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Volume and Carbon Estimates for the Forest Area of the Amhara Region in Northwestern Ethiopia

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Abstract: Sustainable forest management requires a continuous assessment of the forest conditions covering the species distribution, standing tree volume as well as volume increment rates. Forest inventories are designed to record this information. They, in combination with ecosystem models, are the conceptual framework for sustainable forest management. While such management systems are common in many countries, no forest inventory system and/or modeling tools for deriving forest growth information are available in Ethiopia. This study assesses, for the first time, timber volume, carbon, and Net Primary Production (NPP) of forested areas in the Amhara region of northwestern Ethiopia by combining (i) terrestrial inventory data, and (ii) land cover classification information. The inventory data were collected from five sites across the Amhara region (Ambober, Gelawdiwos, Katassi, Mahiberesilasse and Taragedam) covering three forest types: (i) forests, (ii) shrublands (exclosures) and (ii) woodlands. The data were recorded on 198 sample plots and cover diameter at breast height, tree height, and increment information. In order to extrapolate the local terrestrial inventory data to the whole Amhara region, a digital land cover map from the Amhara's Bureau of Agriculture was simplified into (i) forest, (ii) shrubland, and (iii) woodland. In addition, the forest area is further stratified in five elevation classes. Our results suggest that the forest area in the Amhara region covers 2% of the total land area with an average volume stock of 65.7 $m^3 \cdot ha^{-1}$; the shrubland covers 27% and a volume stock of 3.7 $m^3 \cdot ha^{-1}$; and the woodland covers 6% and an average volume stock of 27.6 $m^3 \cdot ha^{-1}$. The corresponding annual volume increment rates are 3.0 $m^3 \cdot ha^{-1}$, for the forest area; 1.0 $m^3 \cdot ha^{-1}$, for the shrubland; and 1.2 $m^3 \cdot ha^{-1}$, for the woodland. The estimated current total volume stock in the Amhara region is 59 million m^3.

Keywords: volume; volume increment; carbon; Net Primary Production (NPP); forest inventory; Ethiopia

1. Introduction

Forest ecosystems provide goods and services [1] and have a higher carbon sequestration potential versus any other terrestrial ecosystems [2]. Deforestation leads to a loss of provided goods and services, induces soil degradation effects and contributes to anthropogenic carbon emissions [3]. Global warming, due to the release of greenhouse gases, is causing unprecedented environmental and social changes. Therefore, the idea of Reducing Emissions from Deforestation and forest Degradation (REDD) was conceived by United Nations Framework Convention on Climate Change (UNFCCC) as the main carbon emission reduction mechanism for developing countries such as Ethiopia [4]. REDD was extended to REDD+ in 2014 by adding the carbon sink potential as well as conservation and sustainable forest management issues [5]. Forest management plays an important role in mitigating impacts of climate change and in sustaining the supply of ecosystem goods and services [6]. Thus, forest inventory data are essential to assess the available forest resources including their productivity potential. They serve as the basic input data for implementing the REDD+ objectives [5].

Forest inventories collect data about forest conditions by estimating the volume, biomass, carbon and net primary production (NPP) [7]. Based on a certain grid design, sampling plots are established to record the forest data. Another option for deriving forest productivity estimates can be obtained from remote sensing information in combination with ecosystem modeling theories. As a result, several studies [8] combine both methods to assess the forest area, species distribution, volume, carbon and NPP [7–12].

Sustainable forest management requires forest inventories. In combination with modeling tools, forest growth information can be derived and sustainable harvesting or cutting plans are developed [13]. While such systems are common in many parts of the world [9], Ethiopia has no standardized forest inventory system in place and no information about the growing stock and increment rates of the limited remaining forest areas available. This lack of information makes sustainable forest management and harvesting difficult or even impossible. A few studies have analyzed the extent of different forest areas and their changes as a result of land use changes [14–20]. These studies are restricted to local forest areas and/or watersheds and provide no information on the forest conditions (e.g., volume or biomass) and/or its change over time (increment rates). In addition, some studies have estimated aboveground biomass and carbon stocks of specific savannah woodland, forest and agroforestry areas [21,22]. However, up until this study, no information is available about the stocking volume, volume increment rates, carbon stocks and NPP for the forest areas in northwestern Ethiopia.

The purpose of this study is to provide a consistent methodology to derive such productivity estimates of different vegetation types in the Amhara region in northwestern Ethiopia. We establish local forest inventories covering different agro-ecological zones and extrapolate these inventory results to the whole Amhara region by obtaining a remotely sensed land cover classification scheme to provide total numbers for the stocking timber volume, volume increment, aboveground carbon, and NPP estimates.

2. Materials and Methods

2.1. Forest Inventrory

2.1.1. Study Area

The Amhara region, in northwestern Ethiopia, has a land area of 15.7 Mha, of which one-third is covered with woody vegetation. For our analysis, we selected study areas covering different agro-ecological zones with typical vegetation types: (i) forests, (ii) shrubland/exclosure, and (iii) woodland.

The selected study areas and vegetation types are Ambober (shrubland), Gelawdiwos (forest), Katassi (forest), Mahibereselassie (woodland), and Taragedam (forest) (Figure 1).

Even though the regional and/or local governments declared these forests as protected, human activities and cattle grazing are still active and common. The Mahibereselassie woodland has the highest cattle population and agricultural activities. The Ambober exclosure is guarded and protected since its establishment in 2009. Human and animal activities are minor at the Gelawdiwos and Katassi sites. The Taragedam forest has a minor anthropogenic disturbance history [18]. The most common types of human activities occurring within these forest areas are cutting and harvesting trees for energy, production of different household and farm implements and clearing for agriculture and grazing activities [23].

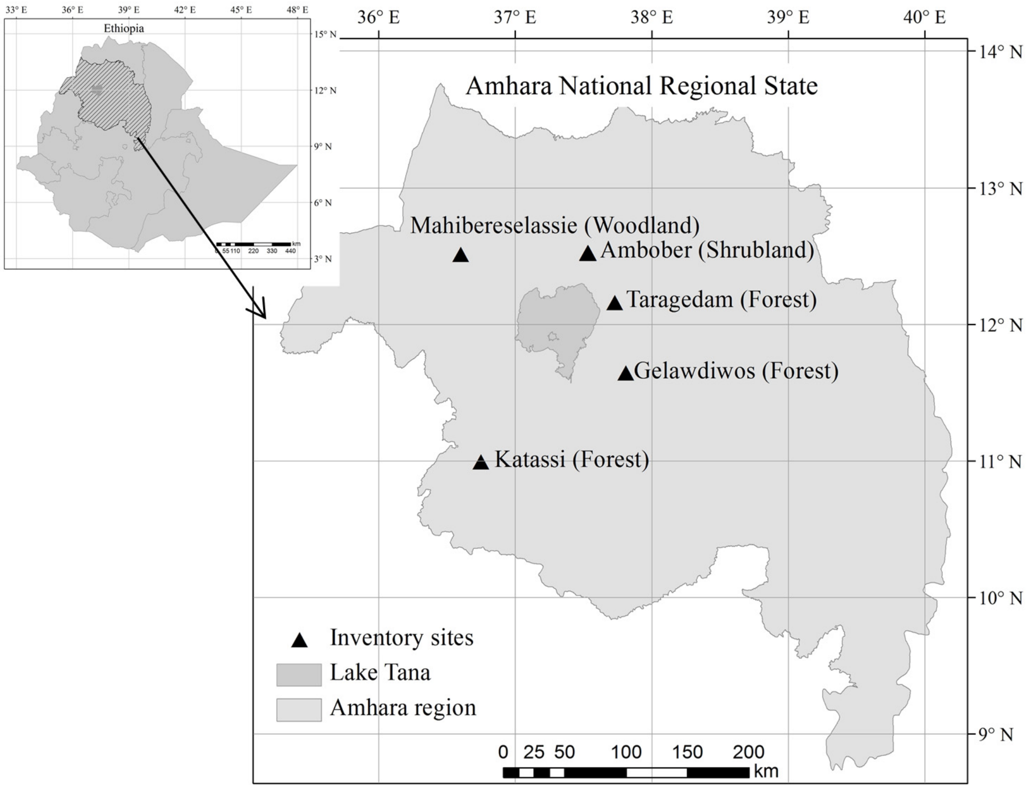

Figure 1. Location of study areas.

2.1.2. Sampling Technique

Our five study regions (see Figure 1) cover the main ecological zones of the area and differ in size: the largest area is the Mahibereselassie woodland with 19,162 ha followed by the forest areas in Katassi (553 ha), Taragedam (324 ha) and Gelawdiwos (68 ha). The Ambober shrubland/exclosure covers 6 ha.

The decision on the grid size, and thus the number of sample plots was derived based on statistical principles by achieving a minimum number of inventory plots. After a number of pilot studies in the different forest inventory areas and test calculations, we defined the following grid size by study region: for the Mahibereselassie woodland area, a 3 km by 3 km grid size with 21 sampling plots was established. For the forest areas in Katassi, a 300 m by 300 m with 63 sampling plots; Taragedam 250 m by 250 m with 52 sampling plots; and for Gelawdiwos, 250 m by 250 m with 34 sampling plots were established. For the Ambober shrubland/exclosure, a 50 m by 50 m sampling design with 28 sampling plots was established. This resulted in a total number of 198 sampling plots. A typical example (Taragedam) is given in Figure 2. The data collection was carried out during the summer 2014 (July to September).

Each sample plot consists of two concentric circles and four rectangular plots (1 m $\times$ 2 m) (see Figure 2). The plot area was corrected as a function of the slope angle [4]. The radius of the larger circle records all trees with a DBH $\geq$ 10 cm and exhibits a radius of 10 m for the study areas in Gelawdiwos, Taragedam, and Ambober and 15 m for Katassi and Mahibereselassie. For each tree found within the specified radial range, we recorded the tree species, diameter at breast height (DBH) in cm, and the tree position on the plot.

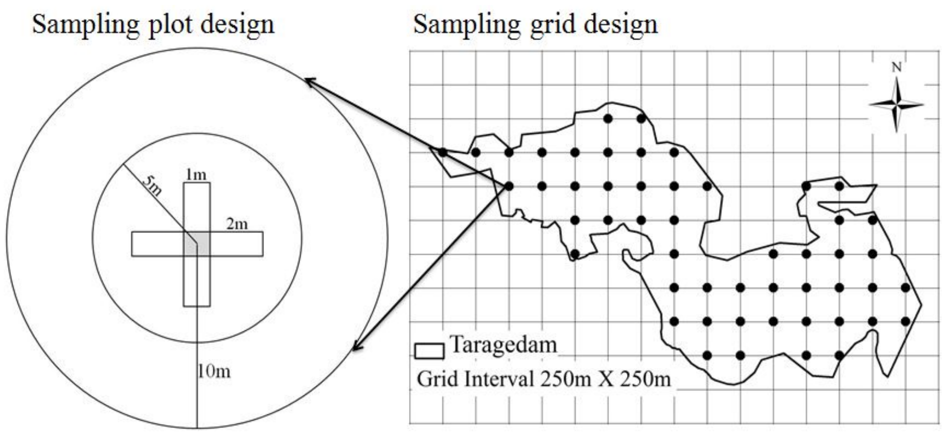

Figure 2. Sampling plot design and sample grid design (Taragedam site). A 10-m radius plot was used in Ambober, Gelawdiwos and Taragedam. A 15-m radius plot was used in Katassi and Mahibereselassie.

One of the important goals of the study is to derive annual growth information. Since we have no repeated tree records, increment cores are taken according to the following procedure: Based on the DBH records on a given sampling plot, we selected the so-called "central" stem or tree—this is the 60 percentile of the DBH distribution—on a given sampling plot. We follow here a procedure suggested by [24], which showed in their studies that the "central" stem represents the "mean" tree (=quadratic mean DBH) on a given plot, and cuts the basal area in two equal halves. The "mean" tree dimension is derived from the per hectare values e.g., the tree represents the quadratic mean DBH (basal area divided by the stem number/ha) and consequently approximately the average volume (volume/ha divided by the stem number/ha). Thus, the growth rates of the "central" stem (60 percentile of the DBH distribution on a given plot) are proportional to the growth rates of the per hectare values assuming that the stem number remains equal for the growth period.

One important precondition of this approach is that each tree ring represents one year. According to Worbes [25] and Zhang et al. [26], distinct tree rings are formed in response to annual precipitation pattern. Sisay et al. [27] confirmed this pattern by showing that the rainy season in the Amhara region is between June and August.

Based on the DBH distribution on a given inventory plot, for each tree species a "central" stem according to the DBH distribution was selected. For this tree, the tree height (h (m)), the height to the live crown base (HLC (m)), and an increment core was taken to derive the ten-year increment rate. Although obtaining full cross-sectional discs may minimize the effect of false and/or missing tree rings [28], destructive sampling (e.g., cutting trees and taking discs to the lab) is forbidden in the area. Moreover, it is neither a requirement nor is it carried out within the scope of routine inventory data collection [29].

For each central plot and species-specific "central" stem, an increment core sample was taken towards the plot center at the DBH to address potential slope effects in the tree form (e.g., ellipse). All sample cores were checked for potentially missing tree rings by comparing the increment core with a so-called "standard" [30], which compares single increment rates of a given core versus so-called "signal" years of the "standard" (>90% of the increment rates increase or decrease versus the previous year). In total, 424 increment cores are available for our study (see Table 1).

Table 1. Summary of the stand characteristics by region, where x is mean, Sd is standard deviation, min is minimum, max is maximum and show the range of the data, and DBH is diameter at breast height.

Variable	Forest			Woodland	Shrubland
	Gelawdiwos x ± Sd (min–max)	**Katassi x ± Sd (min–max)**	**Taragedam x ± Sd (min–max)**	**Mahibereselassie x ± Sd (min–max)**	**Ambober x ± Sd (min–max)**
Number of sample plots	34	63	52	21	28
Number of increment cores	106	196	58	84	-
Number of trees (ha^{-1})	314.5 ± 197.6 (63.7–859.4)	207.1 ± 119.8 (14.1–509.3)	175.1 ± 131.0 (31.8–541.1)	191.4 ± 89.5 (70.7–410.3)	NA
Number of sapling (ha^{-1})	4231.7 ± 3195.8 (0.0–11586.5)	1954.3 ± 1988.6 (0.0–9294.7)	3447.7 ± 3893.1 (0.0–16297.5)	660.9 ± 878.1 (0.0–3310.4)	3676.5 ± 2679.7 (127.3–16170.1)
Quadratic mean DBH (cm)	29.3 ± 12.8 (13.7–73.7)	28.6 ± 14.4 (14.4–111.9)	25.1 ± 13.4 (11.5–69.9)	22.5 ± 4.1 (13.6–31.8)	3.4 ± 0.9 (1.9–6.9)
Tree height (m)	10.2 ± 3.6 (5.1–27.5)	11.0 ± 4.9 (3.5–29.1)	10.5 ± 2.9 (4.2–23.5)	7.7 ± 1.6 (5.0–12.1)	1.9 ± 0.5 (1.7–4.8)

Trees with a tree height >1.3 m and a DBH of <10 cm are considered as saplings and were recorded on the smaller circle with a radius of 5 m. The 5-m radius was applied to all our study areas for recording saplings. Due to the large number of trees, we simplified the design by creating DBH classes ranging from ≤4 cm, 4–6 cm and 7–9.9 cm. We counted all individuals by species and assigned the numbers according to the DBH classes. We selected one representative tree by species and DBH class and recorded the tree height.

All trees with a tree height of ≤1.3 m are seedlings and are recorded on the four 1 m by 2 m rectangular (total 8 m^2) (see Figure 2). Again, the seedlings were grouped in two classes according to tree height: Group 1 (≤50 cm) and Group 2 (50 cm to 1.3 m). The numbers were recorded by species and height class (Table 1).

We recorded the DBH for each tree on a given plot but only the tree height from the central trees. This is a common procedure within routine inventory designs to enhance data collection activities especially in difficult terrain [13,31,32]. However, this approach requires DBH–height functions to derive missing tree heights [31,33]. We also defined the five most frequent tree species within each study area plus a species group "others" and collected at least 20 trees per species, within the study areas (not limited to the plots) covering the full DBH and height range. The only exception was Ambober, where no DBH–tree height data were recorded because the area was covered with shrubs and thus the trees were too small. The Petterson's [34] height–diameter function was chosen to derive missing tree heights:

$$h = \frac{1}{(a_0 + {a_1}/{DBH})^2} + 1.3 \tag{1}$$

where h is the tree height (m) and DBH is the diameter at breast height (cm), a_0 and a_1 are the resulting parameter estimates. We used R standard software package [35] to run non-linear regressions. The results are given in Table 2.

Table 2. Estimated coefficients of Petterson [34] height-diameter function, where N is the number of inventory plots, and R^2 is coefficient of determination.

Species	N	DBH (cm)	Height (m)	Coefficients		R^2
		x ± Sd (min–max)	x ± Sd (min–max)	a_0	a_1	
Acacia abyssinica	50	27.8 ± 10.0 (10.0–55.0)	9.8 ± 3.1 (2.9–20.0)	0.2000	3.8238	0.60
Ameja	28	17.2 ± 4.2 (11.0–29.0)	7.4 ± 1.8 (3.8–10.5)	0.2343	2.8516	0.45
Boswellia papyrifera	33	23.5 ± 4.8 (17.1–37.0)	8.8 ± 1.3 (6.4–12.0)	−0.3113	−1.2048	0.09
Combretum hartmannianum	27	18.5 ± 3.9 (10.0–27.6)	8.9 ± 1.7 (5.2–11.6)	0.2162	2.6838	0.54
Croton macrostachyus	94	18.7 ± 7.9 (10.0–56.0)	10.3 ± 4.4 (4.3–28.3)	0.1818	2.6777	0.43
Eucalyptus camaldulensis	72	24.0 ± 12.8 (10.0–60.0)	16.4 ± 7.8 (4.0–36.3)	0.1589	2.0771	0.60
Juniperus procera	52	27.0 ± 7.3 (11.0–39.0)	12.5 ± 2.8 (4.3–18.5)	0.2473	1.3106	0.19
Lannea fruticose	30	18.3 ± 3.8 (12.0–30.0)	7.6 ± 1.8 (4.7–11.8)	−0.3196	−1.4110	0.08
Olea europaea	27	34.0 ± 21.9 (10.2–103.0)	9.7 ± 4.6 (2.5–28.5)	0.1937	4.6001	0.61
Sterculia setigera	28	28.7 ± 5.7 (16.0–43.0)	8.2 ± 1.0 (6.2–10.3)	−0.3274	−1.4856	0.17
Albizia schimperiana	116	23.1 ± 13.2 (10.0–86.0)	13.0 ± 6.2 (5.3–30.7)	0.1633	2.7559	0.53
Allophylus abyssinicus	35	29.2 ± 12.2 (13.0–54.5)	13.4 ± 4.7 (6.0–23.1)	0.2110	2.0123	0.33
Bugtsi	27	20.6 ± 6.0 (11.0–37.0)	10.8 ± 2.7 (5.7–17.4)	0.2351	1.7723	0.28
Chionanthus mildbraedii	38	49.3 ± 15.8 (11.9–95.0)	14.2 ± 3.9 (4.0–24.2)	−0.2123	−3.0405	0.29
Gimblitini	37	22.0 ± 8.3 (11.0–38.0)	9.2 ± 2.5 (4.6–13.0)	0.2531	2.0776	0.47
Kanabal	37	15.7 ± 4.7 (10.0–28.5)	7.9 ± 2.1 (3.4–11.3)	0.2746	1.7087	0.26
Nuxia congesta	48	15.6 ± 4.1 (10.0–29.0)	8.8 ± 3.2 (3.1–23.1)	0.3273	0.5572	0.01
Podocarpus falcatus	24	20.8 ± 4.9 (12.0–27.0)	13.1 ± 1.7 (9.9–16.2)	−0.2244	−1.3208	0.67
Prunus Africana	42	39.5 ± 20.8 (13.0–132.0)	18.1 ± 6.2 (6.6–34.7)	0.1781	2.2629	0.47
Teclea nobilis	25	21.3 ± 10.5 (10.0–44.0)	9.3 ± 1.7 (7.0–14.4)	−0.3169	−0.6551	0.17
Other Species Gelawdiwos	121	26.0 ± 22.7 (10.0–108.0)	10.4 ± 5.3 (3.5–29.9)	0.2170	2.2612	0.17
Other species Katassi	58	24.1 ± 16.7 (10.0–102.0)	11.1 ± 7.6 (3.8–33.8)	0.1772	3.0084	0.46
Other species Taragedam	33	21.5 ± 17.8 (11.0–114.0)	10.7 ± 4.9 (4.4–28.8)	0.1894	2.6257	0.39
Other species Mahibereselassie	72	21.4 ± 9.5 (10.0–50.0)	8.0 ± 2.7 (3.5–15.9)	0.2514	2.6596	0.33

This dataset is used for calibrating species-specific diameter–height functions for deriving missing tree heights. In total, we recorded more than 1154 trees, of which 870 trees cover the 20 tree species, and 284 trees cover the species groups "other trees" by region.

Timber Volume

Based on the results of Table 2, we calculated the missing tree heights and the corresponding standing timber volume on a given inventory plot. The general formula for deriving standing timber volume for each tree (V) (m^3) can be expressed as [24]:

$$V = \frac{DBH^2 \times \pi}{4} \times h \times f \tag{2}$$

where f is the form factor addressing the shape of the tree, and all other parameters are as previously defined. Since no form factor functions for the tree species in the region exist, we decided to follow the suggestions by [36–38] and use a form factor of 0.5.

Volume Increment

Within sustainable forest management, the assessment of annual volume increment rates is important to ensure sustainable harvesting [13,39]. Up until this point, no such information exists for the forest areas in the Amhara region of northwestern Ethiopia. For our work, we have systematically collected increment cores for all our study regions. As outlined in the sampling technique section, these increment cores were taken from the "central" stem (the mean tree which is approximately the 60 percentile of the DBH distribution) by species on a given plot [24].

After determining the 10-year increment rates (2005 to 2014) with a 0.01 mm precision using the Velmex TA measuring system (Velmex Inc. Bloomfield, New York, NY, USA), the DBH of the "central" stem and inventory plot can be calculated for the year 2005. Applying the DBH–height function (Equation (1)) using the species parameter estimates of Table 2, and inserting in the volume function (Equation (2)), the corresponding volume in 2005 was calculated.

With this information, the volume ratios by plot and tree species can be calculated as:

$$inc_i = \frac{V2005_i}{V2014_i} \tag{3}$$

where inc_i refers to the individual tree volume increment ratio, $V2005_i$ and $V2014_i$ are the timber volume derived from the "central stem" in 2005 and 2014, respectively. Since this tree volume increment ratio is equal to the total volume increment ratio of a given plot, we can multiply the total plot volume V_{2014} with inc_i to derive the plot volume in 2005. With these numbers, we can calculate the 10-year periodic mean annual volume increments (IV) ($m^3 \cdot h^{-1} \cdot year^{-1}$) by inventory plot:

$$IV = \frac{(V_{2014} - V_{2005})}{10} \tag{4}$$

where V_{2014} and V_{2005} are the tree volumes (m^3) in 2014 and 2005, respectively; 10 is the 10-year increment interval. Dead trees due to mortality are included if recorded.

Aboveground Carbon and Carbon Increment

The aboveground carbon estimations through destructive sampling is the most recommended and accurate method [40–42]. Given the small amount of forest resources, the high species diversity and the current forest conservation policy by the state, it is nearly impossible to undertake destructive sampling for the development of allometric functions in Ethiopia as well as for the Amhara region. Thus, we considered existing allometric functions developed for commercial tree species in Ethiopia [43–46]. Since Sileshi [47] has shown that these functions introduce a potential source of uncertainty, especially if applied in a very diverse structured of natural forests, we decided to use the mixed species allometric biomass function developed for tropical forests by Chave et al. [48], which has the following form:

$$ln(AGB) = -2.922 + 0.99 \times ln\left(DBH^2 \times h \times \rho\right), \quad (5)$$

where $ln(AGB)$ is the natural logarithm of the aboveground biomass (kg) and ρ is wood density (ton·m^{-3}).

A wood density of ρ = 0.614 ton·m^{-3} developed for Africa is used [49,50]. A total of 50% of the resulting aboveground biomass (AGB) of Equation (5) provides the final carbon estimates [51,52].

Similar to the volume calculation, we calculated the aboveground biomass and carbon estimates for each tree then at the plot level and finally for each study area. Similar to the periodic mean annual volume increment rates, the periodic mean annual carbon increment rates for the period 2005 to 2014 can be derived. Again, we use here the approach of the "central" tree with the corresponding tree dimensions as outlined in the previous section.

Net Primary Production (NPP)

NPP is the amount of carbon remaining and allocated in the plant parts after autotrophic respiration (cellular and maintenance respiration) per growth period [12,53,54]. The growth period is determined depending on the interval between the repeated measurements which usually vary from 5 to 10 years [12,55]. We calculated NPP (gC·m^{-2}·year^{-1}) as the sum of periodic (2005–2014) carbon accumulation in the fine root turnover, aboveground woody parts and litter fall (Equation (6)) [55,56].

$$NPP = C_{woody} + C_{fineroot} + C_{litter} \quad (6)$$

where C_{woody} (gC·m^{-2}·year^{-1}) is the dry carbon increment of the woody biomass resulting from repeated plot observations between time$_2$ and time$_1$. $C_{fineroots}$ and C_{litter} (gC·m^{-2}·year^{-1}) are the carbon flow in to fine roots and litter, respectively.

The annual aboveground dry carbon in the woody part of the tree (C_{woody}) is calculated as follows:

$$C_{woody} = \left\{ \frac{\left(\frac{g_{2014} - g_{2005}}{10}\right)}{g_{2014}} \right\} \times C_{2014}, \quad (7)$$

where g_{2014} and g_{2005} are the tree basal area (m^2·ha^{-1}) in 2014 and 2005, respectively, 10 is the 10-year increment interval. C_{2014} (gC·m^{-2}) is the aboveground woody dry carbon content in 2014.

For Ethiopia, a reliable model for estimating the proportion of fine root turnover and litter fall does not exist. Malhi [57] and Raich and Nadelhoffer [58] found that for a given time period, the proportion of dry carbon turnover through fine roots and litter fall comprises 60% of the total dry carbon accumulation and that the carbon uptake by fine roots and litter is equal. The proportion of the increment of aboveground dry carbon in the woody part of the tree also comprises 40% of the total dry carbon increment. With this information, we assume that the dry carbon increment in the fine roots and foliage turnovers can be calculated from the dry carbon increment of the aboveground woody biomass. For all trees (DBH $\geq$ 10 cm) and saplings (DBH < 10 cm), the procedure was applied.

2.2. Land Cover Data

The Amhara region in northwestern Ethiopia covers a land area of 15.7 Mha, of which approximately 35% are either forests, shrublands or woodlands. The area is characterized by highly fragmented land use forms and a large variety of growing conditions due to the elevational gradients and the different agro-ecological zones. Mekonnen [17] and Gizachew et al. [59] carried out a land cover classification of the entire Amhara region, however, they failed to provide their methodology and digital data. Therefore, their study could not be verified. Other studies on land use and land cover classification of the Amhara region are limited to small scale areas within the region [14,60–62]. Finally, we obtained the land use and land cover map produced by the office of Amhara National Regional State (ANRS) covering 12 classes with 200 m × 200 m pixel spatial resolution, based on Landsat satellite images (Figure 3). The 12 land cover classes are afro-alpine, bare land, cultivation, grassland, highland bamboo, natural forest, plantation, shrubland, woodland, urban, wetland and water.

We aggregated the 12 land cover classes to six classes based on their vegetation characteristics for fitting our terrestrial inventory land cover types as follows: plantation, highland bamboo and natural forest are grouped as forest. Afro-alpine and shrubland are aggregated into shrubland. Woodland remained as woodland. Bare land, cultivation, grassland and wetland are grouped as non-vegetation. Water and urban classes remained as water and urban, respectively. Our final land cover classes relevant for our analysis are (i) forest, (ii) shrubland, and (iii) woodland. The remaining land cover classes are (iv) non-vegetation areas, (v) water and (vi) urban areas, which are not relevant for our analysis. Figure 3 shows the spatial distribution of land cover classes within the Amhara region.

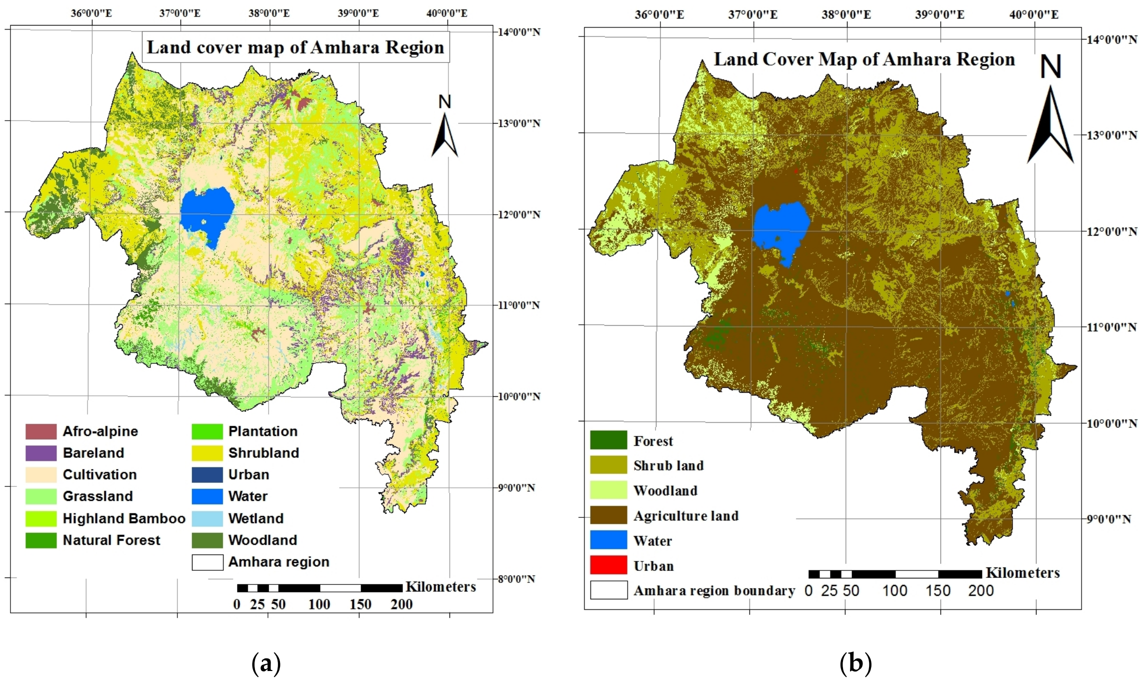

Figure 3. Land cover map of Amhara region (**a**) before land cover aggregation and (**b**) after aggregation of the land cover classes.

The accuracy of our regrouped classified map was evaluated by performing stratified sampling. For land cover classifications, the calculation of the appropriate sample size was computed using the multinomial distribution [63]. With an expected accuracy of 90% and an error probability of 5%, the numbers of samples were determined. In total, 607 stratified sample points were randomly selected and distributed over the areas of the aggregated classes. The class of each of the 607 pixels was assigned with the help of finer resolution reference data combined with visual interpretation [64]. Bing and Google Earth images were used for the independent reference data. Due to the low spatial resolution (200 m × 200 m) of the land cover map and the high land fragmentation in the Amhara region, single pixels are often composed of multiple land cover types. Therefore, we assigned the main (largest areas) class of a pixel as the class (land cover type) of the pixel. Table 3 provides a detailed description of the characterizations of the land cover classes.

Table 3. Land cover classes and characterization features.

Land Cover Class	Characterization Features
Forest	More than or equal to half of the pixel should be first covered with vegetation. The vegetation part was checked for its relative density, color and consistency. If the vegetation is relatively dense and consistently became greater than or equal 1 ha, the class of the pixel is assigned as a forest cover.
Shrubland	Scattered shrubs, bushes: If the half or larger part of the pixel is vegetation with scattered, light green and inconsistent pattern, the class of the pixel is assigned as a shrubland.
Woodland	Woodlands are mainly situated in the northwestern low land parts of Amhara region. The agricultural fields and grass lands in the lowland parts are clearly and easily detectable due to their distinct color and pattern. Woodlands have green and grey color. Unlike to woodlands, shrubs lands have bright color.
Non-Vegetation (Cultivation, Grassland, bare land)	Cultivation: Agricultural fields can be identified with their patterns, proximity to rural resident areas and dark to grey color.
	Grassland: Grasslands appear from bright grey to white areas. It is often between vegetation and agriculture fields.
	Bare land: Similar to grassland but remain grey to white during even the rainy season unlike grasslands.
Urban	Built ups, main roads, bright reflectance.
Water	Lake Tana consists of more than 95% of the water bodies in the Amhara region. The lake is easily detectable. Pond-like structures. Rivers are not included as a water body as they often cover small parts of the 4-ha pixel.

We defined the three simplified forestry relevant land cover classes (see Table 3): (i) forest, (ii) shrubland, and (iii) woodland plus the non-vegetated area. Since elevational gradients are one of the main factors affecting the growing conditions and thus the species distribution of Ethiopian mountains forests [65,66], we adopted Hurni's [67] elevation classes for agro-ecological zonation resulting in five elevation classes: (i) low land (500–1500 meters above sea level (m.a.s.l.)), (ii) mid altitude (1500–2300 m.a.s.l.), (iii) high land (2300–3200 m.a.s.l.), (iv) sub-alpine (3200–3700 m.a.s.l.) and (v) alpine (3700–4530 m.a.s.l.). Then, we assigned the land area derived from Landsat data to each vegetation type and elevation classes.

3. Results

3.1. Terrestrial Inventory

Timber Volume, Aboveground Carbon and NPP

We began our analysis by estimating the height diameter coefficients of the Petterson [34] function using the available tree data (DBH and height measurements) (see Table 1). The results by tree species are presented in Table 2. Next, the plot values for timber volume, aboveground carbon and NPP are calculated and the mean values per hectare plus the corresponding standard deviation by study region are calculated. The mean timber volume ranges from 3.7 $m^3 \cdot ha^{-1}$ (Ambober) to 92.4 $m^3 \cdot ha^{-1}$ (Gelawdiwos). The corresponding mean aboveground carbon values are between 1.11 $Mg \cdot ha^{-1}$ (Ambober) and 54.6 $Mg \cdot ha^{-1}$ (Gelawdiwos). Table 4 provides the results of the stand situation in 2014, the year of the data recording.

The volume increment rates are 3.5 $m^3 \cdot ha^{-1}$ (Gelawdiwos), 3.6 $m^3 \cdot ha^{-1}$ (Katassi) and 1.0 $m^3 \cdot ha^{-1}$ (Taragedam). The mean annual aboveground carbon increments of inventory regions are between 0.22 $Mg \cdot ha^{-1}$ year (Ambober) and 1.9 $Mg \cdot ha^{-1}$ year (Gelawdiwos).

Table 4. Results of the stand situation in 2014.

Region	N	Volume ($m^3 \cdot ha^{-1}$)	Carbon ($Mg \cdot ha^{-1}$)
		x ± sd (min–max)	x ± sd (min–max)
Gelawdiwos	34	92.4 ± 68.1 (6.0–317.4)	54.6 ± 43.6 (2.3–175.4)
Katassi	63	75.9 ± 60.2 (2.5–270.1)	37.7 ± 32.6 (0.0–144.7)
Taragedam	52	28.9 ± 56.5 (0.0–352.8)	13.8 ± 32.7 (0.0–210.4)
Ambober	28	3.7 ± 3.4 (0.3–18.2)	1.11 ± 0.92 (0.1–4.6)
Mahibereselassie	21	27.6 ± 10.7 (7.1–48.5)	11.9 ± 5.2 (2.1–23.7)

The mean NPP of Gelawdiwos forest is 597.2 $gC \cdot m^{-2} \cdot year^{-1}$ followed by Kattassi (486.8 $gC \cdot m^{-2} \cdot year^{-1}$) and Taragedam (305.4 $gC \cdot m^{-2} \cdot year^{-1}$). The NPP at the Ambober shrubland is very low with 55.4 $gC \cdot m^{-2} \cdot year^{-1}$ while the Mahibereselassie woodland NPP exhibited 150.4 $gC \cdot m^{-2} \cdot year^{-1}$. The values for the annual volume and carbon increments and NPP are presented in Table 5.

Table 5. Annual volume increment, carbon increments and Net Primary Production (NPP) of inventory plots by region.

Region	N	Volume Increment ($m^3 \cdot ha^{-1} \cdot year^{-1}$)	Carbon Increment ($Mg \cdot ha^{-1} \cdot year^{-1}$)	NPP ($gC \cdot m^{-2} \cdot year^{-1}$)
		x ± sd (min–max)	x ± sd (min–max)	x ± sd (min–max)
Forest				
Gelawdiwos	34	3.5 ± 2.7 (0.2–11.3)	1.9 ± 1.5 (0.1–6.5)	597.2 ± 393.8 (101.4–1705.5)
Katassi	63	3.6 ± 2.6 (0.0–11.2)	1.7 ± 1.3 (0.0–5.6)	486.8 ± 322.7 (46.5–1306.5)
Taragedam	52	1.0 ± 1.4 (0.0–6.2)	0.5 ± 0.7 (0.0–3.7)	305.4 ± 313.2 (0.0–1506.8)
Shrubland				
Ambober	28	0.9 ± 0.9 (0.0–4.6)	0.22 ± 0.18 (0.02–0.93)	55.4 ± 46.0 (4.8–231.2)
Woodland				
Mahibereselassie	21	1.2 ± 0.5 (0.3–2.6)	0.5 ± 0.2 (0.1–1.1)	150.4 ± 62.9 (61.4–296.2)

3.2. Land Cover Classification

After we have assigned the land cover classes of the 607 pixels, based on the independent reference images, we assessed the accuracy of the map by comparing the land cover map produced by ANRS (Amhara National Regional State) with our independent reference data. The accuracy assessment was applied by using error matrix, according to Olofsson et al. [68], which compares the known reference data with the corresponding results of automated classification [68,69]. Considering the coarse resolution (200 m × 200 m) of the map and the highly land fragmentation within the Amhara region [18], the accuracy of the land cover classification was good (Table 6).

Table 6. Land cover classification accuracy assessment.

Automated Result	Independent Data						Total
	Forest	Shrubland	Woodland	Non-Vegetation	Water	Urban	
Forest	23	1	11	8	1	1	45
Shrubland	19	45	29	28	-	-	121
Woodland	1	20	33	3	-	-	57
Non-vegetation	56	72	27	123	-	-	278
Water	1	-	-	-	99	-	100
Urban	-	-	-	-	-	6	6
Total	100	138	100	162	100	7	607

3.3. The Forest Conditions of the Amhara Region

Fifteen forestry relevant clusters (five elevational classes and three vegetation types) are created. The summary of the results is shown in Table 7.

Table 7. Land cover classes and their respective area by agroecological zones of Amhara region.

Agroecological Zones	Elevation (m.a.s.l.)	Forest (ha)	Shrubland (ha)	Woodland (ha)	Non-Vegetation (ha)	Inventory Sites
Low Land (Kolla)	500–1500	25,098	1,855,284	780,448	1,752,212	Mahibereselassie
Mid Altitude (Weyna Dega)	1500–2300	115,838	1,845,350	131,030	4,643,435	Ambober, Katassi and Taragedam
High Land (Dega)	2300–3200	100,692	473,927	13,621	3,169,069	Gelawdiwos
Sub-Alpine (Wurch)	3200–3700	9354	52,847	5192	355,661	-
Alpine (High Wurch)	3700–4530	104	60,111	93	10,088	-
Total		251,088	4,287,519	930,384	9,930,464	
Grand Total				15,399,456		

We assigned each of our forest inventory areas to the corresponding clusters. The idea here is that we created a kind of a "reference stand approach", where we assumed that regional forest inventory information can be used as a proxy for a given cluster and thus allows us to extrapolate local inventories results (our regional sites) to the whole Amhara region. Considering our regional sites, Mahibereselassie is located in the low land—woodland (500–1500 m.a.s.l.) cluster, Ambober belongs to the mid altitude—shrubland area (1500–2300 m.a.s.l.), Katassi and Taragedam to the mid altitude—forest (1500–2300 m.a.s.l.) and Gelawdiwos to the high land—forest area (2300–3200 m.a.s.l.). Most of the woodland is located in the low land and most of the shrubs are in the elevation class low land and mid altitude. Thus, for the total woodland, we decided to use the results of the forest inventory in Mahibereselassie and for the total shrubland, we decided to use the results of the inventory in Ambober as reference stand information. Most of the forest area is located in the mid altitude and the high land area where our forest inventories in Katassi and Taragedam as well as Gelawdiwos are located. Thus, we decided to create reference productivity values according to the following procedure. We averaged the forest inventory productivity estimates of Katassi and Taragedam. We used these numbers for the low land and the mid altitude clusters. For the remaining elevational classes (high land, sub-alpine and alpine), we used the inventory results of Gelawdiwos as reference numbers. Obtaining the number presented in Tables 5 and 6 and multiplying these numbers with the corresponding land area by vegetation type and elevation class, provides the total productivity estimates for the forested area of the Amhara region (see Table 8).

Table 8. Total volume stock, annual increment, carbon stock, annual increment, and NPP for the Amhara region. The results are obtained through: Total Volume/Carbon = the size of forest areas in elevation classes (Table 7) × corresponding to the mean terrestrial forest inventory volume/carbon estimates (Table 5). We used the mean volume/carbon estimates of Mahibereselassie woodland and Ambober shrubland to extrapolate to the total volume/carbon estimates of woodland and shrubland, respectively found in all elevation classes of the Amhara region.

Land Cover	Volume (million m^3)	Volume Increment (million $m^3 \cdot year^{-1}$)	Carbon (Tg)	Carbon Increment ($Tg \cdot year^{-1}$)	NPP ($gC \cdot m^{-2} \cdot year^{-1}$)
Forest	17.56	0.71	7.78	0.34	484.32
Shrubland	15.86	3.86	4.76	0.95	55.4
Woodland	25.68	1.12	11.07	0.47	150.40

4. Discussion

The Amhara region in northwestern Ethiopia consists of a forested area of about 251,000 ha or 2% of the total land area (15.7 Mha); 4,287,000 ha or 27% of shrubland; and 930,000 ha or 6% of woodland. The total stocking tree volume is 59 million m^3 or 19.1 Tg stored carbon (Tables 7 and 8). Gibbs et al. [70] estimated a total aboveground carbon stock for Ethiopia within a range of 153 to 867 Tg. Note that the total land mass of Ethiopia is about seven times the size of the Amhara region and most of the forest areas are located in the southwestern part of Ethiopia [23].

In our analysis, we estimated, for the forested area (251,000 ha), a stocking timber volume of approximately 17.6 million m^3 and a total carbon of 7.8 Tg with annual volume and carbon increment rates of 0.7 million m^3 and 0.34 Tg, respectively (Table 8). These numbers show that the stocking timber volume and annual productivity rates are fairly low: For example, the volumes of our investigated forests range from 28.9 ± 56.5 $m^3 \cdot ha^{-1}$ in Taragedam to 92.4 ± 68.1 $m^3 \cdot ha^{-1}$ in Gelawdiwos and 75.9 ± 60.2 $m^3 \cdot ha^{-1}$ in Katassi (Table 5). Mokria et al. [40] reported much lower carbon stocks for similar dry afro-montane forests in northern Ethiopia. Compared to other moist afro-montane forests in Southwest Ethiopia [71,72] and Mozambique woodlands [73], our numbers are low. Since the forest sites are highly sensitive, any removal of forest plants leads to erosion problems [18,74], which suggests that careful planning of any harvesting operation is essential to ensure sustainability.

The shrubland area of the Amhara region covers 27% or 4,287,000 ha of the land area in the Amhara region. The estimated total stocking volume is 15.9 million m^3 with an average annual volume increment of 3.86 $m^3 \cdot ha^{-1}$. The total carbon stock stored in the shrublands is 4.8 Tg with 0.95 Tg annual increment (Table 8). The shrubland may be seen as a result of deforestation and cattle grazing activities. In our assessment, the Ambober site provided the reference area for the shrubland assessment. Although the forest inventory covered a rather small area, it may be seen as a typical shrubland in northwestern Ethiopia with an estimated volume stock of 3.7 ± 3.4 $m^3 \cdot ha^{-1}$ and a mean annual volume increment rates of 0.9 m^3 ± 0.9 $m^3 \cdot ha^{-1}$ (Tables 5 and 6).

The Amhara woodland area covers 6% (930,000 ha) of the land area with an estimated total volume and carbon stock of 25.68 million m^3 and 11.1 Tg, respectively. The shrublands exhibited annual volume and carbon increments of 3.86 million m^3 and 0.21 Tg. The inventory in Mahibereselassie served as the reference with a volume stock of 27.6 ± 10.7 $m^3 \cdot ha^{-1}$ and a mean annual volume increment rate of 1.2 ± 0.5 $m^3 \cdot ha^{-1}$ (Tables 5 and 6). Comparing the woodland inventory in Mahibereselassie with the forest inventories in Gelawdiwos, Katassi, and Taragedam (Table 5), one can see that the forest area in Taragedam exhibits a similar stoking volume as the woodland area in Mahibereselassie. This suggests that the historic and current forest management impacts in Taragedam must be high. Wondie et al. [18] showed a strong relationship between population growth and deforestation in the Taragedam area since 1957.

The mean NPP of forests in the Amhara region is 484.3 $gC \cdot m^{-2} \cdot year^{-1}$. The NPP of the shrubland is estimated with 55.4 $gC \cdot m^{-2} \cdot year^{-1}$, while the woodland NPP estimates are with 150.4 $gC \cdot m^{-2} \cdot year^{-1}$ (Table 8).

A literature search revealed that studies in Ethiopia related to biomass and carbon stock are concentrated in the southwestern part of the country where most of the country's larger undisturbed moist montane forests are growing [1,21,45,75]. In contrast, the vegetation types in the Amhara region are fragmented dry-afromontane evergreen forests [40,76–78]. The forest carbon stock decreases from moist to dry vegetation types [70]. Climate, topography and human and animal activity are the main factors for our low productivity estimated numbers versus the moist afro-montane forests [79]. For example, Muluken et al. [65] and Mokria et al. [35] reported carbon stocks above 278.03 $MgC \cdot ha^{-1}$ and 19.3 ± 3.9 $MgC \cdot ha^{-1}$ in southwestern moist-montane community forests and northern dry-afromontane forests in Ethiopia, respectively.

Our aboveground carbon estimations are consistent with estimates provided by Mekuria et al. [80]. The protection of shrublands (=exclosures) from livestock appears to have an important potential to improve vegetation cover and aboveground productivity [23,81,82].

One important result of our study is the development of height–DBH (Diameter at Breast Height) functions for more than 20 tree species in the area for deriving missing tree heights (Table 2) and thus resulting in an easy estimation of tree volume. This substantially improves the data collection in the future, however, we suggest that our calibrated height–DBH functions should be used only within the area where we obtained data for calibration (the Amhara region, Figure 3).

5. Conclusions

For the first time, this study provides forest growth information for the Amhara region as it is essential for sustainable forest management decisions. We developed diameter–height functions for all major tree species in the region. The regional forest inventory data also exhibited tree volume and carbon stocks in combination with the volume and carbon increment data. Prior to this study, no forest productivity information was available and the data collection in the area is extremely difficult. Hence, we selected only five local forest inventories and based our approach on a "reference stand" concept. This assumes that our five established forest inventories cover the key regions and are representative of the remotely sensed vegetation classes (Table 7). With this procedure, we are able to combine regional forest inventory information and remote sensing techniques to provide estimates of the forest productivity in the Amhara region. The methodology is simple and can be easily improved if more local forest inventory data are available. Therefore, this study is critical in pioneering a full forest inventory system in the Amhara region.

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