



Tropentag 2009  
University of Hamburg, October 6-8, 2009  
Conference on International Research on Food Security, Natural  
Resource Management and Rural Development

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**Carbon stock changes with relation to land use conversion in the lowlands of Tigray, Ethiopia**

Wolde Mekuria<sup>a,b</sup>, Edzo Veldkamp<sup>a</sup> and Mitiku Haile<sup>b</sup>

<sup>a</sup> Buesgen Institute, Soil Science of Tropical and Subtropical Ecosystems, Georg-August University of Göttingen, Büsgenweg 2, 37077 Göttingen, Germany

<sup>b</sup> Department of Land Resources Management and Environmental Protection, Mekelle University, P. O. Box 231, Mekelle, Ethiopia

**Abstract**

Reduced emissions from deforestation and degradation are emerging as strategies with big potential for mitigating climate impacts. This study analysed the effects of the conversion of free grazing lands to exclosures on ecosystem carbon sequestration in Tigray, Ethiopia. Replicated ( $n = 3$ ) paired exclosures and adjacent free grazing lands were sampled. Three church forests were also sampled as positive controls. Soil carbon (C), carbon from woody and grass species as well as selected site and vegetation characteristics were determined. These were attained through standard procedures of soil analyses and destructive sampling of the identified sample plants. Significant ( $p < 0.05$ ) differences in soil-C concentration and stock, and woody species carbon were found between exclosures and adjacent free grazing lands. The oldest exclosure (15-year-old) had significantly ( $p < 0.05$ ) higher soil-C concentration and stock compared to the church forest. These differences were primarily attributed to the difference in amount and properties of input materials, inherent soil properties (% sand, silt, clay) and soil erosion. This was verified by the significant ( $p < 0.01$ ) correlation between soil-C with the measured site and vegetation characteristics. The general trend in the ecosystem carbon stock increased in the order of: free grazing lands ( $40.4 \text{ Mg ha}^{-1}$ ) < five year-old exclosure ( $49.0 \text{ Mg ha}^{-1}$ ) < church forest ( $74.0 \text{ Mg ha}^{-1}$ ) < 10 year-old exclosure ( $86.1 \text{ Mg ha}^{-1}$ ) < 15 year-old exclosure ( $94.9 \text{ Mg ha}^{-1}$ ). Our results show that the conversion of free grazing lands to exclosures has a significant potential to increase carbon sequestration, even in strongly degraded free grazing lands, both through additional below- and aboveground carbon storage. Expanding exclosures on degraded free grazing lands can thus contribute to mitigation of climate change. However, it is crucial to sufficiently compensate the local people as exclosure establishment decreases the area of communal lands used for livestock grazing.

**Keywords:** Carbon stock, church forest, exclosures, free grazing lands, land use conversion

**Introduction**

In response to land degradation caused by human activities such as overgrazing, communities in the central and northern part of Ethiopia established exclosures. Exclosures are areas closed from human and animal interference to promote natural regeneration of plants on formerly degraded communal grazing lands. As the exclosures are not fenced, guards are hired by the local

administration on a food-for-work basis (Yayneshet et al. 2009). After establishment of exclosures, natural re-growth of vegetation occurs, this has a positive impact on biophysical properties of formerly degraded commons (Tefera et al. 2005). One of the drawbacks of exclosure establishment is that the grazing pressure on the remaining communal areas increases even more. In view of the high grazing pressure, and scarcity of fuel wood and grazing land, it is important to evaluate the benefits and costs that are inflicted by exclosure establishment (Descheemaeker et al. 2006a).

Despite the fact that exclosures have been implemented in Ethiopia for about two decades, empirical data on the effectiveness of these protected areas in restoring ecosystem carbon stock are lacking. Particularly, a comprehensive study with multiple sites and replications investigating the relationship between exclosure duration and ecosystem carbon stock and the confounding factors which affects exclosures effectiveness to restore ecosystem carbon is needed for an effective management. Therefore, the present study was carried out with the following objectives: (1) to investigate how exclosures affect ecosystem carbon stocks, and (2) to identify which factor control ecosystem carbon stock restoration. Changes in the direction and magnitude of the analyzed ecosystem carbon stocks from the exclosures were compared with ecosystem carbon stocks under the adjacent free grazing lands. The trends in the changes observed were then used to evaluate the impacts of exclosure establishment on ecosystem carbon stock restoration and as indicators of exclosures effectiveness to restore degraded lands.

## Materials and methods

Our study was conducted in three districts of Tigray (12° - 15° N latitude and 36° 30' - 40° 30' E longitude), the northernmost region of Ethiopia (Fig. 1). In the study area, the first exclosures were established two decades ago and accordingly we were able to select replicated ( $n = 3$ ) exclosures of 5, 10 and 15 years old. We also selected separate adjacent free grazing lands, i.e. a control for each exclosure. The area of the selected exclosures ranged from 7.1 to 85 ha whereas that of the adjacent free grazing lands ranged from 2.8 to 38.3 ha. Additionally, we selected three church forests, i.e. forests that are managed and protected by The Ethiopian Orthodox Tewahido church (Wassie *et al.*, 2009). The area of the church forests varied between 5.9 and 15.3 ha. All sites have tropical semi-arid climate. Mean annual rainfall (3-6 years) varied between 488.2 and 644.5 mm yr<sup>-1</sup> with an average of 562 mm yr<sup>-1</sup>. Mean minimum temperature (3-6 years) ranged from 11 to 17 °C and mean maximum temperature ranged from 26 to 34 °C (Ethiopian metrological service agency, 2007). Soils of the study sites were classified into three major groups: Leptosol, Regosols, and Cambisols (WRB, 2006). The most common woody vegetation species included *Acacia seyal*, *Acacia melifera*, *Acacia etbaica*, and *Balanites aegyptiaca*.

In this study we used space-for-time substitution. The inherent assumption of such a study is that the exclosures and adjacent free grazing lands had similar conditions before establishment of the exclosures. We therefore selected separate adjacent free grazing lands for each exclosure to minimize differences in inherent soil properties. Furthermore, we made sure that soil and terrain conditions between the exclosures and the adjacent grazing land sites were as similar as possible.

For soil sampling, five subplots with an area of 2 m × 2 m were set up at the center and along the diagonal lines of each plot laid for vegetation inventory. At each subplot, soil samples were collected from five sampling points at 0-0.2 m soil depth following a zigzag pattern. One core sample was also taken from each slope position for bulk density analysis. The samples collected from each slope position were mixed thoroughly in a large bucket to form a composite soil sample resulting in a total number of 63 samples. Soil samples were air-dried, ground up and then passed through a 2mm sieve prior to analysis. Soil organic carbon, bulk density and particle size were determined using the Walkley–Black method (Walkley - Black 1934), the core method (Blake & Hartge 1986) and the hydrometer method (Gee & Bauder 1982) respectively. Soil organic carbon stock in the 0-0.2 m layer was calculated by the formula:

$SOC (Mg C ha^{-1}) = WBC (\%) \times 10 \times Bd (g cm^{-3}) \times 2$ , where  $WBC$  is the Walkley-Black carbon (Walkley - Black 1934) and  $Bd$  is the bulk density.

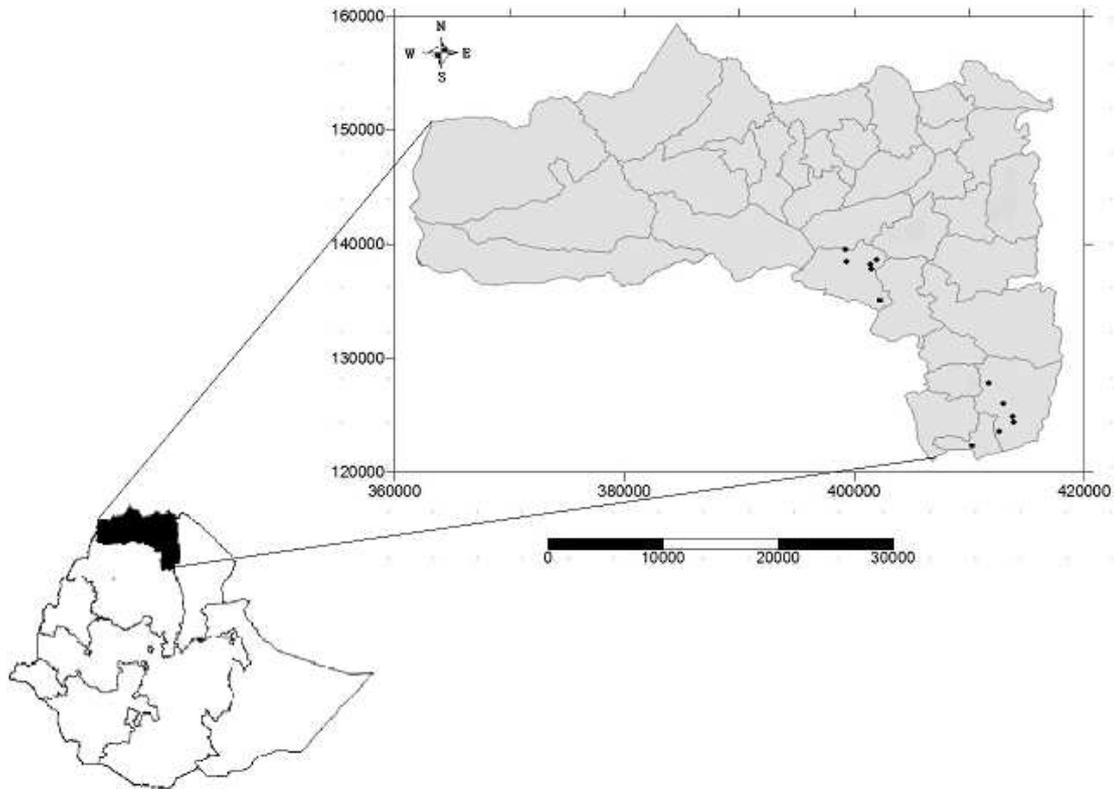


Fig. 1 Location of the study area Tigray in the North of Ethiopia with the distribution of specific sites indicated by (▪)

To estimate aboveground biomass of the dominant woody species, we used destructive weighing in exclosures and free grazing lands and the partial harvest method in church forests (Hoff et al. 2002; Snowdon et al. 2002). In total 294 trees or shrubs (162 from exclosures and 108 from adjacent free grazing lands) were harvested. In the church forests, data on biomass were collected from 24 trees.

For under-canopy species biomass estimation, a subplot with 2 m × 2 m was set up at the center of the vegetation inventory plot. All under-canopy species (mainly grasses and herbs) were harvested and weighed together (Snowdon et al. 2002).

Carbon concentration (%) in woody species was estimated based on 137 vegetation samples from stem, leaves and branches (Armechin & Gabon 2008). Organic matter (%) and organic carbon contents (%) were computed using the following equations:

$$\% OM = \frac{DW - AW}{DW} \times 100;$$

$\% OC = \frac{\% OM}{1.724}$ , where OM = organic matter, OC = organic carbon, AW = ash weight of the sample, DW = dry weight of the sample, 1.724 = van Bemmelen factor (i.e. organic matter contains 58% of OC) (Armechin & Gabon 2008). The % OC was subsequently used to estimate the carbon stock of woody species. Carbon stock in under-canopy species was estimated by multiplying the oven-dried biomass by a factor of 0.5 (Snowdon et al. 2002).

We conducted paired t-tests to test for significant differences in below- and aboveground carbon stocks between each category of exclosures duration and the adjacent free grazing lands.

We also conducted Pearson correlation tests and step-wise regression analyses to examine the relationships between carbon stocks and site and vegetation characteristics.

## Results

### Ecosystem Carbon Stocks in Enclosures and Adjacent Free grazing Lands

Each category of enclosure duration had significant higher soil carbon concentration and stocks than the adjacent grazing lands (Fig. 2). Additionally, the aboveground carbon stocks in each category of enclosure duration were significantly higher than the aboveground carbon stocks in the adjacent grazing lands (Fig. 3). The average difference in soil carbon stock in the 0-0.2 m layer varied between 15.9 and 40.1 Mg C ha<sup>-1</sup> whereas the average difference in aboveground carbon stock varied between 2.3 and 5.6 Mg C ha<sup>-1</sup>. This means soil and aboveground carbon stocks increased by 36-50% and 39-68% through the conversion of degraded grazing lands to enclosures relative to the soil and aboveground carbon stocks in enclosures respectively. The difference in ecosystem carbon stocks found between enclosures and the adjacent grazing lands increased with enclosure duration suggesting enclosure duration influences the amount of carbon stored in enclosures.

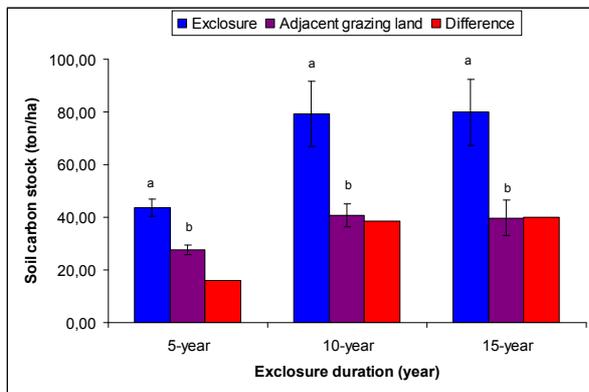


Fig. 2 Soil carbon stocks in relation to enclosure duration

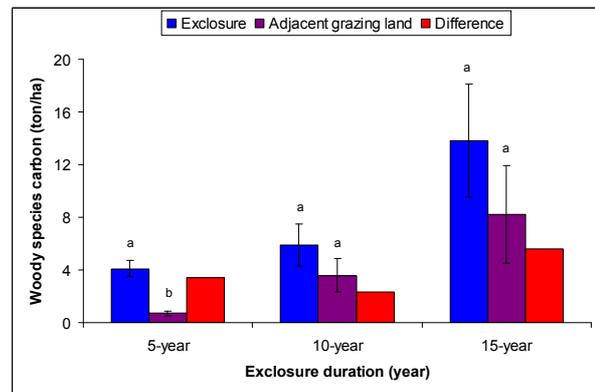


Fig.3 Aboveground carbon stocks in relation to enclosure duration

### Ecosystem Carbon Stocks and Site Characteristics in Church Forests

Soils of the church forest had an average of 59.9% sand, 26% silt and 14.1% clay content. The average vegetal canopy and under-canopy cover of church forest were 65.3 and 34.2% respectively. The average soil carbon stock (in the 0-0.2 m layer) and aboveground carbon stock of church forest were 52.7 Mg C ha<sup>-1</sup> and 21.3 Mg C ha<sup>-1</sup> respectively.

## Discussion

The significant higher below- and aboveground carbon stocks (Fig. 2 and 3) in every category of enclosures duration than the adjacent grazing lands suggesting the significant potential of enclosures to restore degraded lands and enhance ecosystem carbon content. Differences in ecosystem carbon found between enclosures and the adjacent grazing lands increased with enclosure duration indicating that enclosure duration influences the amount of carbon stored in enclosures. This general increment can be explained by the decrease in soil erosion rate and the increase in the overall species diversity and aboveground biomass with enclosure duration.

In enclosures with significantly ( $p < 0.05$ ) greater vegetal canopy and under-canopy cover compared to the adjacent grazing lands, the erosive impact of rainfall could be lower. The

importance of increased vegetation cover in exclosures to reduce soil erosion has been shown in studies where soil loss decreased with exclosure duration (Mekuria et al. 2009). Additionally, with the increase in naturally regenerated plant species diversity and biomass with exclosure duration, inputs to the soil increase as well as the conversion of plant carbon to soil carbon through increased microbial activities. This argument was supported by the significant positive correlation between soil carbon and aboveground vegetation biomass and cover (Table 1). Besides, the positive and significant correlation between naturally regenerated plant species diversity and soil carbon concentration support this (Fig. 4). Other studies also reported increasing soil carbon in ecosystem as the number of plant species and aboveground biomass increases (Mulugeta & Fisseha 2004b; Mulugeta et al. 2005a; Solomon et al. 2002). Solomon et al. (2002) also indicated that land use change affects the amount and composition of soil organic matter through their influence on decomposition and humification processes. Moreover, our results agreed with Lal (2001a) who reported increasing soil organic carbon pool with the addition of biomass to soils when the pool has been depleted as a consequence of land use.

Table 1 Correlation between soil carbon and site and vegetation characteristics

Site and vegetation characteristics	Exclosure C (Mg ha <sup>-1</sup> )	Grazing lands C (Mg ha <sup>-1</sup> )
Woody species biomass (Mg ha <sup>-1</sup> )	0.72 <sup>**</sup>	0.79 <sup>**</sup>
Sand (%)	-0.61 <sup>**</sup>	-0.68 <sup>**</sup>
Silt (%)	0.56 <sup>**</sup>	0.79 <sup>**</sup>
Clay (%)	0.19	0.16
Vegetal canopy cover (%)	0.49 <sup>**</sup>	0.54 <sup>**</sup>
Exclosure duration (year)	0.44 <sup>*</sup>	--

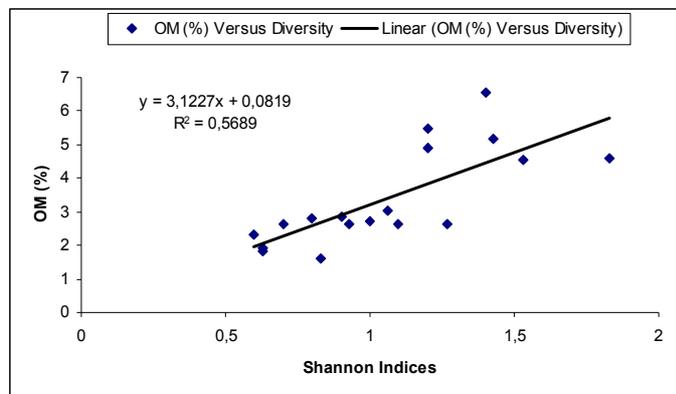


Fig. 4 Correlation between plant species diversity and soil organic matter

## Conclusions

We investigated the effectiveness of exclosures to restore below- and aboveground carbon in the lowlands of Tigray, Ethiopia. Our results showed that the conversion of free grazing lands to exclosures has a significant potential to increase carbon sequestration, even in strongly degraded free grazing lands, through additional below- and aboveground carbon storage. However, expansion of exclosures increases grazing pressure on the remaining communal grazing area aggravating land degradation. As a result, maximizing the ecosystem carbon sequestration and degraded land restoration benefits of exclosures requires balancing the area restored with the remaining communal grazing lands.

## References

- Armecin, R. B., and F. M. Gabon. 2008. Biomass, organic carbon and mineral matter contents of abaca (*Musa textilis* Nee) at different stages of growth. *Industrial crops and products* **28**: 340-345.
- Blake, G. R., and K. H. Hartge. 1986. Bulk density. In: A. Klute (ed.), *Methods of soil analysis: part 1. Physical and mineralogical methods*, ASA Monograph **9**: 363-375.
- Descheemaeker, K., J. Nyssen, J. Rossi, J. Poesen, H. Mitiku, J. Moeyersons, and J. Deckers. 2006a. Sediment deposition and pedogenesis in exclosures in the Tigray Highlands, Ethiopia. *Geoderma* **132**: 291-314.
- Gee, G. W., and J. W. Bauder. 1982. Particle size analysis. In: A. Klute (ed.), *Methods of soil analysis: part 1. Physical and mineralogical methods*, ASA Monograph **9**: 383-411.
- Hoff, C., S. Rambal, and R. Joffre. 2002. Simulating carbon and water flows growth in a Mediterranean evergreen *Quercus ilex* coppice using the FOREST-BGC model. *Forest Ecology and Management* **164**: 121-136.
- Lal, R. 2001a. World cropland soils as a source or sink for atmospheric C. *Advances in Agronomy* **71**: 145-174.
- Mekuria, W., E. Veldkamp, H. Mitiku, G. Kindeya, B. Muys, and J. Nyssen. 2009. Effectiveness of exclosures to control soil erosion and local community perception on soil erosion in Tigray, Ethiopia. *African Journal of Agricultural Research* **4**: 365-377.
- Mulugeta, L., and I. Fisseha. 2004b. Soil carbon stocks and turnovers in various vegetation types and arable lands along an elevation gradient in southern Ethiopia. *Geoderma* **123**: 177-188.
- Mulugeta, L., E. Karlun, and M. Olsson. 2005a. Soil organic matter dynamics after deforestation along a farm field chronosequence in southern highlands of Ethiopia. *Agriculture, Ecosystems and Environment* **109**: 9-19.
- Snowdon, P., J. Raison, H. Keith, P. Ritson, P. Grierson, M. Adams, K. Montagu, B. B. Huiquan, and D. Eamus. 2002. Protocol for sampling tree and stand biomass. National carbon accounting system technical report, Australian greenhouse office. No. 31.
- Solomon, D., F. Fritszhe, J. Lehmann, M. Tekalign, and W. Zech. 2002. Soil organic matter dynamics in the subhumid agroecosystems of the Ethiopian Highlands: Evidence from <sup>13</sup>C abundance and particle size fraction. *Soil Science Society of America Journal* **66**: 969-978.
- Tefera, M., T. Demel, H. Håkan, and Y. Yonas. 2005. The role of exclosures in the recovery of woody vegetation in degraded dryland hillsides of central and northern Ethiopia. *Journal of Arid Environments* **60**: 259-28.
- Walkley, A., and I. A. Black. 1934. An examination of the Degtjareff method for determining organic carbon in soils: effect of variations in digestion conditions and of inorganic soil constituents. *Soil Science* **63**: 251-263.
- Wassie, A., F. J. Sterck, D. Teketay, F. Bongers. 2009. Effects of livestock exclusion on tree regeneration in church forests of Ethiopia. *Forest Ecology and Management* **257**: 765-772.
- WRB. 2006. World reference base for soil resources. 2<sup>nd</sup> edition. World Soil Resources Reports No. 103. FAO, Rome.
- Yayneshet, T., L. O. Eik, and S. R. Moe. 2009. The effects of exclosures in restoring degraded semi-arid vegetation in communal grazing lands in northern Ethiopia. *Journal of Arid Environments* **73**: 542-549.