: The ecosystem service contribution of trees to food production and livelihoods in the tropics. Forest Policy and Economics 84, 62–71. doi:10.1016/j.forpol.2017.01.012

Reyer, C., Guericke, Æ.M., Ibisch, Æ.P.L., 2009. and deforestation avoidance : and what about adaptation to environmental change ? 15–34. doi:10.1007/s11056-008-9129-0

Ross, C.W., Grunwald, S., Myers, D.B., Xiong, X., 2016. Land use, land use change and soil carbon sequestration in the St. Johns River Basin, Florida, USA. Geoderma Regional 7, 19–28. doi:10.1016/j.geodrs.2015.12.001

Running, S.W., Coughlan, J.C., 1988. A general model of forest ecosystem processes for regional applications. Ecological Modelling. doi:10.1016/0304-3800(88)90112-3

Running, S.W., Gower, S.T., 1991. FOREST-BGC, A general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. Tree physiology 9, 147–160. doi:citeulike-article-id:2850231

Schmidt, V.A., 1976. Der rechnerische Ausgleich von BestandeshöShenkurven 370–382.

Sisay, K., Thurnher, C., Belay, B., Lindner, G., Hasenauer, H., 2017. Volume and carbon estimates for the forest area of the amhara region in northwestern Ethiopia. Forests 8. doi:10.3390/f8040122

Sisay, K., Thurnher, C., Hasenauer, H., 2016. Daily climate data for the Amhara region in Northwestern Ethiopia. International Journal of Climatology. doi:10.1002/joc.4880

Six, J., Callewaert, P., Lenders, S., De Gryze, S., Morris, S.J., Gregorich, E.G., Paul, E.A., Paustian, K., 2002. Measuring and understanding carbon storage in afforested soils by physical fractionation. Soil Science Society of America Journal 66, 1981–1987. doi:10.2136/sssaj2002.1981

Skovsgaard, J.P., Vanclay, J.K., 2008. Forest site productivity: A review of the evolution of dendrometric concepts for even-aged stands. Forestry 81, 13–31. doi:10.1093/forestry/cpm041

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., Van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2015. Biophysical and economic limits to negative CO2emissions. Nature Climate Change 6, 42–50. doi:10.1038/nclimate2870

Tadesse, L., Suryabhagavan, K. V., Sridhar, G., Legesse, G., 2017. Land use and land cover changes and Soil erosion in Yezat Watershed, North Western Ethiopia. International Soil and Water Conservation Research 5, 85–94. doi:10.1016/j.iswcr.2017.05.004

Taffesse, A.S., Dorosh, P., Asrat, S., 2011. Crop Production in Ethiopia : Regional Patterns and Trends:ESSP II Working Paper No. 0016. International Food Policy Research Institute.

Thurnher, C., Eastaugh, C.S., Hasenauer, H., 2014. A thinning routine for large-scale biogeochemical mechanistic ecosystem models. Forest Ecology and Management 320, 56–69. doi:10.1016/j.foreco.2014.02.028

Toledo, M., Poorter, L., Pena-Claros, M., Alarco, A., Balcazar, J., Lean, C., Licona, J.C., Llanque, O., Vroomans, V., Balca, J., Zuidema, P., Bongers, F., 2011. Climate is a stronger driver of tree and forest growth rates than soil and disturbance. Journal of Ecology 254–264. doi:10.1111/j.1365-2745.2010.01741.x

UNFCCC, 1997. The Kyoto Protocol. United Nations Framework Convention on Climate Change. FCCC/CP/L.7/Add.1. 10 1–60.

Van Do, T., Sato, T., Saito, S., Kozan, O., 2015. Fine-root production and litterfall: main contributions to net primary production in an old-growth evergreen broad-leaved forest in southwestern Japan. Ecological Research 30, 921–930. doi:10.1007/s11284-015-1295-x

WBISPP (Woody Biomass Inventory and Strategic Planning Project)., 2005. A national strategy plan for the biomass sector. Addis Ababa, Ethiopia.

White, M.A., Thornton, P.E., Running, S.W., Nemani, R.R., 2000. Parameterization and Sensitivity Analysis of the BIOME–BGC Terrestrial Ecosystem Model: Net Primary Production Controls. Earth Interactions 4, 1–85. doi:10.1175/1087-3562(2000)004<0003:PASAOT>2.0.CO;2

Wondie, M., Schneider, W., Katzensteiner, K., Mansberger, R., Teketay, D., 2016. Modelling the dynamics of landscape transformations and population growth in the highlands of Ethiopia using remote-sensing data. International Journal of Remote Sensing 37, 5647–5667. doi:10.1080/01431161.2016.1246773

Yimer, F., Alemu, G., Abdelkadir, A., 2015. Soil property variations in relation to exclosure and open grazing land use types in the Central Rift Valley area of Ethiopia. Environmental Systems Research 4:17. doi:10.1186/s40068-015-0041-2

Zeleke, G., Hurni, H., 2001. Implications of Land Use and Land Cover Dynamics for Mountain Resource Degradation in the Northwestern Ethiopian Highlands Implications of Land Use and Land Cover Dynamics for Mountain Resource Degradation in the Northwestern Ethiopian Highlands 21, 184–191.

Zomer, R.J., Trabucco, A., Bossio, D.A., Verchot, L. V., 2008. Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agriculture, Ecosystems and Environment 126, 67–80. doi:10.1016/j.agee.2008.01.014

9. Appendix

9.1 Paper I

Belay, B., Pötzelsberger, E., Sisay, K., Assefa, D., Hasenauer, H., 2018. The Carbon Dynamics of Dry Tropical Afromontane Forest Ecosystems in the Amhara Region of Ethiopia. Forests 9(1), 18, 1–16. doi:10.3390/f9010018

forests

MDPI

Article

The Carbon Dynamics of Dry Tropical Afromontane Forest Ecosystems in the Amhara Region of Ethiopia

Beyene Belay [1,2], Elisabeth Pötzelsberger [1,*], Kibruyesfa Sisay [1,2], Dessie Assefa [3] and Hubert Hasenauer [1]

1 Institute of Silviculture, University of Natural Resources and Life Sciences, Vienna, Peter-Jordan-Straße 82, 1190 Vienna, Austria; beyene.belay@yahoo.com (B.B.); kibru122@yahoo.com (K.S.); hubert.hasenauer@boku.ac.at (H.H.)
2 Amhara Regional Agricultural Research Institute, P.O. Box 527, Bahir Dar, Ethiopia
3 College of Agriculture and Environmental Sciences, Bahir Dar University, P.O. Box 79, Bahir Dar, Ethiopia; dessiegenet@gmail.com
* Correspondence: elisabeth.poetzelsberger@boku.ac.at; Tel.: +43-1-47654-91332

Received: 22 November 2017; Accepted: 28 December 2017; Published: 4 January 2018

Abstract: Forest degradation due to land use change is a severe problem in Ethiopian Afromontane Forests. We investigated such degradation effects by comparing degraded agricultural land (previously covered with forest) with neighboring natural forests, 40 to 50 years after conversion. We selected four different study areas to cover the eco-climatic conditions of the Amhara region in Northwestern Ethiopia. For a paired-stand comparison we collected soil data on both land use types. We calculated forest biomass to evaluate the biogeochemical-mechanistic ecosystem model Biome-BGC, which is used as a diagnostic tool to assess the site and management impacts on productivity as well as ecosystem carbon and nitrogen accumulation. We applied Biome-BGC to assess rehabilitation options on such degraded land. Afromontane forests in the highlands of Ethiopia showed high soil C stocks, resulting from long lasting biomass accumulation. Removing the tree cover and converting forest areas to crop- or grassland, has led to a loss of 40–85% of the soil C stocks and thus a loss in soil fertility within only 40 to 50 years. Rehabilitation efforts by replanting trees will improve soil fertility, but may require over a thousand years to achieve a similar level in biomass and soil fertility versus the situation prior to the land use change.

Keywords: carbon; land use change; Ethiopia; ecosystem modeling

1. Introduction

Tropical forests account for 50% of the Earth's total plant biomass [1] and store 40% (428 Gt C) of the terrestrial carbon [2]. Tropical forests are threatened by deforestation due to land use changes. A good example is Ethiopia, which experienced a decline in forest covered land area from 40% to less than 10% during the last century [3]. The removal of the forest cover has resulted in severe soil erosion, species extinction, as well as reduction in productivity and carbon sequestration [4]. The main reasons for the rapid land use change is the expansion of agricultural land associated with the demand for fuelwood for a fast growing population [5]. Ethiopia has a population of about 100 million people and an estimated annual increase of 3% or 3 million people, 73% of them working in the agricultural sector [6]. For the rural population, it is increasingly difficult to cover the supply of fuel wood for heating homes and cooking, since only small forest areas are left, and the remaining forests are largely protected. In most of the cases, these forests remained because they are located next to monasteries and are preserved as "church forests". However, these "church forests" are not untouched, since we can observe strong evidence for forest management impacts.

In order to avoid further deforestation and to promote afforestation, the Ethiopian government has selected the forestry sector as one of the green economic pillars to be developed by 2030 [7]. The key goals of the green economy plan are: (i) avoiding further deforestation, (ii) inducing reforestation programs, and (iii) improving forest management by establishing sustainable forest management plans. Ethiopia already takes part in international reforestation programs [8,9] and has expanded its national goal for reforestation and afforestation to reach 7 million hectares of forests [10]. The goals of the green economy plan are consistent with the strategy for reducing emissions from deforestation and forest degradation (REDD+), promoting sustainable forest management, conserving forest carbon stocks, and increasing the forest carbon stocks of developing countries [11–15]. One of the main difficulties in implementing REDD+ activities is measuring and ensuring the sustainability of forest management activities based on consistent and reliable biomass and soil data [12,16].

Out of three different common approaches for assessing the dynamics of forest ecosystems, (i) repeated forest inventories, (ii) repeated forest cover, NPP and NEE estimates from remote sensing (NPP—Net Primary Production, NEE—Net Ecosystem Exchange), and (iii) the application of ecosystem models e.g., biogeochemical-mechanistic models [17], only the latter is applicable for Amhara region. Repeated forest inventories are not available in many developing countries, including Ethiopia whereas remote sensing technology [18–20] has strong limitations when it comes to addressing stand density changes (e.g., changes in the number of trees within a given stand due to forest management) if the crown cover—often expressed by the leaf area index—is assumed to remain closed [21–24]. The third carbon assessment option, the application of biogeochemical-mechanistic ecosystem models (BGC-Models) has several advantages. For a comparison of different BGC-Models, see [25,26]. BGC-Models address carbon, nitrogen, water and energy flux dynamics (above and below ground) within ecosystems and respond to forest management and climate change effects [27–31]. The carbon storage of ecosystems can be calculated based on key input data such as daily weather, atmospheric CO_2 concentration, nitrogen deposition, general soil information (soil depth, texture) and an eco-physiological parameter setting characterizing the vegetation type or species. Biome-BGC specifically has the advantage that it is fully prognostic, applicable on large temporal and spatial scales and includes effects of forest management on carbon and nitrogen stocks [27]. Besides enabling the evaluation of the sustainability of certain management measures, Biome-BGC may also be used for long-term projections of soil development. So far, data on soil recovery from afforestation in Ethiopia only cover the development of 30–40 years [32–34] and most often involve *Eucalyptus* sp., *Cupressus lucitanica* or other exotic species because of their fast growth [35].

In this study, we investigate the impact of deforestation and the long-term recovery process of degraded land expressed by carbon sequestration potential from afforestation to improve our understanding of land-use change and forest management on the soil carbon dynamics. We obtained forest and soil data from different agro-ecological zones and land use types in the Amhara region, and applied the biogeochemical-mechanistic ecosystem model Biome-BGC to assess the flux dynamics within the highlands of Afromontane forests in the Amhara region of Northwestern Ethiopia. The key objectives of our study are:

1. Evaluate the biogeochemical ecosystem model Biome-BGC for Ethiopian Afromontane forests.
2. Assess the degradation effect of land use change from forest to agricultural land.
3. Analyze the rehabilitation processes following afforestation on degraded agricultural land using Biome-BGC.

2. Materials

2.1. Study Areas

We selected four study areas covering different agro-ecological zones within the Amhara region in Northwestern Ethiopia (Figure 1). The four sites were selected to represent different forest ecosystems ranging from low (860 m a.s.l.) to high (2500 m a.s.l.) altitudes, a mean total annual precipitation from 1080 mm to 1708 mm, and a mean annual temperature from 17.1 °C to 26.1 °C (Figure 2). Each study area covers two different land use forms located next to each other: (i) natural forests and (ii) agricultural land. The agricultural land was established on former natural forest about 40 to 50 years ago [32]. This paired-plot approach enabled us to directly address the impact of land use changes, as climatic and site conditions can be assumed having been similar.

The four study areas are located in Gelawdiwos, Injibara/Katassi, Mahibereselassie and Taragedam. The forest areas in Gelawdiwos, Taragedam and Mahibereselassie are owned by the Ethiopian Orthodox Tewahedo Church, whereas the forest in Katassi is owned by the local government. Gelawdiwos represents the growing conditions in the highlands of the Amhara region. The forest composition is mostly dominated by evergreen highland tree and shrub species, such as *Chionanthus mildbraedii* (Gilg & G.Schellenb.) Stearn, *Euphorbia abyssinica* J.F.Gmel. and *Ekebergia capensis* Sparrm. Katassi and Taragedam are both located in mid-high altitudes. The Katassi forest is dominated by the mid-altitude Afromontane tree and shrub species *Albizia schimperiana* Oliv., *Prunus africana* (Hook.f.) Kalkman and *Croton macrostachyus* Hochst. ex Delile. Similarly, Taragedam is composed of many Afromontane forest species, including *Juniperus procera* Hochst. ex Endl., *Teclea nobilis* Delile and *Schefflera* sp. J.R.Forst. & G.Forst.; Mahibereselassie is the typical ecosystem in the lowlands of the Amhara region and contains deciduous and semi-deciduous woodland and savanna grassland tree and shrub species such as *Sterculia setigera* Delile., *Boswellia papyrifera* Hochst. and *Terminalia laxiflora* Engl.

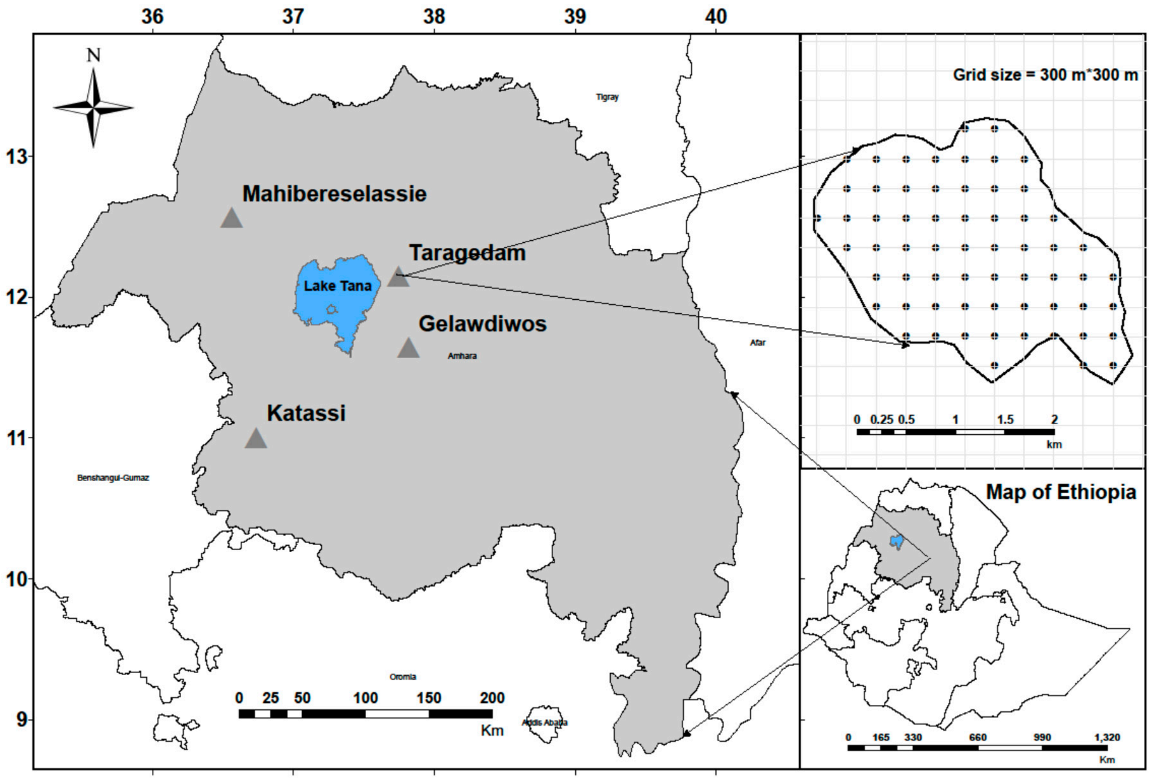

Figure 1. Study site locations in Amhara region and sample plot design used for data collection.

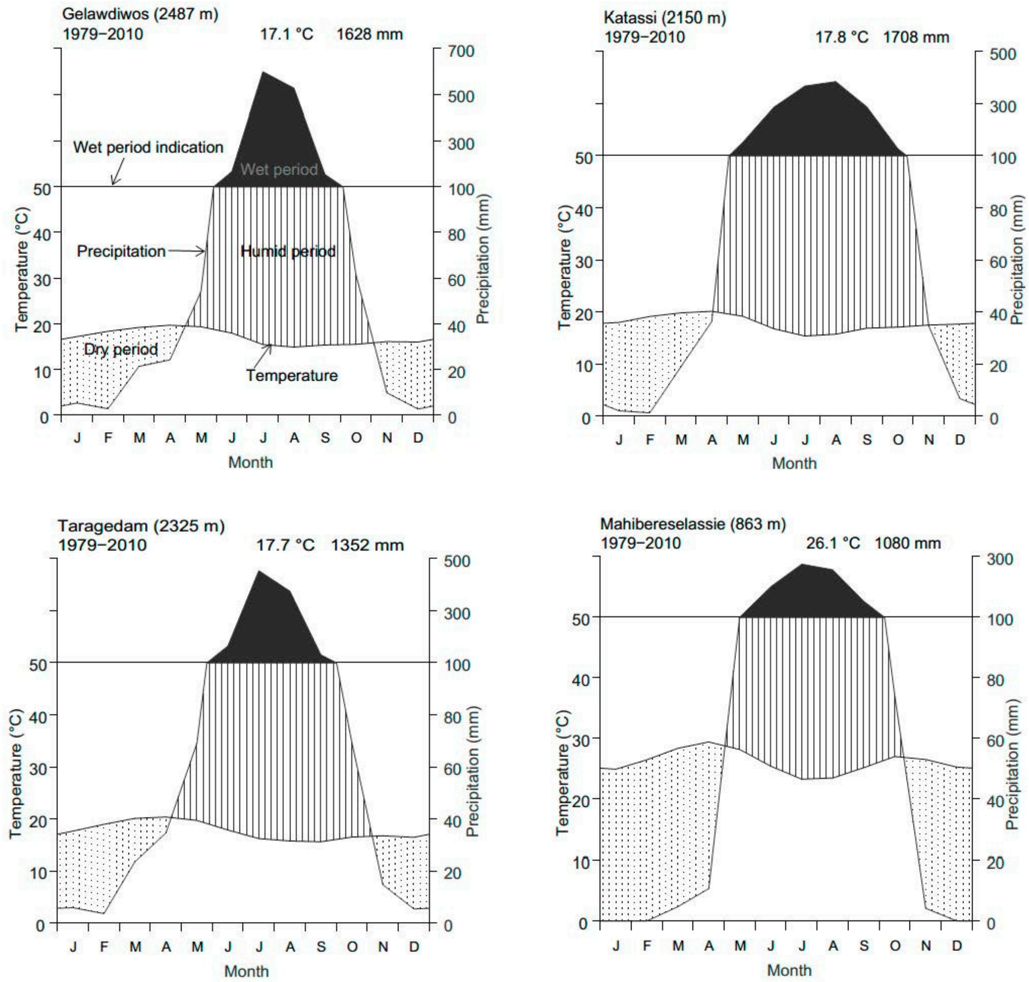

Figure 2. Walter/Lieth climate diagram (Walter and Lieth, 1960) for the four study areas (dotted areas indicate dry periods, hatched area humid periods and black areas wet periods). The graphs also show elevation, climate data recorded period, the mean annual temperature and the mean total annual precipitation.

2.2. Forest Data

Forest data in the four study areas were collected based on a systematic grid sampling approach (Figure 1, Table 1). The grid size of the systematic sampling within each of the four study areas differed according to the size of the forest. Slope, aspect, latitude and elevation were recorded for each plot.

Table 1. Overview of the forest areas of the four study areas Gelawdiwos, Katassi, Mehabereselessie and Tarageedam. The four sites cover different agro-ecological zones. Area refers to the forest area in hectares, for which the sampling point grid design was applied, Grid size refers to the distance between sampling points, *N* is the number of sample plots, Elev: the elevation, Sl: the slope, C: the mean of the periodic (2005–2014) mean annual above ground carbon content of the vegetation in tons per hectare and NPP: the mean of the periodic mean annual NPP for 2005 to 2014 plus the corresponding standard deviations.

Study Area	Forest Area (ha)	Grid Size (m)	*N*	Elev. (m)	Sl (°)	Stem C (t C ha^{-1})	NPP (g C m^{-2} $year^{-1}$)
Gelawdiwos	68	250 × 250	33	2487	10–40	60.4 ± 46.5	640 ± 425
Katassi	553	300 × 300	56	2150	1–36	41.2 ± 34.3	490 ± 327
Mehabereselessie	19,162	3000 × 3000	19	863	3–41	13.0 ± 5.5	150 ± 63
Taragedam	324	250 × 250	36	2325	1–43	19.9 ± 19.5	431 ± 333

Since average stand density varied by study area but forest inventories require a certain average minimum number of trees per plot, we varied the plot size by study area. In Gelawdiwos and Taragedam, information for trees with a DBH (diameter at breast height) >10 cm was collected on plots with a 10 m radius, while for Mahibereselassie and Katassi a plot size radius of 15 m was chosen. On these plots, the following tree information was recorded: tree species, tree location, DBH, crown width in the four cardinal directions, tree height and height to live crown base. In addition, increment core data were collected by major species groups on each sampling plot and for each "central stem". The term "central stem" refers to the 60th percentile of the DBH distribution and follows a suggested procedure by [36], which showed that the central stem represents the "mean tree" (=quadratic mean DBH) on a given plot.

In addition, for trees with DBH <10 cm and a height >1.5 m, the same set of tree variables (except the increment cores) was collected on subplots with a radius of 4 m. All trees (from plots and subplots) with a DBH ≥2.5 cm were used for deriving vegetation carbon and carbon increment. Missing tree heights H were derived from the Petterson height-diameter curve [37]:

$$H = \frac{1}{(a + \frac{b}{DBH})^2} + 1.3 \tag{1}$$

where the parameters a and b were derived for the twenty most important tree species in the study areas [38]. Above ground carbon vegetation C_{veg} was calculated according to the following formulation [39]:

$$C_{veg} = e^{-2.922+0.99\times \ln(DBH^2 \times H \times \varrho)\times 0.5} \tag{2}$$

where DBH and H are as previously defined and ϱ is the mean wood density of African tree species set equal to 0.614 g cm^{-3} [40]. The carbon content was assumed to be 50% of the biomass [41–43].

The annual NPP (g C m^{-2} $year^{-1}$) of the woody part of each tree was calculated as the mean annual woody carbon increment for the 10 year period 2005–2014. The increment was derived from the increment cores of the central stem [38] since the growth rate of the central stem is proportional to the growth rate per hectare, assuming that the stem number remains equal within the growth period. The total annual terrestrial NPP for each inventory plot is the sum of woody carbon increment, the litterfall and the root increment (fine root production and coarse root increment) [44]. Since no litterfall and root data are available, we followed [45], who suggest a wood increment of about 40% of the total carbon increment. The remaining 60% are the litterfall and the root increment (30% each). For further details regarding the sampling method and details related to the calculation of the standing timber volume and volume increment rates, we refer to [38]. Summary statistics of the forest data by study area are shown in Table 1. Note that the number of plots in this study are slightly lower versus [38] because we eliminated plots with no tree coverage at the edge of the sampled forests.

2.3. Soil Data

2.3.1. Forest Area

Soil samples from the forested areas were systematically taken on the same general grid as the forest biomass samples, at about one fourth of the forest sampling grid points (see Figure 1 and Table 1). The litter layer was removed and soil probes were taken with a soil corer (Pürckhauer type, inner diameter 30 mm). The soil samples were taken in 0–10 cm, 10–20 cm, 20–30 cm, and 30–50 cm soil depth and stored in plastic bags. The probes were sieved to 2 mm and soil organic carbon, nitrogen, and texture were determined in the laboratory in Vienna.

The relative weight proportion of the soil organic matter was calculated as the loss of ignition (LOI), heating the soil samples in a muffle furnace [46]. After oven-drying the samples at 105 °C until a constant weight was achieved, the organic matter was combusted to ash at a temperature of 450 °C for 4 h. The LOI was then calculated using the following equation:

$$LOI_{450} = \left(\frac{DW_{105} - DW_{450}}{DW_{105}}\right) \times 100 \quad (3)$$

where LOI_{450} represents LOI at 450 °C (as a percentage), DW_{105} represents the dry weight of the sample before combustion and DW_{450} the dry weight of the sample after heating to 450 °C. The weight loss is proportional to the amount of organic carbon contained in the sample. Carbon stocks were determined on a weight to area basis (kg C m^{-2}). The carbon concentration was corrected for bulk density and soil volume. The total carbon TC (kg C m^{-2}) was calculated as:

$$TC = C \times BD \times V \times 0.001 \text{ kg} \quad (4)$$

where C is carbon concentration (%), BD is bulk soil density and V is volume of soil for each sample plot. Bulk soil density was determined from samples taken separately on the side of each soil carbon sampling point.

Soil texture was determined by a combination of wet sieving and sedimentation methods [47]. Texture classes were defined according to the USDA particle size classes sand (2.0–0.053 mm), silt (0.053–0.002 mm), and clay (<0.002 mm).

Soil depth as needed for Biome-BGC was obtained from the regional soil depth map provided by Amhara Design and Supervision Works Enterprise (ADSWE) [48]. Based on the ADSWE soil depth ranges and the local experience, we defined for the shallow lowland site (Mahibereselassie) a range of 40 cm and the deeper highland sites a range of 1 m (Table 2) to cover uncertainty from natural variation in soil depth.

2.3.2. Agricultural Area

In addition to the forested areas, we obtained soil data from neighboring agricultural sites (cropland and grazing land). A total of 40 sample plots, 10 plots for each study area, were taken on transects at 50 m/100 m intervals. All soil samples were taken at the same time as the forest soil samples. For further details, we refer to [32].

2.4. Atmospheric Data

We obtained downscaled 1 km × 1 km daily meteorological data, i.e., daily minimum and maximum temperatures (°C), daily precipitation (mm) from Sisay et al. [49]. The data cover a 32 years period ranging from 1979 to 2010 and have been downscaled from global precipitation and temperature data on a 1 km × 1 km resolution for the whole Amhara region. The downscaled precipitation was further improved based on the difference in mean annual precipitation between the downscaled dataset and the closest climate station to each study area. Each daily value of the downscaled precipitation was multiplied with the ratio of observed mean annual precipitation to downscaled mean annual precipitation, to ensure correct precipitation sums. Solar radiation (Ws^{-1}), vapor pressure deficit (VPD, Pa) and day-length (from sunrise to sunset) were generated from daily temperature and precipitation using algorithms implemented in the Mountain Climate Simulator (MT-CLIM) [50,51].

Current and preindustrial atmospheric CO_2 concentration and nitrogen deposition, as they are needed for the BGC simulations, were taken from two global datasets published by [52,53]. As current nitrogen deposition values, we used the two different values given by [53] for the entire study area and their mean (Table 2) to address the high variation and uncertainty stemming from the coarse resolution of the dataset. The preindustrial value of atmospheric CO_2 concentration was set to 278 ppm [52,54] and to 0.129 g N m^{-2} year^{-1} for Nitrogen deposition [53].

Table 2. Soil depth classes and atmospheric nitrogen deposition levels for the evaluation of Biome-BGC. For each simulation, we used three different soil depths (compare Section 2.3.1) and 3 different nitrogen deposition rates (min/mean/max of values from [53]) to cover the potential variation. The soil depth numbers are taken from the regional soil depth map provided by Amhara Design and Supervision Works Enterprise (ADSWE) [48] and the nitrogen deposition levels come from [53].

Study Area	Soil Depth (m)	*N* Deposition (g N m^{-2} $year^{-1}$)
Gelawdiwos	2.5/3.0/3.5	0.507/0.747/0.986
Katassi	1.0/1.5/2.0	0.507/0.747/0.986
Mahibereselassie	0.2/0.4/0.6	0.507/0.747/0.986
Taragedam	1.0/1.5/2.0	0.507/0.747/0.986

3. Methods

3.1. The Ecosystem Model

For the simulation of forest carbon storage (objectives 1 and 3), we employed the biogeochemical-mechanistic ecosystem model Biome-BGC [55,56], which simulates flux dynamics of the water, carbon, and nitrogen cycle for a terrestrial ecosystem on a daily time step. For this study, we used Biome-BGC version 4.1.2 [29,51] with an improved self-initialization algorithm to mimic undisturbed ecosystems [57,58] and forest management routines e.g., historic land use changes, thinning, clear-cut and planting [30]. Biome-BGC is fully prognostic and does not require detailed forest data for model initialization. It is initialized by a so called "spin-up" run [27,29,57,59], which mimics the accumulation of soil and vegetation carbon and nitrogen under constant conditions (available climate data recycled, constant preindustrial CO_2 and nitrogen deposition) until a "steady-state" is reached (typically after few thousands of years). Since CO_2 concentration and nitrogen deposition have increased and most forests have experienced some form of forest management, which may have led to forest degradation, the next step is typically to perform "modern-forest-simulations" addressing these changes to realistically mimic the current ecosystem fluxes for a given forest [27,30].

Key processes within Biome-BGC are the photosynthetic carbon assimilation, autotrophic respiration (maintenance respiration plus growth respiration), allocation among different plant compartments, mortality, litterfall, mineralization processes, nutrient and soil water uptake, rainfall interception, soil water infiltration and storage, runoff and evapotranspiration. Leaf area determines potential forest productivity as well as rainfall partitioning (interception, through fall) and evaporation from soil. Carbon assimilation is calculated with the Farquhar photosynthesis routine [60].

Growth respiration is a fixed fraction of the amount of carbon allocated to different plant structural compartments [61], whereas maintenance respiration depends on the nitrogen content of the tissue [62]. CO_2 availability for photosynthesis is regulated by the stomata, where the CO_2 influx depends on maximum conductivity, and stomatal closure is limited by radiation, moisture of the atmosphere and water content in the leaves, which is controlled by the soil water potential. Soil water potential is calculated from the soil water and texture following [63,64]. Key model outputs are Gross Primary Productivity (GPP), Net Primary Productivity (NPP; GPP minus autotrophic respiration), and carbon storage in the living biomass, the litter, coarse woody debris and the soil.

3.2. Eco-Physiological Parameters

Within Biome-BGC, biomes or species are defined by 39 "Eco-physiological parameters", which characterize a forest ecosystem (and are stored in the epc-file). The original Biome-BGC model was developed for seven different biome types (evergreen broadleaf, deciduous broadleaf, evergreen needle, deciduous needle, shrubs, and C_3 grass (temperate or cool-season grasses, using C_3 carbon fixation) and C_4 grass (tropical or warm-season grasses, using C_4 carbon fixation) [65]. Over the years some regional or species-specific parameter sets were published [66,67].

For our study, we selected the parameter set proposed for tropical forests by [66]. For the driest study sites located in the lowland area, Mahibereselassie, we changed the evergreen phenology, because most tree species in the lowland area are dry-deciduous or semi-deciduous and the flushing of leaves as well as litterfall is controlled by the precipitation pattern. Budburst starts at the beginning of the rainy season in April, and the annual litterfall is in December. According to these regional conditions, we changed the date of the vegetation period in the epc-file and set the start date of the growing season in Mahibereselassie to day 90 and the end date (final dropping of the leaves) to the last day of the year (day 365).

3.3. Simulation Procedure

3.3.1. Current Forests

For the simulation of the current forests in the four study areas with Biome-BGC, we used the atmospheric, soil (texture, depth) and eco-physiological input data as described in Sections 2.3, 2.4 and 3.2, respectively. The variations in soil depth and nitrogen deposition we employed are shown in Table 2.

We started with the spin-up run followed by a "realistic" land use history scenario (Figure 3). For the spin-up, the available climate records were used repeatedly, after having been corrected based on the assumption that Ethiopian highlands had experienced long lasting cooling periods during the Holocene [68–70]. We addressed this historic cooler climatic periods in our spin-up runs by reducing the daily mean temperature of the available daily climate data by 3 °C and by increasing the daily precipitation by 20% [69].

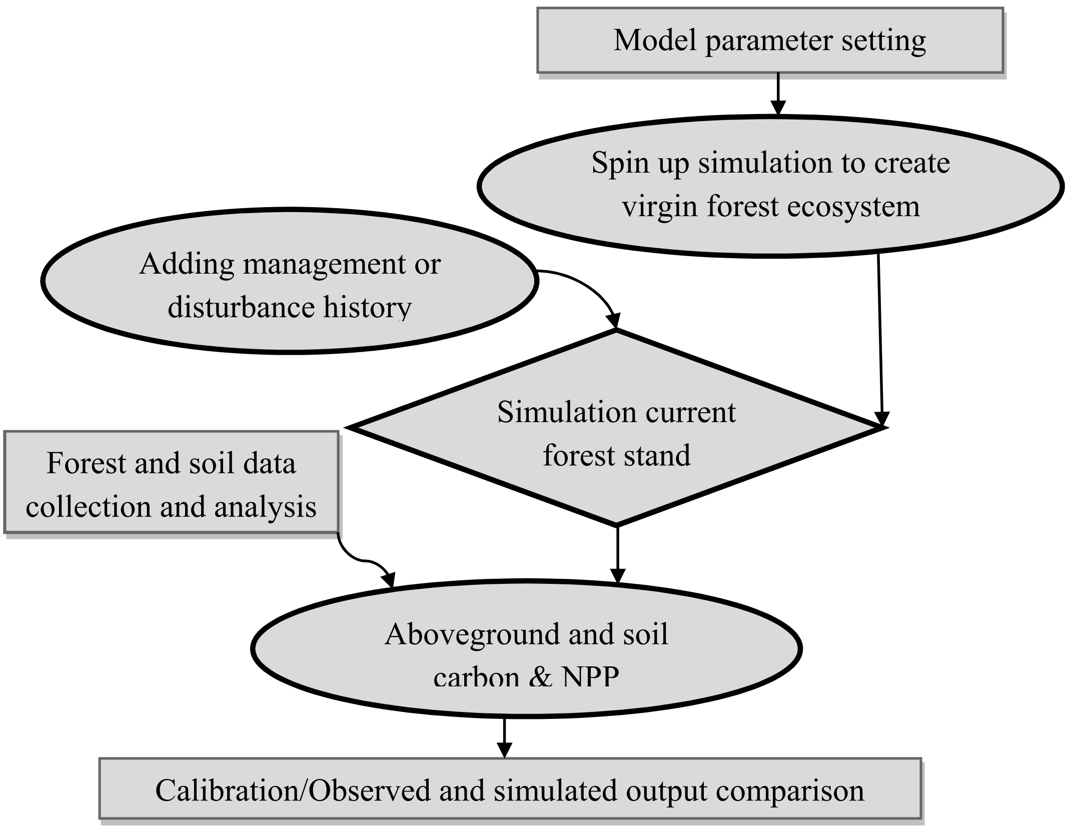

Figure 3. Working procedures of simulation and model evaluation.

Next, the carbon and nitrogen stocks resulting from this self-initialization had to be adjusted for forest management impacts [28]. Note that even the simulated protected "church forests" cannot be considered as pristine forests because some management impacts (e.g., harvesting, etc.) were evident.

For all four forest areas, cutting of selected high valuable trees and the removal of suppressed trees for fuelwood was reported (from interviews, documents, [32]). Based on these indications of intensive and uncontrolled extractions, we assumed an annual harvest of 5% of the biomass, as harvest must be assumed to be clearly more than the 3% mortality from the eco-physiological parameter set [66]. As related to the annual harvest, the same share of leaves and fine roots was transformed into litter and the same share of coarse roots was moved to the woody debris carbon pool.

3.3.2. Rehabilitation Pathways

We also used Biome-BGC to assess the rehabilitation potential of afforestation on degraded agricultural land and the time it may take until a new “equilibrium” or “steady state” in the accumulated biomass and soil carbon stocks is achieved. After manually setting the soil carbon and nitrogen values in the model equal to the recorded values on the degraded agricultural land (see Table 3) and assuming a “standard BGC planting” of forests (using the previous tropical forests epc-file), the simulations were started. For simplicity, the current climate data were repeatedly used without assuming any future changes in climate (because reasonable climate change projections for the next few thousand years do not exist). Since undisturbed forest development seems to be unrealistic due to the enormous demand for fuelwood, we employed three different management scenarios: (i) no management, (ii) 2.5%, and (iii) 5% annual extraction of timber. The corresponding amount of leaves and fine roots was transferred to litter pool, and coarse roots to coarse woody debris, respectively.

Table 3. Summary of the available soil data; The grid data refer to the soil carbon, nitrogen and Sand/Silt/Clay information collected on parts of the forest inventory grid points; The transect data are based on [32] and refer to transects with 10 samples taken every 50–100 m, placed in the agricultural area of our study areas.

Study Area	Grid Data				Transect Data		
	Forest Soil				Agricultural Soil		
	N	Carbon (t ha^{-1})	Nitrogen (t ha^{-1})	Sand/Silt/Clay (%)	*N*	Carbon (t ha^{-1})	Nitrogen (t ha^{-1})
Gelawdiwos	7	207.4 ± 24.0	19.0 ± 2.2	8/40/52	10	116.5 ± 22.4	9.3 ± 1.9
Katassi	14	204.5 ± 31.8	17.6 ± 2.7	15/40/45	10	31.0 ± 9.6	5.1 ± 1.3
Mehabereselessie	15	60.7 ± 38.5	5.5 ± 3.5	55/23/22	10	77.1 ± 29.9	5.5 ± 2.5
Taragedam	7	173.1 ± 28.4	14.9 ± 2.4	13/40/47	10	102.8 ± 34.8	9.0 ± 2.6

4. Results

4.1. Evaluation of Biome-BGC for Ethiopian Afromontane Forests

Observed vegetation carbon stocks, soil carbon and NPP differed markedly among the four study areas. Gelawdiwos, the study area highest in elevation showed the highest productivity and carbon storage, whereas Mahibereselassie, located in the dry lowlands showed the lowest productivity and carbon storage. Taragedam with the second lowest precipitation also showed the second lowest productivity and carbon storage.

Biome-BGC simulations followed this general pattern. Note that the assumed management with 5% extraction annually was identical for the performed simulations in the four study areas. Figure 4 shows the median, the 25th and 75th percentile values of predicted versus observed vegetation and soil carbon. The observed vegetation carbon of the four study locations ranged from 1 t C ha^{-1} to 187 t C ha^{-1}. The corresponding Biome-BGC predictions of the carbon content of the vegetation carbon for nine combinations of soil depth and nitrogen deposition levels ranged from 11 t C ha^{-1} to 67 t C ha^{-1}. The observed soil carbon ranged from 14 t C ha^{-1} to 253 t C ha^{-1} and the modeled numbers ranged between 16 t C ha^{-1} to 242 t C ha^{-1}.

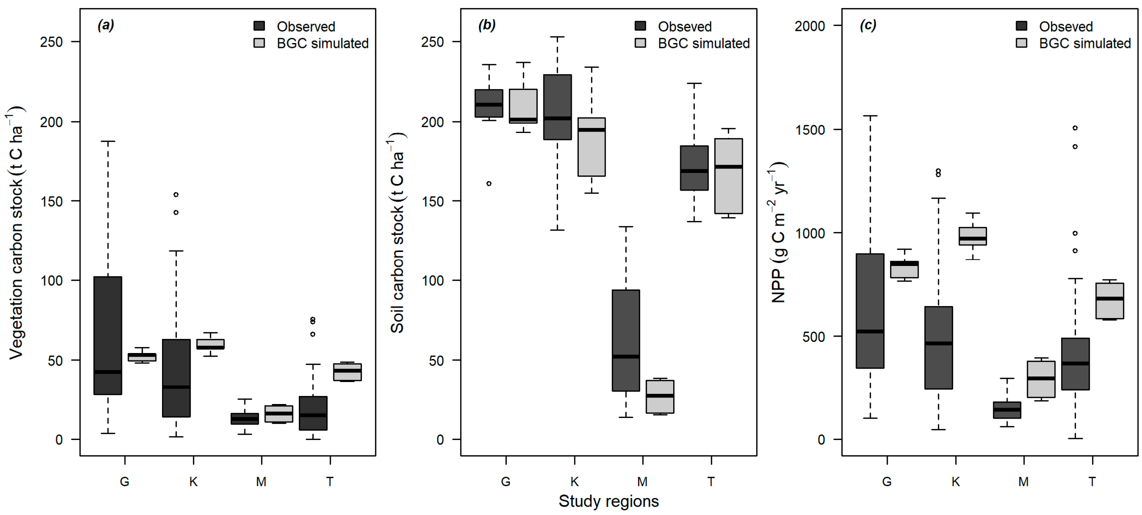

Figure 4. Observed versus Biome-BGC predicted (**a**) vegetation carbon; (**b**) soil carbon and; (**c**) NPP of the four study areas: G = Gelawdiwos (n = 33/7/33 vegetation/soil/NPP), K = Katassie (n = 56/14/56), M = Mahibereselassie (n = 19/15/19), T = Taragedam (n = 36/7/36). The boxplots depict the median (black central line), the 25th and 75th quartile of the samples and outliers (circles). Variation in the model predictions resulted from three variants of soil depth and nitrogen deposition to cover site variation in the study sites (n = 9).

NPP derived from the recorded data, ranged between 4 g C m^{-2} year^{-1} to 1567 g C m^{-2} year^{-1} (Figure 4). Corresponding Biome-BGC predictions were within a range of 186 g C m^{2} year^{1} to 1095 g C m^{-2} year^{-1}. Except for Mahibereselassie, predicted NPP was in the range of observed NPP.

4.2. Land Use Change Effects

We compared the soil carbon and nitrogen content for the forested areas and the neighboring agricultural land (Table 3). For three sites (Gelawdiwos, Katassi and Mahibereselassie), the available soil information came from crop land, while in Taragedam, the soil data came from grazing land since no crop land was available in the area [32]. All sites showed significantly lower soil carbon and nitrogen stocks on the agricultural land compared to the forest, except the dry lowland study area Mahibereselassie. The Mahiberseselassie site is not a typical forest area, since trees do not form closed forest stands due to limitations in precipitation. In addition, the "forest area" experienced intensive grazing and regular grass burning impacts [32]. The most dramatic reduction in soil carbon stocks was observed in Katassi, where 85% of the soil carbon was lost. These differences are the result of approximately 40 to 50 years of intensive farming since the conversion of forest to agricultural land, including the typical erosion effects during the rainy seasons in the highlands of Ethiopia.

4.3. Rehabilitation

Next, we evaluated the soil amelioration potential of afforestation of these degraded soils by simulating afforestation of the three severely degraded sites with Biome-BGC. After degradation, it could take a few decades to over 2000 years until a new steady state in nitrogen and carbon pools would be reached (Figure 5). The steady state of soil carbon for the three highland study areas lie between 100 t C ha^{-1} and 125 t C ha^{-1} for 5% annual extraction, between 130 t C ha^{-1} and 155 t C ha^{-1} for 2.5% annual extraction and 200 t C ha^{-1} to 235 t C ha^{-1} for no management. For our simulation, we used the current climate conditions, since employing climate change scenarios for such a long projection period is unrealistic.

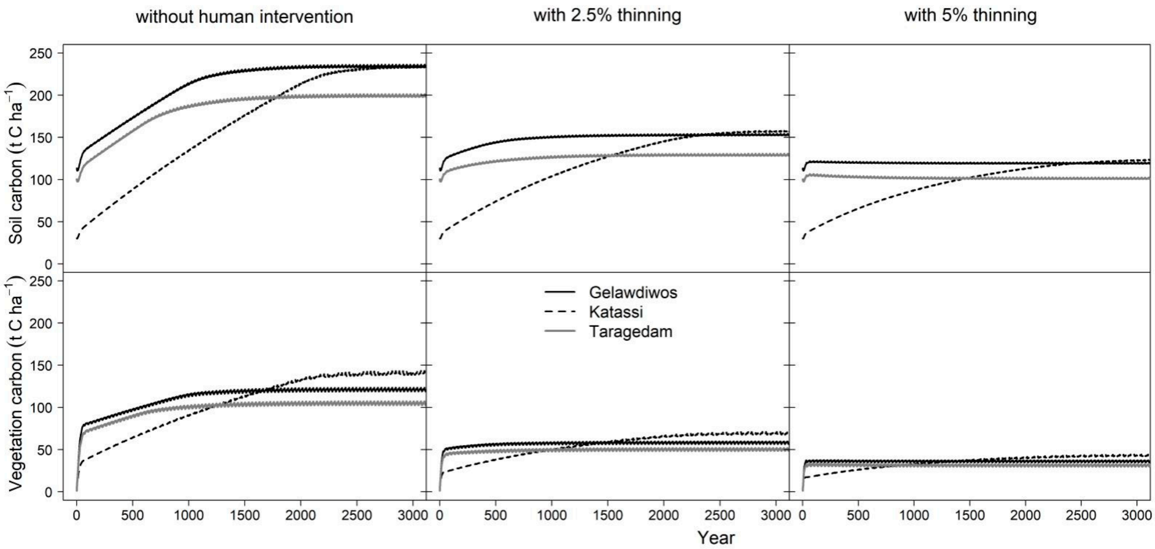

Figure 5. Soil carbon (first row) and vegetation carbon trend (second row) attained on degraded sites after afforestation, without human intervention (left) and with human intervention (2.5% thinning, center and 5% annual thinning, right).

During recovery, two marked changes in accumulation velocity of vegetation and soil carbon can be observed. The first marked change in carbon accumulation velocity takes place after some decades, when the system reaches its equilibrium between the annual biomass accumulation and the biomass loss through mortality and harvesting. Net soil and vegetation carbon build up continue on a slower rate past this point, because the system is still accumulating nutrients (i.e., nitrogen from nitrogen deposition and nitrogen fixation). Only much later (some hundreds or thousands of years later), equilibrium between nutrient accumulation and nutrient loss is reached, and soil and vegetation carbon stocks stay more or less stable.

5. Discussion

Biogeochemical-mechanistic modeling is a powerful diagnostic tool to assess the carbon and nitrogen fluxes within our study areas. Although the species composition of the natural Afromontane forests in Ethiopia is very rich and diverse, the eco-physiological parameter settings suggested by [66] are applicable within the area. After adjusting for the length of the growing season (on the site with predominant deciduous vegetation cover) and addressing harvesting impacts, the above ground biomass, as well as soil carbon and NPP predictions derived with Biome-BGC revealed consistent estimates versus field observations (Figures 4 and 5). This suggests that our chosen approach mimics the ecosystem fluxes (i.e., carbon, nitrogen and water) as well as potential harvesting impacts correctly for Afromontane ecosystems of the Amhara region of Northwestern Ethiopia.

This is an important finding because forests cover about 251,000 ha or 2% of the total land area (15.7 million. ha) in Amhara region [38], but no systematic forest monitoring or empirically driven forest growth and yield model for ensuring sustainable forest management is in place. Considering the enormous pressure of a fast-growing population on the remaining forest resources, this lack of information is one of the key obstacles for sustainable forest management in the region. The option we tested in this study to circumvent this lack of information is the application of biogeochemical-mechanistic modeling theories.

Although the model results fit with the observed data (Figures 4 and 5), the limitations of the modeling approach versus growth and yield models is the level of abstraction in the general modeling approach. This makes forest stand specific predictions, including single tree mortality or specific harvesting operations, difficult [67]. This may be one of the reasons that the model predicted higher vegetation carbon versus the observations in Taragedam (Figure 4), as the study sites in Taragedam experienced stronger human interventions and cattle grazing versus the other study sites [71,72].

The key problem within the highlands of the Amhara region is land use change (the conversion of forests into agricultural area) to feed a fast growing population [4,73,74]. An enormous loss in soil fertility due to erosion is associated with this reduction in forest area. We observed that 40 to 50 years after converting forests into agricultural land, the carbon and nitrogen content in the soil declined by 40% to 85% of the remaining neighboring forested areas (Table 3). The dramatic deterioration of the soils within this short period of time is also reported by other studies showing similar trends [75,76]. The underlying parent material in Amhara is granite with an extremely low release of nutrients from weathering. Removal of the forest cover leads to enormous soil erosion during the heavy and intensive rainy season [34], associated with a removal of the top soil layer. Once the forest vegetation and the top soil layer are gone, the key source for nutrients is gone [32]. Future productivity is therefore jeopardized by two effects, i.e., loss in nutrients through vegetation clearing and erosion, and the low rates of replenishing of the lost nutrients from weathering of the rock and from nitrogen deposition and fixation [77].

One option to stabilize and eventually ameliorate productivity is to replant forests on such degraded sites. Any permanent land cover will decrease further erosion and will lead to nitrogen and litter input due to litterfall and consequently to a recovery of the carbon and nutrient stocks, and the water retention capacity. The rate of carbon pool accumulation varied by harvesting intensity (Figure 5). Regardless of the employed harvesting scenario, soil fertility will increase again, but it will stabilize at different levels according to the harvesting intensity. Remarkably, the soil carbon equilibrium levels for the two management scenarios lie below the current forest soil carbon stocks. This indicates that the current higher forest soil carbon stocks (Figure 4) are a legacy of a former 'better' climate (compare Section 3.2, climate assumption for the spin-up: 20% higher precipitation and 3 °C lower temperature in comparison to today). Thus, although afforestation is strongly recommended since it has a high ameliorating potential of degraded soils, it is questionable if the mistakes from the past can ever be fully repaired under today's climatic conditions. We did not use climate change scenarios for above mentioned reason. However, a scenario of more irregular and intensive precipitation events [78] would increase erosion and slow down the soil recovery especially in the already water-limited lowland areas of Amhara region. In any case, the importance of avoiding deforestation in the first place, is the key message which needs to be conveyed to any government in tropical developing countries around the globe.

6. Conclusions

With this study, we provided insights into how land use changes—converting natural forest areas into agricultural land—affect the soil fertility and thus the productivity expectations of Afromontane forests in the Amhara region of Northwestern Ethiopia. Within 50 years, soil fertility expressed by the carbon and nitrogen content in the soil has dropped by half or more versus areas covered with forests; and rehabilitation may take hundreds or thousands of years if soil fertility prior to the land use change were to be reached. Countries such as Ethiopia, where no forest inventory system exists, urgently needs a tool to assess carbon storage in forest ecosystems and analyze land use impacts as well as associated productivity changes. We could show that the ecosystem model Biome-BGC can serve as such a diagnostic tool, owing to the model's mechanistic representation of natural biogeochemical processes based on the interactions of climate, site, the simulated vegetation type and management. The model could, therefore, be utilized for large-scale forest productivity estimates and afforestation planning for selecting the most suitable sites in Amhara, Ethiopia.

Acknowledgments: This work is part of the project "Carbon storage and soil biodiversity in forest landscapes in Ethiopia: Knowledge base and participatory management". We are grateful for the financial support provided by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management. Special thanks also go to Amhara Regional Agricultural Research Institute in hosting the research project and providing field cars. We thank Hadera Abraha, Khlot Gebrehana, Sibhatu Abera and Tesfaye Teklehaymanot for helping in the data collection. We thank the editor and the three reviewers which helped to improve the manuscript.

Author Contributions: B.B. analyzed the data, did the scenario analysis and wrote the first draft of the manuscript, E.P. helped with model runs and their interpretation and improved the manuscript, K.S. helped with the data collection, D.A. helped with the soil data collection and laboratory analysis, and H.H. designed the project, coordinated and supervised the data collection, the analysis, and the manuscript writing.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kindermann, G.E.; McCallum, I.; Fritz, S.; Obersteiner, M. A global forest growing stock, biomass and carbon map based on FAO statistics. *Silva Fenn.* **2008**, *42*, 387–396. [CrossRef]
2. Ashton, M.S.; Tyrrell, M.L.; Spalding, D.; Gentry, B. *Managing Forest Carbon in a Changing Climate*; Springer Science & Business Media: Berlin, Germany, 2012; pp. 1–414.
3. Bishaw, B. Deforestation and land degradation in the Ethiopian highlands: A strategy for physical Recovery. *Northeast. Afr. Stud.* **2001**, *8*, 7–25. [CrossRef]
4. Zeleke, G.; Hurni, H. Implications of land use and land cover dynamics for mountain resource degradation in the northwestern Ethiopian highlands. *Mt. Res. Dev.* **2001**, *21*, 184–191. [CrossRef]
5. Lemenih, M.; Kassa, H. Re-greening Ethiopia: History, challenges and lessons. *Forests* **2014**, *5*, 1896–1909. [CrossRef]
6. United Nations. *World Statistics Pocketbook*; United Nations Publications: New York, NY, USA, 2016.
7. Federal Democratic Republic of Ethiopia. *Ethiopia's Climate Resilient Green Economy—Green Economy Strategy*; Government of Ethiopia: Addis Abäba, Ethiopia, 2011; pp. 1–188.
8. Ellis, K.; Baker, B.; Lemma, A. *Policies for Low Carbon Growth*; Overseas Development Institute London: London, UK, 2009.
9. UNFCCC (United Nations Framework Convention on Climate Change). *Afforestation and Reforestation Projects under the Clean Development Mechanism: A Reference Manual*; Climate Change Secretariat: Bonn, Germany, 2013; pp. 1–65. ISBN 9789292191207.
10. MOEF(Ministry of Environment and Forests). *Intended Nationally Determined Contribution (INDC) of the Federal Democratic Republic of Ethiopia*; Federal Democratic Republic of Ethiopia: Addis Ababa, Ethiopia, 2015; pp. 1–13.
11. Edenhofer, O.; Pichs-Madruga, R.; Sokona, Y.; Seyboth, K.; Kadner, S.; Zwickel, T.; Eickemeier, P.; Hansen, G.; Schlömer, S.; Von Stechow, C.; et al. *Renewable Energy Sources and Climate Change Mitigation Special Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2011; ISBN 9789291691319.
12. Pearson, T.R.H.; Brown, S.; Murray, L.; Sidman, G. Greenhouse gas emissions from tropical forest degradation: An underestimated source. *Carbon Balance Manag.* **2017**, *12*, 3. [CrossRef] [PubMed]
13. Pearson, T.R.H.; Brown, S.L.; Birdsey, R. Measurement guidelines for the sequestration of forest carbon. *Dep. Agric. For. Serv.* **2007**, *18*, 42. [CrossRef]
14. Van Bodegom, A.J.; Herman, S.; Marieke, W. *Forests and Climate Change: Adaptation and Mitigation*; Tropenbos International: Wageningen, The Netherlands, 2009; ISBN 978-90-5113-100-0.
15. Wei, T.; Yang, S.; Moore, J.C.; Shi, P.; Cui, X.; Duan, Q.; Xu, B.; Dai, Y.; Yuan, W.; Wei, X.; et al. Developed and developing world responsibilities for historical climate change and CO_2 mitigation. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 12911–12915. [CrossRef] [PubMed]
16. Costenbader, J.; Redd, U. *REDD+ Benefit Sharing: A Comparative Assessment of Three National Policy Approaches*; Javier Prado Oeste: San Isidro Lima, Perú, 2011.
17. Hasenauer, H.; Petritsch, R.; Zhao, M.; Boisvenue, C.; Running, S.W. Reconciling satellite with ground data to estimate forest productivity at national scales. *For. Ecol. Manag.* **2012**, *276*, 196–208. [CrossRef]
18. Pachavo, G.; Murwira, A. Remote sensing net primary productivity (NPP) estimation with the aid of GIS modelled shortwave radiation (SWR) in a Southern African Savanna. *Int. J. Appl. Earth Obs. Geoinf.* **2014**, *30*, 217–226. [CrossRef]
19. Hazarika, M.K.; Yasuoka, Y.; Ito, A.; Dye, D. Estimation of net primary productivity by integrating remote sensing data with an ecosystem model. *Remote Sens. Environ.* **2005**, *94*, 298–310. [CrossRef]

20. Rossini, M.; Cogliati, S.; Meroni, M.; Migliavacca, M.; Galvagno, M.; Busetto, L.; Cremonese, E.; Julitta, T.; Siniscalco, C.; Morra Di Cella, U.; et al. Remote sensing-based estimation of gross primary production in a subalpine grassland. *Biogeosciences* **2012**, *9*, 2565–2584. [CrossRef]
21. Takao, G.; Priyadi, H.; Ikbal Nursal, W. *The Operational Role of Remote Sensing in Forest and Landscape Management: Focus Group Discussion Proceedings*; CIFOR: Bogor, Indonesia, 2010; ISBN 9786028693165.
22. Macauley, M.; Morris, D.; Sedjo, R.; Farley, K.; Sohngen, B. *Forest Measurement and Monitoring: Technical Capacity and "How Good Is Good Enough?"*; Resources for the Future: Washington, DC, USA, 2009.
23. Hasenauer, H.; Neumann, M.; Moreno, A.; Running, S. Assessing the resources and mitigation potential of European forests. *Energy Procedia* **2017**, *125*, 372–378. [CrossRef]
24. Neumann, M.; Moreno, A.; Mues, V.; Härkönen, S.; Mura, M.; Bouriaud, O.; Lang, M.; Achten, W.M.J.; Thivolle-Cazat, A.; Bronisz, K.; et al. Comparison of carbon estimation methods for European forests. *For. Ecol Manag.* **2016**, *361*, 397–420. [CrossRef]
25. Fontes, L.; Bontemps, J.D.; Bugmann, H.; Van Oijen, M.; Gracia, C.; Kramer, K.; Lindner, M.; Rötzer, T.; Skovsgaard, J.P. Models for supporting forest management in a changing environment. *For. Syst.* **2010**, *19*, 8–29. [CrossRef]
26. Hanson, P.J.; Amthor, J.S.; Wullschleger, S.D.; Wilson, K.B.; Grant, R.F.; Hartley, A.; Hui, D.; Hunt, E.R.; Johnson, D.W.; Kimball, J.S.; et al. Oak forest carbon and water simulations: Model intercomparisons and evaluations against independent data. *Ecol. Monogr.* **2004**, *74*, 443–489. [CrossRef]
27. Petritsch, R.; Hasenauer, H.; Pietsch, S.A. Incorporating forest growth response to thinning within Biome-BGC. *For. Ecol. Manag.* **2007**, *242*, 324–336. [CrossRef]
28. Pietsch, S.A.; Hasenauer, H. Using mechanistic modeling within forest ecosystem restoration. *For. Ecol. Manag.* **2002**, *159*, 111–131. [CrossRef]
29. Thornton, P.E.; Law, B.E.; Gholz, H.L.; Clark, K.L.; Falge, E.; Ellsworth, D.; Goldstein, A.; Monson, R.; Hollinger, D.; Falk, M.; et al. Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. *Agric. For. Meteorol.* **2002**, *113*, 185–222. [CrossRef]
30. Thurnher, C.; Eastaugh, C.S.; Hasenauer, H. A thinning routine for large-scale biogeochemical mechanistic ecosystem models. *For. Ecol. Manag.* **2014**, *320*, 56–69. [CrossRef]
31. Warren, J.M.; Pötzelsberger, E.; Wullschleger, S.D.; Thornton, P.E.; Hasenauer, H.; Norby, R.J. Ecohydrologic impact of reduced stomatal conductance in forests exposed to elevated CO_2. *Ecohydrology* **2011**, *4*, 196–210. [CrossRef]
32. Assefa, D.; Rewald, B.; Sandén, H.; Rosinger, C.; Abiyu, A.; Yitaferu, B.; Godbold, D.L. Deforestation and land use strongly effect soil organic carbon and nitrogen stock in Northwest Ethiopia. *CATENA* **2017**, *153*, 89–99. [CrossRef]
33. Tesfaye, M.A.; Bravo, F.; Ruiz-Peinado, R.; Pando, V.; Bravo-Oviedo, A. Impact of changes in land use, species and elevation on soil organic carbon and total nitrogen in Ethiopian Central Highlands. *Geoderma* **2016**, *261*, 70–79. [CrossRef]
34. Girmay, G.; Singh, B.R.; Mitiku, H.; Borresen, T.; Lal, R. Carbon stocks in Ethiopian soils in relation to land use and soil management. *L. Degrad. Dev.* **2008**, *19*, 351–367. [CrossRef]
35. Moges, Y.; Eshetu, Z.; Nune, S. *Ethiopian Forest Resources: Current Status and Future Management Options in View of Access to Carbon Finances*; UN-REDD Programme: Geneva, Switzerland, 2010.
36. Assmann, E. *The Principles of Forest Yield Study: Studies in the Organic Production, Structure, Increment and Yield of Forest Stands*; Pergamon Press: Oxford, UK, 1970.
37. Schmidt, W. Herb layer species as indicators of biodiversity of managed and unmanaged beech forests. *For. Snow. Landsc. Res.* **2005**, *125*, 111–125.
38. Sisay, K.; Thurnher, C.; Belay, B.; Lindner, G.; Hasenauer, H. Volume and carbon estimates for the forest area of the Amhara region in Northwestern Ethiopia. *Forests* **2017**, *8*, 122. [CrossRef]
39. Chave, J.; Andalo, C.; Brown, S.; Cairns, M.A.; Chambers, J.Q.; Eamus, D.; Fölster, H.; Fromard, F.; Higuchi, N.; Kira, T.; et al. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* **2005**, *145*, 87–99. [CrossRef] [PubMed]
40. Zanne, A.E.; Lopez-Gonzalez, G.; Coomes, D.A.; Ilic, J.; Jansen, S.; Lewis, S.L.; Miller, R.B.; Swenson, N.G.; Wiemann, M.C.; Chave, J. Data from: Towards a worldwide wood economics spectrum. *Ecol. Lett.* **2009**. [CrossRef]

41. Bert, D.; Danjon, F. Carbon concentration variations in the roots, stem and crown of mature *Pinus pinaster* (Ait.). *For. Ecol. Manag.* **2006**, *222*, 279–295. [CrossRef]
42. Lamlom, S.H.; Savidge, R.A. A reassessment of carbon content in wood: Variation within and between 41 North American species. *Biomass Bioenergy* **2003**, *25*, 381–388. [CrossRef]
43. McGroddy, M.E.; Daufresne, T.; Hedin, O.L. Scaling of C :N :P stoichiometry in forests worldwide: Implications of terrestrial redfield-type ratios. *Ecology* **2004**, *85*, 2390–2401. [CrossRef]
44. Van Do, T.; Sato, T.; Saito, S.; Kozan, O. Fine-root production and litterfall: Main contributions to net primary production in an old-growth evergreen broad-leaved forest in southwestern Japan. *Ecol. Res.* **2015**, *30*, 921–930. [CrossRef]
45. Malhi, Y.; Doughty, C.; Galbraith, D. The allocation of ecosystem net primary productivity in tropical forests. *Philos. Trans. R. Soc. B. Biol. Sci.* **2011**, *366*, 3225–3245. [CrossRef] [PubMed]
46. Heiri, O.; Lotter, A.F.; Lemcke, G. Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *J. Paleolimnol.* **2001**, *25*, 101–110. [CrossRef]
47. Kettler, T.A.; Doran, J.W.; Gilbert, T.L. Simplified method for soil particle-size determination to accompany soil-quality analyses. *Soil Sci. Soc. Am. J.* **2001**, *65*, 849–852. [CrossRef]
48. Amhara Design and Supervision Works Enterprise. *Soil Depth Shape File*; Amhara Design and Supervision Works Enterprise, Laboratory service in soil Chemistry and Water quality Section: Bahir Dar, Ethiopia, 2012.
49. Sisay, K.; Thurnher, C.; Hasenauer, H. Daily climate data for the Amhara region in Northwestern Ethiopia. *Int. J. Climatol.* **2016**, *37*, 2797–2808. [CrossRef]
50. Thornton, P.E. Regional Ecosystem Simulation: Combining Surface- and Satellite-Based Observations to Study Linkages between Terrestrial Energy and Mass Budgets. Ph.D. Thesis, University of Montana, Missoula, MT, USA, 1998.
51. Thornton, P.E.; Hasenauer, H.; White, M.A. Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: An application over complex terrain in Austria. *Agric. For. Meteorol.* **2000**, *104*, 255–271. [CrossRef]
52. Enting, I.G.; Wigley, T.M.L.; Heimann, M. *Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses*; CSIRO Division of Atmospheric Reserch: Canberra, Australia, 1994.
53. Dentener, F.J. *Global Maps of Atmospheric Nitrogen Deposition, 1860, 1993, and 2050*; ORNL DAAC: Oak Ridge, TN, USA, 2006.
54. Intergovernmental Panel on Climate Change. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*; Houghton, J.T., Callander, B.A., Varney, S.K., Eds.; Cambridge University Press: Cambridge, UK, 1992.
55. Running, S.W.; Coughlan, J.C. A general model of forest ecosystem processes for regional applications. *Ecol. Model.* **1988**, *42*, 125–154. [CrossRef]
56. Running, S.W.; Gower, S.T. FOREST-BGC, a general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. *Tree Physiol.* **1991**, *9*, 147–160. [CrossRef] [PubMed]
57. Pietsch, S.A.; Hasenauer, H. Evaluating the self-initialization procedure for large-scale ecosystem models. *Glob. Chang. Biol.* **2006**, *12*, 1658–1669. [CrossRef]
58. Hasenauer, H.; Merganicová, K.; Pietsch, S.A. Modeling biogeochemical cycles within old-growth forest ecosystems. *For. Snow Landsc. Res.* **2005**, *90*, 81–90.
59. Hidy, D.; Barcza, Z.; Haszpra, L.; Churkina, G.; Pintér, K.; Nagy, Z. Development of the Biome-BGC model for simulation of managed herbaceous ecosystems. *Ecol. Modell.* **2012**, *226*, 99–119. [CrossRef]
60. Farquhar, G.D.; von Caemmerer, S.; Berry, J.A. A Biochemical Model of Photosynthetic CO_2 Assimilation in Leaves of C3 Species. *Planta* **1980**, *149*, 78–90. [CrossRef] [PubMed]
61. Penning de Vries, F.W.T. The cost of maintenance processes in plant cells. *Ann. Bot.* **1975**, *39*, 77–92. [CrossRef]
62. Ryan, M.G. Effects of climate change on plant respiration. *Ecol. Appl.* **1991**, *1*, 157–167. [CrossRef] [PubMed]
63. Clapp, R.B.; Hornberger, G.M. Empirical equations for some soil hydraulic properties. *Water Resour. Res.* **1978**, *14*, 601–604. [CrossRef]
64. Cosby, B.J.; Hornberger, G.M.; Clapp, R.B.; Ginn, T.R. A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils. *Water Resour. Res.* **1984**, *20*, 682. [CrossRef]

65. White, M.A.; Thornton, P.E.; Running, S.W.; Nemani, R.R. Parameterization and sensitivity analysis of the BIOME-BGC terrestrial ecosystem model: Net primary production controls. *Earth Interact.* **2000**, *4*, 1–85. [CrossRef]
66. Ichii, K.; Hashimoto, H.; Nemani, R.; White, M. Modeling the interannual variability and trends in gross and net primary productivity of tropical forests from 1982 to 1999. *Glob. Planet. Chang.* **2005**, *48*, 274–286. [CrossRef]
67. Pietsch, S.A.; Hasenauer, H.; Thornton, P.E. BGC-model parameters for tree species growing in central European forests. *For. Ecol. Manag.* **2005**, *211*, 264–295. [CrossRef]
68. Kuzmicheva, E.A.; Khasanov, B.F.; Krylovich, O.A.; Savinetsky, A.B. Vegetation and climate reconstruction for the bale mountains (Ethiopia) in the Holocene according to the pollen analysis and radiocarbon dating of zoogenic deposits. *Dokl. Biol. Sci.* **2014**, *458*, 281–285. [CrossRef] [PubMed]
69. Lamb, A.L.; Leng, M.J.; Mohammed, M.U.; Lamb, H.F. Holocene climate and vegetation change in the Main Ethiopian Rift Valley, inferred from the composition (C/N and $\delta^{13}C$) of lacustrine organic matter. *Quat. Sci. Rev.* **2004**, *23*, 881–891. [CrossRef]
70. Mohammed, U.M. *The Relative Importance of the Different Forcings on the Environment in Ethiopia during Holocene*; Cambridge University Press: Cambridge, UK, 2005.
71. Zegeye, H.; Teketay, D.; Kelbessa, E. Diversity and regeneration status of woody species in Tara Gedam and Abebaye forests, northwestern Ethiopia. *J. For. Res.* **2011**, *22*, 315–328. [CrossRef]
72. Wondie, M.; Schneider, W.; Katzensteiner, K.; Mansberger, R.; Teketay, D. Modelling the dynamics of landscape transformations and population growth in the highlands of Ethiopia using remote-sensing data. *Int. J. Remote Sens.* **2016**, *37*, 5647–5667. [CrossRef]
73. Nyssen, J.; Frankl, A.; Haile, M.; Hurni, H.; Descheemaeker, K.; Crummey, D.; Ritler, A.; Portner, B.; Nievergelt, B.; Moeyersons, J.; et al. Environmental conditions and human drivers for changes to north Ethiopian mountain landscapes over 145 years. *Sci. Total Environ.* **2014**, *485–486*. [CrossRef] [PubMed]
74. Rembold, F.; Carnicelliz, S.; Nori, M.; Ferrari, G.A. Use of aerial photographs, Landsat TM imagery and multidisciplinary field survey for land-cover change analysis in the lakes region (Ethiopia). *Agriculture* **2000**, *2*, 181–189. [CrossRef]
75. Gebremariam, M.; Kebede, F. Land use change effect on soil carbon stock, above ground biomass, aggregate stability and soil crust: A case from Tahtay Adyabo, North Western Tigray, Northern Ethiopia. *J. Drylands* **2010**, *3*, 220–225.
76. Solomon, D.; Fritzsche, F.; Tekalign, M.; Lehmann, J.; Zech, W. Soil Organic Matter Composition in the Subhumid Ethiopian Highlands as Influenced by Deforestation and Agricultural Management. *Soil Sci. Soc. Am. J.* **2002**, *66*, 68–82. [CrossRef]
77. Tamene, L.; Vlek, P.L.G. Soil erosion studies in northern Ethiopia. In *Land Use and Soil Resources*; Braimoh, A.K., Vlek, P., Eds.; Springer: Berlin, Germany, 2008; pp. 73–100.
78. Jury, M.R.; Funk, C. Climatic trends over Ethiopia: Regional signals and drivers. *Int. J. Climatol.* **2013**, *33*, 1924–1935. [CrossRef]

9.2 Paper II

Belay, B., Pötzelsberger, E., Hasenauer, H., 2018. The Carbon Sequestration Potential of Degraded Agricultural Land in the Amhara Region of Ethiopia. Forests 9(8), 470, 1–24. doi:10.3390/f9080470

forests

MDPI

Article

The Carbon Sequestration Potential of Degraded Agricultural Land in the Amhara Region of Ethiopia

Beyene Belay [1,2], Elisabeth Pötzelsberger [1,*] and Hubert Hasenauer [1]

1 Institute of Silviculture, University of Natural Resources and Life Sciences, Peter-Jordan Straße 82, 1190 Vienna, Austria; beyene.belay@yahoo.com (B.B.); hubert.hasenauer@boku.ac.at (H.H.)
2 Amhara Regional Agricultural Research Institute, P.O. Box 527, 6000 Bahir Dar, Ethiopia
* Correspondence: elisabeth.poetzelsberger@boku.ac.at

Received: 10 July 2018; Accepted: 30 July 2018; Published: 1 August 2018

check for updates

Abstract: Forests are a key player within the global carbon cycle and reforestation is an important climate change mitigation mechanism. In this study, we identify potentially suitable areas for reforestation to assess the carbon sequestration potential in the highly deforested and degraded Amhara region of Ethiopia. We apply biogeochemical mechanistic ecosystem modelling to predict the amount of carbon that can be potentially sequestered within different time horizons. Since human intervention plays a key role within the Amhara region, three different forest management scenarios and five different rotation periods following reforestation are tested: (i) unthinned; (ii) removal of 5% of the stem carbon every 20 years (thinning 1); and (iii) removal of 10% stem carbon every 20 years (thinning 2), as well as a rotation period of 10, 30, 50, 100, and 150 years. Sustainable management of reforested land is addressed by implementing the so called 'Normal-forest' system (equal representation of every age class). This ensures the long term sequestration effect of reforested areas. The study shows that 3.4 Mha (Mha = Million hectare) of land, including bare land (0.7 Mha), grass land (1.2 Mha), and shrub land (1.5 Mha) can be considered as ecologically potentially suitable for reforestation. Assuming a 100 year rotation period in a 'Normal-forest' system, this shows that a total net carbon sequestration potential of 177 Tg C (10.8 Tg C in the soil and 165.9 Tg C aboveground; Teragram = 10^{12} g) is possible, if all 3.4 Mha are replanted. The highest total net carbon sequestration (soil and aboveground) was evident for the Highland-wet agro-ecological zone, whereas the lowest values are typically in the Midland-dry zone. The highest net aboveground carbon sequestration was predicted for reforestations on current grass land and shrub land versus bare land, whereas the highest net soil carbon sequestration was predicted on current bare land, followed by grass land and shrub land.

Keywords: reforestation; carbon sequestration; forest management; Normal-forest; Ethiopia

1. Introduction

Information on forest carbon dynamics, carbon stocks, and the sequestration potential of forests is increasingly necessary, as forests play a significant role in mitigating climate change. The highest proportion of terrestrial carbon is stored in forest ecosystems [1]. Thus forests are important to balance global carbon dioxide (CO_2) [2–4]. Human activities are important considerations because land use change and forest management directly affect the forest conditions and thus the carbon cycle.

In Ethiopia, population growth and investment followed by deforestation and land use change have led to a dramatic decline in forest land during the last decades [5–7]. Additionally, we see heavy disturbances in the remaining natural forests, such as cattle grazing or logging that result in severe soil degradation [8–10]. A study in the north-western highlands of Ethiopia revealed a decrease in natural forest cover from 27% in 1957 to 2% in 1982 and to 0.3% in 1995 [11]. The study also shows that between 1957 and 1995 about 99% of the forest cover was mainly lost to land cultivation, with an increase of 77% in cultivated land. This depicts a huge loss of biomass and soil carbon following land use changes [9,10,12]. Houghton et al. [13] reported that land use changes may account for 33% of the total anthropogenic carbon emission between the years 1850 to 2000. A study by Pan et al. [1] reported that about one petagram of carbon is emitted yearly due to tropical land-use change.

Forest management may create a carbon sink through reforestation and rehabilitation of degraded land or may result in a carbon source due to overexploitation [14–16]. Studies on forest carbon stock under different management regimes have shown inconsistent findings. While some studies report a loss of carbon stock following management activities, others show no detectable differences between managed versus unmanaged forests. For example, Achat et al. [4] compared conventional with intensive harvesting using 284 forest sites and found a 22% loss of carbon in the forest floor carbon following conventional harvesting. However, no significant differences were reported in the lower soil layers. Hoover [17] found no significant differences between three different forest management scenarios (unthinned, minor thinning, and heavy thinning) in both the forest floor and soil carbon. Certainly, the intensity and management type (ranging from light thinning to clear cut), as well as the thinning interval determines the impact on the carbon pools of forests [18].

Increasing the forest area and implementing sustainable forest management practices are important cost-effective options for climate change mitigation [19,20]. Sustainable forest management helps to sequester carbon and provides timber and fuelwood, a renewable energy source. The Intergovernmental Panel on Climate Change (IPCC) identifies three types of climate mitigation options in the forestry sector, namely afforestation, reforestation, and reducing/avoiding deforestation [21]. This suggests activities for reducing emissions from land use change, as it is included in the climate mitigation objectives of the United Nations Framework Convention on Climate Change (UNFCCC) [22]. At the UNFCCC 2005 meeting, this topic was negotiated and activities were put forward that are known under the term REDD (REDD-Reducing Emissions from Deforestation and forest Degradation) and REDD+, the latter of which explicitly adds the role of sustainable forest management and its role for carbon management in developing countries.

REDD+ has gained enormous attention in many developing countries, including Ethiopia since it is also seen as a financial mechanism to improve the environmental conditions by avoiding deforestation and promoting reforestation/afforestation programs [23]. The implementation of REDD+ will also lead to social and environmental benefits by providing timber for various purposes and supports biodiversity conservation [24]. According to these political goals, in 2011 the Ethiopian government developed a Climate Resilient and Green Economy (CRGE) strategy to transform the economy by 2025 [25,26]. The plan aims for protection of the environment and to decrease the CO_2 emissions. In Ethiopia, about one third of the emissions come from forestry (55 Mt CO_{2e} of the total 150 Mt CO_{2e} in 2010) [26] and 50% are the result of deforestation. Under CRGE, the government has set a target to reforest 7 million ha by the year 2030. The National Forest Sector Development Program of the recent national REDD+ Strategy [27] has set a target of 16.1 Mha reforested land by 2030, which would double the current forest area in Ethiopia.

Land use conflicts (crop production, grazing, infrastructure etc.) and uncertainties in user rights [28] may impose serious limitations for successful reforestation activities. Planting activities may compete with food security [29]. Many Ethiopian farmers convert their crop land to plantations due to the growing market for construction and fuelwood [30]. Today, *Eucalyptus* sp. L'Hér. accounts for about 90% of Ethiopian plantations and studies show that these *Eucalyptus* sp. plantations strongly affect the soil conditions, the ground water, the wetland areas, and the biological diversity [31–33]. Thus, experts are increasingly pushing the government to ratify rules that ban Eucalypt plantations on cropland, along rivers, lakes, and in wetland areas. As a result, the current Ethiopian REDD+ implementation strategies focus on (i) the reforestation of grass and shrub land areas; (ii) the enhancement of agroforestry practices with indigenous species; and (iii) sustainable forest management of the remaining natural forests [26,34].

The remaining natural forest areas, even though they are often degraded, are banned from human intervention [11,16,35] as they are highly important for implementing the CRGE strategy of the Ethiopian government. Information from available studies in Ethiopia focuses on the aboveground and soil carbon stock of current forests using plot level information [14,15]. However, only a few studies [25,26,34,36] address the carbon sequestration potential due to reforestation and sustainable forest management in Ethiopia.

The purpose of this study is to estimate the reforestation potential and carbon storage options of degraded dry tropical Afromontane landscapes in the Amhara region of Ethiopia. Since forests are an important source of fuel and construction material for the local population, we include (a) three different thinning scenarios and (b) five different rotation lengths (10, 30, 50, 100, and 150 years), assuming a so called 'Normal-forest' system (equal representation of every age class). No climate change scenarios are considered, though, because of the high additional uncertainty different climate change trajectories would cause over such long simulation periods, when one purpose of this study is to compare the impact of different rotation lengths. As a diagnostic tool, we chose the process-based biogeochemical (BGC) ecosystem-flux model Biome-BGC to estimate the carbon sequestration potential of reforestations in different agro-ecological zones, for different current land uses, and under different forest management options. The model was chosen because it simulates forest growth and soil development by simulating major carbon, nitrogen, and water pools in fluxes in response to climatic and soil variables and different forest management options. In a previous study, the model had been tested and evaluated with measured vegetation carbon, soil carbon, and net primary production (NPP) data across different agro-ecological zones (across elevation, temperature, and precipitation gradients) within the Amhara region [10].

The main working steps can be summarized as follows. (i) Identifying the potentially suitable reforestation areas; (ii) predicting the soil and aboveground carbon sequestration potential in different agro-ecological zones according to different land use types; and (iii) assessing management impacts (thinning and rotation length) on the forest soil and aboveground carbon stocks.

2. Materials and Methods

2.1. Study Area

Our study area, the Amhara region in Northern Ethiopia, extends 9°20′–14°20′ N and 36°20′–40°20′ E, and covers 15.7 Mha (Million Hectares). The current land use distribution, according to the Bureau of Agriculture [37], consists of 12 land use classes (Figure 1a). The region has a high altitudinal gradient, ranging from lowland (500 m) to high alpine areas, with Ras Dejen as the highest peak (4620 m above sea level) (Figure 1b). The mean daily temperature is 17.1 °C. The mean annual precipitation is 1270 mm, with 80% of the annual rainfall recorded between June and September. The natural vegetation in the Amhara region according to Friis et al. [38] is classified as follows:

- Combretum-Terminalia woodland and wooded Grassland in the lowlands (<1800 m);
- Dry evergreen Afromontane forest and Grassland (1800–3200 m);
- Afro-alpine vegetation and Ericaceous belt (>3200 m).

The 'Combretum-Terminalia woodland and wooded grassland' is dominated by deciduous lowland small tree/shrub species such as *Sterculia setigera* Delile., *Boswellia papyrifera* Hochst., *Terminalia laxiflora* Engl., and *Acacia* species and a well-developed grass layer. The 'Dry evergreen Afromontane forest and grassland' covers a high diversity of Afromontane species, including *Chionanthus mildbraedii* (Gilg & G.Schellenb.) Stearn, *Ekebergia capensis* Sparrm, *Albizia schimperiana* Oliv., *Prunus africana* (Hook.f.) Kalkman, *Juniperus procera* Hochst. ex Endl., and Schefflera species J.R.Forst. & G.Forst. In the 'Afro-alpine vegetation and Ericaceous belt', species such as *Erica arborea* L., Lobelia *rhynchopetalum* Hemsl., and *Helichrysum citrispinum* Delile are common.

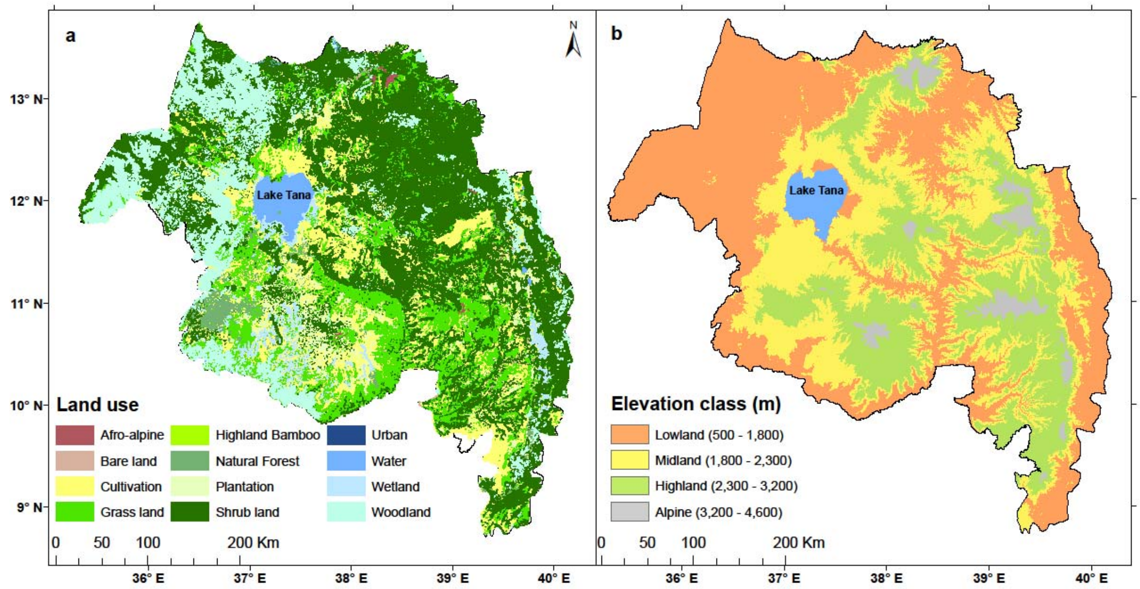

Figure 1. (**a**) Land use, provided by the Bureau of Agriculture [37], and (**b**) elevation class (30 m by 30 m resolution) in the Amhara region in Ethiopia.

2.2. Model Description and Simulation Procedure

We used the process-based biogeochemical mechanistic ecosystem model Biome-BGC [39,40] version 4.1.2 [41] to assess the impact of reforestation/afforestation (hereafter called reforestation) and different forest management scenarios on carbon storage across the highly diverse landscape of Amhara. The model was chosen because it simulates forest growth and soil development in response to atmospheric (climate, CO_2 concentration, nitrogen deposition) and soil variables (i.e., total soil depth and texture) and different forest management measures, such as planting of specific forest types, clear cuts, and different types and intensities of thinning. The advantage of the model is that it simulates pools and, compared to other ecosystem models, it does not require tree populations to initialize a simulation run. Furthermore, in a previous study we evaluated Biome-BGC for different forest and agro-ecological zones (across elevation, temperature and precipitation gradients) in the Amhara region, using measured vegetation carbon, mineral soil carbon, and net primary production data [10].

Biome-BGC simulates the pools and fluxes of carbon, nitrogen, and water in a specific ecosystem. Carbon is stored in different plant and soil compartments, characterized by specific C/N-ratios, lifespan, and degradability. Carbon assimilation (gross primary production—GPP) is simulated with the Farquhar-photosynthesis routine. The supply with CO_2 for photosynthesis is regulated by stomatal conductance. Growth and maintenance respiration lower the amount of carbon that can be used for the build-up of the plant compartments (GPP-respiration = NPP). Dead organic matter is decomposed and builds up the soil carbon stocks. The velocity of decomposition depends on the content of labile organic carbon, cellulose, and lignin in the different plant compartments. Decomposition provides mineralized nitrogen for plant growth. The main water cycle processes are interception (leaf area index—LAI and leaf type dependent), storage in the soil (soil depth and texture dependent), and evapotranspiration from the soil or through the leaves (stomatal conductance dependent). The processes in Biome-BGC typically also are temperature and moisture dependent and are interconnected through various feedback-loops within and among the carbon, nitrogen, and water cycles. All details on the processes have been previously published [39–43]. Biome-BGC uses either biome or species specific eco-physiological parameters to simulate pools and fluxes of a given forest ecosystem [43–46]. Within Biome-BGC, a typical ecosystem or biome type is defined by 35 eco-physiological parameters, which can be obtained from the literature [43], or intensive monitoring sites [44]. For this study, we selected the eco-physiological parameters for the biome type 'tropical evergreen broadleaved forest', suggested by Ichii et al. [47] for several reasons: (1) We had already successfully used and evaluated this parameter set for its applicability on diverse Ethiopian dry Afromontane forest ecosystems [10]; (2) We assumed a reforestation with a natural species mix as opposed to frequent plantations with non-natives such as *Eucalyptus* sp.; (3) There is no other suitable parameter setting available for Ethiopian Afromontane forests.

As a fully prognostic model, Biome-BGC has two main working steps: the 'spin-up' and the current simulation run. The first step, the spin-up, initializes the model for a given ecosystem by mimicking the development of a theoretical virgin forest ecosystem [41,42]. In the spin-up run, the model accumulates carbon and nitrogen until the carbon content of the mineral soil has reached a 'steady state'. After the spin-up, the second modelling step addresses potential historic impacts due to management, changes in forest type/species, and atmospheric conditions as they affect the carbon balance of ecosystems.

The forest simulations are performed on a systematic grid size resolution of 0.083°, which means that every tenth climate grid point is simulated (see Section 2.3). Every simulation grid point represents an area of 9 km by 9 km. With this approach, we ensure the necessary level of detail (sufficient number of grid points within the expected vegetation groupings) and are flexible enough to increase the level of detail (more grid points) within a specific area of interest, if needed.

2.3. Climate and Geospatial Data

2.3.1. Daily Climate Data

For the study area, 32 years (1979–2010) of daily climate data, namely, minimum and maximum temperature (°C) and precipitation (mm), are available from Sisay et al. [48]. This data set consists of downscaled global precipitation and temperature data at a 0.0083° resolution and has been validated with local meteorological stations from the Amhara region [48]. In addition to the daily minimum and maximum temperature and precipitation, solar radiation, vapor pressure deficit, and day-length are required for running Biome-BGC and for calculating the aridity index.

With daily minimum and maximum temperature, as well as daily precipitation, we derived solar radiation (Wm^{-2}), vapor pressure deficit (Pa), and day-length (s), using the algorithms implemented in the Mountain Climate Simulator (MT-CLIM) [49,50].

2.3.2. Aridity Index

With the available climate data we derived the aridity index (AI), defined as a ratio of the mean annual precipitation (P) versus the mean annual potential evapotranspiration (MEP) [51]:

$$AI = P/MEP, \tag{1}$$

Potential evapotranspiration is a measure for the 'drying power' of the atmosphere in removing water through evapotranspiration from the surface at optimal crop and soil water conditions [52,53]. We used the formula of Hargreaves et al. [54] to calculate the MEP, which is similar to the FAO Penman–Monteith method [52]. It has the advantage of requiring fewer climate parameters [23]. Potential evapotranspiration (PEP, mm/month) for every month was calculated according to the following formula and later summed up to an annual estimate:

$$PEP = 0.0023 \times RA \times (Tmean + 17.8) \times TD^{0.5} \tag{2}$$

where Tmean is the mean monthly temperature (°C), TD the mean monthly temperature range (°C), and RA solar radiation ($MJ\ m^{-2}\ day^{-1}$).

2.3.3. Initial Soil Conditions

Realistic estimates of the current aboveground carbon as well as of the soil carbon and nitrogen stocks of potential reforestation areas are important for our analysis. These numbers are important for assessing growth and productivity of planted trees [18] and deriving realistic starting conditions for our Biome-BGC simulations. Current stocks are also necessary to calculate the carbon gain after reforestation. Typically, it is impossible to find detailed field inventory data at a larger scale. For our study, only few empirical mineral soil data were available from local inventories, including data collected in one of our previous studies [5,9,55–61]. From these published results, we derived mean soil carbon and nitrogen by land use type and a correction factor for soil carbon and nitrogen from a preparatory spin-up simulation to obtain spatially explicit soil carbon and nitrogen stocks across the study area as a starting condition for the reforestation simulations.

The starting conditions were generated according to the following procedure: (i) From available literature we calculate the current mean soil carbon ($SoilC_L$) and current mean nitrogen ($SoilN_L$) content by land use type (Table 1); (ii) as a result of the spin-up simulations with Biome-BGC (see Section 2.2), we have a theoretical maximum soil carbon stock ($SoilC_M$) by land use type for each grid point; (iii) using the reported literature values and the spin-up results, we can derive a soil correction factor (CF) as the ratio of the mean $SoilC_L$ versus theoretical mean $SoilC_M$; (iv) we use this correction factor to calculate the individual current (='initial') carbon stock ($SoilC_I$) for each simulation point by multiplying the spin-up values of each simulation point ($SoilC_M$) with the correction factor (CF) by land use type; (v) finally, we determine the individual initial soil nitrogen ($SoilN_I$) for each simulation point by dividing $SoilC_I$ with the observed C/N ratios from the literature ($SoilC_L/SoilN_L$). All above mentioned parameters are shown by land use type in Table 1.

2.3.4. Other Site and Atmospheric Data

The physical site variables soil depth and texture were derived for every simulation point from the regional soil depth and texture map, provided by Amhara Design and Supervision Works Enterprise [62]. Slope, aspect, and elevation for each simulation grid point were extracted from the regional Digital Elevation Model (DEM, 30 m by 30 m). According to Friis et al. [38] and Hurni [63], the Ethiopian Afromontane area can be classified in Lowlands, Midlands, Highlands, and Alpine elevation areas (see Figure 1b).

Preindustrial atmospheric CO_2 concentration and nitrogen deposition information, as needed for Biome-BGC, was set to 278 ppm [50,64] and to 0.129 gN m^{-2} $year^{-1}$ [65], respectively. The current average nitrogen deposition rate is 0.747 gN m^{-2} $year^{-1}$, calculated as the mean of two different values (0.507 and 0.986 gN m^{-2} $year^{-1}$) given by Dentener et al. [65] for the study area.

Table 1. Site characteristics and initial conditions of identified reforestation areas. The size of each land use in million hectares (Area), number of simulation points (Points), mean daily minimum temperature (T_{min}), mean daily maximum temperature (T_{max}), mean annual precipitation (P_{mean}), literature derived current soil carbon ($SoilC_L$), aboveground carbon ($AboveC_L$) and soil nitrogen ($SoilN_L$), median soil carbon from spin-up simulations ($SoilC_M$) representing the theoretical maximum, correction factor (CF) calculated as the ration of $SoilC_L$ and $SoilC_M$ and results for the initial soil carbon stocks ($SoilC_I$) derived from the spin-up results of each simulation point multiplied with the correction factor, and averaged over all simulation points per land use type. Initial soil nitrogen stocks ($SoilN_I$) was calculated as $SoilC_I$ devided by the C/N ratio from the literature ($SoilC_L/SoilN_L$). The values in the parenthesis give the minimum and maximum.

Land Use	Area (Mha)	Points	T_{min} (°C)	T_{max} (°C)	P_{mean} (mm)	$SoilC_L$ (t C ha^{-1})	$AboveC_L$ (t C ha^{-1})	$SoilN_L$ (t N ha^{-1})	$SoilC_M$ (t C ha^{-1})	CF (%)	$SoilC_I$ (t C ha^{-1})	$SoilN_I$ (t N ha^{-1})
Bare land	0.7	81	9.2 (5.0–15.7)	23.5 (18.0–29.8)	1130 (440–2240)	25.3 [a]	0.0	2.0 [f]	146 (43.2–57.2)	17.1	26.9 (7.4–61.4)	2.6 (0.7–6.1)
Grass land	1.2	135	9.9 (4.8–14.6)	23.7 (17.4–28.8)	1440 (550–2960)	52.1 [b]	2.4 [d]	5.0 [g]	145 (54.1–58.1)	35.9	58.8 (19.4–128.2)	5.9 (1.9–12.8)
Shrub land	1.5	160	10.4 (4.7–14.7)	24.7 (18.5–28.4)	1170 (500–2670)	50.0 [c]	7.1 [e]	5.1 [h]	111 (47.9–39.6)	45.0	58.5 (21.5–152.5)	5.8 (2.2–15.2)

[a] Calculated mean soil carbon (t C ha^{-1}) of: 26.3 [60], 14.2 [59], 35.5 [61]; [b] Calculated mean soil carbon (t C ha^{-1}) of: 48 [57]; 52.6 [58], 40.9 [5], 67 [9]; [c] Calculated mean soil carbon (t C ha^{-1}) of: 50.9 [57], 26.2 [59], 54.0 [61], 69 [9]; [d] Calculated mean aboveground carbon (t C ha^{-1}) of: 1.3 [61], 1.0 [55], 2 [15], 5.2 [56]; [e] Calculated mean aboveground carbon (t C ha^{-1}) of: 9.1 [61], 5.3 [55], 3.9 [15], 1.1 [14], 15.9 [56]; [f] Calculated mean soil nitrogen (t C ha^{-1}) of: 2 [60]; [g] Calculated mean soil nitrogen (t C ha^{-1}) of: 5 [57], 4.9 [58], 5 [5], 6 [9]; [h] Calculated mean soil nitrogen (t C ha^{-1}) of: 5 [57], 5.2 [9].

2.4. Forest Management Scenarios

Forest management type, the management interval, and intensity may differ depending on the goals of the land owner. In Ethiopia, it is difficult to find documented forest management practices, which are implemented in private or state owned forest areas. Furthermore, sustainable forest management, as is common in Europe or other parts of the world, is unknown in Ethiopia. As a result, species selection and management type in private plantations are driven by the demands of the timber market.

In this study, we address potential forest management options according to REDD+ ideas (i.e., optimizing carbon sequestration and providing social and environmental benefits) and define three different thinning regimes: (i) unthinned (control scenario); (ii) thinning 1, with tree removal of 5% of the standing volume every 20 years; and (iii) thinning 2, with a removal of 10% of the standing volume every 20 years. The first tree removal was assumed at age 40 years in the latter two scenarios. Thinning as simulated with Biome-BGC involves a certain proportion of live biomass either being removed from the system or transformed to other carbon pools.

All leaves and fine roots of the cut trees are translocated into the so called 'litter' carbon pool, which is characterized by the fasted degradation, and coarse roots are translocated into a 'coarse wood debris pool', where the cellulose and the lignin content are responsible for a much slower degradation as compared to the 'litter' pool. The degradation of litter and coarse woody debris (stemming from thinning and natural mortality) contributes to the build-up of the soil carbon stocks. As timber and fuelwood consumption is assumed, the thinned stem carbon is removed from the system.

In addition to the thinning scenarios, we propose the implementation of the 'Normal-forest' approach, which provides a simple framework for ensuring sustainability based on an equal distribution of the land area by age and a defined rotation length. With this implementation design we ensure sustainable forest management by providing a sustainable income option for the land owners so that a mutual interest in planting trees, income and a reduction of deforestation or even recovery of land can be generated. For example, if we reforest 500 ha of land with a defined rotation length of 100 years, we start by reforesting 5 ha every year to ensure an equal age class distribution after 100 years. From the year 100 onwards, a sustainable annual harvest of 5 ha per year is ensured. The cut 5 ha may then regenerate naturally or be replanted. In addition, thinning options are possible to allow the harvest of forest resources throughout the rotation period and to improve the growing conditions of the remaining trees.

This concept was developed in Europe during the late 18th century by Hundeshagen and Heyer [66,67] and was successfully implemented in large parts of the world to address conditions to those in Ethiopia today—significant loss or exploitation of forest resources, followed by large degradation effects and a rapid decline of soil productivity.

3. Results

3.1. Identification of Potential Reforestation Areas

The selection of areas for reforestation needs to consider ecological and socioeconomic constraints and follow three criteria: (1) land use suitability; (2) potential elevation/vegetation belt; and (3) the aridity index. Only if all three criteria are within the suitable range for replanting, the area will be suggested for reforestation.

3.1.1. Land Use Suitability

Based on the land use map of the Bureau of Agriculture [37] (Figure 1a), we classified three key land use types relevant for reforestation: (i) bare land; (ii) grass land; and (iii) shrub land (Table 1). Bare land includes abandoned crop or other land use forms due to low productivity or severe erosion problems.

3.1.2. Potential Elevation/Vegetation Belt

As dense high forest only naturally occurs in the 'Dry evergreen Afromontane forest and grassland' vegetation belt between 1800 m and 3200 m [38] (Section 2.1), reforestation is only proposed in this vegetation belt. Following the classification of Hurni [63], reforestations in this elevation/vegetation belt can be divided into Midlands (<2300 m) and Highlands (>2300 m) (see Figure 1b). In addition, each vegetation belt is distinguished in dry areas with <900 mm precipitation, moist areas with 900 mm to 1400 mm, and wet areas with >1400 mm of annual precipitation. This results in six agro-ecological zones (Table 2).

Table 2. Agro-ecological zones (Agro-ecology), Elevation ranges (Elevation), and Annual precipitation ranges (P_{mean}), area size of each agro-ecological zone in million hectare (Area), number of simulation points (Points), and annual NPP (10-year mean, years 91–100 after reforestation) from Biome-BGC simulations (unthinned) averaged over the simulation points.

Land Use	Agro-Ecology	Elevation (m)	P_{mean} (mm)	Area (Mha)	Points	NPP (t C ha^{-1} year^{-1})
Bare land	Highland-dry	2300–3200	<900	0.10	11	1.8
	Highland-moist	2300–3200	900–1400	0.19	22	2.3
	Highland-wet	2300–3200	≥1400	0.10	11	3.1
	Midland-dry	1800–2300	<900	0.10	12	1.8
	Midland-moist	1800–2300	900–1400	0.14	16	2.2
	Midland-wet	1800–2300	≥1400	0.08	9	2.6
Grass land	Highland-dry	2300–3200	<900	0.06	7	2.1
	Highland-moist	2300–3200	900–1400	0.28	31	3.3
	Highland-wet	2300–3200	≥1400	0.23	26	4.7
	Midland-dry	1800–2300	<900	0.09	10	2.0
	Midland-moist	1800–2300	900–1400	0.22	25	3.0
	Midland-wet	1800–2300	≥1400	0.32	36	4.2
Shrub land	Highland-dry	2300–3200	<900	0.08	8	2.7
	Highland-moist	2300–3200	900–1400	0.25	27	3.5
	Highland-wet	2300–3200	≥1400	0.07	7	4.4
	Midland-dry	1800–2300	<900	0.28	30	2.2
	Midland-moist	1800–2300	900–1400	0.61	65	3.1
	Midland-wet	1800–2300	≥1400	0.22	23	3.7

3.1.3. Aridity Index

We applied the aridity index (AI) as calculated according to Equations (1) and (2) (Section 2.3.2) Figure 2a) as numerical indicators for each grid point to classify the climatic zones [68]. Areas with an aridity index AI < 0.65 are excluded from reforestation, because they do not support dense forests but only more xeric vegetation types [23].

Combining our selection criteria (1) land use suitability; (2) potential elevation/vegetation belt; and (3) an AI > 0.65, for selecting potential reforestation areas for the Amhara region, suggests that 3.4 Mha or 22% of the total land area are ecologically suitable for reforestation. This includes 0.7 Mha of bare land, 1.2 Mha of grass land, and 1.5 Mha of shrub land. Summary statistics are given in Table 1, the spatial patterns are provided in Figure 2b. Most of the bare land and shrub land is located in the central, eastern, and north-eastern part of the Amhara region (Figure 2b), areas often rugged and mountainous. Grass land is predominantly located in flat and crop dominated areas, especially in the southern and western part of Amhara.

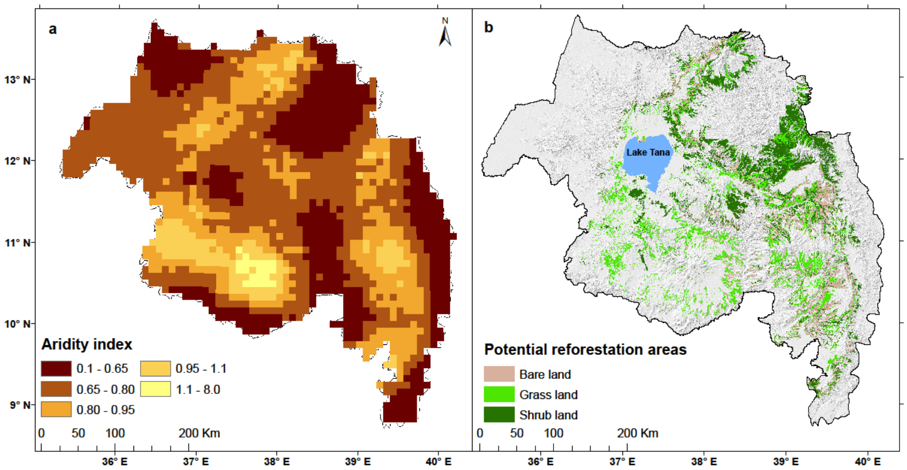

Figure 2. (**a**) Aridity index and (**b**) potential reforestation area in the Amhara Region. Climate data (0.083° resolution) for deriving the Aridity index came from Sisay et al. [48].

3.2. Temporal Development of Carbon Sequestration by Land Use Type and Thinning Scenarios

Next, we were interested in the carbon sequestration potential of the identified reforestation areas according to the three land use types including the determined soil carbon and nitrogen starting conditions at the time of reforestation.

For each grid point (0.083°~9 km by 9 km), we simulated the carbon accumulation over 150 years. As starting conditions for soil carbon and nitrogen, we used the grid point specific initial carbon values as determined by the procedure described in Section 2.3.3. The simulations involved the three thinning scenarios. The mean development of soil and aboveground carbon of the 81 simulation points in the bare land area, the 135 points within the grass land, and 160 grid points of shrub land area is shown in Figure 3. Soil carbon increase over 150 years could be shown to be highest on bare land, but to start from the lowest initial soil carbon values of about 27 t C ha^{-1}, as opposed to an average initial soil carbon across all grass land and shrub land grid points of about 59 t C ha^{-1} (Table 1). The development of aboveground carbon shows a slower development on bare land and fast growth for shrub land and especially grass land (see Figure 3d–f). In contrast to the soil, the impact of the thinning intervention is visible as a direct drop of aboveground carbon immediately after each thinning and at a lower aboveground carbon stock after 150 years with increasing thinning intensity.

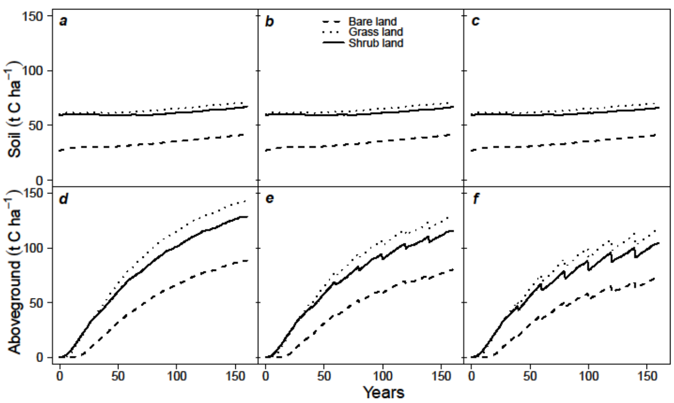

Figure 3. The simulated development of gross soil carbon (**a**–**c**) and gross aboveground carbon (**d**–**f**) over 150 years after reforestation under different management scenarios (unthinned = **a**,**d**; thinning 1 = **b**,**e**; and thinning 2 = **c**,**f**), aggregated per land use type from all simulation points (Bare land n = 81, Grass land n = 135, Shrub land n = 160).

3.3. Gross and Net Carbon Sequestration Potential by Agro-Ecological Zone

As productivity follows topographic conditions and climatic patterns, we clustered our Biome-BGC simulation results for NPP, soil, and aboveground carbon according to the six agro-ecological zones (Table 2). The productivity differences across the agro-ecological zones are directly visible from the NPP, which is highest for Highland-wet and lowest for Midland-dry (Table 2). The results of the 100 year soil and aboveground carbon stock predictions by agro-ecological zone and thinning scenario are shown in Table 3. The highest accumulated soil carbon stocks ('gross', including initial carbon and carbon gain after reforestation) is evident on grass land, zone Highland-wet (91 t C ha^{-1}, no thinning), while the lowest stocks can be expected at bare land, zone Midland-dry (26 t C ha^{-1}, no thinning, Table 3). Similarly, the highest and lowest aboveground carbon stocks are found in grass land, zone Highland-wet (150 t C ha^{-1}, no thinning), and bare land, zone Midland-dry (51 t C ha^{-1}, no thinning), respectively. The spatial distributions of predicted soil and aboveground carbon and annual NPP across the reforestation areas are depicted in Figure 4.

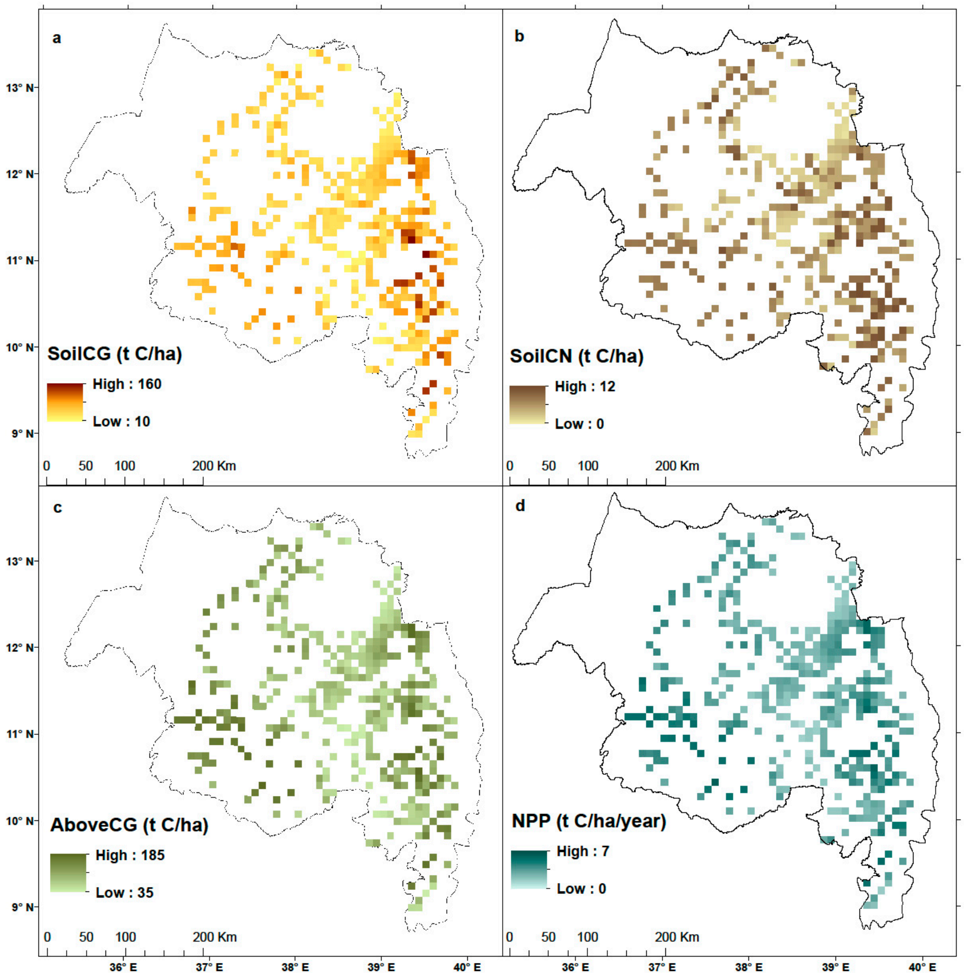

Figure 4. Spatial distributions of predicted soil and aboveground carbon and annual NPP 100 years after reforestation (unthinned) for the selected reforestation areas on the 9 km by 9 km resolution. (**a**) SoilC$_G$—Gross soil carbon stock (t C ha^{-1}); (**b**) SoilC$_N$—Net soil carbon stock (t C ha^{-1}), calculated as the difference between SoilC$_G$ and the initial soil carbon stock SoilC$_I$ (compare Tables 1 and 3); (**c**) AboveC$_G$—Gross aboveground carbon stock (t C ha^{-1} year^{-1}); (**d**) annual net primary production (NPP, 10-year mean, years 91–100 after reforestation).

Table 3. Model predicted carbon sequestered through reforestation after 100 years for different current land uses, in different agro-ecological zones and under different managements. Initial soil carbon ($SoilC_I$) and aboveground carbon ($AboveC_L$) are obtained as described in Table 1. Net carbon stock ($SoilC_N$, $AboveC_N$) is the difference between gross carbon stock ($SoilC_G$, $AboveC_G$) and the corresponding initial carbon stock ($SoilC_I$ and $AboveC_L$).

Land Use	Agro-Ecology	$SoilC_I$ (t C ha^{-1})	$AboveC_L$ (t C ha^{-1})	Gross Carbon Stock (t C ha^{-1})						Net Carbon Stock (t C ha^{-1})					
				Unthinned		Thinning 1		Thinning 2		Unthinned		Thinning 1		Thinning 2	
				$SoilC_G$	$AboveC_G$	$SoilC_G$	$AboveC_G$	$SoilC_G$	$AboveC_G$	$SoilC_N$	$AboveC_N$	$SoilC_N$	$AboveC_N$	$SoilC_N$	$AboveC_N$
Bare land	Highland-dry	23.9	0	32.8	52.7	32.9	47.1	32.9	42.1	8.9	52.7	9.0	47.1	9.0	42.1
	Highland-moist	31.3	0	41.1	69.1	41.2	61.8	41.1	55.2	9.8	69.1	9.9	61.8	9.8	55.2
	Highland-wet	41.2	0	51.3	90.1	51.3	80.6	51.2	72.0	10.1	90.1	10.1	80.6	10.0	72.0
	Midland-dry	18.1	0	26.2	51.4	26.3	45.9	26.2	41.0	8.1	51.4	8.2	45.9	8.1	41.0
	Midland-moist	19.5	0	28.3	61.4	28.3	54.9	28.3	48.9	8.8	61.4	8.8	54.9	8.8	48.9
	Midland-wet	21.5	0	31.3	75.4	31.3	67.2	31.2	60.0	9.8	75.4	9.8	67.2	9.7	60.0
Grass land	Highland-dry	44.9	2.4	50.5	70.0	50.5	62.2	50.4	55.1	5.6	67.6	5.6	59.8	5.5	52.7
	Highland-moist	71.4	2.4	77.8	106.9	77.9	94.9	77.8	84.3	6.4	104.5	6.5	92.5	6.4	81.9
	Highland-wet	83.3	2.4	91.0	149.7	91.0	132.7	90.9	117.7	7.7	147.3	7.7	130.3	7.6	115.3
	Midland-dry	30.4	2.4	35.1	64.2	35.1	57.0	35.0	50.5	4.7	61.8	4.7	54.6	4.6	48.1
	Midland-moist	44.6	2.4	50.4	93.6	50.4	83.2	50.4	73.8	5.8	91.2	5.8	80.8	5.8	71.4
	Midland-wet	51.2	2.4	58.3	135.3	58.3	119.9	58.2	106.4	7.1	132.9	7.1	117.5	7.0	104.0
Shrub land	Highland-dry	69.9	7.1	73.9	92.9	73.9	82.5	73.9	73.1	4.0	85.8	4.0	75.4	4.0	66.0
	Highland-moist	82.2	7.1	86.2	115.0	86.3	102.2	86.3	90.7	4.0	107.9	4.1	95.1	4.1	83.6
	Highland-wet	76.1	7.1	80.7	143.1	80.8	126.8	80.8	112.5	4.6	136.0	4.7	119.7	4.7	105.4
	Midland-dry	43.7	7.1	46.3	73.3	46.4	65.0	46.2	57.4	2.6	66.2	2.7	57.9	2.5	50.3
	Midland-moist	53.3	7.1	56.5	98.9	56.6	87.9	56.5	77.8	3.2	91.8	3.3	80.8	3.2	70.7
	Midland-wet	52.7	7.1	56.8	119.2	56.9	105.9	56.8	93.8	4.1	112.1	4.2	98.8	4.1	86.7

An important step of the reforestation programs is the assessment of the expected change in stored carbon, the 'net' carbon storage. The net carbon stock (see Table 3) was calculated as the difference between the carbon stock and the corresponding initial carbon stocks for soil ($SoilC_I$) and above ground ($AboveC_L$), which were obtained from the published literature (Section 2.3.2, Table 1). Results of the net carbon storage by land use type, agro-ecological zone, and management scenario after 100 years following reforestation are shown in Table 3. In contrast to gross carbon, the highest net soil carbon stock is found on bare land, zone Highland-wet, (10.1 t C ha^{-1}, no thinning), and the lowest at shrub land, zone Midland-dry (2.6 t C ha^{-1}, no thinning), whereas the highest aboveground net carbon stock is again found in grass land, zone Highland-wet (147 t C ha^{-1}, no thinning), and the lowest in bare land, zone Midland-dry (51 t C ha^{-1}, no thinning).

3.4. Sequestration Potential in a 'Normal-Forest' System

Tested forest management options include different rotation lengths in a Normal-forest system and three thinning scenarios (unthinned, thinning 1 and thinning 2). Table 4 shows the results of gross and net soil and aboveground carbon storage for a 100 year rotation 'Normal-forest' system by land use type, agro-ecological zone, and management scenario.

Since the rotation length is an important element for the total carbon storage of age classes of a 'Normal-forest' system, we were next interested in the effect of different rotation lengths. The principle approach remains the same (equal share of land area according to rotation lengths). We defined five different examples for rotation length (10, 30, 50, 100, and 150 years) and calculated the equal share according to the 'Normal-forest' concept. Table 5 shows the results according to the defined rotation lengths for soil and aboveground carbon stocks per hectare for bare land, grass land, and shrub land and the three management scenarios. Again, gross and net carbon stocks are shown (net = gross minus initial/current).

The final step of our study was to provide an estimate for the total potential carbon storage in the Amhara region, assuming that the 'Normal-forest' system would be in place for the whole identified potential reforestation area of 3.4 Million hectares (compare Figure 2b). Table 6 provides the gross and net carbon gain by land use type, rotation length, and management regime. The potential net carbon storage over 100 years for the whole proposed reforestation land of the study area is estimated to be, in the unthinned scenario, 176.7 Tg C (10.8 Tg C in soil and 165.9 Tg C aboveground) (Table 6) or, if given per hectare, 52 t C ha^{-1} (3.2 t C ha^{-1} in soil and 48.8 t C ha^{-1} aboveground, Table 5). Allowing for heavier thinning (thinning 2, 10% every 20 years), the total sequestration potential would be 158.5 Tg C (10.9 Tg C in soil and 147.6 Tg C aboveground) (Table 6).

Table 4. Model predicted carbon sequestration potential through reforestation in a 'Normal-forest' system with a 100 year rotation period for different current land uses, in different agro-ecological zones and under different managements. Initial soil carbon ($SoilC_I$) and aboveground carbon ($AboveC_L$) are obtained as described in Table 1. Normal-forest gross carbon stock ($SoilC_{NF\text{-}G}$, $AboveC_{NF\text{-}G}$) is derived by summing model predicted carbon stock from year 0 to 100 and divided by the rotation period (100 year). Net carbon stock ($SoilC_{NF\text{-}N}$, $AboveC_{NF\text{-}N}$) is the difference between gross carbon stock and the corresponding initial carbon stock ($SoilC_I$ and $AboveC_L$).

Land Use	Agro-Ecology	$SoilC_I$ (t C ha^{-1})	$AboveC_L$ (t C ha^{-1})	Normal-Forest Gross Carbon Stock (t C ha^{-1})						Normal-Forest Net Carbon Stock (t C ha^{-1})					
				Unthinned		Thinning 1		Thinning 2		Unthinned		Thinning 1		Thinning 2	
				$SoilC_{NF\text{-}G}$	$AboveC_{NF\text{-}G}$	$SoilC_{NF\text{-}G}$	$AboveC_{NF\text{-}G}$	$SoilC_{NF\text{-}G}$	$AboveC_{NF\text{-}G}$	$SoilC_{NF\text{-}N}$	$AboveC_{NF\text{-}N}$	$SoilC_{NF\text{-}N}$	$AboveC_{NF\text{-}N}$	$SoilC_{NF\text{-}N}$	$AboveC_{NF\text{-}N}$
Bare land	Highland-dry	23.9	0	28.9	23.9	28.9	22.7	28.9	21.5	5.0	23.9	5.0	22.7	5.0	21.5
	Highland-moist	31.3	0	36.8	31.3	36.8	29.7	36.8	28.1	5.5	31.3	5.5	29.7	5.5	28.1
	Highland-wet	41.2	0	47.1	40.2	47.1	38.1	47.1	36.1	5.9	40.2	5.9	38.1	5.9	36.1
	Midland-dry	18.1	0	22.6	24.3	22.6	23.1	22.6	21.9	4.5	24.3	4.5	23.1	4.5	21.9
	Midland-moist	19.5	0	24.3	29.2	24.3	27.7	24.3	26.2	4.8	29.2	4.8	27.7	4.8	26.2
	Midland-wet	21.5	0	26.9	36.0	26.9	34.0	26.9	32.2	5.4	36.0	5.4	34.0	5.4	32.2
Grass land	Highland-dry	44.9	2.4	48.1	36.9	48.1	34.9	48.1	33.1	3.2	34.5	3.2	32.5	3.2	30.7
	Highland-moist	71.4	2.4	75.1	55.8	75.1	52.9	75.1	50.1	3.7	53.4	3.7	50.5	3.7	47.7
	Highland-wet	83.3	2.4	87.5	79.7	87.5	75.3	87.5	71.2	4.2	77.3	4.2	72.9	4.2	68.8
	Midland-dry	30.4	2.4	32.9	34.6	33.0	32.8	33	31.1	2.5	32.2	2.6	30.4	2.6	28.7
	Midland-moist	44.6	2.4	47.6	50.0	47.6	47.3	47.6	44.9	3.0	47.6	3.0	44.9	3.0	42.5
	Midland-wet	51.2	2.4	54.8	74.0	54.8	70.0	54.8	66.3	3.6	71.6	3.6	67.6	3.6	63.9
Shrub land	Highland-dry	69.9	7.1	72.3	50.3	72.3	47.7	72.3	45.2	2.4	43.2	2.4	40.6	2.4	38.1
	Highland-moist	82.2	7.1	84.4	61.7	84.5	58.5	84.5	55.5	2.2	54.6	2.3	51.4	2.3	48.4
	Highland-wet	76.1	7.1	78.3	78.6	78.4	74.4	78.4	70.6	2.2	71.5	2.3	67.3	2.3	63.5
	Midland-dry	43.7	7.1	45.2	40.5	45.2	38.4	45.2	36.4	1.5	33.4	1.5	31.3	1.5	29.3
	Midland-moist	53.3	7.1	54.9	54.2	54.9	51.4	54.9	48.7	1.6	47.1	1.6	44.3	1.6	41.6
	Midland-wet	52.7	7.1	54.5	65.8	54.6	62.4	54.6	59.2	1.8	58.7	1.9	55.3	1.9	52.1

Table 5. Model predicted carbon sequestration potential through reforestation for different 'Normal-forest' rotations periods (10, 30, 50, 100, and 150 years) in different land use types and under different managements. Initial soil carbon ($SoilC_I$) and aboveground carbon ($AboveC_L$) are obtained as described in Table 1. All carbon values are in (t C ha^{-1}). Since, according to our management scenarios, no management is applied in the first two rotation period options (10 and 30, see Section 3.3), we present only 'Unthinned' in the first two rotation period options.

Land Use	$SoilC_I$ (t C ha^{-1})	$AboveC_L$ (t C ha^{-1})	Normal-Forest Gross Carbon Stock (t C ha^{-1})						Normal-Forest Net Carbon Stock (t C ha^{-1})					
			Unthinned		Thinning 1		Thinning 2		Unthinned		Thinning 1		Thinning 2	
			$SoilC_{NF\text{-}G}$	$AboveC_{NF\text{-}G}$	$SoilC_{NF\text{-}G}$	$AboveC_{NF\text{-}G}$	$SoilC_{NF\text{-}G}$	$AboveC_{NF\text{-}G}$	$SoilC_{NF\text{-}N}$	$AboveC_{NF\text{-}N}$	$SoilC_{NF\text{-}N}$	$AboveC_{NF\text{-}N}$	$SoilC_{NF\text{-}N}$	$AboveC_{NF\text{-}N}$
10 years rotation														
Bare land	26.9	0.0	28.7	0.4	-	-	-	-	1.9	0.4	-	-	-	-
Grass land	58.8	2.4	61.4	1.1	-	-	-	-	2.6	0.0	-	-	-	-
Shrub land	58.5	7.1	60.3	2.3	-	-	-	-	1.8	0.0	-	-	-	-
Average	52.1	3.8	54.2	1.5	-	-	-	-	2.1	0.1	-	-	-	-
30 years rotation														
Bare land	26.9	0.0	30.0	2.9	-	-	-	-	3.3	2.9	-	-	-	-
Grass land	58.8	2.4	61.5	13.9	-	-	-	-	2.7	11.6	-	-	-	-
Shrub land	58.5	7.1	60.4	15.2	-	-	-	-	1.9	8.1	-	-	-	-
Average	52.1	3.8	54.5	12.2	-	-	-	-	2.5	8.2	-	-	-	-
50 years rotation														
Bare land	26.9	0.0	30.4	10.6	30.4	10.3	30.4	10.1	3.6	10.6	3.6	10.3	3.6	10.1
Grass land	58.8	2.4	61.6	29.3	61.6	28.8	61.6	28.3	2.8	26.8	2.8	26.3	2.8	25.8
Shrub land	58.5	7.1	60.2	28.3	60.2	27.9	60.2	27.5	1.7	21.2	1.7	20.7	1.7	20.3
Average	52.1	3.8	54.6	25.0	54.6	24.6	54.6	24.2	2.5	21.0	2.5	20.6	2.5	20.2
100 years rotation														
Bare land	26.9	0.0	32.0	31.1	32.0	29.4	32.0	27.9	5.3	31.1	5.3	29.4	5.3	27.9
Grass land	58.8	2.4	62.5	61.7	62.5	58.3	62.5	55.3	3.7	59.3	3.7	55.9	3.7	52.8
Shrub land	58.5	7.1	60.3	55.9	60.4	53.0	60.4	50.3	1.9	48.7	1.9	45.9	1.9	43.1
Average	52.1	3.8	55.3	52.8	55.3	50.0	55.3	47.4	3.2	48.8	3.2	46.0	3.2	43.4
150 years rotation														
Bare land	26.9	0.0	34.3	46.9	34.3	43.1	34.1	39.7	7.4	46.9	7.4	43.1	7.4	39.7
Grass land	58.8	2.4	64.3	84.1	64.3	77.3	64.2	71.3	5.4	81.8	5.4	74.8	5.3	68.8
Shrub land	58.5	7.1	61.5	75.8	61.5	69.7	61.5	64.3	3.0	68.7	3.1	62.6	3.0	57.1
Average	52.1	3.8	56.9	72.8	56.9	66.9	56.8	61.7	4.8	68.8	4.8	62.9	4.7	57.7

Table 6. Carbon stock sums over the total potential reforestation area in Amhara, i.e., initial soil carbon ($SoilC_I$) and aboveground carbon ($AboveC_L$) obtained as described in Table 1, model predicted gross and net soil and aboveground carbon sequestration potential for different 'Normal-forest' rotations periods (10, 30, 50, 100, and 150 years) in different land use types and under different managements. All carbon values are in Teragram (Tg C= 10^{12} g C). Since, according to our management scenarios, no management is applied in the first two rotation periods (10 and 30, see Section 2.4), we present only 'Unthinned'.

Land Use	Area (Mha)	$SoilC_{I-T}$ (Tg C)	$AboveC_{L-T}$ (Tg C)	Total Normal-Forest Gross Carbon Stock (Tg C)						Total Normal-Forest Net Carbon Stock (Tg C)					
				Unthinned		Thinning 1		Thinning 2		Unthinned		Thinning 1		Thinning 2	
				$SoilC_{NF-GT}$	$AboveC_{NF-GT}$	$SoilC_{NF-GT}$	$AboveC_{NF-GT}$	$SoilC_{NF-GT}$	$AboveC_{NF-GT}$	$SoilC_{NF-NT}$	$AboveC_{NF-NT}$	$SoilC_{NF-NT}$	$AboveC_{NF-NT}$	$SoilC_{NF-NT}$	$AboveC_{NF-NT}$
10 years rotation															
Bare land	0.7	18.8	0.0	20.1	0.3	-	-	-	-	1.3	0.3	-	-	-	-
Grass land	1.2	70.6	2.9	73.7	1.3	-	-	-	-	3.1	0	-	-	-	-
Shrub land	1.5	87.7	10.7	90.4	3.4	-	-	-	-	2.7	0	-	-	-	-
Total	3.4	177.1	13.6	184.2	5.1	-	-	-	-	7.1	0.3	-	-	-	-
30 years rotation															
Bare land	0.7	18.8	0.0	21.0	2.0	-	-	-	-	2.3	2.0	-	-	-	-
Grass land	1.2	70.6	2.9	73.8	16.7	-	-	-	-	3.2	13.9	-	-	-	-
Shrub land	1.5	87.7	10.7	90.6	22.8	-	-	-	-	2.9	12.1	-	-	-	-
Total	3.4	177.1	13.6	185.4	41.6	-	-	-	-	8.4	28.0	-	-	-	-
50 years rotation															
Bare land	0.7	18.8	0.0	21.3	7.4	21.3	7.2	21.3	7.1	2.5	7.4	2.5	7.2	2.5	7.1
Grass land	1.2	70.6	2.9	73.9	35.1	73.9	34.5	73.9	33.9	3.3	32.2	3.3	31.6	3.3	31.0
Shrub land	1.5	87.7	10.7	90.3	42.5	90.3	41.8	90.3	41.2	2.6	31.8	2.6	31.1	2.6	30.4
Total	3.4	177.1	13.6	185.5	85.0	185.5	83.6	185.5	82.2	8.4	71.4	8.4	70.0	8.4	68.6
100 years rotation															
Bare land	0.7	18.8	0.0	22.4	21.8	22.4	20.6	22.4	19.5	3.7	21.8	3.7	20.6	3.7	19.5
Grass land	1.2	70.6	2.9	75.0	74.0	75.0	70.0	75.0	66.3	4.4	71.1	4.4	67.1	4.4	63.4
Shrub land	1.5	87.7	10.7	90.5	83.8	90.6	79.5	90.6	75.4	2.8	73.1	2.8	68.8	2.8	64.6
Total	3.4	177.1	13.6	187.9	179.5	188.0	170.1	188.0	161.2	10.8	165.9	10.9	156.5	10.9	147.6
150 years rotation															
Bare land	0.7	18.8	0.0	24.0	32.8	24.0	30.2	23.9	27.8	5.2	32.8	5.2	30.2	5.2	27.8
Grass land	1.2	70.6	2.9	77.1	100.9	77.1	92.7	77.0	85.5	6.5	98.1	6.5	89.8	6.4	82.6
Shrub land	1.5	87.7	10.7	92.3	113.7	92.3	104.6	92.2	96.4	4.5	103.0	4.6	93.9	4.5	85.7
Total	3.4	177.1	13.6	193.3	247.5	193.4	227.5	193.1	209.7	16.2	233.9	16.3	213.9	16.0	196.1

4. Discussion

The Amhara region in Ethiopia has an estimated area potentially suitable for reforestation of about 3.4 million ha or 22% of the total land area (Figure 2). Considering the current forest coverage of about 250,000 ha, which is less than 2% of the Amhara region [14], the potential is great and reforestation in the region could substantially contribute to the suggested REDD activities within Ethiopia. Note that Amhara represents 14% of Ethiopia's land area but could contribute around 20% of Ethiopia's 2030 target for afforestation with 16.1 Mha [27].

Any successful implementation of the proposed potential reforestation areas will depend on a practical implementation plan. We suggest the implementation of the Normal-forest approach (e.g., equal share of area by age according to a pre-defined rotation period) and improvements of the forest management regulations and a clarification of the forest user rights [28]. Furthermore, important factors determining forest productivity and thus carbon sequestration potential are (i) site elevation and the associated climatic conditions; (ii) initial land use as an indicator for soil degradation; as well as (iii) forest management [69–72].

In Amhara, the Midlands (elevation range from 1800 m to 2300 m) and especially the Highlands (2300 m to 3200 m) are the most productive, but also highly populated areas, versus the sparsely populated Lowlands (500 m to 1800 m) and Alpine areas (>3200 m). Our recommendations in focusing on reforestation activities at elevations between 1800 m and 3200 m is in line with common practices since already established forest plantations are mainly in the Midlands and Highlands [11,73]. Aridity and frequent fires limit forest growth in the 'Combretum-Terminalia woodland and wooded grassland' of the Lowlands (see Figure 2 and Equations (1) and (2) for Aridity index, a measure for water stress). Forest plantations in this Lowland vegetation belt would be jeopardized by severe water stress, followed by salinity problems, by free livestock grazing [74] and a dense layer of tall grasses. Drought together with a dense grass layer promotes forest fires in the Lowlands, which may occur several times per year [38]. Thus, only so called 'exclosures' [15,75], which are fenced and guarded areas with natural regeneration and no or reduced grazing may help to restore the woodland areas in the Lowlands [76]. Unfortunately, it is especially the Combretum-Terminalia woodlands that are suffering from recent deforestations [27].

Within the determined suitable elevation belt for reforestation in Amhara region, the Highlands show higher NPP and aboveground as well as soil carbon stocks versus the Midlands (Tables 2–4). These productivity variables are also higher on wet versus dry sites, for example, agro-ecology 'wet' vs. agro-ecology 'dry'. This indicates that the climatic condition in the Highland-wet zone induces less drought stress and favors vegetation growth [77]. Another observed effect is the trend in the contribution of soil carbon storage to the total storage across the moisture gradient. Both in Midlands and Highlands, and similarly for all initial land use types, the contribution of net soil carbon stock to the total net carbon stock is highest in dry conditions (compare Tables 3 and 4). Dry conditions result in a reduction of forest growth and the decomposition processes, the former leading to lower aboveground carbon storage, the latter to higher carbon accumulation in the soil.

The estimated 3.4 Mha of ecologically suitable reforestation areas include different current land use types, namely, 0.7 Mha (Million hectares) of bare land, 1.2 Mha of grass land, and 1.5 Mha of shrub land (Figure 2). The land use distribution follows regional topographic conditions and climatic patterns (Figure 1). This confirms previous findings from several studies [38,78–80], which demonstrated that the crop production and other farming activities (grazing etc.) follow vegetation patterns and thus are a constraint by ecological growing conditions.

Although differences among agro-ecological zones (Tables 3 and 4) may be more pronounced than differences between the three land use types, interesting differences in soil and above ground soil carbon sequestration among the three land use types could be revealed. Under comparable climate conditions, reforestation on bare land exhibits lower productivity rates (NPP and aboveground carbon storage) (Tables 2 and 3) versus the other land use types. We can expect that these sites have experienced the highest degradation effects, as expressed by the lowest initial soil carbon and especially nitrogen stocks (compare Table 1). However, reforested areas on bare land showed the highest relative or net carbon and nitrogen gain (Figure 3) versus reforested grass land and shrub land (see Tables 3 and 4). This suggests that the reforestation of bare land is not just important for avoiding further soil erosion but it is also the land use type where the highest net soil carbon gain can be expected. The highest net carbon gain of the aboveground biomass can be expected for reforested areas on shrub land and grass land, versus bare land (Tables 3 and 4). These areas are often highly populated and replanting activities in these areas would address the high demand for fuel wood and timber. Some existing small-scale plantations could already show that this is possible, providing more timer and fuel wood for the local population and reduced pressure on the remaining forests [34].

In our study, we identified 1.2 Mha of grassland suitable for reforestation; however a potential land use conflict should not be ignored. Grass land is mainly used as a feed source for livestock. A study by Tschopp et al. [81] in the highlands of Ethiopia showed that more than half of interviewed farmers (58%) grazed their animals on communal grass land. Livestock numbers and thus the demand for grazing land increases with an increasing population [81] while grassland is increasingly converted to crop land, either illegally or legally by government initiatives to feed the fast growing Ethiopian population (2.5% increase per year) [82].

Any successful reforestation project must be simple and should include a forest management plan that integrates harvesting options. Forest management strategies that address both the local people's wood demand and a maximum carbon sequestration potential are an effective incentive for large-scale reforestation programs [83]. Therefore, we analyzed three thinning scenarios (unthinned, thinning 1–5% every 20 years, and thinning 2–10% every 20 years) and a Normal-forest system with different rotation lengths.

In all applied thinning scenarios, the aboveground and soil carbon stock increased compared to the initial stock (Figure 3), indicating a gain in soil fertility (Figure 3). Thinning allows the harvest of a certain portion of biomass [18]. Lowered stand density reduces competition, improves the light conditions, and activates decomposition processes, which leads to higher individual growth rates. Note that the thinning impact on the soil conditions by scenario is negligible (Tables 3–6).

An important conceptual goal of our study was to provide a long term implementation path for establishing sustainable forest management, including options for a sustainable production and continuous wood supply [84] for the farmers in the region. Practical considerations at the beginning of a large reforestation program need to involve the limitations in the production of planting material, education, and limitation in the work force [85]. Furhtermore the weather conditions at the time of and preceding the planting activity planting are important (i.e., to avoid local droughts and only plant when soils are well saturated). In our study we suggested to expand the planting activities over several years. This helps to organize the logistics but also establishing the proposed 'Normal-forest' system. This approach will also provide a patchy forest landscape of different development stages, which favors biodiversity [86].

We provide examples (see Table 5) for the expected gain in biomass by different rotation lengths and land use forms. It is clear that the rotation length will affect both the gross and the net aboveground carbon stock ($AboveC_{NF}$ in Table 5), and therefore the total sequestration potential of reforestation in Amhara (see Table 6). The current CO_2 emissions from forestry are estimated to be 55 Mt CO_{2e} year^{-1} [26], which is an equivalent of 15 Tg C year^{-1}. Our proposed reforestations in Amhara have the potential to sequester between 159 Tg C (thinning 2) and 177 Tg C (no thinning) within 100 years (100 year rotation Normal-forest system, compare Table 6). This would balance more than 10% of the annual CO_2 emissions from forestry or around 4% of the total emissions in Ethiopia. Prolonging the rotation period to 150 years increases the carbon sequestration by 5–6%, depending on the thinning intensity. Clear cutting and replanting the forest stands after 50 years would reduce the sequestration potential to less than 2% of the emissions from the forestry sector. It is important that if the potential reforestation area is reforested according to the 'Normal-forest' approach (step wise annual reforestation of an area calculated as the total potential area divided by the chosen rotation length), any further net carbon sequestration from that forest area can only be attributed to the soil (compare with Figure 3 and Table 3), because the areas where trees are cut and replanted is equal.

Beside the replanting activities, a cascading use of wood should be promoted to build up an anthropogenic carbon storage pool with a considerable additional storage potential, where even a substitution for fossil fuel burning may be considered [87]. Thus, the fate of the cut timber decides the potential for additional carbon storage, whether the timber is burnt directly or whether the timber is stored in wood products. Higher above ground carbon stocks resulting from an increase in rotation length also lead to thicker trees and thus a wider potential use. While short rotation forestry, as is typical in private small-scale plantations of Ethiopia [88], mainly produces fuelwood, with increasing rotation length the production of saw timber will increase and more carbon will be sequestered.

5. Conclusions

Ethiopia has ambitious reforestation goals, aiming at increasing the forest area of 16.1 Mha by 2030. In our study, we show that the Amhara region of north-western Ethiopia has a potential of 3.4 Mha (22% of Amhara) of bare land, grass land, and shrub land, which are ecologically potentially suitable for reforestation. The proposed reforestation directly supports the REDD+ goals and directly meets the sustainable development goals (SDG) of the United Nations [89]. Our study suggests a re-establishment of forests based on the 'Normal-forest system'. If successful, the replanted forest could balance in a 100 year rotation scheme about 10% of the annual carbon emissions from forestry or 4% of the total emissions in Ethiopia. However to ensure the long term reforestation success, resolution for land use conflicts and careful implementation plans for reforestation and sustainable forest management must be put in place. We consider a controlled and sustainable harvesting within the replanted areas by the local population that gives the people immediate benefits and increases the acceptance of the plantations, as a key for the long term success of the established forests.

Author Contributions: B.B. developed the concept for the selection the reforestation areas, did the model runs including the scenario analysis, and wrote the first draft of the manuscript; E.P. helped with the design of the scenarios, the model runs and their interpretation and improved the manuscript; and H.H. designed the project, coordinated and supervised the analysis and the manuscript writing.

Funding: This research was funded by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, grant number BMLFUW-UW.1.3.2/0122-V/4/2013.

Acknowledgments: This work is part of the project 'Carbon storage and soil biodiversity in forest landscapes in Ethiopia: Knowledge base and participatory management'. We are grateful for the financial support provided by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management. We thank the Amhara Regional Agricultural Research Institute in hosting the research project and helping with the field work.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Pan, Y.; Birdsey, R.A.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Shvidenko, A.; Lewis, S.L.; Canadell, J.G.; et al. A large and persistent carbon sink in the world's forests. *Science* **2011**, *333*, 988–993. [CrossRef] [PubMed]
2. Chuai, X.; Huang, X.; Wang, W.; Zhao, R.; Zhang, M.; Wu, C. Land use, total carbon emissions change and low carbon land management in Coastal Jiangsu, China. *J. Clean. Prod.* **2015**, *103*, 77–86. [CrossRef]
3. Deng, L.; Zhu, G.; Tang, Z.; Shangguan, Z. Global patterns of the effects of land-use changes on soil carbon stocks. *Glob. Ecol. Conserv.* **2016**, *5*, 127–138. [CrossRef]
4. Achat, D.L.; Fortin, M.; Landmann, G.; Ringeval, B.; Augusto, L. Forest soil carbon is threatened by intensive biomass harvesting. *Sci. Rep.* **2015**, 1–10. [CrossRef] [PubMed]
5. Berihu, T.; Girmay, G.; Sebhatleab, M.; Berhane, E.; Zenebe, A.; Sigua, G.C. Soil carbon and nitrogen losses following deforestation in Ethiopia. *Agron. Sustain. Dev.* **2017**, *37*. [CrossRef]
6. Girmay, G.; Singh, B.R.; Mitiku, H.; Borresen, T.; Lal, R. Carbon stocks in Ethiopian soils in relation to land use and soil management. *Land Degrad. Dev.* **2008**, *19*, 351–367. [CrossRef]

7. Meshesha, D.T.; Tsunekawa, A.; Tsubo, M.; Ali, S.A.; Haregeweyn, N. Land-use change and its socio-environmental impact in Eastern Ethiopia's highland. *Reg. Environ. Chang.* **2014**, 757–768. [CrossRef]
8. Miheretu, B.A.; Yimer, A.A. Land use/land cover changes and their environmental implications in the Gelana sub-watershed of Northern highlands of Ethiopia. *Environ. Syst. Res.* **2018**, *6*, 7. [CrossRef]
9. Assefa, D.; Rewald, B.; Sandén, H.; Rosinger, C.; Abiyu, A.; Yitaferu, B.; Godbold, D.L. Deforestation and land use strongly effect soil organic carbon and nitrogen stock in Northwest Ethiopia. *Catena* **2017**, *153*, 89–99. [CrossRef]
10. Belay, B.; Pötzelsberger, E.; Sisay, K.; Assefa, D.; Hasenauer, H. The Carbon Dynamics of Dry Tropical Afromontane Forest Ecosystems in the Amhara Region of Ethiopia. *Forests* **2018**, *9*, 18. [CrossRef]
11. Zeleke, G.; Hurni, H. Implications of land use and land cover dynamics for mountain resource degradation in the northwestern Ethiopian highlands. *Mt. Res. Dev.* **2001**, *21*, 184–191. [CrossRef]
12. Kassa, H.; Dondeyne, S.; Poesen, J.; Frankl, A.; Nyssen, J. Agriculture, ecosystems and environment impact of deforestation on soil fertility, soil carbon and nitrogen stocks: The case of the Gacheb catchment in the White Nile Basin, Ethiopia. *Agric. Ecosyst. Environ.* **2017**, *247*, 273–282. [CrossRef]
13. Houghton, R.A. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus* **1999**, *51B*, 298–313. [CrossRef]
14. Sisay, K.; Thurnher, C.; Belay, B.; Lindner, G.; Hasenauer, H. Volume and Carbon Estimates for the Forest Area of the Amhara Region in Northwestern Ethiopia. *Forests* **2017**, *8*, 122. [CrossRef]
15. Mekuria, W.; Langan, S.; Johnston, R.; Belay, B.; Amare, D.; Gashaw, T.; Desta, G.; Noble, A.; Wale, A. Restoring aboveground carbon and biodiversity: A case study from the Nile basin, Ethiopia. *For. Sci. Technol.* **2015**, *11*, 86–96. [CrossRef]
16. Amare, D.; Mekuria, W.; T/wold, T.; Belay, B.; Teshome, A.; Yitaferu, B.; Tessema, T.; Tegegn, B. Perception of local community and the willingness to pay to restore church forests: The case of Dera district, northwestern Ethiopia. *For. Trees Livelihoods* **2016**, *8028*, 1–14. [CrossRef]
17. Hoover, C.M. Management Impacts on Forest Floor and Soil Organic Carbon in Northern Temperate Forests of the US. *Carbon Balance Manag.* **2011**, *6*, 17. [CrossRef] [PubMed]
18. Jandl, R.; Lindner, M.; Vesterdal, L.; Bauwens, B.; Baritz, R.; Hagedorn, F.; Johnson, D.W.; Minkkinen, K.; Byrne, K.A. How strongly can forest management influence soil carbon sequestration? *Geoderma* **2007**, *137*, 253–268. [CrossRef]
19. Bolin, B. *Climate Change 1995: IPCC Second Assessment Report*; 1995, pp. 1–63. Available online: https://www.ipcc.ch/pdf/climate-changes-1995/ipcc-2nd-assessment/2nd-assessment-en.pdf (accessed on 9 July 2018).
20. Reyer, C.; Guericke, M.; Ibisch, P.L. Climate change mitigation via afforestation, reforestation and deforestation avoidance: And what about adaptation to environmental change? *New For.* **2009**, *38*, 15–34. [CrossRef]
21. IPCC. *Land Use, Land-Use Change, and Forestry*; Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J., Dokken, D.J., Eds.; Cambridge University Press: Cambridge, UK, 2000; ISBN 0521800838.
22. UNFCCC. Report of the Conference of the Parties Serving as the Meeting of the Parties to the Kyoto Protocol on Its First Session, Held at Montreal from 28 November to 10 December 2005, Addendum, Part Two: Action Taken by the Conference of the Parties Serving as the Meeting of the Parties to the Kyoto Protocol at its First Session. Available online: http://203.187.160.132:9011/www.scientia.hu/c3pr90ntc0td/klimavaltozas/dok/08.pdf (accessed on 9 July 2018).
23. Zomer, R.J.; Trabucco, A.; Bossio, D.A.; Verchot, L.V. Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agric. Ecosyst. Environ.* **2008**, *126*, 67–80. [CrossRef]
24. IPCC. Climate Change 2007: Synthesis Report. In *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Pachauri, R.K., Reisinger, A., Eds.; IPCC: Geneva, Switzerland, 2007; ISBN 9291691224.
25. FDRE. *Ethiopia's Climate-Resilient Green Economy—Green Economy Strategy*; Federal Democratic Republic of Ethiopia (FDRE): Addis Ababa, Ethiopia, 2011.
26. MEFCC. *Strategic Environmental and Social Assessment (SESA) for the Implementation of REDD+ in Ethiopia—Final Report*; Ministry of Environment, Forest and Climate Change (MEFCC): Addis Ababa, Ethiopia, 2017.

27. MEFCC. *National REDD+ Strategy (2018–2030)*; Ministry of Environment, Forest and Climate Change (MEFCC): Addis Ababa, Ethiopia, 2018.
28. Kissinger, G.; Herold, M.; de Sy, V. *Drivers of Deforestation and Forest Degradation: A Synthesis Report for REDD+ Policymakers*; The Government of the UK and Norway: Vancouver, BC, Canada, 2012.
29. Kreidenweis, U.; Humpenöder, F.; Stevanovi, M.; Bodirsky, B.L.; Kriegler, E.; Lotze-Campen, H.; Popp, A. Afforestation to mitigate climate change: Impacts on food prices under consideration of albedo effects. *Environ. Res. Lett.* **2016**, *11*. [CrossRef]
30. Lemenh, M.; Campbell, B. The role and management of Eucalyptus in Lode Hetosa District, Central Ethiopia. *For. Trees Livelihoods* **2012**, *8028*. [CrossRef]
31. Chanie, T.; Collick, A.S.; Adgo, E.; Lehmann, C.J.; Steenhuis, T.S. Eco-hydrological impacts of Eucalyptus in the semi humid Ethiopian Highlands: The Lake Tana Plain. *J. Hydrol. Hydromech.* **2013**, *61*, 21–29. [CrossRef]
32. Alebachew, M.; Amare, T.; Wendie, M. Investigation of the Effects of *Eucalyptus camaldulensis* on Performance of Neighbouring Crop Productivity in Western. *Open Access Libr. J.* **2015**, *2*. [CrossRef]
33. Joshi, M.; Palanisami, K. Impact of Eucalyptus Plantations on Ground Water Availability in South Karnataka. In Proceedings of the ICID 21st International Congress on Irrigation and Drainage, Tehran, Iran, 15–23 October 2011; pp. 255–262.
34. Vuorinen, P.; Tesemma, M.; Laxen, J.; Hamalainen, J.; Pieper, G.; Hailu, B.; Roba, B.; Bekele, M. *Study of Causes of Deforestation and Forest Degradation in Ethiopia and the Identification and Prioritization of Strategic Pptions to Address those—Final Report*; National REDD+ Secretariat, Ministry of Environment, Forest and Climate Change, The Federal Democratic Republic of Ethiopia: Addis Ababa, Ethiopia, 2016.
35. Amare, D.; Mekuria, W.; Belay, B. Willingness and Participation of Local Communities to Manage Communal Grazing Lands in the Lake Tana Biosphere, Ethiopia. *Soc. Nat. Resour.* **2017**, *1920*. [CrossRef]
36. ECFF. *Ethiopia: Mapping REDD+ Finance Flows 2009–2012—A REDDX National Report*; Environment and Coffee Forest Forum (ECFF): Addis Ababa, Ethiopia, 2013.
37. BoA. *GIS Based Forest Resources Assessment, Quantification and Mapping in Amhara Region*; Bureau of Agriculture (BoA): Bahir Dar, Ethiopia, 2012.
38. Friis, I.; Demissew, S.; van Breugel, P. *Atlas of the Potential Vegetation of Ethiopia Atlas of the Potential Vegetation of Ethiopia*; Nielsen, M.A., Ed.; The Royal Danish Academy of Sciences and Letters: Copenhagen, Denmark, 2010.
39. Running, S.W.; Coughlan, J.C. A general model of forest ecosystem processes for regional applications. *Ecol. Modell.* **1988**, *42*, 125–154. [CrossRef]
40. Running, S.W.; Gower, S.T. FOREST-BGC, A general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. *Tree Physiol.* **1991**, *9*, 147–160. [CrossRef] [PubMed]
41. Thornton, P.E.; Law, B.; Gholz, H.L.; Clark, K.L.; Falge, E.; Ellsworth, D.; Goldstein, A.; Monson, R.; Hollinger, D.; Falk, M.; et al. Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. *Agric. For. Meteorol.* **2002**, *113*, 185–222. [CrossRef]
42. Pietsch, S.A.; Hasenauer, H. Evaluating the self-initialization procedure for large-scale ecosystem models. *Glob. Chang. Biol.* **2006**, *12*, 1658–1669. [CrossRef]
43. White, M.; Thornton, P.E.; Running, S.W.; Nemani, R.R. Parameterization and Sensitivity Analysis of the BIOME–BGC Terrestrial Ecosystem Model: Net Primary Production Controls. *Earth Interact.* **2000**, *4*, 1–85. [CrossRef]
44. Pietsch, S.A.; Hasenauer, H.; Thornton, P.E. BGC-model parameters for tree species growing in central European forests. *For. Ecol. Manag.* **2005**, *211*, 264–295. [CrossRef]
45. Warren, J.M.; Pötzelsberger, E.; Wullschleger, S.D.; Thornton, P.E.; Hasenauer, H.; Norby, R.J. Ecohydrologic impact of reduced stomatal conductance in forests exposed to elevated CO_2. *Ecohydrology* **2011**, *4*, 196–210. [CrossRef]
46. Hidy, D.; Barcza, Z.; Haszpra, L.; Churkina, G.; Pintér, K.; Nagy, Z. Development of the Biome-BGC model for simulation of managed herbaceous ecosystems. *Ecol. Modell.* **2012**, *226*, 99–119. [CrossRef]
47. Ichii, K.; Hashimoto, H.; Nemani, R.; White, M. Modeling the interannual variability and trends in gross and net primary productivity of tropical forests from 1982 to 1999. *Glob. Planet. Chang.* **2005**, *48*, 274–286. [CrossRef]

48. Sisay, K.; Thurnher, C.; Hasenauer, H. Daily climate data for the Amhara region in Northwestern Ethiopia. *Int. J. Climatol.* **2016**. [CrossRef]
49. Thornton, P.E.; Hasenauer, H.; White, M. Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: An application over complex terrain in Austria. *Agric. For. Meteorol.* **2000**, *104*, 255–271. [CrossRef]
50. Enting, I.G.; Wigley, T.M.L.; Heimann, M. *Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses*; CISRO: Aspendale, Victoria, Australia, 1994; Available online: https://www.aimes.ucar.edu/docs/koala.report.pdf (accessed on 9 July 2018).
51. Gamo, M.; Shinoda, M.; Maeda, T. Classification of arid lands, including soil degradation and irrigated areas, based on vegetation and aridity indices. *Int. J. Remote Sens.* **2013**, *1161*. [CrossRef]
52. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements*; FAO Irrigation and Drainage Paper 56; FAO: Rome, Italy, 1998.
53. Trabucco, A.; Zomer, R.J.; Bossio, D.A.; Van Straaten, O.; Verchot, L.V. Climate change mitigation through afforestation/reforestation: A global analysis of hydrologic impacts with four case studies. *Agric. Ecosyst. Environ.* **2008**, *126*, 81–97. [CrossRef]
54. Hargreaves, G.H. Defining and using reference evapotranspiration. *J. Irrig. Drain. Eng. ASCE* **1994**, *120*, 1132–1139. [CrossRef]
55. Mekuria, W.; Aynekulu, E. Exclosure land management for restoration of the soils in degraded communal grazing lands in northern Ethiopia. *L. Degrad. Dev.* **2013**, *24*, 528–538. [CrossRef]
56. Solomon, N.; Birhane, E.; Tadesse, T.; Treydte, A.C.; Meles, K. Carbon stocks and sequestration potential of dry forests under community management in Tigray, Ethiopia. *Ecol. Process.* **2017**, *6*, 20. [CrossRef]
57. Feyisa, K.; Beyene, S.; Angassa, A.; Said, M.Y.; De Leeuw, J.; Abebea, A.; Megersa, B. Effects of enclosure management on carbon sequestration, soil properties and vegetation attributes in East African rangelands. *Catena* **2017**, *159*, 9–19. [CrossRef]
58. Gelaw, A.M.; Singh, B.R.; Lal, R. Agriculture, Ecosystems and Environment Soil organic carbon and total nitrogen stocks under different land uses in a semi-arid watershed in Tigray, Northern Ethiopia. *Agric. Ecosyst. Environ.* **2014**, *188*, 256–263. [CrossRef]
59. FDRE. *Ethiopia—Land Degradation Neutrality National Report*; Federal Democratic Republic of Ethiopia (FDRE): Addis Ababa, Ethiopia, 2015; pp. 1–45. Available online: https://knowledge.unccd.int/sites/default/files/inline-files/ethiopia-ldn-country-report-final.pdf (accessed on 9 July 2018).
60. Tesfaye, M.A.; Bravo, F.; Ruiz-Peinado, R.; Pando, V.; Bravo-Oviedo, A. Impact of changes in land use, species and elevation on soil organic carbon and total nitrogen in Ethiopian Central Highlands. *Geoderma* **2016**, *261*, 70–79. [CrossRef]
61. Gessesse, T.A. Above-and Belowground Carbon Stocks in Semi-Arid Land-Use Systems under Integrated Watershed Management in Gergera Watershed, Ethiopia. Ph.D. Thesis, The University of Bonn, Bonn, Germany, 2016.
62. ADSWE. *Amhara Region Ssoil Depth and Soil Texture*; Amhara Design and Supervision Works Enterprise (ADSWE) - Laboratory Service in Soil Chemistry and Water Quality Section: Bahir Dar, Ethiopia, 2012.
63. Hurni, H. *Agroecological Belts of Ethiopia. Explanatory Notes on Three Maps at a Scale of 1:1,000,000*; Soil Conservation Research Programme Ethiopia: Addis Ababa, Ethiopia, 1998.
64. IPCC. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*; Houghton, J.T., Callander, B.A., Varney, S.K., Eds.; Cambridge University Press: Cambridge, UK, 1992.
65. Dentener, F.; Drevet, J.; Lamarque, J.F.; Bey, I.; Eickhout, B.; Fiore, A.M.; Hauglustaine, D.; Horowitz, L.W.; Krol, M.; Kulshrestha, U.C.; et al. Nitrogen and sulfur deposition on regional and global scales: A multimodel evaluation. *Glob. Biogeochem. Cycles* **2006**, *20*. [CrossRef]
66. Hundeshagen, J. *Die Forstabschätzung auf Neuen Wissenschaftlichen Grundlagen (The Forestry Assessment on New Scientific Foundations, in German)*; H. Laupp: Tübingen, Germany, 1826.
67. Heyer, C. *Die Waldertragsregelung (The Forest Yield Regulation, in German)*; Ferber: Gießen, Germany, 1841.
68. Maliva, R.; Missimer, T. *Arid Lands Water Evaluation and Management*; Springer: Berlin, Germany, 2012; pp. 21–40. [CrossRef]
69. Berthrong, S.T.; Piñeiro, G.; Jobbágy, E.G.; Jackson, R.B. Soil C and N changes with afforestation of grasslands across gradients of precipitation and plantation age. *Ecol. Appl.* **2012**, *22*, 76–86. [CrossRef] [PubMed]

70. Barnes, M.L.; Moran, M.S.; Scott, R.L.; Kolb, T.E.; Ponce-Campos, G.E.; Moore, D.J.P.; Ross, M.A.; Mitra, B.; Dore, S. Vegetation productivity responds to sub-annual climate conditions across semiarid biomes. *Ecosphere* **2016**, *7*, 20. [CrossRef]
71. Josephson, A.L.; Ricker-Gilbert, J.; Florax, R.J.G.M. How does population density influence agricultural intensification and productivity? Evidence from Ethiopia. *Food Policy* **2014**, *48*, 142–152. [CrossRef]
72. Toledo, M.; Poorter, L.; Pena-Claros, M.; Alarco, A.; Balcazar, J.; Lean, C.; Licona, J.C.; Llanque, O.; Vroomans, V.; Balca, J.; et al. Climate is a stronger driver of tree and forest growth rates than soil and disturbance. *J. Ecol.* **2011**, 254–264. [CrossRef]
73. Mekonnen, M.; Sewunet, T.; Gebeyehu, M.; Azene, B.; Melesse, A.M. GIS and Remote Sensing-Based Forest Resource Assessment, Quantification, and Mapping in Amhara Region, Ethiopia. In *Landscape Dynamics, Soil and Hydrological Processes in Varied Climates*; Springer: Basel, Switzerland, 2016; pp. 9–29, ISBN 9783319187877.
74. Chamshama, S.A.O.; Nwonwu, F.O.C. *Lessons Learnt on Sustainable Forest Management in Africa: Forest Plantations in Sub-Saharan Africa*; Sokoine University of Agriculture: Morogoro, Tanzania, 2004.
75. Mokria, M.; Mekuria, W.; Gebrekirstos, A.; Aynekulu, E.; Belay, B.; Gashaw, T.; Bräuning, A. Mixed-species allometric equations and estimation of aboveground biomass and carbon stocks in restoring degraded landscape in northern Ethiopia. *Environ. Res. Lett.* **2018**, *13*, 15. [CrossRef]
76. Lemenih, M.; Kassa, H. Re-greening Ethiopia: History, challenges and lessons. *Forests* **2014**, *5*, 1896–1909. [CrossRef]
77. Rahman, M.S.; Akter, S.; Al-Amin, M. Forest and agro-ecosystem productivity in Bangladesh: A climate vegetation productivity approach. *For. Sci. Technol.* **2015**, *11*, 126–132. [CrossRef]
78. Friis, I.; Gilbert, M.G.; Weber, O.; Demissew, S. Two distinctive new species of *Commicarpus* (Nyctaginaceae) from gypsum outcrops in eastern Ethiopia. *Kew Bull.* **2016**, *71*, 1–19. [CrossRef]
79. Headey, D.; Dereje, M.; Taffesse, A.S. Land constraints and agricultural intensification in Ethiopia: A village-level analysis of high-potential areas. *Food Policy* **2014**, *48*, 129–141. [CrossRef]
80. Taffesse, A.S.; Dorosh, P.; Asrat, S. *Crop Production in Ethiopia: Regional Patterns and Trends. Ethiopia Strategy Support Program II (ESSP II)—Working Paper No. 0016*; International Food Policy Research Institute: Washington, DC, USA, 2011.
81. Tschopp, R.; Aseffa, A.; Schelling, E.; Zinsstag, J. Farmers' Perceptions of Livestock, Agriculture, and Natural Resources in the Rural Ethiopian Highlands. *Mt. Res. Dev.* **2010**, *30*, 381–390. [CrossRef]
82. Mengistu, A.; Kebede, G.; Feyissa, F.; Assefa, G. Review on Major Feed Resources in Ethiopia: Conditions, Challenges and Opportunities. *Acad. Res. J. Agric. Sci. Res.* **2017**, *5*, 176–185. [CrossRef]
83. Jackson, R.B.; Baker, J.S. Opportunities and Constraints for Forest Climate Mitigation. *Bioscience* **2010**, *60*. [CrossRef]
84. Leslie, A.J. A review of the concept of the normal forest. *Aust. For.* **1966**, *30*, 139–147. [CrossRef]
85. Chamshama, S.A.O. *Forest Plantations and Woodlots in the Eastern and North Eastern African Countries—A Regional Overview*; African Forest Forum: Nairobi, Kenya, 2011.
86. Schall, P.; Gossner, M.M.; Heinrichs, S.; Fischer, M.; Boch, S.; Prati, D.; Jung, K.; Baumgartner, V.; Blaser, S.; Böhm, S.; et al. The impact of even-aged and uneven-aged forest management on regional biodiversity of multiple taxa in European beech forests. *J. Appl. Ecol.* **2018**, *55*, 267–278. [CrossRef]
87. Härtl, F.H.; Höllerl, S.; Knoke, T. A new way of carbon accounting emphasises the crucial role of sustainable timber use for successful carbon mitigation strategies. *Mitig. Adapt. Strateg. Glob. Chang.* **2017**, *22*, 1163–1192. [CrossRef]
88. Bekele, M. *Forest Plantations and Woodlots in Ethiopia*; African Forest Forum Working Paper Series; African Forest Forum: Nairobi, Kenya, 2011.
89. UNDP. *Sustainable Development Goals*; UNDP-United Nations Development Programme: New York, NY, USA, 2015.