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

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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.

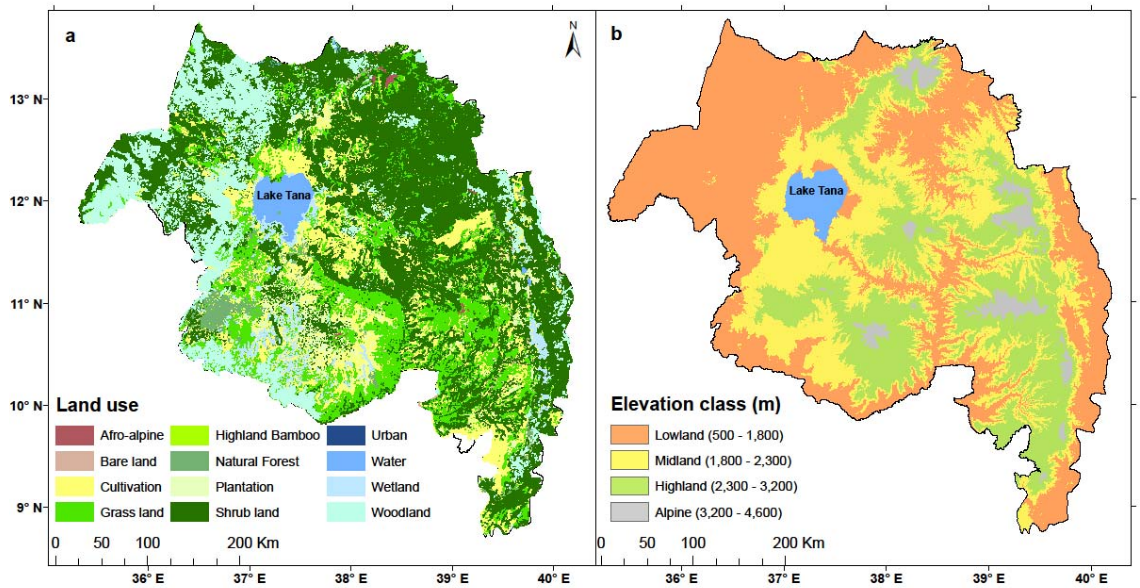

Figure 1. (**a**) Land use, provided by the Bureau of Agriculture [37], and (**b**) elevation class (30 m by 30 m resolution) in the Amhara region in Ethiopia.

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]:

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

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:

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

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

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.

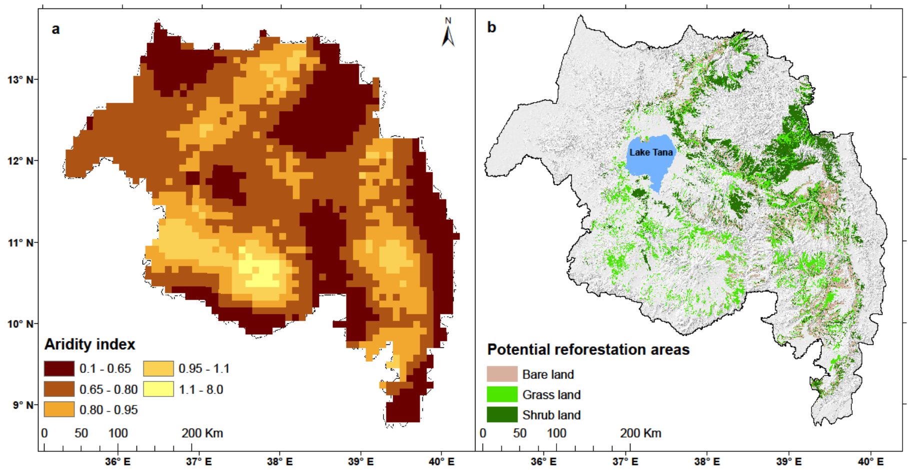

Figure 2. (**a**) Aridity index and (**b**) potential reforestation area in the Amhara Region. Climate data (0.083° resolution) for deriving the Aridity index came from Sisay et al. [48].

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.

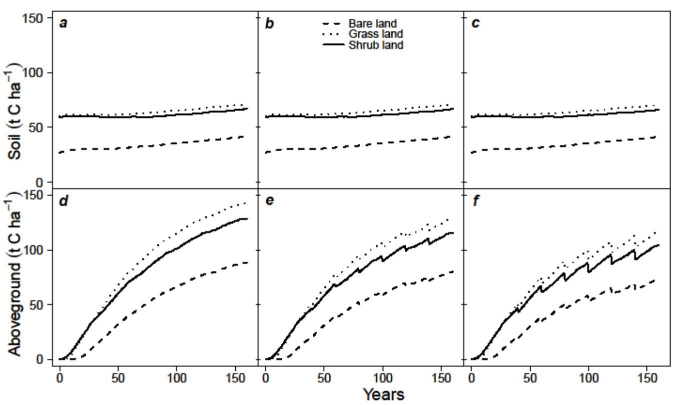

Figure 3. The simulated development of gross soil carbon (**a**–**c**) and gross aboveground carbon (**d**–**f**) over 150 years after reforestation under different management scenarios (unthinned = **a**,**d**; thinning 1 = **b**,**e**; and thinning 2 = **c**,**f**), aggregated per land use type from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

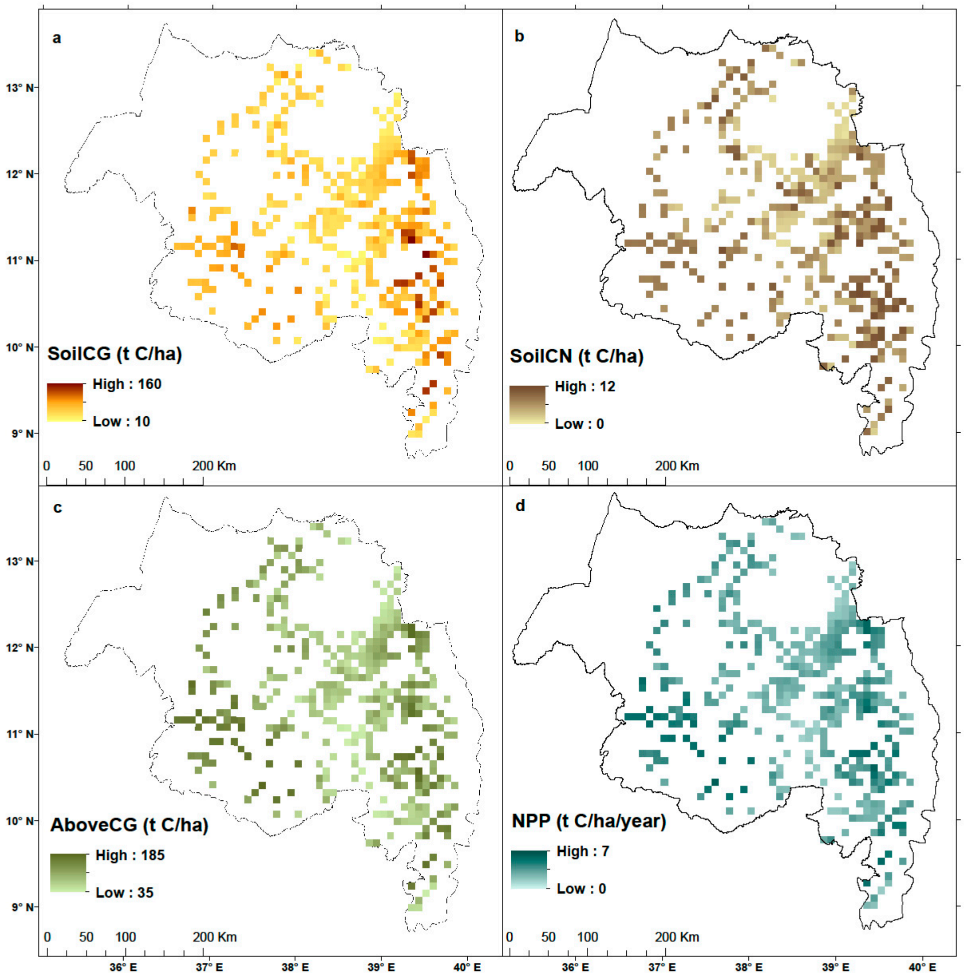

Figure 4. Spatial distributions of predicted soil and aboveground carbon and annual NPP 100 years after reforestation (unthinned) for the selected reforestation areas on the 9 km by 9 km resolution. (**a**) SoilC$_G$—Gross soil carbon stock (t C ha^{-1}); (**b**) SoilC$_N$—Net soil carbon stock (t C 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	
			$SoilC_{NF-G}$	$AboveC_{NF-G}$	$SoilC_{NF-G}$	$AboveC_{NF-G}$	$SoilC_{NF-G}$	$AboveC_{NF-G}$	$SoilC_{NF-N}$	$AboveC_{NF-N}$	$SoilC_{NF-N}$	$AboveC_{NF-N}$	$SoilC_{NF-N}$	$AboveC_{NF-N}$
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.

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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.