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Grazing exclosures increase soil organic carbon stock at a rate greater than "4 per 1000" per year across agricultural landscapes in Northern Ethiopia

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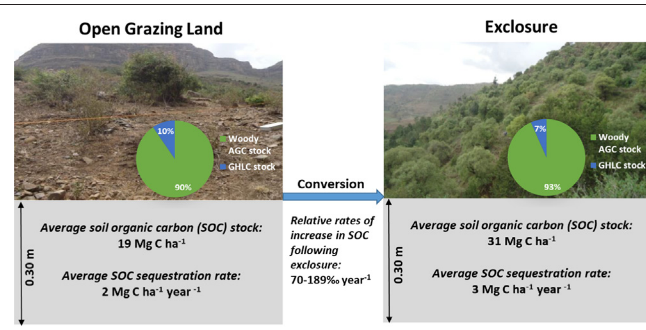
HIGHLIGHTS

- Conversting degraded grazing land to exclosure considerably increased soil organic carbon (SOC) stock in the 0–30 cm depth.
- Rates of SOC accrual were several folds higher than the 4‰ year^{-1} target.
- SOC sequestration rates tend to saturate after about 2 decades of grazing exclosure.
- Exclosures can contribute to climate change mitigation under the 4‰ Initiative.

GRAPHICAL ABSTRACT



The pie charts show the contribution of abovegound carbon (AGC), including that of woody vegetation and grass, herb and litter (GHL)

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ABSTRACT

The establishment of grazing exclosures is widely practiced to restore degraded agricultural lands and forests. Here, we evaluated the potential of grazing exclosures to contribute to the "4 per 1000" initiative by analyzing the changes in soil organic carbon (SOC) stocks and sequestration (SCS) rates after their establishment on degraded communal grazing lands in Tigray region of Ethiopia. We selected grazing areas that were excluded from grazing for 5 to 24 years across the three agroecological zones of the region and used adjacent open grazing lands (OGLs) as control. Soil samples were collected from two depths (0–15 cm and 15–30 cm) and SOC and aboveground C stocks were quantified in both exclosures and OGLs. The mean SOC stock and SCS rate in exclosures (0–30 cm) were 31 Mg C ha^{-1} and 3 Mg C ha^{-1} year^{-1}, which were respectively 166% and 12% higher

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than that in the OGLs, indicating a positive restoration effect of exclosures on SOC storage. With increasing exclosure age, SOC stock and SCS rate increased in the exclosures but decreased in the OGLs. Higher SOC stock and SCS rate were recorded in 0–15 cm than in 15–30 cm. The relative (i.e., to the SOC stock in OGLs) rates of increase in SOC stocks (70–189‰ year^{-1}) were higher than the 4‰ year^{-1} and were initially high due to low initial SOC stock but declined over time after a maximum value of SOC stock is reached. Factors such as aboveground biomass, altitude, clay content and precipitation promoted SOC storage in exclosures. Our study highlights the high potential of exclosures for restoring SOC in the 0–30 cm soil depth at a rate greater than the 4‰ value. We argue that practices such as grazing exclosure can be promoted to achieve the climate change mitigation target of the "4‰" initiative.

1. Introduction

Over the past decades, rising global average temperature and its implications for human life have triggered the promotion of several local and international initiatives aimed at climate change adaptation and mitigation while improving food security. One of such initiatives is the "4 per 1000 Soils for Food Security and Climate" initiative (https://www.4p1000.org/), which advocates that an annual increase rate of 4‰ year^{-1} in the soil organic carbon (SOC) stocks to 30–40 cm depth through the promotion of economically viable and environmentally sound management practices would significantly reduce the CO_2 concentration in the atmosphere related to human activities (Chabbi et al., 2017; Corbeels et al., 2019; de Vries, 2018; Lal, 2016; Minasny et al., 2017; VandenBygaart, 2018). Criticisms of the initiative have questioned its achievability, emphasizing the significance of the "4‰" value, the limitation of SOC sequestration with time and the large nutrient requirements (Baveye et al., 2018; de Vries, 2018; Minasny et al., 2018; Schiefer et al., 2018; VandenBygaart, 2018; White et al., 2018). In response to these criticisms, there is a need for additional empirical evidence on the potential of achieving the "4‰" target (e.g., Minasny et al., 2018).

Adopting and scaling up best soil management practices which result in increases in SOC stocks are imperative for the accomplishment of the 4‰ year^{-1} or even higher SOC sequestration rates (Lal, 2016; Minasny et al., 2017; Poulton et al., 2018). However, knowledge on the likely range of ecosystem management practices where the 4‰ target might be achieved in practice remains limited. Previous studies have reported several management practices that can increase SOC stocks, including organic additions, reduced soil disturbances (e.g., reduced or no tillage) and land use change (e.g., conversion of arable cropping land to woodland) (Chen et al., 2018; Galati et al., 2015, 2016; Poulton et al., 2018). On the one hand, despite the potential of these practices to increase SOC stocks even at rates well above the 4‰ year^{-1}, many of them may not be widely adopted because of biophysical and socio-economic limitations (Poulton et al., 2018; Rumpel et al., 2019). For example, the addition of organic materials or application of nitrogen (N) fertilizer is constrained by high demands for organic residues and large amounts of N as dictated by basic stoichiometric considerations, risk of nitrate and phosphate pollution and lack of financial resources in some developing countries (Baveye et al., 2018; Goulding et al., 2000; Poulton et al., 2018; van Groenigen et al., 2017). On the other hand, land management practices aiming to increase SOC sequestration rates through the re-vegetation of degraded lands using natural regeneration of plants may be environmentally friendly and economically feasible options (e.g., Deng et al., 2017; Liu et al., 2017). In particular, excluding degraded agricultural lands from grazing to allow the natural regeneration to progress into woodland reportedly led to large carbon accumulations both in the soil and aboveground vegetation (e.g., Bikila et al., 2016; Deng et al., 2017; Mekuria et al., 2011).

It has been established that SOC storage is mainly determined by the balance between carbon inputs (e.g., plant litter production, root exudate and root contributions) and outputs (e.g., microbial decomposition of plant inputs and existing soil organic matter) (Amundson, 2001; Jastrow et al., 2007). Root-derived carbon inputs are mainly responsible for the long-term accumulation of SOC due to the long residence time of root-derived SOC (Rasse et al., 2005). On restored degraded agricultural lands, primary carbon inputs to the soil may originate from aboveground (i.e., woody and herbaceous) biomass and root litter and rhizodeposits. In particular, increased aboveground biomass as a result of vegetation recovery on the degraded lands can enhance litter and root inputs to soils, thereby increasing SOC directly via increased recalcitrant plant components or indirectly via accumulation of microbial necromass (Chen et al., 2020).

Local environmental conditions such as soil physical and chemical properties, soil type and climate are important factors that influence SOC storage (Johnston et al., 2009; Minasny et al., 2018). For example, high SOC stocks have been observed in areas with low temperature and high precipitation (e.g., Minasny et al., 2018). Another important aspect of SOC storage and sequestration is the "sink saturation", which suggests that sequestration rates are high during initial years but decline as time progresses and soils approach a new equilibrium, such that the potential decreases to zero when this new equilibrium is reached (Smith, 2014, 2016). Therefore, understanding the response of SOC sequestration to variations in environmental factors and accounting for the sink saturation effect will support the design of best management practices for a long-term accumulation of SOC at rates equal or greater than the 4‰ year^{-1}.

Grazing exclosure is a well-known land management practice used to restore degraded agricultural ecosystems (e.g., gazing lands) and promote carbon sequestration (Deng et al., 2017; Liu et al., 2017; McSherry and Ritchie, 2013; Mekuria et al., 2011; Noulèkoun et al., 2021; Schönbach et al., 2011). The practice consists of excluding grazing areas from human and animal interferences to promote natural regeneration of plants and thus restore soil nutrient content and properties as well as vegetation composition (Aerts et al., 2009; Birhane et al., 2017; Mekuria et al., 2017; Seyoum et al., 2015). The practice is particularly appealing, considering the potential for SOC accumulation in situations where soils are highly degraded and less productive with limited resources (Albanito et al., 2016; Minasny et al., 2017; Smith et al., 2013).

In arid and semi-arid environments of Ethiopia, the practice of exclosure has emerged in response to the widespread land degradation as a consequence of deforestation and overgrazing (Lemenih et al., 2005; Mekuria et al., 2011; Mengistu et al., 2005). The establishment of exclosures has been recognized and promoted over the last four decades as a promising and viable option for restoring the soils of degraded communal grazing lands, particularly, in the Tigray region of Northern Ethiopia, where degradation of natural resources has been considerably higher than in other parts of the country (Birhane et al., 2017; Mekuria et al., 2011; Mengistu et al., 2005; Seyoum et al., 2015). Previous studies showed that exclosures were effective in increasing SOC stocks in the region but such increase varied with exclosure age and soil depth (Descheemaeker et al., 2006; Gebregergs et al., 2019; Gessesse et al., 2020; Girmay et al., 2009; Mekuria et al., 2011). Reported increases in SOC following the conversion of degraded grazing lands to exclosures in the highlands of Tigray ranged between 22.6 Mg C ha^{-1} in the 0–15 cm depth after 8 years of exclosure (Girmay et al., 2009) to 75.0 Mg C ha^{-1} in the 0–30 cm depth after 20 years of exclosure (Descheemaeker et al., 2006). However, most of these studies have focused on the highlands of the region only and did not investigate the influence of vegetation, edaphic and climatic factors on the effectiveness of exclosures to restore SOC stock. This information is however also crucial for the promotion and scaling up of the exclosure practice as a viable strategy for increasing SOC storage.

Here, we assessed the SOC storage potential of grazing exclosure in the Tigray region of Ethiopia and examined the extent to which this practice may increase SOC stock and contribute to the 4‰ initiative. We did so by quantifying SOC stocks at two soil depths (0–15 cm and 15–30 cm) in grazing exclosures of different age (i.e., number of years since establishment; 5–24 years) and their adjacent open grazing lands (OGLs). We then evaluated (a) how SOC stocks and sequestration rates varied between exclosure and OGL with regard to exclosure age and soil depth and (b) the extent to which vegetation, topography, soil properties and climate influenced SOC stocks in grazing exclosures to identify controlling vegetation and environmental factors. We hypothesized that (i) grazing exclosures would exhibit higher rates of SOC storage and sequestration compared to OGLs due to greater vegetation and soil C inputs on grazing exclosures; (ii) SOC storage and sequestration would increase with exclosure age in grazing exclosures but would decline with age in OGLs due to continuous grazing on OGLs; (iii) SOC storage and sequestration rates would decrease with soil depth in both grazing exclosures and OGLs; (iv) exclosures would increase SOC stock at a rate similar or even greater than 4‰ $year^{-1}$ but the rate of SOC increase would decrease over time due to the sink saturation effect and (v) a range of vegetation and environmental (i.e., topographic, edaphic and climatic) variables would influence SOC stocks in grazing exclosures.

2. Materials and methods

2.1. Study sites

The study was carried out in the Tigray region, which is located in the northern part of Ethiopia and covers a total area of 5.2 million ha (Fig. 1). Data were collected from nine grazing exclosures, selected on the basis of well-defined ecological and socio-economic indicators of successful forest management and restoration, with the aim of identifying the "best" exclosure practices for future scaling-up (Birhane et al., 2017; Pagdee et al., 2006). Therefore, the nine selected grazing exclosures were identified as the "best" in terms of biophysical features (e.g., vegetation cover, soil physical and chemical properties) mainly. More details on the methods used to select the grazing exclosures are presented in Birhane et al. (2017).

Grass harvesting using a cut and carry method is allowed in the grazing exclosures because one of the objectives of exclosure establishment is the production of grass fodder. Local communities are allowed to harvest grasses once a year, which starts from the fifth year after exclosure establishment depending on the speed of natural regeneration. We did not quantify the proportion of grass harvested annually because it varies according to the amount of available grass in the grazing exclosure in a given year and at a given location. However, local communities are allowed to harvest up to 80% of the grass produced in exclosures in the region (e.g., Descheemaeker et al., 2006).

Adjacent to the selected exclosures, there were parts of the communal lands that were not excluded from grazing (i.e., OGLs). These OGLs

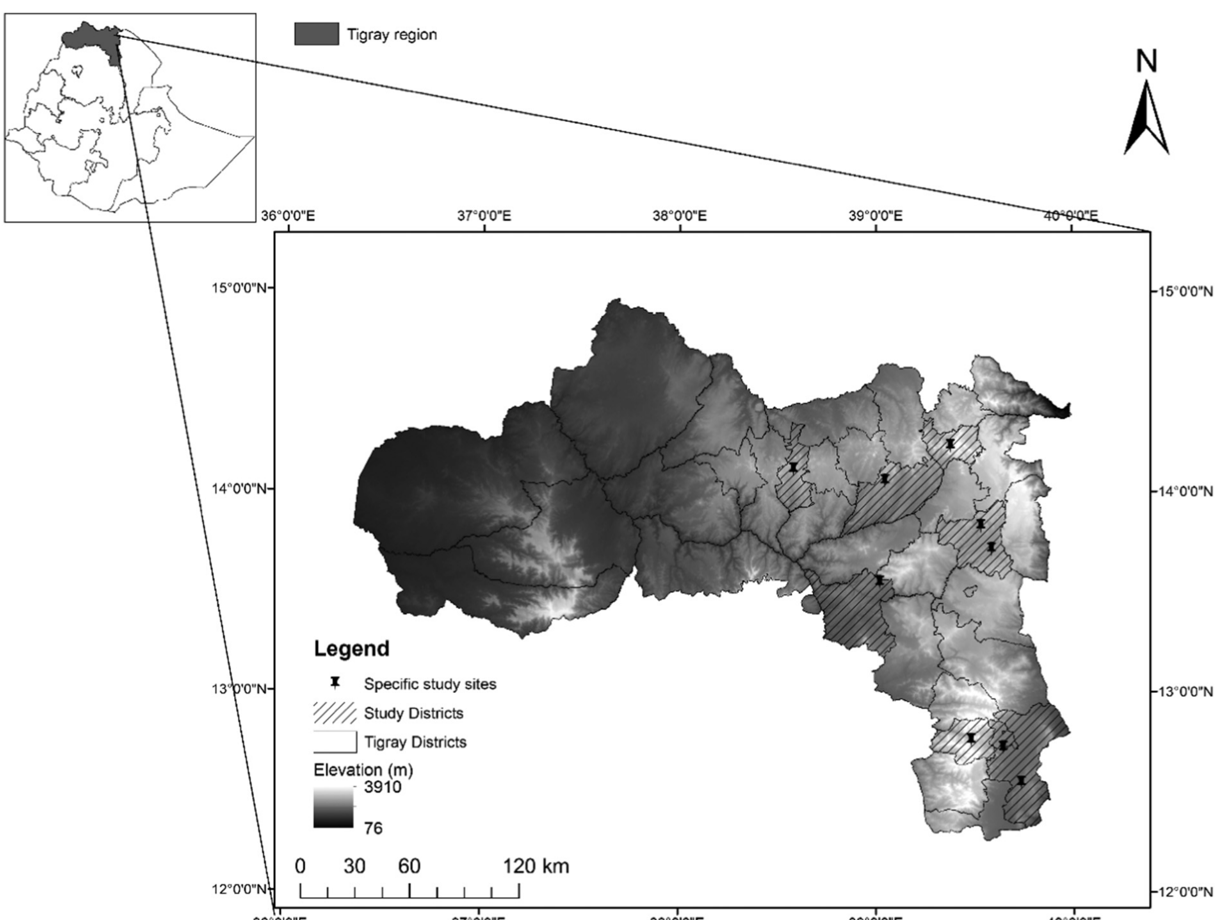

Fig. 1. Location and distribution of the districts where the study sites are found across the elevation range of Tigray region, Northern Ethiopia.

are exposed to high grazing pressure and severe land degradation because of free grazing throughout the year and overgrazing. The OGLs are grazed mainly by cows, oxen, goats and sheep.

The climate in the study region is of (semi-) arid type. The selected exclosure sites were distributed across the three main climatic zones (also referred to as agroecological zones, AEZs) of the region (Table S1): highlands, midlands and lowlands (Abrha and Simhadri, 2015; Birhane et al., 2017). The highlands are found at higher altitudes (>2400 m.a.s.l.) and are characterized by a higher annual rainfall and cooler temperatures, while the lowlands occur at low altitudes (<1800 m.a.s.l.) and experience lower amount of rainfall and higher temperatures (Table S1). The midlands extend between 1800 and 2400 m.a.s.l. and experience medium amount of rainfall along with moderate temperatures (Table S1).

According to the agricultural and rural development offices, the major land uses in the study areas include cultivated lands (20–35% of the total area), communal grazing lands (8–27%), exclosures (11–39%) and forest lands (11–79%). Mixed crop and livestock farming represents the main source of households' livelihood in all the study areas. The major cultivated crops include teff [*Eragrostis tef* (Zucc.) Trotter], barley (*Hordeum vulgare* L.), maize (*Zea mays* L.), sorghum [*Sorghum bicolor* (L.) Moench] and wheat (*Triticum aestivum* L.). The main livestock types include cattle, sheep, goat, donkey and poultry. *Vachellia etbaica* (Schweinf.) Kyal. & Boatwr, *Euclea schimperi* L. and *Dodonaea viscosa* Lf. are the common species in degraded forests and exclosures (Birhane et al., 2017).

Soil type varied between the study sites. The major soil groups in the high- and lowlands of the region include Regosols, Cambisols and Leptosols, while Fluvisols and Vertisols are the dominant soil groups in the midlands (WRB, 2006). Selected soil physical and chemical properties are presented in Fig. S1.

2.2. Sampling layout

The space-for-time or synchronic approach was used to quantify the changes in SOC stocks following the conversion of degraded grazing lands to exclosures (Corbeels et al., 2019; Fukami and Wardle, 2005; Mekuria et al., 2011). The approach requires a paired-site design, whereby the OGL adjacent to each selected grazing exclosure was used as a control site. An implicit assumption to this approach is that each paired exclosure-OGL should have had similar land use histories and comparable initial conditions at the time of exclosure establishment so that changes in SOC stocks are a result of the sole effect of the establishment of the exclosure (Mekuria et al., 2011). We used two approaches to meet this assumption in this study. First, we ensured that the selected exclosures were established on some parts of the communal OGLs. Second, we ensured that each paired exclosure-OGL was located on the same soil type and position in the landscape so that soil, terrain conditions (e.g., altitude and aspect) and vegetation were as similar as possible to account for the variations in soil type and topography (de Koning et al., 2003). Moreover, soil cores (to 1 m depth) were extracted at selected locations in each land use and compared during the site establishment to ensure that soil types were similar. The geographic coordinates and altitude of each study site were recorded and the boundary of the grazing exclosures and OGLs was delineated before starting the data collection. The age of each exclosure was also recorded (Table S1).

We used a systematic transect sampling method to collect vegetation and soil data from the paired exclosure-OGL sites. At each site, parallel transect lines were laid out at 300 m interval (Fig. S2a). The first and last transect lines were installed at about 40 m from the borders to avoid edge effects. On each transect line, the distance between subsequent sampling plots was 100 m. The number and length of the transect lines and the number of sampling plots per site (Table S2) depended on the spatial heterogeneity and diversity of the vegetation (Mengistu et al., 2005). Rectangular plots of 10 m × 20 m (200 m^2) were used for woody vegetation data collection in both exclosures and OGLs (Fig. S2b). Five smaller plots of 1 m × 1 m (1 m^2) were nested in the four corners and at the center of the 200 m^2 plots for the sampling of soil and grasses, herbs, and surface litter (GHL) biomass (Fig. S2b). A total of 210 plots of 200 m^2 were established for the sampling of woody vegetation, whereas GHL and soil samples were taken from 1685 plots of 1 m^2.

2.3. Soil sampling and organic carbon stock calculation

Soil samples were taken at 0–15 cm and 15–30 cm depths from May to July 2014. After careful removal of the litter layer, soil profile pits of about 30 cm length and 50 cm width were opened at the center of the plots. Undisturbed soil samples were taken from one of the four walls of the profile pits for each soil depth using a core sampler of 10 cm length and 3.4 cm diameter for soil bulk density (BD) determination. Five additional soil samples of equal volume were also taken using auger from the five 1 m^2 plots, pooled and mixed together according to the sampling depth to form a composite sample. The composite sample was divided in five equal parts, of which one was randomly chosen. The soil samples were stored into cloth bags, labelled and transported to the Mekelle University soil laboratory. Following the removal of debris and gravel by means of sieve of 2 mm of diameter from the core samples, the BD was calculated after oven drying the remaining soil sample at 105 °C for 24 h by dividing the dry mass by the volume of the core sampler. The SOC content was determined by the Walkley-Black method (Walkley and Black, 1934). The SOC stock was calculated at soil sample level using the following formula (Pearson et al., 2017):

$$SOC\ stock = C\ content \times BD \times Layer\ tickness \quad (1)$$

where BD (g cm^{-3}) is the bulk density and C content is the carbon concentration (% C) determined through the Walkley-Black method. The SOC stock was expressed and presented in Mg C ha^{-1}. The SOC stock in the 0–30 cm depth was estimated as the cumulative SOC stocks in the 0–15 cm and 15–30 cm depths.

2.4. Aboveground vegetation sampling and carbon stock estimation

For plant surveys, all woody vegetation including trees and shrubs were identified, counted and measured for their height and stem diameter. Diameter measurements were taken at breast height (130 cm above ground level; DBH) and/or at stump height (30 cm above ground level; DSH) in each 200 m^2 plot using a digital caliper. For single-stemmed trees or shrubs, DBH and DSH were measured directly whereas for multi-stemmed woody plants (i.e., trees and shrubs that fork below 130 cm or 30 cm), each stem was measured individually and DBH and DSH were determined as the average value of the individual stems (Ubuy et al., 2018). The height of the woody species was measured using bamboo sticks of 5 m height, graduated with 10 cm markings. A clinometer was used to determine the height of the trees taller than 5 m.

A non-destructive sampling method was adopted to estimate the biomass and C stocks of dominant trees and shrubs (thereafter referred to as trees) having a DBH ≥ 2.5 cm (Gebregergs et al., 2019; Pearson et al., 2007). The allometric equation (Eq. (2)) developed by Ubuy et al. (2018) for trees and shrubs of exclosures in the drylands of Tigray was used to estimate the woody aboveground biomass (AGB, kg):

$$AGB = 0.2050 \times DSH^{1.8548} \times H^{0.2948} \quad (2)$$

where DSH is the diameter at stump height (cm) and H is the height (m) measured for individual tree and shrub. The woody AGB was converted into woody aboveground carbon (AGC) stock using a conversion factor of 0.5 (Liu et al., 2017).

A destructive method was employed to sample herbaceous vegetation in the 1 m^2 plots. Grasses and herbs were harvested using hand shears. The chopped samples and collected litter were pooled together, mixed and weighed in the field for their fresh mass using a balance (precision 0.1 g). A subsample of the total weight was placed in a marked bag and taken to the laboratory to determine the oven-dry-to-wet mass ratio, which was used to calculate the total dry mass. The fresh GHL subsample was oven dried at 80 °C until a constant weight was reached (Rau et al., 2009) and the dry mass was recorded. The GHL carbon (GHLC) stock (Mg C ha^{-1}) was then estimated as 50% of the dry mass.

2.5. Data analyses

Our first three hypotheses were tested using linear mixed effects models. First, we analyzed the differences in all soil and vegetation variables between paired exclosure-OGL and between the AEZs (Table 1 and Fig. S3). Second, we did not deny the partial confounding effects of grazing exclosure age and AEZs including sites on SOC stocks, since there was a gradient in age across the AEZs. In addition, we found a significant interaction effect of AEZs and grazing land management practices (i.e., exclosure vs. OGL) on SOC stocks (Table S3 and Fig. S3). Therefore, we first controlled for AEZs and sites, by removing their potential effect on SOC stock and sequestration (SCS) rate with simple linear regressions (Tables S4 and S5). The SCS rate was computed as the absolute annual rate of change in SOC stock (i.e., the ratio of SOC stock and exclosure age; Mg C ha^{-1} $year^{-1}$). SOC stock and SCS rate were square root- and log-transformed respectively to meet the normality assumption after Shapiro-Wilk statistics indicated that they were not normally distributed (p-value < 0.001). Next, we used the residuals of the linear regressions on SOC stock and SCS rate as dependent variables in the mixed effect models testing for the significant main and interaction effects of grazing land management practices, exclosure age and depth. In these models, plots and sites were considered as random factors to account for unknown heterogeneity effects. In addition to the results of the mixed models, we constructed boxplots to explore the variation in SOC stock and SCS rate between grazing land management practices and soil depths.

To test our fourth hypothesis, we re-calculated the SOC stocks on an equivalent soil mass (ESM) basis for each study site (Appendix A in Supplementary data and Table S6) to account for differences in BD between the exclosures and the OGLs (Cardinael et al., 2017; Ellert and Bettany, 1995; Lee et al., 2009), because the exclosure of grazing lands led to a decrease in soil BD (Table S7). For each paired exclosure-OGL site, we computed the effect size as the natural log of response ratio (Shi et al., 2018), which is referred to as the restoration effect (RE):

$$RE = \ln\left(\overline{X_1}/\overline{X_2}\right) = \ln\left(\overline{X_1}\right) - \ln\left(\overline{X_2}\right) \tag{3}$$

where $(\overline{X_1})$ is the mean value of the SOC stock in the grazing exclosure and $(\overline{X_2})$ is the mean SOC stock in the adjacent OGL. The use of mean site values accounted for pseudo-replication. RE gives the log of the proportional difference between the groups (Shi et al., 2018). The log RE was back-transformed and expressed as percentage SOC stock change ($(exp^{RE} - 1) \times 100$) for easier interpretation of the results. Using the RE, we further computed the mean relative (i.e., to initial value of SOC represented by the SOC stock in the OGLs) rate of change in SOC (‰ $year^{-1}$) as follows:

$$Relative\ rate\ of\ change\ in\ SOC = \left(\frac{LE}{\Delta Age}\right) * 10 \tag{4}$$

where LE is the back-transformed log (RE) in %, ΔAge is the number of years since the exclosure was established and 10 is the conversion factor to ‰. We then explored the trend in the relative rate of change in SOC with increasing age and initial SOC stock using scatterplots.

Our fifth hypothesis was that a range of vegetation, topographic, edaphic and climatic variables would influence SOC storage in exclosures. For the analysis, we used AGB as a vegetation property and considered a set of environmental variables including (a) climatic factors: mean annual temperature (MAT), minimum temperature of the coldest month (MTCM), maximum temperature of the warmest month (MTWM), mean annual precipitation (MAP), precipitation of the driest month (PDM), precipitation of the wettest month (PWM) and precipitation seasonality (PS); (b) topography: altitude; (c) soil properties: sand, silt, clay and coarse fragments contents, pH and cation exchange capacity (CEC). The climate data were downloaded from the WorldClim database at a resolution of 30 s (Hijmans et al., 2005) and the soil data from the SoilGrids database for a depth of 30 cm at 250 m resolution (Hengl et al., 2017). Separate linear mixed effects models were performed to test for the fixed effects of vegetation property, topography, soil properties and climate on SOC stocks in the exclosures. In these models, we considered plot as a random factor. For the linear mixed effects models with more than two predictors (i.e., for edaphic and climate variables), we (i) explored the correlation between the predictors using the Pearson based correlation matrix (Fig. S4), (ii)

Table 1
Mean (standard error) values of soil organic carbon (SOC) stock and sequestration (SCS) rate, woody aboveground carbon (AGC), grass, litter and herb carbon (GLHC), tree density and basal area in the paired grazing exclosures-open grazing lands (OGLs) across the studies sites.

Study site (Age in years)	Management practice	SOC (Mg ha^{-1})	SCS rate (Mg ha^{-1} $year^{-1}$)	Woody AGC (Mg ha^{-1})	GHLC (Mg ha^{-1})	Tree density (Stem ha^{-1})	Basal area (m^2 ha^{-1})
Dabre (24)	Exclosure	41.36^a (2.34)	1.72^a (0.12)	17.09^a (2.03)	0.36^a (0.00)	1308^a (108)	8.13^a (1.06)
	OGL	27.94^b (3.79)	1.16^b (0.16)	1.75^b (0.49)	0.01^b (0.00)	384^b (150)	3.22^b (1.20)
Mugulat (23)	Exclosure	36.11^a (1.60)	1.57^a (0.07)	12.42^a (2.42)	0.48^a (0.01)	468^a (41)	6.08^a (1.00)
	OGL	21.81^b (2.10)	0.95^b (0.09)	5.58^b (2.88)	0.02^b (0.01)	125^b (63)	3.31^b (1.24)
Gereb Hara (21)	Exclosure	24.44^a (1.18)	1.16^a (0.06)	5.43^a (1.14)	0.62^a (0.01)	593^a (74)	2.88^a (0.49)
	OGL	14.33^b (1.59)	0.68^b (0.08)	0.70^b (0.23)	0.08^b (0.02)	198^b (110)	0.28^b (0.76)
Ziban Serawat (19)	Exclosure	30.87^a (1.74)	1.62^a (0.09)	1.88^a (0.22)	–	311^a (27)	1.03^a (0.10)
	OGL	19.10^b (1.72)	1.00^b (0.09)	0.88^b (0.15)	–	125^b (39)	0.52^b (0.15)
Abreha Atsbeha (17)	Exclosure	22.79^a (1.82)	1.31^a (0.11)	4.62^a (0.50)	–	463^a (49)	2.45^a (0.22)
	OGL	9.52^b (1.65)	0.56^b (0.10)	1.45^b (0.36)	–	275^b (69)	0.55^b (0.31)
Enda-chiwa (16)	Exclosure	28.63^a (1.56)	1.80^a (0.10)	5.60^a (0.77)	–	575^a (56)	2.96^a (0.34)
	OGL	12.75^b (1.56)	0.80^b (0.10)	0.98^b (0.22)	–	217^b (79)	0.52^b (0.49)
Erbba (8)	Exclosure	26.05^a (1.39)	3.26^a (0.14)	3.75^a (0.44)	0.78^a (0.07)	53^b (44)	1.89^a (0.23)
	OGL	18.98^b (1.73)	2.37^b (0.08)	2.50^a (0.72)	0.21^b (0.05)	1.89^a (0.2)	1.39^a (0.28)
Rafael (6)	Exclosure	29.48^a (0.98)	4.91^a (0.16)	4.30^a (0.64)	0.64^a (0.04)	150^b (20)	3.21^a (0.43)
	OGL	21.48^b (1.17)	3.58^b (0.19)	5.03^a (0.84)	0.32^b (0.05)	2.40^b (0.4)	1.23^a (0.08)
Enda-medihanialem (5)	Exclosure	33.43^a (1.25)	6.69^a (0.25)	12.37^a (1.89)	0.04^a (0.00)	239^b (84)	6.63^a (0.82)
	OGL	24.90^b (1.54)	4.98^b (0.31)	2.60^b (0.56)	0.42^b (0.05)	6.63^a (0.8)	1.42^b (1.13)

"–": missing GLHC data due to the absence of grass, herb and litter at the time of sampling, as a result of the annual grass and herb harvesting using a cut and carry method. For each study site, the means with the same superscript within the same column are not significantly different at $p < 0.05$ between exclosure and OGL.

iteratively checked for multicollinearity by means of variance inflation factor (VIF) with VIF > 5 indicating multicollinearity (Table S8) (Mensah et al., 2021) and (iii) calculated the relative variable importance (RVI) value of each predictor. Highest correlation values were found between sand and clay, clay and pH, and coarse fragments content and pH (Fig. S4). Both sand and pH were removed from the final model (Table S8). Following a similar approach, we found that MAT, MTCM and PWM had the highest VIF values and excluded them from the final model (Table S8 and Fig. S4).

All the statistical analyses were performed in the R statistical software version 4.0.0 (R Core Team, 2020). The parameters of the mixed-effects models were estimated using *lme4* package with the restricted maximum likelihood (REML) method (Bates et al., 2015). The *p*-values reported for the mixed effects models were computed based on the Satterthwaite approximations to the degrees of freedom using the *lmerTest* package (Kuznetsova et al., 2017).

3. Results

3.1. Soil organic carbon stock and sequestration rate across land management practice, exclosure age and soil depth

The results of the mixed effects models testing for the individual and interaction effects of grazing land management practices and age on SOC in the 0–30 cm depth revealed that SOC stock and SCS rate varied significantly between the land management practices (Table 2 and Fig. 2-A and -B). For the SOC stock and SCS rate, OGLs had regression coefficients that were respectively 0.68 ± 0.21 and 0.28 ± 0.09 significantly lower than that of exclosures (Table 2), suggesting lower values of SOC stock and SCS rate in OGLs compared to exclosures (Table 1). Overall, the SOC stock and SCS rate in the exclosures were on average 31 Mg C ha^{-1} and 3 Mg C ha^{-1} year^{-1}, which were respectively 166% and 12% higher than the SOC stock and SCS rate in the adjacent OGLs when compared on ESM basis (Fig. 2). There was no significant main effect of age but the interaction age-land management practices indicated that the effect of age varied according to the management practices (Table 2). Accordingly, the SOC stock and SCS rate slightly increased with increasing age in the exclosures while a pronounced decrease in these factors was observed with increasing age on OGLs (Fig. S5).

The results also showed that SOC stock and SCS rate differed significantly between the soil depths (Table 3). Across land management practices and age, significantly greater SOC stock and SCS rate were measured in 0–15 cm compared to 15–30 cm (Fig. 2-C and -D). Moreover, there were two-way significant interactions between land management practice-age and age-depth, suggesting that age influenced the variation of SOC stock and SCS rate between the management practices and soil depths (Table 3 and Fig. 3). With increasing age, the storage and sequestration of SOC in the 0–15 cm soil layer remained higher in grazing exclosures compared to OGLs as evidenced by the lower slope in the OGLs (Table 3 and Fig. 3). Furthermore, we found that with increasing age, SOC stock and SCS rate decreased in the 0–15 cm depth but increased in the 15–30 cm depth for both grazing exclosures and OGLs (Fig. 3).

Table 2
Results of mixed effects models testing for main and interaction effects of grazing land management practices (i.e., exclosure vs. open grazing land-OGL) and exclosure age on soil organic carbon (SOC) stock and sequestration (SCS) rate in 30 cm soil depth. The residuals of the initial linear regressions with SOC stock and SCS rate (see Table S4) were used as dependent variables in the models.

	Fixed effects			Random effects			R^2 (%)	
	Est	SE	*p*	σ^2_{Site}	σ^2_{Plot}	σ^2_{Rsd}	Marg	Cond
SOC stock (Mg ha^{-1})								
Intercept	0.26	0.12	0.030	0.00	0.00	0.34	0.49	0.49
Management practice|OGL	−0.68	0.21	**0.001**					
Age	0.00	0.01	0.255					
Management practice|OGL: Age	−0.03	0.01	**0.006**					
SCS rate (Mg ha^{-1}year^{-1})								
Intercept	0.11	0.05	0.035	0.00	0.00	0.62	0.49	0.49
Management practice|OGL	−0.28	0.09	**0.002**					
Age	0.00	0.00	0.229					
Management practice|OGL: Age	−0.02	0.01	**0.004**					

Est: coefficient estimates; SE: standard errors; σ^2: variance; Rsd: Residual; Marg: Marginal; Cond: Conditional. Exclosure was used here as baseline for land management practices. Significant effects (p-values) are bolded.

3.2. Rates of change in soil organic carbon in relation to exclosure age

The relative rates of change in SOC induced by the establishment of grazing exclosure were positive and ranged between 70 and 189‰ year^{-1} across sites, indicating an increase in SOC stock after grazing exclusion. The rates of increase fluctuated with exclosure age, depicting a hump-shaped trend (Fig. 4). The rates of increase in SOC initially dropped until about age 8 before increasing steadily to reach a maximum value and then declined as time progressed (Fig. 4-A). These results were supported by the decreasing trend observed in the Fig. 4-B, suggesting a tendency of a higher rate of increase with low initial SOC stock.

3.3. Aboveground carbon inputs

AGC and GHLC stocks, tree density and basal area were significantly higher in the grazing exclosures than in their adjacent OGLs for the majority (90%) of the study sites (Table 1). Although there was no consistent trend with exclosure age, the highest values of woody AGC stock, GHLC stock, tree density and basal area were observed in the oldest grazing exclosures (Fig. S3).

3.4. Factors affecting soil organic carbon stocks in grazing exclosures

The results of the linear mixed effects models showed that several factors influenced SOC stock in the grazing exclosures (Table 4). AGB ($\beta = 0.008$; $p < 0.001$) and altitude ($\beta = 0.004$; $p = 0.044$) had significantly positive effects on SOC stock. Among the soil factors, clay and coarse fragments contents and CEC were the most important predictors of SOC stock. Clay content had a significantly positive effect on SOC stock, while coarse fragments content and CEC had negative effects. Among the climatic factors, only MAP was the most important variable and had a positive influence on SOC stock.

4. Discussion

4.1. Variation of SOC storage and sequestration across grazing land management practices, exclosure duration and soil depth

Our first hypothesis that grazing exclusion would positively influence SOC storage and sequestration was confirmed as exclosures had significantly greater SOC stocks than the OGLs. The positive effect of grazing exclosures on SOC storage was previously reported by studies conducted in the (semi-) arid areas of Ethiopia (Bikila et al., 2016; Gebregergs et al., 2019; Mekuria et al., 2011). The increases in SOC stock after the conversion of degraded agricultural lands to exclosures can be attributed to the reduced intensity and frequency of grazing as well as the increased vegetation cover in the exclosures as a result of increased tree cover and herbaceous and litter biomass (Table 1), which would enhance organic matter production and inputs into the soil (Descheemaeker et al., 2006; Gessesse et al., 2020; Mekuria et al., 2011). Organic matter inputs to the soil come mainly from the trees (e.g., through litter, fine roots and exudates) and from the herbaceous vegetation (Amundson, 2001; Jastrow et al., 2007; Schneider et al.,

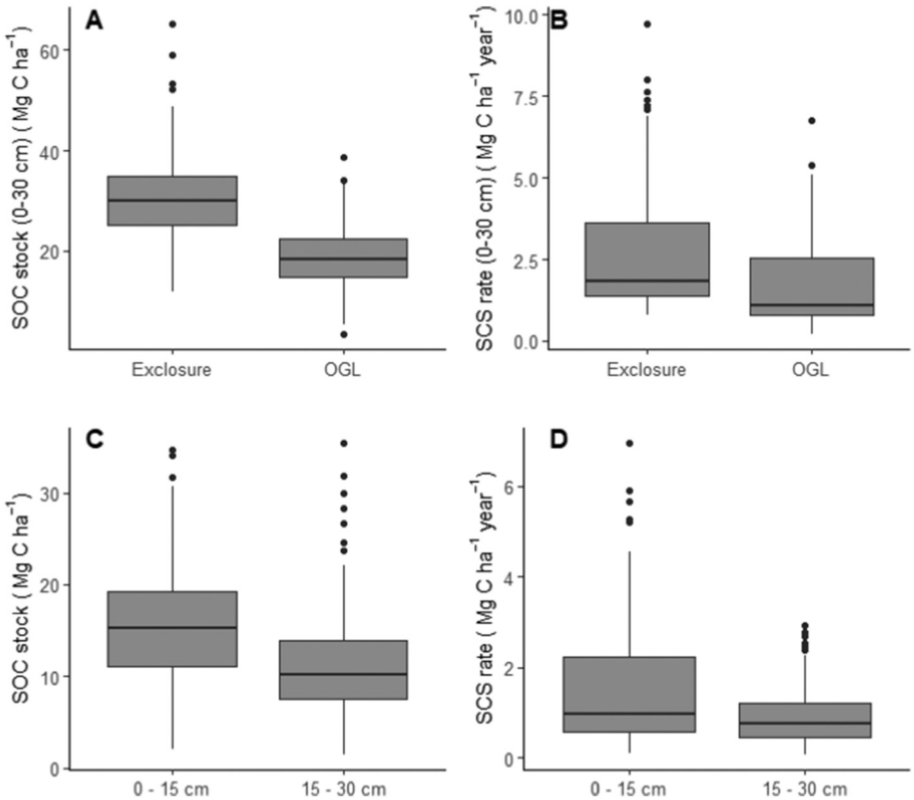

Fig. 2. Boxplots of the variation in soil organic carbon (SOC) stock and sequestration (SCS) rate between grazing land management practices (exclosure vs. open grazing land-OGL; A–B) and soil depths (C–D).

2020). However, the GHLC stock represented less than 20% of the total (woody and herbaceous) aboveground carbon stock in most (92%) of the exclosures probably because of grass harvesting, suggesting that woody vegetation is likely the main source of organic carbon inputs to the soil. Moreover, the availability of higher ground cover in the exclosures compared to the OGLs may have also led to reduced erosion, resulting in less carbon loss in exclosures compared to OGLs (Mekuria et al., 2009).

As predicted, soil C stocks and sequestration potentials were influenced by exclosure age for both grazing exclosures and OGLs. Previous studies have reported that the age since land use change has an influence on SOC sequestration after the conversion of degraded agricultural sites to forests (Deng et al., 2014, 2016; Mekuria et al., 2011; Shi et al., 2013; Wei et al., 2014). Our results indicated that the establishment of grazing exclosure sustained and even increased SOC stock and SCS rate over time, which would otherwise decrease as evidenced by the decline observed on OGLs (Fig. S5). This result supports our second hypothesis that grazing exclosure would have a positive effect on SOC storage and sequestration with increasing exclosure duration. The higher SOC stock and SCS rate in the older exclosures than in the younger ones may result from a higher tree-mediated carbon inputs in the older exclosures because of their higher tree biomass production (Table 1), which can enhance litter carbon inputs (e.g., Chen et al., 2020; Chen et al., 2018). This finding is also supported by the evidence that tree-mediated SOC sequestration is lower at the early tree age because most of the photosynthetically-produced carbon is used to support growth (Shi et al., 2018; Takimoto et al., 2008).

Soil depth was another important factor that influenced SOC storage and sequestration. Our results revealed that SOC accumulation was higher in the 0–15 cm than in the 15–30 cm, thereby confirming the common claim that SOC stock decreases with increasing soil depths in agroecosystems, i.e., our third hypothesis (e.g., Bikila et al., 2016; Hiederer, 2009). Moreover, there was a higher SOC accumulation in the 0–15 cm in the grazing exclosures than in the OGLs, which is likely due to the higher litter and root inputs from trees and herbaceous vegetation in the exclosures (Shi et al., 2018). Interestingly, we found that SOC shifted from the upper layer to the lower layer with increasing age in both grazing exclosures and OGLs. In the exclosures, this observation may be attributed to the tree-related transport of C to deeper soil layers through rhizodeposition and fine root turnover (Shi et al., 2018; Thakur et al., 2015), which increases with increasing tree age. Conversely, erosion may have contributed to lower SOC stocks closer to the soil surface in the OGLs due to the reduced vegetation cover. These findings are relevant for the long-term C sequestration and nutrient conservation, especially in exclosures, given that C stored in deeper soil layers is stable and has a long mean residence time (Schneckenberger and Kuzyakov, 2007; Zang et al., 2018).

4.2. SOC storage potential of grazing exclosures

Consistent with our fourth hypothesis, our data demonstrated that exclosures have the potential to sequester SOC at rates multifold greater than the 4‰ target under (semi-) arid conditions. The relative rates of increase in SOC were high in the initial years after exclosure establishment and remained well above the 4‰ year^{-1} after 20 years of exclosure. The high SOC storage rate during initial years suggests a high potential for SOC storage under newly established grazing exclosures. Furthermore, a higher SOC sequestration potential was observed with low initial SOC stock. Given the low SOC levels of grazing lands in Northern Ethiopia and in many African countries, the establishment and promotion of grazing exclosures could be effective in mitigating climate change under the "4 per 1000" initiative.

The age of the grazing exclosure was another important factor that determine SOC storage rates. The rates of SOC change did not increase indefinitely with time and decreased after SOC stocks reached a maximum value. This finding likely reflects the effect of "sink saturation" on SOC sequestration (Johnston et al., 2009; Smith, 2014, 2016), which entails that the capacity of grazing exclosure to store SOC is finite

Table 3
Results of mixed effects models testing for main and interaction effects of grazing land management practices (i.e., exclosure vs. open grazing land-OGL), exclosure age and depth on soil organic carbon stock (SOC) and sequestration (SCS) rate in 15 cm soil layers. The residuals of the initial linear regressions with SOC stock and SCS rate (see Table S5) were used as dependent variables in the models.

	Fixed effects			Random effects			R^2 (%)	
	Est	SE	*p*	σ^2_{Site}	σ^2_{Plot}	σ^2_{Rsd}	Marg	Cond
SOC stock (Mg ha^{-1})								
Intercept	1.06	0.11	<0.001	0.00	0.00	0.28	0.53	0.53
Management practice |OGL	−0.49	0.19	**0.009**					
Age	−0.03	0.01	**<0.001**					
Depth|15–30	−1.76	0.16	**<0.001**					
Management practice |OGL: Age	−0.03	0.01	**0.003**					
Management practice |OGL:Depht|15-30	0.09	0.27	0.730					
Age: Depth |15–30	0.06	0.01	**<0.001**					
Management practice |OGL: Age: Depht |15–30	0.02	0.02	0.308					
SCS rate (Mg ha^{-1}year^{-1})								
Intercept	0.58	0.07	<0.001	0.00	0.00	0.11	0.51	0.51
Management practice |OGL	−0.21	0.12	**0.073**					
Age	−0.01	0.00	**0.001**					
Depth|15–30	−0.97	0.09	**<0.001**					
Management practice |OGL: Age	−0.02	0.01	**0.001**					
Management practice |OGL:Depht|15–30	−0.08	0.17	0.614					
Age: Depth |15–30	0.04	0.01	**<0.001**					
Management practice |OGL: Age: Depht|15–30	0.01	0.01	0.165					

Est: coefficient estimates; SE: standard errors; σ^2: variance; Rsd: Residual; Marg: Marginal; Cond: Conditional. Exclosure and 0–15 cm soil depth were used as baseline for land management practice and depth factors, respectively. Significant effects (p-values) are bolded.

and the net CO_2 removals under grazing exclosures are of limited duration, as also observed for agroforestry systems in sub-Saharan Africa by Corbeels et al. (2019). Similarly, Minasny et al. (2018) reported that high SOC sequestration rates can be achieved in the first 20 years after implementation of best management practices. Thus, the decrease in the rate of SOC increase after about 20 years of grazing exclosure suggests that after a minimum of two decades, appropriate management strategies such as pruning, thinning and organic amendment would be required to maintain SOC stocks over time and avoid the reversibility of SOC sequestration (Smith, 2012, 2016).

4.3. Drivers of SOC storage in grazing exclosures

As hypothesized, we found that altitude, AGB, MAP and texture (i.e., mainly clay content) influenced SOC storage in exclosures. The observed increase in SOC with increasing altitude can be attributed to the slow decomposition of soil organic matter at high altitude, possibly due to the prevailing low temperature (e.g., Dai and Huang, 2006). Aboveground biomass is the primary driver of productivity and more biomass generally implies more production of litter, providing more carbon inputs to soil through litter decomposition and mineralisation (Lohbeck et al., 2015). The finding that SOC stock related positively with MAP underlines the importance of water availability for SOC storage in the exclosures, if precipitation is considered as a proxy for water availability (Mekuria et al., 2011). With increased precipitation, soil moisture could foster the downward movement of carbon from the litter layer to the soil (Chen et al., 2016). In addition, higher SOC under increased MAP may result from a mediation role of increased root biomass leading to carbon input to mineral soil in the forms of root exudates. The positive relationship between clay content and SOC suggests that finer soil particles prevent the loss of SOC through leaching or erosion after decomposition (Takimoto et al., 2008). This finding also accords with the

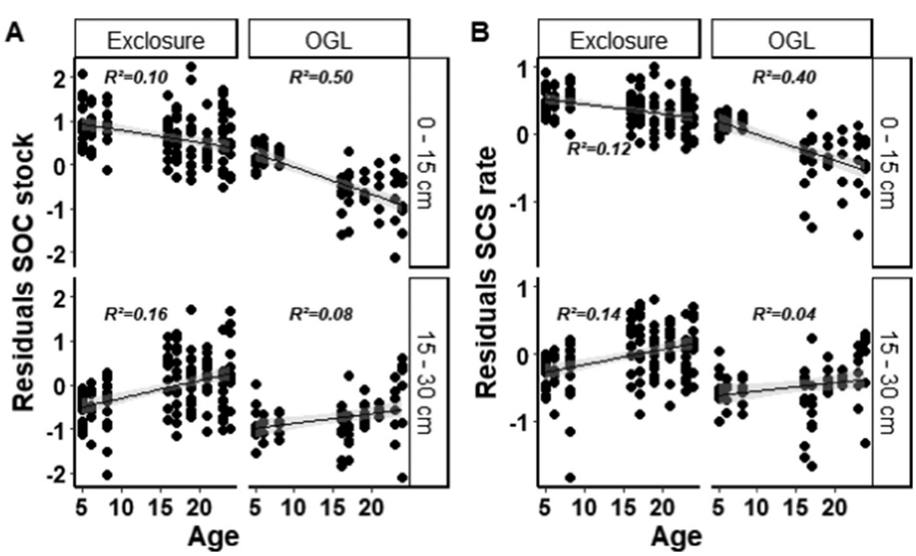

Fig. 3. Scatterplots of age with soil organic carbon (SOC) stock (A) and sequestration (SCS) rate (B) for grazing exclosure and open grazing land (OGL) at 0–15 cm and 15–30 cm soil depths. Residuals were obtained from the linear models testing the effects of agroecological zones (AEZs) and site on SOC stock and SCS rate (Table S5).

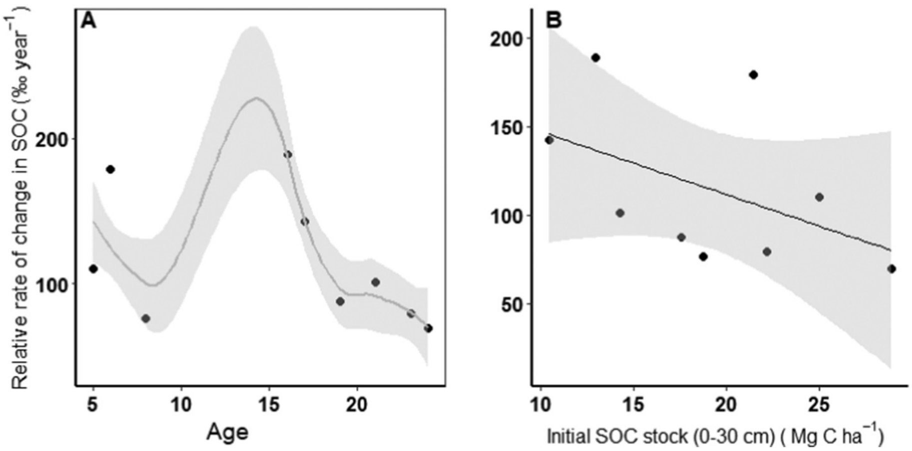

Fig. 4. Trend in relative rate of soil organic carbon (SOC) increase with increasing age (A) and initial SOC stock (B) in the 0–30 cm soil depth.

general knowledge that finer-textured soils promote SOC storage because of the physico-chemical stabilization of clay particles (Corbeels et al., 2019; Torn et al., 1997). Together, the effects of clay particles and MAP on SOC stock may be operating via greater water holding capacity and water availability, which may promote plant growth and productivity, thereby increasing carbon inputs into the soil. In addition, SOC stock was influenced by coarse fragments content and CEC, illustrating the importance and collective role of soil physical and chemical properties in driving SOC fluxes.

4.4. Limitations of the study

There are obvious considerations related to the estimation of SOC storage and sequestration in this study, which are worth mentioning. First, the lack of data on the initial SOC stock before exclosure establishment led to the use of the space-for-time substitution approach, whereby the SOC stocks in the OGLs were considered as baseline values. However, this approach may yield biased estimates if the confounding effect of land-use history and spatial variability of soil properties are not accounted for (de Koning et al., 2003; Takimoto et al., 2008). In this study, we dealt with this problem by investigating the variations in soil properties that are less dependent on land use (e.g., texture) between the two land management practices, as suggested by de Koning et al. (2003). The results revealed no difference of sand, silt and clay contents, CEC and pH between the exclosure and OGL plots at most (>80%) of the sites (Fig. S1), thereby confirming that the paired sites were comparable and estimates of SOC stocks are reliable. Second, the space-for-time substitution approach and the limited range of exclosure age covered by the study prevented the quantification of the sequential changes in SOC sequestration rates for a time period greater than 24 years. Repeated measurements of SOC stock over a longer period of time would be essential for rigorous projections of the future SOC sequestration potential of exclosures, as showed by Poulton et al. (2018). Third, we emphasized on aboveground (i.e., woody and herbaceous) carbon as the main source of carbon inputs to the soil in this study. However, root carbon input derived from root litter and exudates may have also made important contributions to SOC accumulation in the grazing exclosures (Bais et al., 2006; Chen et al., 2018; Jackson et al., 2017; Rasse et al., 2005), deserving further studies. Finally, we used a relatively small number of paired grazing exclosure-OGL sites and extracted some environmental data from global databases. While these data may not fully capture the variability in environmental factors at smaller scales, the lack of locally-available data and the landscape scope of our study support their consideration in our analyses (e.g., Sullivan et al., 2017). Thus, measurements of climate and soil parameters at a site level and more observations would be needed to establish relationships between SOC dynamics and environmental factors in future studies.

5. Conclusions

The present study demonstrated that the conversion of degraded communal grazing lands to woodlands using the practice of exclosure led to considerable increase in SOC sequestration at rates higher than the 4‰ year^{-1}. The study, thus, provided the much-needed evidence-base for policy makers and land managers to consider exclosure as a viable strategy for climate change mitigation under the "4‰" initiative. However, the current rates of SOC sequestration may not be maintained over time unless appropriate soil and vegetation management techniques based on influential vegetation, topographic, edaphic and

Table 4
Results of the final linear mixed models testing the effects of topography, vegetation properties, soil properties and climatic factors on soil organic stock (SOC) stock in 30 cm depth in the grazing exclosures.

Independent variables	Beta	*P*	VIF	RVI	Rand.Var(Plot)	Resid
Aboveground biomass (AGB)	0.0077	**<0.001**	–	–	0.00	0.07
Altitude	0.0040	**0.044**	–	–	0.00	0.07
Silt content (%)	−0.0309	0.082	1.24	0.04	0.00	0.07
Clay content (%)	0.0484	**<0.001**	2.99	0.49		
Cation exchange capacity (CEC; cmol+/kg)	−0.0283	**<0.001**	1.84	0.46		
Coarse fragments content (volumetric, %)	−0.0077	**0.001**	1.77	0.22		
Mean annual precipitation (MAP)	0.0767	**<0.001**	1.22	0.87	0.00	0.07
Max temperature of warmest month (MTWM)	−0.0070	0.785	1.19	0.03		
Precipitation of driest month (PDM)	−0.0544	0.059	1.47	0.54		
Precipitation seasonality (PS)	0.0333	0.249	1.49	0.23		

Significant effects are marked in bold. VIF: Variance Inflation Factor; RVI: Relative Variable Importance; Rand.Var = Random variable; Resid = Residuals.

climatic factors are designed and implemented to avoid a potential future decrease in SOC sequestration rate. Further studies on the spatial and temporal variations of SOC storage and sequestration, the effect of projected decrease in precipitation on SOC stock and other important ecological processes driving SOC sequestration such as the decomposition and assimilation of organic matter by the soil biota are needed to capture the whole dynamics of SOC sequestration and storage in exclosures.

CRediT authorship contribution statement

Florent Noulèkoun: Conceptualization; Data curation; Formal analysis; Writing - original draft; Writing - review & editing.

Emiru Birhane: Conceptualization; Funding acquisition; Project Administration; Supervision; Writing - review & editing.

Habtemariam Kassa: Funding acquisition; Project administration; Supervision; Writing - review & editing.

Alemayehu Berhe: Field data collection.

Zefere Mulaw Gebremichael: Field data collection.

Nuru Mohammed Adem: Field data collection.

Yigremachew Seyoum: Funding acquisition; Project administration.

Tefera Mengistu: Funding acquisition; Project administration.

Bekele Lemma: Funding acquisition; Supervision; Writing - review & editing.

Nigussie Hagazi: Funding acquisition; Project administration.

Haftu Abrha: Formal Analysis; Writing - review & editing.

Meley Mekonen Rannestad: Conceptualization; Funding acquisition; Review & editing.

Sylvanus Mensah: Conceptualization; Data analysis; Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.146821.

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