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EXCLOSURE LAND MANAGEMENT FOR RESTORATION OF THE SOILS IN DEGRADED COMMUNAL GRAZING LANDS IN NORTHERN ETHIOPIA

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ABSTRACT

In the northern highlands of Ethiopia, establishment of exclosures to restore degraded communal grazing lands has been practiced for the past three decades. However, empirical data on the effectiveness of exclosures in restoring degraded soils are lacking. We investigated the influence of exclosure age on degree of restoration of degraded soil and identified easily measurable biophysical and management-related factors that can be used to predict soil nutrient restoration. We selected replicated ($n=3$) 5-, 10-, 15-, and 20-year-old exclosures and paired each exclosure with samples from adjacent communal grazing lands. All exclosures showed higher total soil nitrogen (N), available phosphorus (P), and cation exchange capacity than the communal grazing lands. The differences varied between 2·4 (±0·61) and 6·9 (±1·85) Mg ha^{-1} for the total N stock and from 17 (±3) to 39 (±7) kg ha^{-1} for the available P stock. The differences in N and P increased with exclosure age. In exclosures, much of the variability in soil N ($R^2=0{\cdot}64$) and P ($R^2=0{\cdot}71$) stocks were explained by a combination of annual average precipitation, woody biomass, and exclosure age. Precipitation and vegetation canopy cover also explained much of the variability in soil N ($R^2=0{\cdot}74$) and P ($R^2=0{\cdot}52$) stocks in communal grazing lands. Converting degraded communal grazing lands into exclosures is a viable option to restore degraded soils. Our results also confirm that the possibility to predict the changes in soil nutrient content after exclosure establishment using regression models is based on field measurements. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: exclosures; field measurements; native vegetation; restoration of degraded lands; soil properties; Ethiopia

INTRODUCTION

Natural resources are the primary source of livelihood support for the poor, and efforts to rehabilitate them could become a valuable strategy for livelihood improvement (Shylendra, 2002). However, in many developing countries, the resource base has been deteriorating over time. In the highlands of Ethiopia, deforestation and subsequent unsustainable agricultural management, as well as use of dung and crop residues for energy, have resulted in soil organic matter and nutrient depletion, hydrological instability, reduced primary productivity, and low biological diversity (Solomon *et al*., 2002; Mulugeta *et al*., 2005). For example, Brhane and Mekonen (2009) reported soil loss of 35 t ha^{-1} y^{-1} from cultivated steep slopes (30–50%) in the Northern Highlands of Ethiopia, which is about twice the maximum tolerable soil loss of the region. Furthermore, owing to overgrazing, the natural vegetation in the Northern Highlands of Ethiopia has virtually disappeared, leaving degraded communal grazing lands with irregularly spaced trees and shrubs and vast areas of bare lands devoid of vegetation (Nedessa *et al*., 2005).

In response to the environmental problems, communities in the Northern Highlands of Ethiopia started to establish exclosures about three decades ago. Exclosures are areas closed off from the interference of human and domestic animals with the goal of promoting natural regeneration of plants and reducing land degradation of formerly degraded communal grazing lands. Exclosures are usually established in steep, eroded, and degraded areas that have been used for grazing in the past (Descheemaeker *et al*., 2006). In Ethiopia, the inception of exclosures dates back to the 1980s and coincided with the introduction of large-scale land rehabilitation and soil and water conservation programmes (Nedessa *et al*., 2005). Priority areas for establishing exclosures are normally identified as a joint initiative of local communities and governmental and nongovernmental organizations (Descheemaeker *et al*., 2006). As the exclosures are not fenced, guards are hired by the local administration on a food-for-work basis (Yayneshet *et al*., 2009). According to the local agricultural offices, exclosures now

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cover 3–16% of the total area in the study districts of Atsbi Womberta, Douga Tembein, Axum, and Enda Mehoni.

Grazing impacts on soil properties have generally been shown to be dependent on grazing intensity. With moderate grazing of 33 years compared with an ungrazed control, higher values were found for pH, available P, and Mg. Concentrations of available P, total N, Ca, Mg, and K decreased after 1·5 years of heavy grazing compared with an ungrazed control in a tropical pasture (Ajorlo *et al*., 2011). In addition, heavy grazing resulted in lower water infiltration (Hiernaux *et al*., 1999) and higher soil loss (Tadesse and Penden, 2002) compared with moderately grazed sites. Indeed, in semi-arid ecosystems, areas used by domestic livestock have shown less plant cover and less soil organic carbon and N compared with relict sites browsed by native ungulates (Fernandez *et al*., 2008). In Tunisia, Jeddi and Chaieb (2010) documented that 12-year exclosures enhance the total plant cover, dry matter yield, species richness, contents of soil organic matter, total nitrogen, and water infiltration rate compared with continually grazed area. Similarly, Cheng et al. (2011) indicated that 20-year exclusion of livestock grazing significantly increased aboveground and belowground biomass and species richness for five different communities compared with that before exclusion of livestock grazing in a typical steppe of the Loess plateau, northwest China.

Similar trends were also reported from case studies conducted on exclosures in the central and northern highlands of Ethiopia: exclosures had twice the plant species richness and diversity value compared with communal grazing lands after 22 years of exclosure establishment (Tefera *et al*., 2005), an increase in woody species richness of 13 after 8 years of exclosure establishment (Emiru *et al*., 2006), and an increase in soil organic matter of 1·1%, total N of 0·1%, and available P of 1·8 mg kg^{-1} after 10 years of exclosure establishment (Mekuria *et al*., 2007). Also, a considerable decrease in soil loss was reported after the establishment of exclosures on communal grazing lands (Descheemaeker *et al*., 2006; Girmay *et al*., 2009; Mekuria *et al*., 2009). The study by Mekuria et al. (2007) is limited in one district, only covered two exclosure ages, and did not investigate the edaphic and environmental factors that influence the effectiveness of exclosures to restore degraded soils. A replicated study across multiple sites is needed to investigate the relationship between soil nutrient stocks, soil properties, native vegetation composition, exclosure duration, and environmental factors affecting restoration of degraded soils. Such information is crucial for planning further establishment of exclosures.

We carried out the present study in the northern highlands of Ethiopia with the following objectives: (i) to investigate how exclosure age affects restoration of soil nutrient stocks and properties and (ii) to identify which easily measurable biophysical and management-related factors, such as exclosure age, can be used to predict restoration of soil nutrient stocks. Easily measurable variables that we considered in this study are variables related to climate (e.g., precipitation), soil (e.g., texture), and vegetation (e.g., vegetation cover and woody biomass). Based on a review of existing case studies, we formulated the following hypotheses: (i) soil nutrient content and properties will be improved after establishing exclosures on communal grazing lands, and (ii) a considerable proportion of the variability in soil nutrient stocks in exclosures and grazing lands can be explained by a combination of edaphic and site variables as well as exclosure age. The analyzed soil nutrient content from exclosures was compared with those of adjacent communal grazing lands. The trends in the changes observed were then used as indicators of exclosure effectiveness to restore degraded soils.

MATERIALS AND METHODS

Study Area and Experimental Design

Our study was conducted in four districts: Atsbi Womberta (13°53′N, 39°45′E), Douga Tembein (13°37′N, 39°13′E), Axum (14°12′N, 38°42′E), and Enda Mehoni (13°37′N, 39°13′E) located in the eastern, southeastern, central, and southern zone of the Tigray region (12°–15° N latitude and 36°30′–40°30′ E longitude), the northernmost region of Ethiopia, respectively (Figure 1). These four districts were selected because they all have an extensive exclosure system and adjacent communal grazing lands that have comparable edaphic and topographic features. All the sites have a tropical, semi-arid climate. The mean annual rainfall (for 2000–2006) varied between 578 and 671 mm y^{-1}, with an average of 609 mm y^{-1}. The mean minimum temperature (2000–2006) ranged from 7·8 to 11·6 °C, and the mean maximum temperature ranged from 22·2 to 28·2 °C (Ethiopian Meteorological Service Agency, 2007). The altitude of the study sites ranged from 2232 to 2937 m above sea level. The rainy season usually occurs between June and September, with a growing season of between 90 and 120 days. Soils of the study sites were classified into four major groups: Luvisols, Regosols, Cambisols, and Calcisols (WRB, 2006). Selected soil and vegetation characteristics are given in Table I. The most common woody vegetation species in exclosures and in adjacent grazing lands included *Acacia etbaica* Schweinf., *Acacia seyal* Del., *Becium grandiflorum* (Lam.) Pichi-Serm., *Euclea racemosa* ssp. *schimperi* (A.DC.) Dandy, and *Maytenus arbutifolia* (Hochst. ex. A. Rich) Wilczek. Understory vegetation of the exclosures and the adjacent communal grazing lands were dominated by grass species such as *Hyparrhenia hirta* L. and *Digitaria velutina* (Forssk) P. Beauv.

We selected replicated ($n = 3$) 5-, 10-, 15-, and 20-year-old exclosures that were adjacent to corresponding communal grazing lands. Before establishment, exclosures and the

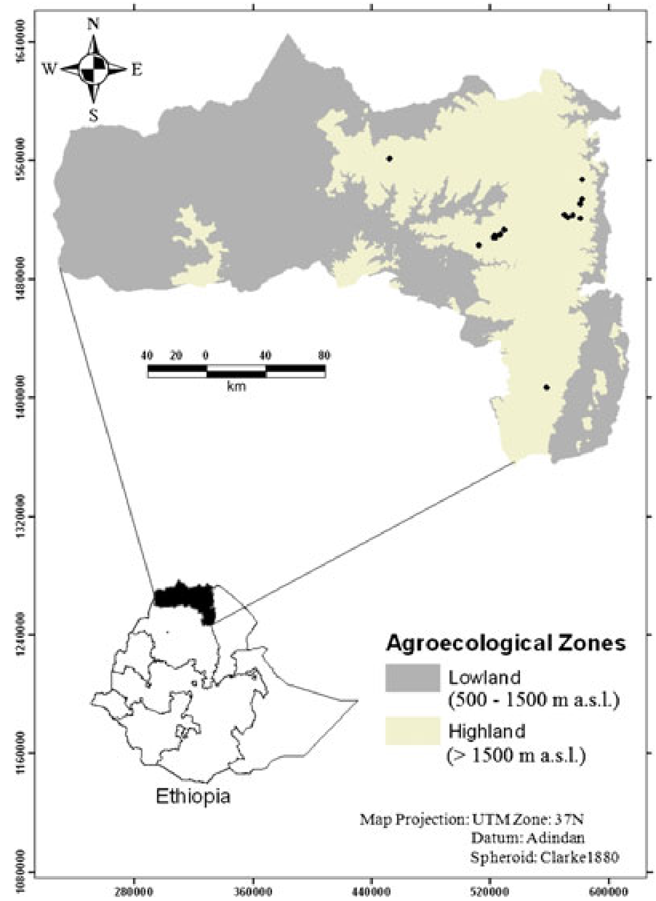

Figure 1. Location of the study area in the highlands of Tigray, Northern Ethiopia, with the distribution of specific sites indicated by (▪). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

adjacent grazing lands had similar conditions because the exclosures were established on parts of the degraded communal grazing lands that were used for livestock grazing (Mekuria *et al*., 2011). In exclosures, grass harvesting (using a cut-and-carry system) is allowed and is conducted once a year, typically after seeding stage, starting 3 to 5 years after exclosure establishment. The main reason to restrict grass harvesting is to restore the soil seed bank. On the adjacent communal grazing lands, unlimited access for free grazing is practiced. The stocking rate of the communal grazing lands, determined using the average animal weight method (Pratt and Rasmussen, 2001), varied between 97 and 201 animals per month. The area of the exclosures ranged from 7 to 28 ha, whereas the adjacent communal grazing lands ranged from 2 to 12 ha. Accordingly, the total available forage that can be obtained from the grazing lands can only support 8·1 to 16·8 animals for a 12-month period (Mekuria *et al*., 2011). Given that a minimum of 80 livestock (mainly cows and oxen) graze on the communal grazing lands throughout the year, the communal grazing lands are under heavy grazing pressure resulting in severe land degradation.

Table I. Mean values ($n = 3$, SE in parentheses) of selected soil and vegetation characteristics in paired exclosures and adjacent grazing lands

Variables	Exclosure age (year)	Exclosures	Adjacent grazing lands
Plant species richness (number)	5	20·0 (1·7)*	10·0 (0·3)*
	10	15·7 (1·8)	6·7 (4·1)
	15	30·0 (6·8)*	10·7 (2·7)*
	20	31·3 (4·2)*	11·7 (4·8)*
Diversity (Shannon–Wiener index)	5	1·4 (0·1)	1·3 (0·1)
	10	1·4 (0·1)*	0·7 (0·2)*
	15	2·0 (0·1)*	0·9 (0·2)*
	20	2·1 (0·1)*	1·4 (0·2)*
Aboveground standing biomass (Mg ha^{-1})	5	4·2 (0·6)*	0·7 (0·2)*
	10	9·9 (1·7)*	1·1 (0·4)*
	15	13·6 (1·8)*	0·1 (0·0)*
	20	15·0 (2·8)*	2·0 (0·6)*
Canopy cover (%)	5	28·4 (3·4)*	14·1 (2·6)*
	10	28·9 (3·3)*	9·4 (3·4)*
	15	34·0 (3·6)*	10·4 (3·5)*
	20	43·1 (4·1)*	15·1 (2·7)*
Under-canopy cover (%)	5	56·8 (4·1)*	17·6 (3·6)*
	10	46·7 (5·8)*	20·2 (5·8)*
	15	60·9 (3·7)*	23·9 (2·3)*
	20	54·4 (6·3)*	21·5 (10·9)*
Area of the total sampled plots (ha)	5	0·96	0·96
	10	1·08	0·60
	15	0·96	0·72
	20	1·08	0·96
Sand (%)	5	58·1 (2·8)	64·6 (1·9)
	10	53·9 (4·3)	57·9 (4·7)
	15	60·4 (3·4)	55·1 (2·7)
	20	48·9 (4·1)	49·3 (3·2)
Silt (%)	5	29·1 (1·9)	24·4 (2·1)
	10	26·4 (2·5)	27·4 (3·9)
	15	23·8 (1·9)	28·0 (2·6)
	20	30·0 (3·1)	27·3 (1·7)
Clay (%)	5	12·8 (1·1)	11·0 (0·9)
	10	19·7 (2·6)	14·7 (0·9)
	15	15·8 (2·8)	16·9 (3·4)
	20	21·1 (3·8)	23·3 (4·0)
Bulk density (g cm^{-3})	5	1·3 (0·1)	1·3 (0·1)
	10	1·3 (0·1)	1·3 (0·1)
	15	1·1 (0·1)	1·2 (0·1)
	20	1·1 (0·0)	1·3 (0·0)
pH (1:5 H_2O)	5	6·2 (0·1)	6·3 (0·1)
	10	5·9 (0·1)	5·8 (0·2)
	15	6·2 (0·1)	6·1 (0·1)
	20	6·0 (0·1)	6·1 (0·1)

*Differences between exclosures age and the adjacent grazing lands are significant at $P < 0{\cdot}05$ after paired *t*-test.

We used a space-for-time substitution approach to monitor changes in soil nutrient stock and properties after conversion of communal grazing lands to exclosures with ages of 5, 10, 15, and 20 years. Thus, we selected replicated ($n = 3$) 5-, 10-, 15-, and 20-year-old exclosures that were adjacent to a corresponding communal grazing lands, ensuring that soil and terrain conditions were as similar as possible between each pair. We also selected three isolated forest fragments that remain around churches, also called "church forests," to detect whether exclosures had reached soil nutrient stock levels of these forests. In each exclosure, grazing land and church forest, we randomly established two to three transects spaced at a minimum distance of 75 m. The number of transects per site was based on vegetation density, spatial heterogeneity of vegetation, and area of the site (Tefera *et al*., 2005). To avoid edge effects, the first transect was laid 30 to 50 m inside the exclosures, grazing land, or church forest. Transects were parallel to each other and to the topography of the landscape. In each transect, we delineated three landscape positions (upper slope, mid-slope, and foot slope), and in each landscape position, we established a sampling plot of 20 m × 20 m for quantitative vegetation inventory. In each 20 m × 20 m plot, we measured the following individual plant variables: diameter at breast height or, for smaller and multi-stemmed shrub, diameter at stump height or at the height of 30 cm (d_{30}) from the ground, crown diameter, and total height. We also identified the species identity of plants encountered in each plot. During the entire study, we examined 210 plots, of which 105 were in exclosures, 81 in communal grazing lands, and 24 in church forests. In each 20 m × 20 m plot, five 2 m × 2 m subplots were set up for soil sampling (one at the center and two along each of the two diagonal lines that crosses at the center of the plot). Soil, vegetation, and management-related data were collected from November 2007 to October 2008.

Soil Sampling, Analyses, Soil Nutrient Stocks Calculation, and Collection of Site Variables

In each 2 m × 2 m subplot, soil samples at 0- to 0·2-m depth were collected at five random sampling points. One soil core sample was also taken from the central plot of each landscape position for bulk density determination (i.e., we collected 81 soil core samples during the entire study). The samples collected from each landscape position per replicate (i.e., 50–75 random sampling points from two to three transects) were mixed thoroughly in a large bucket to form one composite soil sample. During the entire study, we collected a total number of 81 composite soil samples. Soil samples were air-dried, sieved through a 2-mm sieve, and ground before analysis. Total soil N (N) was analyzed using the Kjeldahl method (Bremmer and Mulvaney, 1982), available P was analyzed using the Olsen-P method (Olsen and Sommers, 1982), bulk density was measured using the core method (Blake and Hartge, 1986), particle size was determined using the hydrometer method (Gee and Bauder, 1982), and pH was determined using a suspension of 1:5 soil : water ratio. Ammonium and sodium acetate extracts were used to determine exchangeable cations and cation exchange capacity (CEC), respectively (Thomas, 1982).

Total soil N and available P stocks in the 0- to 0·2-m layer were calculated as follows:

$$N\left(\mathrm{Mg\,N\,ha^{-1}}\right) = \left(N[\%] \times 10^{-2}\right) \times Bd(Mg\ \ m^{-3}) \times depth(m) \times 10000\ \ m^2\,ha^{-1}$$

and

$$Olsen\text{-}P\ \ \left(\mathrm{Mg\,P\,ha^{-1}}\right) = \left(P(ppm) \times 10^{-6}\right) \times Bd(Mg\ \ m^{-3}) \times depth(m) \times 10000\ \ m^2\,ha^{-1}$$

Where: N, *Olsen-P*, and *Bd* are the total soil N, available P, and bulk density, respectively. The average bulk density of the oldest exclosure was used to calculate the total soil N and available P stocks in all exclosures, grazing lands, and church forests. We used this conservative approach to avoid overestimation of the total soil N and available P stocks due to changes in bulk density (Veldkamp, 1994).

We used the methods of Hoff *et al*. (2002) and Snowdon *et al*. (2002) for aboveground woody biomass measurement. We harvested altogether 423 trees and shrubs (276 from exclosures and 147 from communal grazing lands). In the church forests, the partial harvest method was used because tree felling is strictly forbidden; biomass was collected from 60 individuals. Fresh mass of the aboveground vegetation was adjusted to the dry mass using the measured moisture contents, determined by oven-drying subsamples of stems, branches, and leaves at 65 °C until constant mass was attained (about 78 h). Vegetation canopy cover was determined using crown diameter measurements and by assuming a tree or shrub of elliptical shape (Snowdon *et al*., 2002). The average annual rainfall for the years 2000 to 2006 of the study sites was obtained from Ethiopian Meteorological Service Agency. The altitude and slope of the study sites were measured at each landscape position using an altimeter and clinometer, respectively. Stone cover was quantified using the line–point intercept method (Herrick *et al*., 2005).

Statistical Analyses

We first conducted tests for normality (Kolmogorov–Smirnov *D* statistic) and equality of variance (Levene statistic) of the total soil N and available P concentrations, total soil N and P stocks, and CEC. We also tested the differences among the landscape positions in the soil nutrient content and properties for each exclosure age and communal grazing land using one-way analysis of variance (ANOVA). The differences in soil nutrient content and soil properties between an exclosure age and adjacent communal grazing land were assessed at each landscape position using a paired *t*-test with separate variances because the tested parameters did not show homogenous variances. The patterns of changes in the total soil N and available P stocks (i.e., difference between an exclosure age and adjacent grazing lands) across exclosure ages (5, 10, 15 and 20 years) were assessed using Kruskal–Wallis test (nonparametric ANOVA) with nonparametric Tukey's test. Spearman correlation tests were conducted to examine the relationships between soil nutrient content and properties and independent variables using the mean values of the three landscape position for each land use type ($n = 12$). Finally, stepwise multiple regression analysis was done to establish predictive relationships between soil N and P stocks and easily measurable independent variables: precipitation, woody biomass, vegetation canopy cover, under-canopy cover, exclosure age, percentage clay, percentage silt, percentage sand, soil pH, bulk density, and stone cover. We selected the best predictive variables using a forward stepwise procedure that uses a sequence of F tests at $P < 0{\cdot}05$. We did not detect any colinearity among the input predictive variables used in the regression models.

RESULTS

Soil Nutrient Content and Soil Properties in Exclosures and Adjacent Grazing Lands

We did not detect differences among landscape positions ($P > 0{\cdot}05$) in soil nutrient content and properties within any of the exclosure ages and adjacent grazing lands, suggesting that landscape position was not a significant conditioning factor affecting soil nutrient content and soil properties. At each landscape position, exclosures showed significantly higher total soil N content, available P content, and CEC than the adjacent grazing lands (Table II).

The difference in soil properties between exclosures and adjacent grazing lands in the 0- to 0·2-m depth, averaged across landscape positions at each exclosure age, varied between 2·4 (±0·61) and 6·9 (±1·85) Mg ha^{-1} for the total N stocks, from 17 (±3) to 39 (±7) kg ha^{-1} for the available P stocks, and between 13·0 (±1·2) and 20·4 (±2·8) for CEC. These values translated to an increase of 28–48% for the total soil N stocks, 26–39% for the available P stocks, and 47–71% for the CEC after conversion of the degraded grazing lands to exclosures. The influence of exclosure age on the total soil N, available P stocks, and CEC was not linear with time because the increase in the total soil N and available P stocks was only significant between 5- and 20-year-old exclosures, and we observed marginally significant differences ($P = 0{\cdot}058$) in CEC between 5- and 20-year-old exclosures (Figure 2a–c).

Soil, Vegetation, and Climatic Variables Explaining Soil Nutrient Content and Soil Properties

The total soil N and available P concentrations and stocks as well CEC in exclosures and their differences from adjacent grazing lands were positively correlated with woody biomass, vegetation canopy cover, clay content, precipitation, and exclosure age but were inversely correlated with bulk density (Table III). In grazing lands, the total soil N concentration and stock did not show significant positive and significant negative correlations with the independent variables. Available P stock and CEC were positively correlated only with vegetation canopy cover.

Using multiple linear regression models, we were able to explain much of the variability in the total soil N and available P stored in exclosures and communal grazing lands (Table IV). The total soil N stock in exclosures was predicted by woody biomass (ranging from 3·3 to 17·5 Mg ha^{-1}), precipitation (ranging from 578 to 671 mm y^{-1}), and exclosure age (ranging from 5 to 20 years), whereas the available P stock was predicted by exclosure age and woody biomass. In grazing lands, the total soil N stock was predicted only by annual average precipitation (ranging from 578 to 671 mm y^{-1}), whereas available P stock was predicted by precipitation and vegetation canopy cover (ranging from 5% to 18%). The differences between exclosures and grazing lands in the total soil N and available P stocks were predicted by clay content (ranging from 11·7% to 26%) and woody biomass (ranging from 3·3 to 17·5 Mg ha^{-1}).

Soil Nutrient Content and Soil Properties in Church Forests

Soils of the church forest had 0·68% (±0·13%) total soil N, 40·4 (±1·37) mg kg^{-1} available P, and 43·8 (±1·81) cmol$_c$ kg^{-1} CEC. The total soil N and available P stocks were 15·7 (±3·29) Mg ha^{-1} and 0·09 (±0·0) Mg ha^{-1}, respectively. The 20-year-old exclosure had reached the total soil N and available P levels (Table II) comparable with the church forests.

DISCUSSION

Variation of Soil Nutrient Content on Communal Grazing Lands

The studied communal grazing lands displayed different degrees of land degradation, which is illustrated by the variation in vegetation composition, aboveground biomass, and soil nutrient content and properties (Tables I and II). The variation in soil degradation among the studied communal grazing lands could arise from the difference in the interference of human and domestic grazing animals, which consequently resulted in different degrees of vegetation degradation (Table I). Other studies also indicated that anthropogenic disturbance and livestock grazing have a strong negative effect on species composition, germination, seedling growth, and mortality of many of the plant communities and in turn results in less species richness and poor soil quality in severely grazed sites (Singh and Singh, 1987; Wassie *et al*., 2009).

Table II. Mean values (±SE, $n = 3$) of the total soil N and available P concentration, total soil N and P stocks, and CEC in the 0- to 0·2-m depth in exclosures, adjacent grazing lands, and their differences

		Exclosure					Adjacent grazing lands					Differences [b]				
Exclosure age (years) [a]	Landscape position	N (%)	P (mg/g)	CEC (cm[+]kg^{-1})	N (Mg ha^{-1})	P (Mg ha^{-1})	N (%)	P (mg/g)	CEC (cm[+]kg^{-1})	N (Mg ha^{-1})	P (Mg ha^{-1})	N (%)	P (mg/g)	CEC (cm [+]kg^{-1})	N (Mg ha^{-1})	P (Mg ha^{-1})
5	Upper	0·34 (0·0)	34·6 (2·1)	40·1 (2·2)	8·3 (0·2)	0·08 (0·01)	0·27 (0·0)	27·7 (4·6)	26·6 (3·3)	6·5 (0·4)	0·07 (0·01)	0·08* (0·02)	6·9 (2·5)	14* (2·1)	1·8* (0·6)	0·02 (0·01)
	Mid	0·38 (0·0)	32·8 (3·6)	39·6 (0·8)	8·4 (0·6)	0·07 (0·01)	0·24 (0·0)	28·7 (3·8)	27·3 (3·1)	5·3 (0·6)	0·06 (0·01)	0·14* (0·01)	4·1 (0·2)	12* (3·0)	3·1* (0·2)	0·01 (0·00)
	Foot	0·39 (0·1)	35·5 (2·5)	41·2 (2·7)	8·6 (1·7)	0·08 (0·01)	0·29 (0·0)	24·3 (4·0)	28·1 (2·4)	6·4 (0·7)	0·05 (0·01)	0·10 (0·09)	11·2 (1·7)	13* (1·5)	2·2 (1·9)	0·03 (0·00)
10	Upper	0·45 (0·1)	34·2 (0·9)	41·9 (0·9)	10·9 (1·1)	0·08 (0·00)	0·23 (0·0)	22·3 (3·8)	23·6 (1·4)	5·5 (0·4)	0·05 (0·01)	0·22** (0·05)	11·9 (3·8)	18** (1·9)	5·4** (1·2)	0·03 (0·01)
	Mid	0·43 (0·1)	34·1 (6·7)	40·0 (0·9)	9·5 (0·9)	0·08 (0·01)	0·25 (0·0)	24·4 (2·3)	24·7 (1·4)	5·4 (0·2)	0·05 (0·01)	0·18* (0·04)	9·7 (5·8)	15** (0·7)	4·0* (1·0)	0·02 (0·01)
	Foot	0·41 (0·1)	35·7 (0·7)	40·1 (1·4)	9·2 (1·0)	0·08 (0·00)	0·24 (0·0)	25·2 (2·5)	28·3 (2·8)	5·3 (0·7)	0·06 (0·01)	0·17* (0·02)	10·5* (2·0)	12* (2·8)	3·9* (0·4)	0·02* (0·00)
15	Upper	0·41 (0·0)	35·2 (0·7)	38·9 (0·7)	9·9 (0·4)	0·09 (0·00)	0·26 (0·0)	25·9 (3·1)	25·5 (1·5)	6·3 (0·4)	0·06 (0·01)	0·15** (0·03)	9·3 (3·2)	13** (2·2)	3·6** (0·8)	0·02 (0·01)
	Mid	0·57 (0·2)	39·3 (1·9)	40·9 (1·2)	12·6 (3·2)	0·09 (0·00)	0·32 (0·0)	26·6 (2·6)	24·0 (0·7)	7·1 (0·7)	0·06 (0·01)	0·25 (0·11)	12·7* (4·4)	17** (1·8)	5·5 (2·5)	0·03* (0·01)
	Foot	0·54 (0·1)	49·5 (9·3)	42·0 (1·7)	12·0 (1·6)	0·11 (0·02)	0·25 (0·0)	26·7 (1·6)	24·3 (0·4)	5·5 (0·3)	0·06 (0·00)	0·29* (0·07)	22·8 (8·3)	18** (1·8)	6·5* (1·6)	0·05 (0·02)
20	Upper	0·52 (0·0)	41·7 (1·5)	48·0 (0·2)	12·6 (0·6)	0·10 (0·00)	0·21 (0·1)	23·9 (1·2)	28·8 (2·9)	5·0 (0·8)	0·06 (0·00)	0·31** (0·05)	17·8** (2·0)	19* (2·9)	7·6** (1·1)	0·04** (0·00)
	Mid	0·50 (0·2)	37·9 (2·6)	46·2 (2·9)	11·1 (3·2)	0·08 (0·01)	0·41 (0·1)	24·6 (1·4)	28·8 (2·0)	9·1 (0·5)	0·05 (0·00)	0·09 (0·17)	13·3* (2·7)	17* (4·9)	2·0 (3·6)	0·03* (0·01)
	Foot	0·85 (0·0)	45·9 (10·2)	52·8 (6·5)	19·0 (0·3)	0·10 (0·02)	0·35 (0·1)	26·4 (1·2)	28·2 (1·3)	7·9 (2·1)	0·06 (0·00)	0·50* (0·10)	19·5 (9·9)	25* (7·0)	11·1** (2·3)	0·04 (0·02)

[a]Duration of time after the conversion of communal grazing lands to exclosure.
[b]Values are calculated as exclosure values – adjacent grazing land value.
*Differences in soil nutrients concentrations and stocks and soil properties were significant at $P < 0{\cdot}05$ (paired t-test with separate/unequal variances).
**Differences in soil nutrients concentrations and stocks and soil properties were significant at $P < 0{\cdot}01$ (paired t-test with separate/unequal variances).

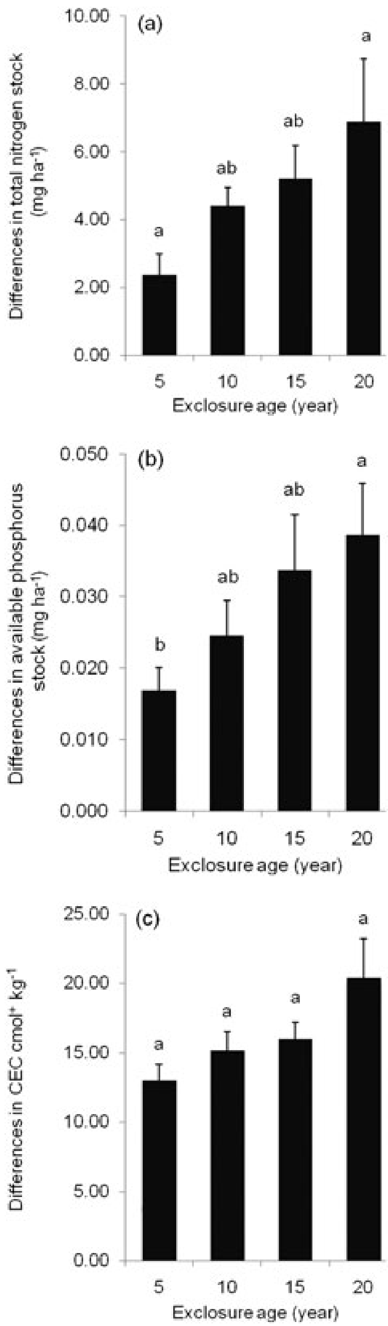

Figure 2. Differences between exclosures and adjacent communal grazing lands in the total soil N stock (a), available P stock (b), and CEC (c) in relation to exclosure age. Means ($n = 3$, SE bars) followed by different letters indicate significant differences among categories of exclosure age (one-way ANOVA with Kruskal–Wallis test at $P \leq 0{\cdot}05$).

The insignificant and less strong positive correlation of soil nutrient content in communal grazing lands with woody species biomass and vegetation canopy cover (Table III) indicates that free grazing influenced soil nutrient restoration through reducing organic input to the soil. Other studies also indicated that a direct impact of grazing on the rangeland ecosystems is the removal of a major part of the aboveground biomass, consequently the input of the aboveground litter to the soil decreases, which may have important consequences for soil nutrient conservation and cycling (Abule *et al*., 2005; Savadogo *et al*., 2007). Furthermore, livestock grazing could deteriorate hydrological soil properties, mainly structure of the soils, consequently reducing the rate of microbial process and nutrient retention (Neff *et al*., 2005). The poor positive correlation between soil nutrient and clay content (Table III) could arise from the decrease in clay content with time in the communal grazing lands due to soil erosion, which in turn reduced the positive effect of clay in restoring soil nutrient content.

Our field-based regression models open up possibilities to predict soil nutrient content in communal grazing lands, which is important baseline information for the evaluation of exclosures established on degraded communal grazing lands. The range covered by the independent variables in these models is typical of the highlands of Tigray because more than 80% of the highlands of Tigray receives annual rainfall between 500 and 800 mm y^{-1} (Abay *et al*., 2008), and the majority of the communal grazing lands are severely degraded supporting only sparse vegetation (Nedessa *et al*., 2005).

Changes in Soil Nutrient Content and Properties in Relation to Exclosure age

The inherent assumption of our space-for-time substitution approach is that the exclosures and adjacent communal grazing lands had similar conditions before exclosure establishment. We tested this assumption using variables measured in the paired exclosures and grazing lands that are less dependent of land use (Mekuria *et al*., 2011), and we verified that the paired sites were comparable, and differences in soil nutrient content, soil properties, and native vegetation richness and diversity measured between the paired exclosures and adjacent grazing lands were caused by land use change and not by inherent site variability.

The higher soil nutrients content and properties in all exclosures indicate that exclosures have a significant positive effect on the restoration of degraded soils because of overgrazing (Table II). Similar results were reported from case studies conducted on exclosures established within the last two decades in the Central Highlands of Ethiopia: an increase of 0·67% organic matter, 8·85 mg kg^{-1} increase in available P, and 9·18 $cmol_c\,kg^{-1}$ increase in CEC after 9 years of exclosure establishment (Mamo, 2008) and 2·33%, 0·08%, 7·89 $cmol_c\,kg^{-1}$ increases in organic matter, total soil N, and CEC, respectively, after 20 years of exclosure establishment (Tsetargachew, 2008). The considerable differences in soil nutrient content and properties between exclosures and communal grazing lands can be explained either by increased grazing pressure in the reduced areas of communal grazing lands after establishment of exclosures

Table III. Spearman correlation coefficients ($n = 12$) between soil nutrients content and properties and site and vegetation characteristics within exclosures and communal grazing lands

Site and vegetation characteristics	Exclosure					Adjacent grazing lands					Differences [a]				
	N (%)	P (mg/g)	CEC (cm [+]kg^{-1})	N (Mg ha^{-1})	P (Mg ha^{-1})	N (%)	P (mg/g)	CEC (cm [+]kg^{-1})	N (Mg ha^{-1})	P (Mg ha^{-1})	N (%)	P (mg/g)	CEC (cm [+]kg^{-1})	N (Mg ha^{-1})	P (Mg ha^{-1})
Woody biomass (Mg ha^{-1})	0·8*	0·7*	0·7*	0·9*	0·8*	0·0	0·3	0·4	0·0	0·5	0·8*	0·8*	0·8*	0·8*	0·8*
Vegetation canopy cover (%)	0·7*	0·6*	0·8*	0·8*	0·6*	0·5	0·6	0·8*	0·3	0·6*	0·6	0·8*	0·9*	0·5	0·8*
Under-canopy cover (%)	0·2	0·4	0·1	0·2	0·5	0·2	0·1	0·4	0·3	0·0	0·4	0·1	0·2	0·4	0·1
Sand (%)	−0·4	−0·3	−0·6*	−0·3	−0·1	−0·2	−0·4	−0·5	−0·2	−0·3	−0·4	−0·5	−0·4	−0·4	−0·5
Silt + clay (%)	0·4	0·3	0·7*	0·3	0·1	0·2	0·4	0·5	0·2	0·3	0·4	0·5	0·4	0·4	0·5
Clay (%)	0·5	0·3	0·4	0·5	0·4	0·1	0·4	0·6	0·1	0·3	0·7*	0·4	0·6*	0·7*	0·5
Bulk density (g cm^{-3})	−0·9*	−0·6*	−0·6*	−0·9*	−0·8*	−0·1	−0·3	−0·1	−0·1	−0·4	−0·9*	−0·8*	−0·8*	−0·9*	−0·8*
Stone cover (%)	−0·4	−0·6*	−0·6	−0·5	−0·5	−0·1	−0·5	−0·5	0·0	−0·5	−0·2	−0·4	−0·5	−0·2	−0·5
Slope (%)	−0·4	−0·4	−0·2	−0·3	−0·5	−0·0	−0·3	−0·0	0·1	−0·3	−0·6	−0·4	−0·1	−0·5	−0·4
Precipitation (mm y^{-1})	0·8*	0·7*	0·6*	0·9*	0·7*	0·3	0·5	0·5	0·3	0·4	0·6*	0·7*	0·7*	0·6*	0·7*
Exclosure age (year)	0·7*	0·6*	0·3*	0·7*	0·8*						0·6*	0·8*	0·7*	0·6*	0·8*

*$P < 0·05$.
[a]Differences are calculated as exclosure values minus adjacent grazing land values and are correlated with site and vegetation characteristics under exclosures.

Table IV. Multiple regression models for the prediction of soil nutrient stocks in the 0- to 0·2-m depth in exclosures, communal grazing lands, and their differences

Land use group	Model	*P*-value	R^{2a}
Total soil nitrogen (N) stock in the 0- to 0·2-m depth			
Exclosures	Mg N $ha^{-1} = -12.4 + 0.13 \times$ *woody biomass* (Mg ha^{-1}) $+ 0.03 \times$ *precipitation* (mm y^{-1}) $+ 0.2 \times$ *exclosure age* (year)	0·01	0·64
Grazing lands	Mg N $ha^{-1} = -12 + 0.03 \times$ *precipitation* (mm y^{-1})	0·00	0·74
Soil available phosphorus (P) stock in the 0- to 0·2-m depth			
Exclosures	Mg P $ha^{-1} = 0.07 + 0.001 \times$ *exclosure age* (year) $+ 0.001 \times$ *woody biomass* (Mg ha^{-1})	0·00	0·71
Grazing lands	Mg P $ha^{-1} = 0.006 + 0.0001 \times$ *precipitation* (mm y^{-1}) $+ 0.001 \times$ *vegetation canopy cover* (%)	0·05	0·52
Differences between paired exclosures and grazing lands in the total soil nitrogen and available phosphorus stocks			
Total soil N (Mg ha^{-1}) $= -2.7 + 0.3 \times$ *clay* (%) $+ 0.2 \times$ *woody biomass* (Mg ha^{-1})		0·00	0·79
Soil available P (Mg ha^{-1}) $= 0.002 + 0.002 \times$ *woody biomass* (Mg ha^{-1}) $+ 0.0006 \times$ *clay* (%)		0·00	0·72

[a]We used adjusted R^2 values for predictive models with more than two independent variables.

and susceptibility to erosion due to sparse vegetation cover (Table I) or by increased vegetation cover in the exclosures (Table I), which would reduce soil erosion and increase organic \matter input into the soil. In contrast to our study, Tsetargachew (2008) found a higher value of available phosphorous (9·96 mg kg^{-1}) in communal grazing land compared with the 20-year-old exclosure (9·33 mg kg^{-1}). This variation could arise from the less dependence of farmers in Central Highlands of Ethiopia on the use of cow dung to meet their household energy demand compared with farmers living in the northern highlands of Ethiopia where the natural vegetation is entirely disappeared, which resulted in increased dependence on the use of cow dung and crop residues for household energy demand (Zenebe, 2007). This in turn resulted in the removal of all cow dung from the communal grazing lands and reduction of organic inputs and soil nutrients to the soil.

Soil nutrient content, mainly the total soil N and available P restoration, was also influenced by exclosure age. The relatively large increase in the total soil N and available P storage in the first 5 years after establishing exclosures (Figure 2a and b) may have resulted from the management rule that restricts grass harvesting for 3 to 5 years after exclosure establishment and subsequent increased organic matter input derived from herbaceous species biomass, from reduced soil erosion through effective ground cover, and from relatively slow decomposition under drier and cooler climate (Mekuria *et al*., 2011). Furthermore, the 20 years of exclosures had reached the total soil N and available P levels of church forests, suggesting that a minimum of two decades is required to increase the soil nutrient content in the communal grazing lands to the level of soil nutrient content in church forests through exclosure establishment. However, there could be further potential to restore more total soil N and available P after about 20 years as the studied church forests were influenced by human and domestic grazing animals and are not considered as in climax condition.

The positive correlation of soil nutrient content and soil properties in exclosures with woody species biomass, vegetation canopy cover, and exclosure duration (Table III) indicate that exclosures influenced soil nutrient content and soil properties through a higher organic matter input into the soil with time (Table I). Other studies also reported increasing soil nutrient retention in ecosystem along with the number of plant species and aboveground biomass (e.g., Johannes and David, 2000; Loreau et al., 2001). Furthermore, the increases in canopy cover with the increase in exclosure duration could decrease sediment-associated soil nutrient losses by reducing the erosive impact of raindrops and soil erosion (Tsetargachew, 2008; Girmay *et al*., 2009; Mekuria *et al*., 2009).

Using a combination of climate, soil, vegetation, and management-related (e.g., exclosure age) variables as independent predictors, we were able to explain a considerable part of the variation in soil nutrient content after the establishment of exclosures (Table IV). The independent predictor clay content together with precipitation indicates the importance of water availability to restore degraded soils, whereas the biomass from woody species indicates the importance of organic inputs. Furthermore, the independent vegetation predictor percentage canopy cover shows the importance of vegetation cover for reducing soil erosion and sediment-associated soil nutrient losses and minimizing degradation process. Our regression models based on field data proved useful for investigating the time dynamics of soil nutrient stocks after the establishment of exclosures, and the results can provide information for land managers to plan future exclosures as well as to take into account the ecological importance of such resources in their management decisions.

CONCLUSIONS

The results of the present study confirm that the establishment of exclosures on degraded communal grazing lands can be effective in improving soil nutrient content and properties. Our study also confirms that it is possible to generate baseline information and to make quantitative prediction of the changes in soil nutrient content after the establishment of exclosures using relatively simple field measurements and regression models. Such information is critical for evaluating the ecological importance of exclosures and to assist policy makers to consider the value of exclosures in natural resource planning and management. Further studies are needed to investigate the degree to which nutrient enrichment in exclosures is due to soil and nutrient deposition from surrounding areas, as this may affect the sustainability of scaling up the area of exclosures.

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