Regular Article
pISSN: 2288-9744, eISSN: 2288-9752
Journal of Forest and Environmental Science
Vol. 36, No. 1, pp. 25-36, March, 2020
https://doi.org/10.7747/JFES.2020.36.1.25

JFES
Journal of Forest and
Environmental Science

Acacia Dominated Area Exclosures Enhance the Carbon Sequestration Potential of Degraded Dryland Forest Ecosystems

Zenebu Halefom[1], Fassil Kebede[2], Ibrahim Fitwi[3], Zenebe Abraha[3], Girmay Gebresamuel[3] and Emiru Birhane[3,4,*]
[1]*Mekelle Zone Bureau of Agriculture, Mining and Energy, Mekelle 38, Ethiopia*
[2]*Gonder University, College of Agriculture and Veterinery, Gonder 196, Ethiopia*
[3]*Mekelle University, College of Dryland Agriculture and Natural Resources, Mekelle 231, Ethiopia*
[4]*Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås 5003, Norway*

Abstract

Area exclosure is a widely practiced intervention of restoring degraded lands though its impact in sequestering terrestrial and soil carbon is scanty. The study was initiated to investigate the effect of exclosure of different ages on carbon sequestration potential of restoring degraded dryland ecosystems in eastern Tigray, northern Ethiopia. Twelve plots each divided into three layers were randomly selected from 5, 10 and 15 years old exclosures and paired adjacent open grazing land. Tree and shrub biomasses were determined using destructive sampling while herb layer biomass was determined using total harvest. The average total biomass obtained were 13.6, 24.8, 27.1, and 55.5 Mg ha^{-1} for open grazing, 5 years, 10 years, and 15 years exclosures respectively. The carbon content of plant species ranged between 48 to 53 percent of a dry biomass. The total carbon stored in the 5 years, 10 years and 15 years age exclosures were 39 Mg C ha^{-1}, 46.3 Mg C ha^{-1}, and 64.6 Mg C ha^{-1} respectively while in the open grazing land the value was 24.7 Mg C ha^{-1}. Carbon stock is age dependent and increases with age. The difference in total carbon content between exclosures and open grazing land varied between 14.3-40 Mg C ha^{-1}. Although it is difficult to extrapolate this result for a longer future, the average annual carbon being sequestered in the oldest exclosure was about 2.7 Mg C ha^{-1} yr^{-1}. In view of improving degraded area and sequestering carbon, area exclosures are promising options.

Key Words: area exclosure, biomass, carbon sequestration, vegetation, northern Ethiopia

Introduction

Ethiopian population relies heavily on wood and biomass fuel for household energy (Badege and Abdu 2003). Scarcity of firewood has become acute in many parts of the country causing a continuous rise in prices, and thus increasing the economic burden on the household budget. This forced the people to clear forest for domestic use. Also animal dung and crop residues are increasingly being used for household fuel rather than being added to the soil to improve soil fertility. Associated with the environmental changes that resulted from deforestation and poor land management, there has been loss of carbon to the atmosphere which contributed to the climate change (Itana et al. 2011). Soils of the world are potentially sources and sinks for atmospheric carbon depending on the management of

---

Received: January 4, 2018. Revised: December 13, 2019. Accepted: December 15, 2019.

Corresponding author: Emiru Birhane

Mekelle University, College of Dryland Agriculture and Natural Resources, Mekelle 231, Ethiopia
Tel: 251344409018, Fax: 251344409304, E-mail: emiru.birhane@mu.edu.et

ecosystem in place. The concentration of carbon in the atmosphere can be reduced by improving land management. Increasing vegetation cover, introducing minimum/zero tillage, applying crop residue are some of the land management options to enhance terrestrial carbon sequestration (Girmay et al. 2008). Altering land management to increase terrestrial carbon sequestration will often result in additional environmental benefits. However, the type and location of land management activity undertaken can determine to what extent, additional environmental benefits are realized. Upon good soil management and keeping under a natural forest cover, terrestrial ecosystem could serve as a carbon sink. Sequestering carbon in soils and trees is likely to be an essential element of any mitigation scenario that achieve safe climate stabilization, making land restoration works such as exclosures in Ethiopia. The increase in forest resources through protecting the existing forests and bringing back the degraded forest lands is a recommended strategy for mitigating climate change (Pacala and Socolow 2004). To see the role of forests for mitigating climate change estimating and monitoring carbon stocks is a necessary first step (Gibbs et al. 2007). Quantifying biomass stocks in mature and regenerating forests is important for constructing carbon budgets and for designing local policy and management tools designed to sequester and store carbon.

In Ethiopia, throughout the country, various measures aimed at the conservation of natural resources have been undertaken since 1970s. The focus was mainly on implementations of physical soil conservation measures and plantation. The results, however, have been insufficient and didn't address conserving the natural resources base and improving livelihood. As a result, recently, there has been a growing interest to introduce new land management employing area exclosure to address land degradation and biodiversity lose over much of the degraded lands mainly in northern Ethiopia. Exclosure allows degraded lands to rest for several years and this encourages the regeneration of natural vegetation (Bendz 1986). The main objective of such exclosures is to allow native vegetation to regenerate as a way to reduce soil erosion, increase rain water infiltration, and provide fodder and woody biomass (Aerts et al. 2007). Exclosures aim to contribute to the overall objectives of environmental rehabilitation and poverty reduction. Exclosures refer to formerly degraded communal grazing lands that are protected from human and animal interference, to promote natural regeneration of plants and reduce land degradation (Mekuria et al. 2009), and increase the biodiversity of indigenous species. Exclosures have been reported to be effective in restoring native plants (Mengistu et al. 2005; Aerts et al. 2007), improving soil attributes (Mekuria and Aynekulu 2013), and reducing soil erosion (Descheemaeker et al. 2006a, 2006b).

As a result, establishing area exclosures has emerged as one of the mechanisms to restore degraded ecosystem in the central and northern highlands of Ethiopia (Mengistu et al. 2005). Area exclosures are expected to be carbon sinks through increasing plant and soil biomass. Exclosures significantly enhance ecosystem carbon stocks and this increase with age of exclosure (Mekuria et al. 2011). Though there are case studies indicating that exclosures enhance carbon stocks, more studies are required to predict the expected ecosystem carbon sequestration under exclosure. There has been extensive studies on the vegetation regeneration role of exclosures (Tekele 2001; Mengistu et al. 2005; Yami et al. 2006; Wassie et al. 2009; Yayneshet et al. 2009). Restoration impact of exclosures (Asefa et al. 2003; Abebe et al. 2006; Bongers et al. 2006; Descheemaeker et al. 2006b), provide economic benefits (Tilahun et al. 2007; Mekuria et al. 2011). However, all of these studies have been conducted in two-three villages that cannot adequately represent the diversity in soil, slope, exclosure management, climate, and topography in the Ethiopian highlands. In addition, the changes in aboveground biomass and carbon and biodiversity following the establishment of exclosures have not been inventoried systematically at a watershed or landscape level. Moreover the study on carbon sequestration potential of area exclosures is limited. Therefore the objectives of this study were to investigate the impact of area exclosure of different ages on plant biomass and carbon sequestration potential using exclosures as a land rehabilitation model in the degraded dryland of Northern Ethiopia. We hypothesized that exclosures can be effective in sequestering carbon and the rate of sequestration increases with an increase in age of exclosure.

Materials and Methods

Study area

The study area is conducted in Tigray region located at 12o15′ to 14o50′ latitude, and 36o27′ to 39o59′ longitude (Fig. 1). The study area is a region with long history of agriculture, and located in the northernmost part of the country. Most of the region is arid or semi-arid. Due to its varied topographic features, the region has diverse and distinctive agro ecological zones that make it a center of diversity. The vegetation of the region is also diverse, and ranges from Afro alpine to desert. However, the biological resources of the region have been seriously depleted as a result of anthropogenic factors. Land degradation is a notable phenomenon in the region. Some of the natural forest remnants indicate that the northern highlands were once covered with high canopy forest. The main forest relics of the region are found in protected areas near churches and in inaccessible areas such as river gorges, and they are highly fragmented (Aerts et al. 2007). Approximately 37% of the land in the region is agricultural land, followed by shrub land (27%), forest/dense shrub land (19%), bare land (10%), mixed *Boswellia* and other trees (3.5%), grassland (1.8%), *Boswellia* woodland (1.3%) and approximately 0.08% is covered by bodies of water (Debesaye Agricultural Development and Processing Technology Consultancy Plc 2014). The vegetation of the region's highlands is primarily Afromontane forests (White 1983). The dominant species among the natural forest remnants are *Olea europaea* ssp. *Cuspidata and Juniperus procera*, while *Acacia etbaica*, *Euclea schimperi*, and *Dodonea viscosa* are commonly found in degraded forests and exclosures. *Boswellia-Commiphora* woodlands cover most of the western lowlands.

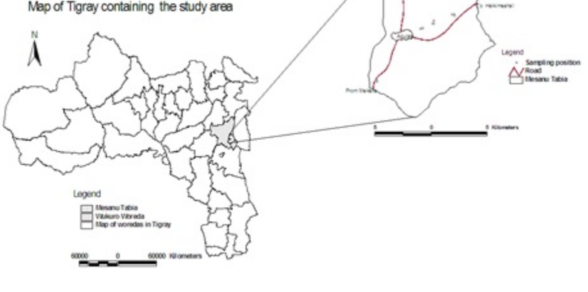

Fig. 1. Location of the study area.

Experimental design

A space-for-time substitution approach was used to monitor changes in biomass, carbon stock and CO_2 stored after conversion of open grazing lands to area exclosures. Three area exclosures having age of 5, 10 and 15 years located adjacent to each other were purposely selected. The implicit assumption of this approach is that grazing land and area exclosures with different age had comparable initial conditions such that changes in biomass, carbon stocks, and carbon dioxide are a consequence of the land use change (i.e. area exclosure establishment).

The criterion for study site selection includes age of area exclosures and the management practice. These aspects bring difference in the rate of forest regeneration and consequently benefits obtained out of it. Furthermore, they influence carbon sequestration. Hence, age is the factor and other physical parameters (slope, soil, geological formation, topography, drainage, and amount of rainfall) and type of management system are assumed to be similar for selected study sites. Consequently three area exclosures which are having the same biophysical and management systems but closed at different years have been purposely identified for this study. Accordingly, young area exclosure with 5 year old or less, medium aged exclosure with 10 years old and old area exclosure with 15 years old were selected. For comparison open grazing /non closed land with the same landscape and climatic characteristic with that of the area exclosures were included in the study. In each exclosure and open grazing land sites, three sampling positions (three plots) were randomly chosen and a plot of 10×10 m, 5×5 m, and 1×1 m size was laid down to study trees, shrubs and herbs respectively (Penman 2003). The latter two quadrate sizes placed inside the 10×10 m quadrant in a nested arrangement. The same plots were used for soil sampling. Overall, with four treatments (three area exclosures with different ages and one open grazing land for comparison) and three replications, a total of twelve samples were taken for vegetation and soil samples.

Total biomass estimation

Stratified random sampling was used to select the sites and sampling plots for total biomass estimation. The area exclosures were stratified by age and in each selected site a replicated sampling plots were identified randomly to collect data on trees, shrubs and herbs. The total biomass was estimated as a sum of biomass of individuals in each layer. Finally, total biomass for each plot was converted to hectare basis.

Regression model was developed to estimate tree biomass. Vegetation inventory was made on 306 individual trees using tree height (H), crown diameter and diameters at stump height (DSH) as parameters to develop the model. For trees forking below 1.3 m but above 0.3 m, DSH was measured at 0.3 m diameter at stump height (DSH, at 0.3 m from the ground). The trees were classified into five diameter classes (<4 cm, 4.1-6 cm, 6.1-8 cm, 8.1-10 cm and >10 cm) based on DSH results to narrow the variation in tree biomass resulted from difference in DSH. Two sample trees were cut from each diameter class representing every site for biomass analysis. All sites did not have same diameter classes, e.g. open grazing land fall only in the first diameter class. Following this, a total of 24 individual trees were harvested from the dominant species. Sample disk was taken from the stem, branch and root of individual trees. The biomass from fine branches and fine roots was harvested with hand sorting.

All sample disks dried in an oven at 65°C until obtaining constant weight. Dry to fresh weight ratio of samples were calculated to estimate total tree dry biomass. Wood density was calculated using volume estimation for irregular shape objects (volume of the object=volume of displaced water). Finally the data was regressed to develop a model applicable to the area. The model was developed using MINITAB software. Biomass estimated by this model was compared with results obtained using existing model Ketterings et al. (2001). Better estimation was found from our model and therefore we used this model for tree biomass estimation. Similar procedures were used as that of above ground biomass to estimate below ground tree biomass

Shrub biomass estimation done by harvesting three individual shrubs per species randomly from all sites and average biomass estimate was taken. For grasses and herbs all species in 1 m×1 m plot was harvested, washed and air dried, and then oven dried at 65°C until constant weight was obtained. The estimated grass and herb biomass was corrected by using the basal area (average of 3 m^2 ha^{-1} of woody species) (Mekuria et al. 2010) because the grasses didn't cover the entire space. Grass and herb samples of each plot were added to estimate grass and herb biomass per site and converted to hectare basis. Similar approach was used for shrub biomass calculations where roots of three individuals per species were harvested from all sites and the average estimated biomass was taken.

Estimation of total biomass and scaling factor

The biomass samples were taken from different layers having difference in area or size of plots that need to convert to same size. Therefore the plot layers were converted to same unit of measurement which is a hectare. To convert into hectare we use scaling factor of 100, 400 and 10,000 for tree, shrub and grass and herb layers respectively. Because trees, shrubs and herbs were inventoried in 100 m^2, 25 m^2 and 1 m^2 respectively. Finally all layers had the same unit and their biomasses were estimated for each sampling plots and study sites. The total biomass was estimated using the calculated biomass of tree, shrub and herb layers (equation 1).

Total biomass=Tree biomass+Shrub biomass+Herb and grass biomass ··1

Plant biomass carbon determination

The total carbon fractions in the plant samples were estimated through conversion of dry tree, shrub, grasses and herbs biomass to ash in the furnace at 550°C for 8 hours. The samples were taken from branches, stems and roots of woody vegetation and from above and below ground parts of grasses and herbs. The organic carbon content was determined from the biomass using oxidation method calculated from organic matter (Armecin and Gabon 2008). From the same materials used for biomass measurement, organic matter and organic carbon contents were estimated separately for the stem, branches and roots based on the method shown in equation 2.

$$\mathrm{OM}\ (\%)=\frac{DM-AM}{DM}\times 100 \text{ and } \mathrm{OC}\%=\frac{\%OM}{1.724} \quad \cdots\cdots\cdots 2$$

Where OM: organic matter, DM: dry mass of the sample at 65°C, AM: ash mass of the sample after combustion in a furnace at 550°C for 8 hours, OC: organic carbon, and 1.724: van Bemmelen factor i.e., OM contains 58 % of OC (Armecin and Gabon 2008). The estimated organic carbon was subsequently used to calculate carbon stock for the sampled species.

Soil sampling and total organic carbon determination

Three pits were dug in each sites and sampling was made from 0-30 cm, 30-60 cm and 60-90 cm soil depths for soil sampling. Hard rock was found in some of the profiles after 30 cm and in some profiles after 60 cm as a result all profiles did not have the same depth. A total of 25 samples were collected for OC, pH and Textural analysis. The collected soil samples were air dried, homogenized and passed through a 2 mm sieve before undertaking chemical analysis. Similarly undisturbed soil samples were collected from each soil depth using core sampler to determine bulk density.

The soil samples subjected to chemical and physical analysis using standard procedures. Texture was analyzed using Boycous hydrometer method after the organic matter was removed by H_2O_2 and the soil be dispersed by sodium hexametaphosphate. Soil organic carbon determined using the Walkley-Black oxidation method. For the determination of bulk density the core samples were dried in oven at 105°C for 24 hours. Weight for the oven dried core sample was taken using sensitive balance, and this data along with the fresh weight was used to calculate bulk density. Bulk density was determined by the core method. Soil Carbon stock (Mg C ha^{-1}) for each sampling depths were computed using equation 3.

$$\text{Carbon stock} = d \times \rho b \times OC \times CFst \times 10 \cdots\cdots\cdots\cdots\cdots\cdots 3$$

Where d=soil layer thickness (m); ρb=bulk density (kg m^{-3}) of each sample depth, OC=carbon concentration (g g^{-1}) of each soil sample, CF_{st} (%)=correction factor for fraction of fragments > 2 mm. Carbon stock of the area exclosures with different ages and the adjacent open grazing land was calculated by summing C stock contained in each depth. Stones and gravel contents were corrected after passing the soil samples through 2 mm sieve.

Estimation of total carbon and carbon sequestration potential

Total carbon was estimated as the sum of the plant biomass carbon and soil carbon stock calculated from each plots of a given site. Plant biomass carbon was determined through conversion of dry biomass to ash and this value was used to calculate total plant biomass carbon. Soil carbon stock calculation was done using equation 3. Carbon sequestration potential was determined through multiplying the total carbon by molar conversion factor of 3.67 (44/12).

Statistical analysis

One-way analysis of variance (ANOVA) was used to test the effect of age of area exclosure and open grazing land on plant biomass, biomass carbon, soil carbon and total carbon stock. The differences in the variables within area ex-

Table 1. Measured vegetation variables for tree biomass model development

DSH (cm)	Tree height (m)	Wood density ($g\ cm^{-3}$)	Total tree dry biomass (kg)
2.2	1.4	1.22	5.4
2.4	1.6	0.74	1.1
3.2	2.4	0.83	3.5
2.1	2.1	1.52	3.9
4.1	2.6	0.76	7.4
5.1	3.45	0.8	13.3
3.8	1.73	0.74	3.7
3.1	2.7	1.63	4.8
5.4	2.0	0.81	10.5
7.2	2.4	0.74	28.5
4.2	2.2	0.76	3.8
7.0	3.55	0.63	19.0
9.0	2.53	0.76	23.5
8.1	3.9	0.51	15.1
5.5	2.2	0.77	17.3
10.5	2.8	0.22	43.4
9.0	2.0	0.51	33.6
9.5	2.7	0.33	38.8
7.0	2.1	0.34	13.5
11.0	3.1	0.33	55.2
3.4	1.3	0.56	2.5
4.8	2.25	0.84	13.1
7.1	2.25	0.67	17.4
3.0	1.15	0.69	3.5

closures, and between age of exclosures and the adjacent open grazing land were assessed using treatment mean difference comparison Tukey HSD (JMP5). When we evaluated the models, the residual plots exhibited heteroscedasticity (i.e. non-constant residual variance) and hence we transformed the data using natural logarithm to account the heteroscedasticity problem.

Results and Discussion

Effect of area exclosure on biomass

Tree biomass

A model was developed based on tree height (H), diameter at stump height (DSH) and wood density (WD), and fitting with DSH (Table 1), resulted in a model given in equation 4, where the Model determination was ($R^2=0.91$, $p=0.000$).

$$TDB=0.554DSH^2-2.044DSH+0.441 \cdots\cdots\cdots\cdots\cdots 4$$

Where; TDB, total single tree dry biomass; DSH, diameter at stump height.

The average tree biomass for 5 years, 10 years and 15 years old area exclosures were 18.9 Mg ha^{-1}, 19.3 Mg ha^{-1} and 42 Mg ha^{-1} respectively (Table 2). The average tree biomass for the open grazing land was 13.6 Mg ha^{-1}. Tree biomass contributed more to the total biomass in all area exclosures as well as in the open grazing land (Table 2). The ratio of tree biomass to total biomass contribution ranged from 71 to 75.7% in area exclosures and 62.5% in open grazing land. Area exclosures showed higher tree biomass compared to the open grazing land ranged between 10.4-33.5 Mg ha^{-1}. Biomass in area exclosures increased with age related to an increase in size of trees in exclosures. This result was in agreement with Mekuria et al. (2010) who found higher biomass in older exclosure than in young ones. However, the increase in tree biomass among area exclosures is not linear as there is no significant difference between 5 years old and 10 years old area exclosures. The difference is boldly shown between 5 years old and 15 years old and, between 10 years old and 15 years old area exclosures. This reflects those tree biomasses gets significantly different and produces better biomass after 15 years old (Table 3).

Table 2. Tree diameter and tree biomass under different ages of area exclosures (AC) and open grazing land (OG)

Land use	Tree diameter range inventoried (cm)	Estimated total tree biomass range (kg/tree)
OG	1.6-4	3.45- 6.18
5 years AC	2-7.5	3.47- 21.35
10 years AC	2.2-8.8	3.55- 30.37
15years AC	3-12.6	4.28- 67.23

Tree biomass is highly dependent on diameter at stump height or diameter at breast height (Table 3). Diameter increase with age of area exclosure and consequently increases tree biomass. The variability in tree biomass is resulted from the variation in DSH. Tree diameter, number of trees or coverage of tree species in a given plot are also determinant factors for tree biomass, total biomass and consequently for total biomass carbon.

Shrub biomass varies between 3.1-8.1 Mg ha^{-1}, lowest in 5 years old exclosure and higher in 15 year old exclosure. Shrub biomass from open grazing was closer to 10 year old exclosure (Table 3). Shrub biomass was significantly higher in 15 years old exclosure than grazing land and exclosures with 5 and 10 years old. This indicated that shrubs are

Table 3. Tree biomass, shrub biomass, grass and herbs biomass and total biomass of area exclosures and grazing land ($n=12$; Mean±SE)

Variable	OG	5 years AC	10 years AC	15 years AC	p-value
Tree biomass (Mg ha^{-1})	8.5 (1.8)^{c}	18.9 (2.7)^{b}	19.3 (1.4)^{b}	42 (2.3)^{a}	<0.0001
Shrub biomass (Mg ha^{-1})	4.2 (2)^{b}	3.1 (1.7)^{b}	4.5 (0.2)^{b}	8.1 (1.7)^{a}	0.018
Herbaceous biomass (Mg ha^{-1})	0.9 (0.2)^{b}	2.7 (0.8)^{ab}	3.4 (0.4)^{ab}	5.4 (1.7)^{a}	0.05
Total biomass (Mg ha^{-1})	13.6 (3.5)^{c}	24.8 (3.2)^{b}	27.1 (1.8)^{b}	55.5 (3.8)^{a}	<0.0001

Values with same letters across the row denote no significant difference.
OG, open grazing land; AC, area exclosure.

dominant during the first few years of establishment of exclosures, with time shrubs will be replaced by trees due to ecological succession. The substantial increase in vegetation biomass within the older area exclosures is a reflection of vegetation succession explained by the increase in abundance and biomass of large shrubs and trees. On the oldest area exclosure, tree biomass and shrub biomass were significantly higher compared to the younger exclosures and open grazing. This shows that age has significant influence on biomass.

The herb biomass was similar for all sites except for the oldest area exclosure. Significant difference was found between open grazing land and 15 years old area exclosure. Though the number is minimum, there is slightly increase in herbaceous species biomass as age increase. This might be due to ecological succession or time of harvest (the grass and herbs layer biomass was harvested during the peak season). At peak season all sites produce high biomass as trees and shrubs in the study site are not broad leaf and the shading effect is not high.

Total biomass varies between 13.6-55.5 Mg ha^{-1} lowers in open grazing land and higher in 15 years old exclosure. Total biomass found in the 15 years old exclosure was significantly higher than younger and open grazing land. On the other hand, total biomass found from the open grazing land is significantly lower than exclosures of different ages ($p < 0.0001$). The reason could be due to increase in total number of tree species and their diameter in the older exclosures. Tree biomass contributes and influences more to the total biomass because of the size. Herbs also contributes significant amount because of their higher coverage. However, shrubs only showed significant difference in the oldest area exclosure compared to the open grazing and this may have less influence on total biomass.

Table 4. Carbon content of studied plant species

Scientific name	Carbon content (%)	Vegetation type
Acacia etbaica Schweinf.	53	Tree
Rhus vulgaris Meikle	53	Shrub
Aloe berhana Tad.	48	Shrub
Carissa edulis (Forssk.) Vahl	52	Shrub
Maytenus senegalensis (Lam.) Exell	52	Shrub
Euclea schimperi (A.D.C) Dandy var.	52	Shrub
Dodonea angustifolia (L.) Jack	50	Shrub
Commiphora africana (A.Rich.) Engl.	50	Tree
Senna singueana. (Del).Lack	50	Shrub
Maytenus arbutiflia (Thunb.) Blakelock	51	Shrub
Shewha (Local name In Tigrigna)	52	Shrub
Grasses and herbs*	52	Understory

*Carbon content of herb layer biomass (not single species).

The effect of area exclosure on carbon stock

Plant biomass carbon

The carbon content of the biomass was in a range of 48 to 53% of the dry biomass (Table 4). The estimated biomass carbon for open grazing land was 7.2 Mg C ha^{-1} while for the 5, 10 and 15 years old area exclosures was 13.3 Mg C ha^{-1}, 14.5 Mg C ha^{-1} and 29.3 Mg C ha^{-1} respectively (Table 5). Biomass carbon was higher in exclosure than open grazing land regardless of age of exclosures. The higher amount of carbon in all area exclosures indicated that area exclosures have a significant positive effect on the restoration of ecosystem carbon even in highly degraded areas. Carbon on tree biomass was significantly higher on the oldest area exclosure compared to the younger and open grazing land ($p < 0.0001$). This is the effect of age on bio-

Table 5. Estimated biomass carbon in area exclosure and the adjacent open grazing land (n=12; Mean±SE)

Variable	OG	5 years AC	10 years AC	15years AC	p- value
Tree biomass carbon (Mg ha^{-1})	4.5 (0.9)^{c}	10.2 (1.4)^{b}	10.5 (0.7)^{b}	22.3 (1.2)^{a}	<0.0001
Shrub biomass carbon (Mg ha^{-1})	2.2 (1)^{a}	1.8 (1)^{a}	2.07 (0.2)^{a}	4.2 (0.9)^{a}	0.26
Herbaceous biomass carbon (Mg ha^{-1})	0.5 (0.1)^{b}	1.4 (0.4)^{ab}	1.9 (0.2)^{ab}	2.8 (0.8)^{a}	0.05
Total biomass Carbon (Mg ha^{-1})	7.2 (1.9)^{b}	13.3 (1.7)^{b}	14.5 (1.1)^{b}	29.3 (2)^{a}	<0.0001

Values with same letters denotes across the row shows no significant difference.
OG, open grazing land; AC, area exclosure.

mass that in turn influences biomass carbon. Similar trend was observed on the total biomass carbon. The difference between area exclosures and adjacent grazing land in biomass carbon across all area exclosure age ranged from 6.1 to 22.1 Mg C ha^{-1}.

The difference in biomass carbon between area exclosures and the adjacent open grazing land could be explained by increase in vegetation cover in the area exclosures and increase in the size and number of tree species. Similarly increase in number of shrub species in area exclosure influenced the biomass carbon. Tree biomass carbon and grass biomass carbon consistently increased with age of area exclosures while there was no significant difference in biomass carbon of shrubs. The influence of age on carbon content was not clearly seen between 5 and 10 years area exclosure; and difference is observed when compared with 15 years old area exclosures.

The carbon stock in the area exclosure and open grazing land is influenced by plant biomass mainly tree biomass, and grass and herb biomass. This is due to higher coverage of herbaceous species providing significant amount of carbon storage and relatively high biomass of tree species. The difference in biomass carbon between area exclosures and the adjacent open grazing land could be explained in different ways. On one hand increased grazing pressure on open grazing land after establishment of area exclosures reduce vegetation cover in grazed land. On the other hand, area exclosures might have reduced the carbon loss by fuel wood consumption because of their protection. Gebreegziabher (2007) reported that fuel consumption from exclosure reduced after exclosure.

Ecosystem carbon storage was also influenced by the age of area exclosures. Since establishment, the relatively increase of ecosystem carbon storage from 5 years to 15 years of area exclosure was slow. This could be due to unfavorable biophysical and climatic condition. The area where the exclosures were established was on limestone dominated area with high alkaline soils. Soils developed from limestone are inherently less fertile and higher pH with low nutrient availability affecting vegetation growth and carbon nutrient building. This could be also possibly a demonstration of vegetation succession and of the partial removal of biomass through harvesting of grass and herbs (Mekuria et al. 2010). Shrub and tree species abundance increase with area exclosure ages resulting in increase in biomass of trees and shrubs (Yayneshet et al. 2009) this in turn influences the biomass carbon.

Soil carbon stock distribution and soil properties

Soil carbon stock observed in 5 years, 10 years and 15 years old area exclosures were 26 Mg C ha^{-1}, 30.7 Mg C ha^{-1} and 35.3 Mg C ha^{-1} respectively and in open grazing land it was 17.5 Mg C ha^{-1} (Table 6). Soil carbon stocks found in exclosures are higher in the range of 11.6 to 25.1 Mg C ha^{-1} than what was found from open grazing land. Soil carbon contributed about 69.9 to 73 % of the total carbon in area exclosures and 76.5% in the open grazing land.

In the present study, there was no statistically significant difference in soil carbon stock between area exclosures and the open grazing land. Although the restoration of natural vegetation and subsequent increase in above and below ground biomass was observed, this was not translated to increasing in soil carbon stock. Several reasons could be responsible for this variation. One could be supply of animal execrate in the grazing area which could contribute to soil carbon content. Addition of soil organic carbon through animal excrements could contribute to achieve comparable carbon storage (Franzluebbers et al. 2001). Hence, livestock can exert both beneficial and detrimental effect on grazing land that can be explained in terms of improving or degrading soil carbon depending up on number of livestock and grazing intensity (Girmay and Singh 2012). Removal

Table 6. Soil carbon stock in area exclosures and adjacent open grazing land (n= 12; Mean±SE)

Variable	OG	5 years old AC	10 years old AC	15 years old AC	p value
Soil carbon (Mg ha^{-1})	17.5 $(8)^{a}$	26 $(3)^{a}$	30.7 $(4)^{a}$	35.3 $(2.8)^{a}$	0.1
Total carbon stock (Mg ha^{-1})	24.7 $(6)^{c}$	39 $(3.6)^{bc}$	46.3 $(3.6)^{ab}$	64.6 $(2.3)^{a}$	0.001

A value with same letters across the row denotes no significant difference.
OG, open grazing land; AC, area exclosure.

of above ground biomass could have also subsequent effect on the reducing litter addition to soils (Burke 1999; Girmay and Singh 2012). Other factor could be related to minimum litter production and supply into the soil by the area exclosures. During the sample collection in the field, we have observed that the vegetation composition was dominated with the same type of species although there was variation in density. Broad leaf trees and shrub species were not common whereas needle leaf and stress resistant dry land species like Acacia etbica are very common species dominantly observe inside area exclosures and the adjacent open grazing land. The other reason could be similarity in soil quality and plant species. Similar to our result, a study in northern Tigray reported that amount of carbon stored in forest is influenced by forest type and soil quality (Girmay and Singh 2012) and soil organic carbon is tree species dependent (Lemma et al. 2006).

SOC and bulk density distribution with soil depth

Soil organic carbon in the area exclosure and open grazing land is determined by soil depth, bulk density (BD), organic carbon (OC) and course fragment (CF) of the soil. The top soil depth (0-0.3 m) showed higher organic carbon content than the two depths (0.3-0.6 and 0.6-0.9 m) (Table 7). The reason is higher OM accumulation in the top soil. Consequently OC significantly varied with soil depth ($p < 0.0001$) where higher was found on top and declines with depth. The same result was reported in the study conducted in the northern Ethiopia (Girmay and Singh 2012). On contrary with this bulk density increase with the soil depth, and the reason could be because of decreasing trend in OM. Hence, bulk density is inversely related with organic. No significant difference was observed in pH and CF with depths.

Total carbon

Total carbon stock in 5, 10 and 15 years exclosures were estimated as 39 Mg C ha^{-1}, 46.3 Mg C ha^{-1} and 64.6 Mg C ha^{-1} respectively. For open grazed land the carbon stock was 24.7 Mg C ha^{-1} (Table 8). Open grazed land had statistically lower total carbon stock than 10 and 15 years exclosures. These variations are reflections of differences mainly in the above and below ground biomass supply and carbon stored in the soil system. Soil carbon contributed relatively higher to the total carbon storage of all sites (i.e. 70.8% for open grazing land and 57 to 67% for area exclosures). The aboveground carbon stock of Dire area rangelands in Ethiopia was 29.5 t C ha^{-1}where as the soil car-

Table 7. Soil physical and chemical properties in relation to soil depth

Depth (m)	BD (g/m^{3})	OC(g/g)	CF(g/g)	SOC (%)	pH	Texture			
						Sand%	Silt%	Clay%	TC
0-0.3	1,193 (26)^{b}	(0.026)^{a}	(0.19)^{a}	(1.8)^{a}	(8.1)^{a}	34.5 (2)^{a}	29.6 (2)^{a}	35.8 (2)^{b}	Clay loam
0.3-0.6	1,269 (28)^{ab}	(0.013)^{b}	(0.2)^{a}	1 (0.09)^{b}	(8.2)^{a}	26.2 (2)^{ab}	28.4 (2.)^{a}	45.4 (2)^{a}	Clay
0.6-0.9	1,373 (51)^{a}	(0.006)^{b}	(0.25)^{a}	0.6 (0.2)^{b}	(8.2)^{a}	24.3 (4)^{b}	28.3 (4)^{a}	47.3 (4)^{a}	Clay
p value	0.01	$<$0.0001	0.07	$<$0.0001	0.055	0.01	0.9	0.003	

A value with different letters along column denotes significant difference.
TC, textural class.

Table 8. Total carbon storage in area exclosures and the adjacent open grazing land (n=12; Mean±SE)

Variable	OG	5 years old AC	10 years old AC	15 years old AC	p value
Total biomass carbon (Mg ha^{-1})	7.2 (1.9)^{b}	13.3 (1.7)^{b}	14.5 (1.1)^{b}	29.3 (2)^{a}	$<$0.0001
Soil carbon (Mg ha^{-1})	17.5 (8)^{a}	26 (3)^{a}	30.7 (4)^{a}	35.3 (2.8)^{a}	0.1
Total carbon stock (Mg ha^{-1})	24.7 (6)^{c}	39 (3.6)^{bc}	46.3 (3.6)^{ab}	64.6 (2.3)^{a}	0.001

A value with same letters in a row denotes no significant difference ($p < 0.05$).
OG, open grazing land; AC, area exclosure.

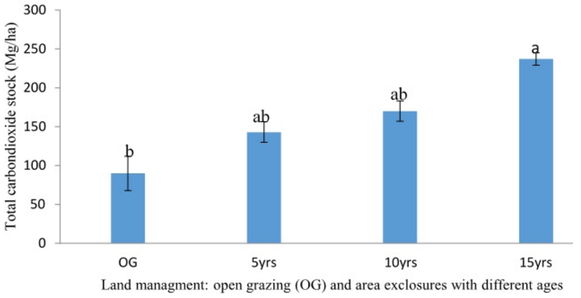

Fig. 2. Estimated total carbon dioxide in the ecosystem in area exclosures and the adjacent open grazing land.

bon stock ranges between 326-394 t C ha^{-1} (Beruer 2012). The magnitude of this figure varies with the extent of rangeland management practices in Ethiopian and elsewhere in the world. Study conducted in selected sites of Borana rangeland, Oromia region shows that there is higher C stock of above ground biomass in exclosure as compared to grazed one (Niles et al. 2010).

In the 15 years old exclosure site about 2.7 Mg C ha^{-1} yr^{-1} of total carbon was sequestered annually since its establishment. This result was comparable with the 1.5 Mg C ha^{-1} yr^{-1} by Abiy (2008), 3.8 Mg C ha^{-1} yr^{-1} by Girmay et al. (2009), 3.1 Mg C ha^{-1} yr^{-1} in 20 years old area exclosure by Mekuria et al. (2010). The slight variation in carbon sequestration could be as a result of variation in agro-ecology where high accumulation of organic matter is often found in highlands than mid lands and lowlands due to low temperature and landscape positions (Lal 2008) and soil quality (Mekuria et al. 2010).

Effect of area exclosure on carbon sequestration potential

The amount of total CO_2e sequestered in area exclosures were 147 CO_2e ha^{-1}, 170 CO_2e ha^{-1} and 237 CO_2e ha^{-1} for 5, 10 and 15 years old area exclosures, and the values are higher than what was found in open grazing land (90 CO_2e ha^{-1}). And the proportion is higher in soils than biomass (Fig. 2). The difference in total carbon dioxide sequestration potential between the two land management systems goes as high as 147 Mg CO_2e ha^{-1}. These results reflect sequestration potentials of area exclosures. The sources for difference/variation in carbon sequestration potential are those that affect carbon storage in the terrestrial system. Exclosures are viable options to restores ecosystem carbon sequestration and working on them is important to establish baseline data for carbon financing projects to benefit from carbon finance premium and encourage farmers/pastoralist to participate in land management practices (Mekuria et al. 2010).

Conclusion

The study showed that the establishment of area exclosures in the study area is a viable option to store significant amount of carbon. Higher biomass and carbon storage was recorded in the oldest area exclosure. Although it is difficult to determine the equilibrium state of carbon dynamics in area exclosures, this study demonstrated that carbon storage increased with increasing age of area exclosure and a relatively high carbon storage was found in 15 years old area exclosure. This implies that the optimum intervention period to gain ecological benefit is in more aged exclosures. However, there is a need for further research to determine the maximum age where higher benefit could be obtained under different landscape and vegetation conditions.

Acknowledgements

The authors gratefully thank Agroecology in practice project based at Mekelle University for sponsoring the study. We also thank Mr. Abebe Damtie, staff of Mekelle University, for his guidance during field and lab work. Mekelle University provides support to carry our part of lab analysis and we are grateful for that. We are grateful to the two anonymous referees for constructive comments on an earlier version of this manuscript.

References

Abebe MH, Oba G, Angassa A, Weladji RB. 2006. The role of area enclosures and fallow age in the restoration of plant diversity in northern Ethiopia. Afr J Ecol 44: 507-514.

Abiy T. 2008. Area closure as a strategy for land management: A case study at Kelala Dalacha enclosure in the central rift valley of Ethiopia. MS thesis. Addis Ababa University, Addis Ababa, Ethiopia.

Aerts R, Negussie A, Maes W, November E, Hermy M, Muys B. 2007. Restoration of Dry Afromontane Forest Using Pioneer Shrubs as Nurse-Plants for *Olea europaea* ssp. cuspidata. Restor Ecol 15: 129-138.

Armecin RB, Gabon FM. 2008. Biomass, organic carbon and mineral matter contents of abaca (*Musa textilis* Nee) at different stages of growth. Ind Crops Prod 28: 340-345.

Asefa DT, Oba G, Weladji RB, Colman JE. 2003. An assessment of restoration of biodiversity in degraded high mountain grazing lands in northern Ethiopia. Land Degrad Develop 14: 25-38.

Badege B, Abdu A. 2003. Agroforestry and Community Forestry for Rehabilitation of Degraded Watersheds in the Ethiopian Highlands. In: Proceeding of EAF International Symposium on Contemporary Development Issues in Ethiopia (Assefa S, Lemi A, eds). Western Michigan University, Addis Ababa, Ethiopia.

Bendz M. 1986. Hill side closures in Wollo. Ethiopian Red Cross Society Mission Report. Ethiopian Red Cross Society, Vaxjo, Sweden.

Bongers F, Wassie A, Sterck FJ, Bekele T, Teketay D. 2006. Ecological restoration and church forests in northern Ethiopia. J Drylands 1: 35-44.

Breuer B. 2012. Effects of vegetation type and species composition on carbon stocks in semi-arid Ethiopian Savannahs. MS thesis. University of Hohenheim, Stuttgart, Germany.

Burke IC, Lauenroth WK, Riggle R, Brannen P, Madigan B, Beard S. 1999. Spatial Variability of Soil Properties in the Shortgrass Steppe: The Relative Importance of Topography, Grazing, Microsite, and Plant Species in Controlling Spatial Patterns. Ecosystems 2: 422-438.

Debesaye Agricultural Development and Processing Technology Consultancy Plc. 2014. Multi Temporal Land Cover Study of Tigray Region. Mekelle, Ethiopia: Tigray National Regional State Bureau of Agriculture and Rural Development, pp 122.

Descheemaeker K, Nyssen J, Poesen J, Raes D, Haile M, Muys B, Deckers S. 2006a. Runoff on slopes with restoring vegetation: A case study from the Tigray highlands, Ethiopia. J Hydrol 331: 219-241.

Descheemaeker K, Nyssen J, Rossi J, Poesen J, Haile M, Raes D, Muys B, Moeyersons J, Deckers S. 2006b. Sediment deposition and pedogenesis in exclosures in the Tigray highlands, Ethiopia. Geoderma 132: 291-314.

Franzluebbers AJ, Haney RL, Honeycutt CW, Arshad MA, Schomberg HH, Hons FM. 2001. Climatic influences on active fractions of soil organic matter. Soil biol Biochem 32: 1103-1111.

Gebreegziabher Z. 2007. Household fuel consumption and resource use in rural-urban Ethiopia. PhD thesis. Wageningen University, Wageningen, Netherlands.

Gibbs HK, Brown S, Niles JO, Foley JA. 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environ Res Lett 2: 1-13.

Girmay G, Singh BR, Mitiku H, Lal BR. 2008. Carbon stocks in Ethiopian soils in relation to land use and soil management. Land degrad and develop 19: 351-367.

Girmay G, Singh BR. 2012. Changes in soil organic carbon stocks and soil quality: land-use system effects in northern Ethiopia. Acta Agric Scand B Soil Plant Sci 62: 519-530.

Itanna F, Olsson M, Stahr K 2011. Effect of land use changes on soil carbon status of some soil types in Ethiopian Rift Valley. Journal of dry lands 4(1): 289-299.

Ketterings QM, Coe R, van Noordwijk M, Ambagau Y, Palm CA. 2001. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. For Ecol Manag 146: 199-209.

Lal R. 2008. Soil carbon stocks under present and future climate with specific reference to European ecoregions. Nutr Cycl Agroecosys 81: 113-127.

Lemma B, Kleja DB, Nilsson I, Olsson M. 2006. Soil carbon sequestration under different exotic tree species in the southwestern highlands of Ethiopia. Geoderma 136: 886-898.

Mekuria W, Aynekulu E. 2013. Exclosure land management for restoration of the soils in degraded communal grazing lands in Northern Ethiopia. Land Degrad and Develop 24: 528-538.

Mekuria W, Veldkamp E, Corre MD, Haile M. 2010. Restoration of Ecosystem Carbon Stocks Following Exclosure Establishment in Communal Grazing Lands in Tigray, Ethiopia. Soil Sci Soc Am J 75: 246-256.

Mekuria W, Veldkamp E, Corre MD, Haile M. 2011. Restoration of ecosystem carbon stocks following exclosure establishment in communal grazing lands in Tigray, Ethiopia. Soil Science Society of America Journal 75: 246–256.

Mekuria W, Veldkamp E, Haile M, Gebrehiwot K, Muys B, Nyssen J. 2009. Effectiveness of exclosures to control soil erosion and local community perception on soil erosion in Tigray, Ethiopia. Afr J Agric Res 4: 365-377.

Mengistu T, Teketay D, Hulten H, Yemshaw Y. 2005. The role of enclosures in the recovery of woody vegetation in degraded dryland hillsides of central and northern Ethiopia. J Arid Environ 60: 259-281.

Niles JO, Cleland E, Gibbs H, Orcutt B. 2010. Carbon finance in Ethiopian rangelands: opportunities for save the children leadership, final TFG report submitted to save the children, Save the children, UK, Addis Ababa, Ethiopia.

Pacala S, Socolow R. 2004. Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. Science 305: 968-972.

Penman J; IPCC. 2003. Good practice guidance for land use, land-use change and forestry. IPCC, Kanagawa, pp 3-178.

Tekle K. 2001. Natural regeneration of degraded hillslopes in Southern Wello, Ethiopia: a study based on permanent plots. Applied Geography 21: 275-300.

Tilahun M, Olschewski R, Kleinn C, Gebrehiwot K. 2007. Economic analysis of closing degraded *Boswellia papyrifera* dry forest from human interventions - A study from Tigray, Northern Ethiopia. Forest Policy Econ 9: 996-1105.

Wassie A, Sterck FJ, Teketay D, Bongers F. 2009. Effects of livestock exclusion on tree regeneration in church forests of Ethiopia. Forest Ecol and Manag 257: 765-772.

White F. 1983. The Vegetation of Africa: a descriptive memoir to accompany the Unesco/AETFAT/UNSO vegetation map of

Africa. UNESCO, Paris, pp 356.

Yami M, Gebrehiwot K, Stein M, Mekuria W. 2006. Impact of area enclosures on desnity, diversity, and population structure of woody species: The case of may Ba' Ati-Douga Tembien, Tigray, Ethiopia. EJNR 8: 99-121.

Yayneshet T, Eik LO, Moe SR. 2009. The effects of exclosures in restoring degraded semi-arid vegetation in communal grazing lands in northern Ethiopia. J Arid Environ 73: 542-549.