Soil Carbon and Nitrogen Stock and Their Spatial Variability Along an Exclosure Chronosequence at Kewet District, Central Dry Lowlands of Ethiopia

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ABSTRACT: Empirical evidence and a better explanation of the effect of exclosures on soil properties are needed to rehabilitate degraded land and properly utilize the restored ecosystem. This study was conducted to determine soil organic carbon (SOC) and total nitrogen (TN) stocks and to map their spatial distribution and aggregate stability along open grazing land, 5, 15, and 20 years exclosure, and three slope positions. To map the spatial distribution of SOC and TN stocks an ordinary kriging interpolation method was applied. The results showed that the age of exclosure had significantly ($p < .05$) affected SOC and TN stock. Soil organic carbon stock was the highest in the 15-year-old (18.43 Mg ha^{-1}) and lowest (14.22 Mg ha^{-1}) in the 5-year-old exclosures. Similarly, the 15-year-old (1.81 Mg ha^{-1}) and 5-year-old (1.41 Mg ha^{-1}) exclosures had the highest and the lowest TN stock, respectively. Soil organic carbon associated with macroaggregates (>250 μm) and microaggregates (<250 μm) varied significantly ($p < .05$) between ages of exclosures and adjacent open grazing land. Significantly ($p < .05$) higher SOC stock (16.99 Mg ha^{-1}) and macroaggregate associated SOC (3.05%) were recorded in the upper slope position as compared to the middle and lower slope positions. Due to the variation in vegetation cover and density and topography of the area, both SOC and TN stock showed high spatial variability across all ages of exclosure and adjacent open grazing land. Despite its inconsistency, the age of exclosure had affected SOC and TN stock, mean weight diameter, water-stable aggregates, and aggregate associated SOC. It is suggested that exclosure as a restoration measure of degraded landscapes can sequester and stock a significant amount of atmospheric CO_2. Further study on soil organisms and litterfall is suggested to understand the dynamics of SOC and TN stocks in these exclosures.

KEYWORDS: Geostatistics, land degradation, slope position, soil restoration, spatial autocorrelation

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Introduction

Continued soil degradation is a common problem in most sub-Saharan countries (Ussiri & Lal, 2019). It poses serious obstacles to the efforts for food security and the ability of local communities to adapt to the impacts of climate change (Appanah et al., 2015). Rehabilitation of degraded lands is, therefore, a crucial task for sub-Saharan countries. Recently, the restoration of severely degraded lands through the exclusion of unmanaged grazing by livestock is being encouraged (Hu et al., 2019; Tang et al., 2016; Zhao et al., 2017). Severely degraded lands and poor grazing lands are being excluded from animal and human interference as a reclamation strategy. Since the 1980s, exclosures were introduced as a strategy for soil and water conservation measures in North Ethiopia (Alemayehu et al., 2009; Descheemaeker, 2006; Frankl et al., 2013; Munro et al., 2008). These area exclosures were further expanded to the central part of Ethiopia (Lemenih & Kassa, 2014). Though the establishment of area exclosure can be initiated either by the government or non-governmental organizations, its management and utilization are undertaken by the local community based on local bylaws (Aerts et al., 2006; Girmay et al., 2008).

Exclosure is conceived as a viable practice in environmental rehabilitation. Studies have indicated that the establishment of exclosures on degraded lands has a high potential of restoring native woody vegetation (Mekuria & Yami, 2013; Mekuria et al., 2007, 2018; Teketay et al., 2018), increasing litter biomass (Descheemaeker, Muys et al., 2006; Özcan et al., 2013). Exclosure can also increase soil microorganisms that is, arbuscular mycorrhiza (Birhane et al., 2017). Improvement of soil nutrients that is, total nitrogen (TN), available phosphorus, and potassium (Damene et al., 2013; Girmay & Singh, 2012; Mekuria, 2013; Tang et al., 2016), control runoff and reduce soil erosion (Descheemaeker, Nyssen et al., 2006; Girmay et al., 2009; Mekuria et al., 2007, 2009) are some of its benefits of area exclosure.

Moreover, exclosure is believed to have the potential to sequester atmospheric CO_2 through photosynthesis and to stock it in soils and aboveground vegetation (Bikila et al., 2016). This can increase TN accumulations in the soil (Chen et al., 2012). Several studies had shown that exclosure greatly positively affects soil organic carbon (SOC) stock (Damene et al., 2013; Girmay & Singh, 2012; Girmay et al., 2009; Mekuria, 2013). On the other hand, Aynekulu et al. (2017) and

Mekuria et al. (2017) have shown in their study that exclosures did not bring positive change on SOC in comparison to their adjacent open grazing land.

Depending on the degradation status of grazing land before it is excluded from free grazing and age of exclosure, the effects of exclosure on the SOC may show variability. For example, a study conducted by Mekuria et al. (2017) suggested that it required more than 7 years after the establishment of exclosures to detect significant improvements in soil properties. Contrary to this, Feyisa et al. (2017) and Damene et al. (2013) had shown that age of exclosure did not affect SOC stock and the restoration rate had decreased with increasing exclosure age, respectively.

As a result of reduced erosion and improvement of soil aeration, soil aggregation can sustain soil fertility (Zhao et al., 2017) and soil quality (Xiao-li et al., 2010). Soil aggregates, as a component of soil structure, play a key role in several soil processes (Li et al., 2019). Soil aggregate stability is considered as one of the main soil characteristics regulating soil erodibility (Environ et al., 2014). Furthermore, soil aggregation gives physical protection to SOC from degradation and mineralization by microorganisms attack (Li et al., 2019; Safadoust et al., 2016; Zhao et al., 2017; Zhong et al., 2009).

The physical protection of SOC by soil aggregates and retention in microaggregates due to the binding action of humic substances and other microbial by-products is particularly important for long-term soil carbon sequestration (Environ et al., 2014; Gelaw et al., 2015; Li et al., 2019; Zhong et al., 2009). With changes in land use, soil microaggregates may form macroaggregates through the action of temporary and transient binding agents (Xiao-li et al., 2010). Due to the labile nature of their binding agents, macroaggregates contain more SOC and TN than microaggregates (Ashagrie et al., 2007). However, the retained SOC and TN in macroaggregates are short-term in nature (Gelaw et al., 2015). The dynamics of macroaggregates may play a vital role in SOC stabilization in disturbed ecosystem soil (Li et al., 2019). Previous studies on soil aggregates in Ethiopia focused on the comparison of agricultural land to other land use types (Ashagrie et al., 2007; Gelaw et al., 2015; Mesfin et al., 2018). Understanding the SOC content distribution of soil aggregates is essential to investigate the mechanisms to regulate SOC dynamics in exclosures.

Reliable information on the spatial distribution and variability of soil properties is vital for predicting and understanding many ecosystem processes and services (Shit et al., 2016; Tesfahunegn et al., 2011). Due to its importance in ecological modeling and as an important indicator of soil quality (Bhunia, Shit, & Maiti, 2018), quantification of the spatial distribution of SOC is fundamental (Chabala et al., 2017). Knowledge of SOC spatial variability is particularly important for the promotion and scaling up of the exclosure practice as a viable strategy for increasing SOC storage (Noulèkoun et al., 2021) and the introduction of carbon credits (Chabala et al., 2017), and sustainable restoration of degraded lands (Tesfahunegn et al., 2011). It is also useful to assist in the development of sound environmental management policies (Bhunia, Shit, & Maiti, 2018) and decisions (Kumar et al., 2012).

In the Kewet district, it was in the early 1990s that exclosures were initiated to rehabilitate open degraded grazing lands. As a result of these interventions, vegetation coverage of these grazing lands has improved since then. The inconsistency of findings on the effect of exclosures on soil properties, particularly SOC and TN, suggests that further empirical evidence on exclosures is required. Empirical data on the effectiveness of exclosures in restoring degraded soils are lacking in many areas (Mekuria & Aynekulu, 2013). A better understanding of the effect of exclosures on SOC and TN stocks and their spatial distribution and SOC associated with aggregates of various sizes is needed to rehabilitate degraded land and properly utilize the restored ecosystems. This study hypothesized that SOC and TN stock, their spatial distribution, and soil aggregates will be affected by exclosure age and slope position. Thus, this study was designed to (1) determine SOC and TN stock along exclosure age and slope position, (2) map the spatial variability of SOC and TN stock along exclosure age and adjacent open grazing land; (3) determine soil aggregate size distribution, mean weight diameter, and water-stable aggregates along exclosure age and slope position, and (4) determine SOC associated with soil aggregates along exclosure age and slope position in the central dry lowlands of Ethiopia.

Material and Methods

Study area

Kewet district, the area where this study was conducted is located in the North Shewa Zone of the Amhara National Regional State, Ethiopia (Figure 1). The district covers an area of 746 km^2. Geographically, the area is located between 9°49′–10°11′N latitude and 39°45′–40°6′E longitude coordinates. The elevation of the district ranges from 1,062 to 3,148 m above sea level (m a.s.l). Nevertheless, over 69% and 24% of the landscape in the district is below 1,500 and between 1,500 and 2,300 m a.s.l, respectively. The climate of the district is characterized by dry lowlands (Hurni, 1998). Annually Kewet district receives 916 mm of rainfall and the annual mean minimum and maximum temperatures are 16°C to 31°C, respectively.

Transitional and sub-alkaline basalt which is derived from early Tertiary age basalt rock has covered widely the district (Tefera et al., 1996). Several rhyolite hills occur along the margin of the Robit graben (small rifts) (Williams, 2016). All alluvial and colluvial deposits in the valley are derived from these rocks. The dominant soil types at the alluvial fan area are Eutric Cambisols and Pellic Vertisols and the lower Piedmont areas are dominantly covered by Calcric Gleysols and Calcic Cambisols (Paris, 1986). Apart from these areas, a large part of

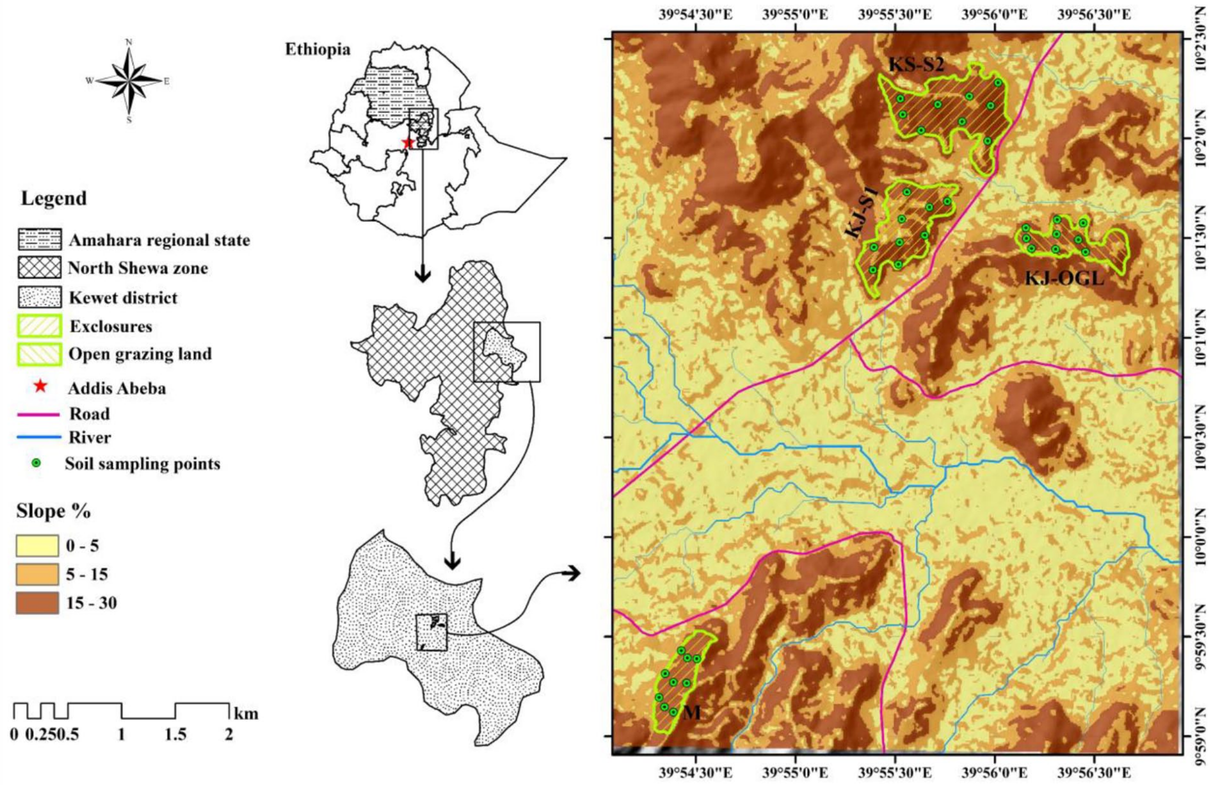

Figure 1. Location of study exclosures, slope gradient (%), and soil sampling points.
Note. M = Merye site 20-year-old exclosure; KJ-S1 = Karajejeba 15-year-old exclosure; KJ-S2 = Karajejeba 5-year-old exclosure; KJ-OGL = Karajejeba open grazing land.

Table 1. Description of Exclosures and Open Grazing Land Used in this Study.

EXCLOSURE AGE/TREATMENT	YEAR EST.	AREA (HA)	SLOPE%	SOIL TYPE	TREES DENSITY HA^{-1}*
Open grazing land	-	-	15–30	Lithic Leptosols	200
5 years exclosure	2011	~60	15–30	Lithic Leptosols	469
15 years exclosure	2002	~44	15–30	Lithic Leptosols	483
20 years exclosure	1996	~20	15–30	Lithic Leptosols	559

*Ibrahim et al. (2021).

the district is covered by Lithic Leptosols. Cultivated land and forest and shrubland coveres 41% and 26%, respectively of the district land is covered. According to Ethiopia's Central Statistical Agency population projection for all regions at the district level, in 2017 the district has a total population of 147,093 with a population density of 197 persons per km^2 (CSA, 2013). For livelihood, over 92% of the household in the district are fully engaged in agricultural activities and 77% and 24% of the household own cattle and goats, respectively.

Soil sampling and analysis

To conduct this study, three exclosures which are about 5 (Karajejeba area), 15 (Karajejeba area), and 20 (Merye area) years old, and one open grazing land adjacent to the respective exclosures were selected from Kewet district (Figure 1). Area exclosure refers to a practice of land management whereby unmanaged humans' intervention and unwanted livestock are excluded from openly accessing severely degraded lands to promote natural regeneration (self- restoration) of vegetation cover and foster natural ecological succession (Aerts et al., 2009; Descheemaeker, Muys et al., 2006).

The open grazing land is dominated by remnant woody species which are old, have large DBH, and are taller and scattered over the landscape. Woody species such *Acacia tortilis* (Forssk.) Hayne., *Acacia nilotica* (L.) Willd. Ex Del. and *Acacia etbaica* Schweinf are the common woody species in the open grazing land. Tree density in the exclosures ranged from 469 trees ha^{-1} in the young age exclosure to 559 trees per hectare in the old exclosure (Table 1). Though there is a difference in the importance value index of woody species between each site, *Acacia senegal* (L.) Willd., *Acacia nilotica*

(L.) Willd. Ex Del., *Acacia brevispica* Harms., *Acacia tortilis* (Forssk.) Hayne., *Acacia etbaica* Schweinf., *Ehretia cymosa* Thonn. and *Dichrostachys cinerea* (L.) Wight & Am are the dominant woody species in all exclosures (Ibrahim et al., 2021). These exclosures were under open degraded grazing land before they were excluded from unmanaged human interference and free livestock grazing and browsing. All exclosures and open grazing land exist on a moderately steep slope (15%–30%) gradient (Figure 1) and from 1,239 to 1,486 m a.s.l elevation gradient. Both the open grazing land and exclosures lay on lithic Leptosols soil type and strongly sloping landscapes. Orderly, cattle, goats and sheep, equines, and camels are the dominant livestock species that graze and browse on open grazing lands (CSA, 2020).

Sampling points in each exclosure and the adjacent open grazing land were located following a systematic sampling method. Within each age class of exclosures and the adjacent open grazing land, three parallel line transects perpendicular to contour lines were laid. The distance between line transects was decided based on the size of the area exclosures. At regular distances along each transect line, three sampling points at upper, middle, and lower slope positions were located (Anderson & Ingram, 1993). The line transects were considered as replication. Soil sample was obtained from 0 to 10 cm soil depth. A total of 36 (4 (three exclosures and one open grazing land) × 3 slope positions × 3 line transects) composite soil samples (approximately 0.5 kg of each) from each sampling point were sampled (Figure 1). Soil samples were air-dried at room temperature (25℃) and passed through different mesh sizes based on the requirements for laboratory analysis. For the analysis of soil aggregates, separate soil samples with similar weight to the above ones were also collected from each sampling point. For the determination of bulk density and rock fragments, additional undisturbed core samples were collected using a cylindrical soil core (5 cm diameter × 5 cm height) from 0 to 10 cm depth.

The core method was used to determine soil bulk density (Blake & Hartge, 1986) and the coarse fragment was determined as a percentage weight of stones and gravel with a diameter >2 mm. As described in Thomas (1996) a pH meter (glass–calomel combination electrode) was used to measure soil pH in a water suspension of 1:2.5 (soil: liquid ratio). The Walkley and Black method as described in Nelson and Sommers (1982) was used to determine soil organic carbon (SOC). The Kjeldahl digestion method was followed to determine total nitrogen (TN) (Bremner & Mulvaney, 1982).

Dry aggregates size distribution analysis was carried out using the technique indicated in Klute et al. (1986). Bulk air-dried soil samples were passed through an 8 mm sieve, then a subsample of 100 g was placed on the top of a nest of sieves of 5, 2, 1, 0.5, and 0.25 mm size with a pan at the bottom and shaken on rotary sieve shaker for 10 minutes (Nimmo & Perkins, 2002). The weight of each aggregate retained on each sieve was recorded and collected on two separate bags by categorizing as macroaggregates (>0.25 mm) and microaggregates (<0.25 mm) (Tisdall & Oades, 1982). Furthermore, from these categorized samples, SOC associated with micro and macroaggregates was determined according to the Walkley and Black method (Nelson & Sommers, 1982).

Wet aggregate stability was determined using a single-sieve wet-sieving procedure with a 0.25 mm sieve and a dispersing agent (Nimmo & Perkins, 2002). Using a single sieve procedure to determine wet aggregates stability requires less investment and is basically well correlated with practically important field conditions (Kemper & Rosenau, 1986). The procedure consists of air-dried 4 g subsamples that pass through a 2 mm sieve and were prewetted with distilled water by spraying to protect from slaking. After filling weighed cans with distilled water sufficient to cover the soil in the sieve on the bottom stroke of the apparatus, the sieve was raised and lowered 35 times min^{-1} for 3 minutes. To determine sand content (to correct the presence of any sand), an additional air-dried 4 g sub-sample was dispersed using a solution of NaOH and sieved using a similar sieve size until only sand particles are left on the sieve. Both sets of samples (soil aggregate and sand) retained on the sieve were placed in an oven and dried at 105°C until a constant weight is reached. Then, the dry weight of each set of samples was recorded.

Determination of SOC and soil TN stocks, aggregate size distribution, and water-stable aggregates

Soil organic carbon stock was calculated using the following equation (Henry et al., 2009):

$$\text{SOC(orTN)stock} = \frac{Conc.}{100} \times \rho_b \times D \times (1 - frag) \times 100$$

where SOC (or TN) Stock = Soil Organic Carbon or Soil Total Nitrogen Stock (Mg ha^{-1}), Conc. = soil organic carbon or soil total nitrogen concentration (mg/100 g) of fines (fraction <2 mm) determined in laboratory, ρb = soil bulk density (g cm^{-3}), D = depth of the sampling layer (cm), frag = % volume of coarse fragments/100 and 100 is used to convert the unit to Mg SOC ha^{-1}.

Aggregate size distribution after dry sieving can be expressed as a single empirical unit called Mean Weight Diameter (MWD), calculated according to the following equation (Hillel, 2003):

$$\text{MWD} = \frac{\sum_{i=1}^{n} x_i w_i}{\sum_{i=1}^{n} w}$$

where: x_i = is the mean diameter of any particular size range of aggregates separated by sieving (mm) (eg, soil found in 1.00 diameter sieve has a maximum of 2.00 diameter and a minimum of 1.00 mm diameter) and w_i = is the weight of the soil aggregates retained on each sieve.

Percentage of water-stable aggregates (WSA) was calculated according to the following equation (Márquez et al., 2004):

$$\mathrm{WSA\%} = \left[\frac{(weightretained) - (weightofsand)}{(totalsampleweight) - (weightofsand)}\right] \times 100$$

Spatial distribution of SOC and soil TN stocks

To map the spatial distribution of SOC and TN stocks in the area exclosure, an ordinary kriging interpolation method was applied. Ordinary kriging is the best linear unbiased (Behera & Shukla, 2015; McGrath & Zhang, 2003), and the most commonly used (Kucuker et al., 2015; Saito et al., 2005) geostatistical predictor of the spatial attributes for a random process. It provides a model of the unsampled value z(u) as a linear combination of neighboring observations n(u) (Saito et al., 2005):

$$z^{*}_{OK}(u) = \sum_{\alpha=1}^{n(u)} \lambda_{\alpha}(u) z(u_{\alpha})$$

where; λα (u) = is the Ordinary Kriging weight assigned to datum z(uα).

The ordinary kriging method uses semivariograms to quantify spatial autocorrelations and provide input parameters for spatial interpolation (Liu et al., 2011). The semivariogram is a measure of the variability of the attribute values obtained at two locations as a function of the separation vector between those locations. In practice, the experimental semivariogram is computed as half the average squared difference between the values of data pairs (Saito et al., 2005):

$$\acute{Y}(h) = \frac{1}{2N(h)} \sum_{\alpha=1}^{N(h)} \left[z(u_{\alpha}) - z(u_{\alpha} + h)\right]^2$$

where N(h) is the number of data pairs for a given separation vector h and z is the attribute. A model is then fit to the experimental semivariogram (ie, linear model of regionalization) so that semivariogram values across a continuous range of separation distances can be derived. Evaluation of several semivariogram functions were tested using cross-validation to choose the best fit with the dataset. The Gaussian semivariogram was used for the present dataset for the ordinary kriging prediction and is described in the following equation:

$$Y(h) = C_0 + C_1\left[1 - exp\left(-\frac{h^2}{k^2}\right)\right]$$

where C_0 = the nugget variance, C_1 = the partial sill, and k = the range of spatial autocorrelation to reach the sill variance ($C_0 + C_1$). The experimental semivariograms (Gaussian model) were fitted to the theoretical semivariogram to produce geostatistical parameters including nugget variance (C_0), partial sill (C_1), sill variance ($C_0 + C_1$), and distance parameter (k). The nugget variance (C_0) represents the residual variances of sampling errors together with spatial variations that occur over distances much shorter than the minimum sample spacing, and that consequently cannot be resolved (Thomson et al., 2008). Partial sill (C_1) is the difference between nugget variance and sill variance (Krasilnikov et al., 2008). Sill variance ($C_0 + C_1$) is the value that the semivariogram model attains at the range or at which the plotted points level off. The sill variance ($C_0 + C_1$) value represents the overall variability inside the variables (Xiao et al., 2016). The larger the ($C_0 + C_1$) is, the greater the spatial variation of the soil properties (Nie et al., 2019). The range (k) is a distance at which the variogram levels (the zone of influence) becomes off (Krasilnikov et al., 2008). Range defines the distance over which the soil property values are correlated with each other (Tesfahunegn et al., 2011). Samples separated by a distance larger than the range are spatially independent (Thomson et al., 2008). The nugget/sill ratio [C_0/($C_0 + C_1$)] reflects the spatial heterogeneity of the data. Ratio of <0.25%, 0.25%–0.75%, and >0.75% present strong, moderate and weak spatial autocorrelation/dependence in soil properties, respectively (Cambardella et al., 1994). The interpolation method of ordinary kriging was directly implemented using the spatial analysis module of ArcGIS 10.5 for Windows.

Cross-validation

Cross-validation was used to choose the best semivariogram model among candidate models (Spherical, Exponential, and Gaussian) and to evaluate how well the model predicted SOC and TN stocks values at the unsampled locations (Chabala et al., 2017; Johnston et al., 2003). Leave-one-out cross-validation is usually applied to compare the different spatial models (Varouchakis, 2019). Mean absolute estimation error (MAEE), root mean square error (RMSE), and root mean square standardized error (RMSSE) were estimated to evaluate the accuracy of the interpolation method (Chabala et al., 2017; Mousavifard et al., 2013). Root mean square error indicates how closely a model predicts the measured values. The smaller the RMSE value, the better the prediction is. Root mean square standardized error should be close to one if the prediction standard errors are valid. The following equations were followed to calculate the cross-validation indices:

$$\mathrm{MAEE} = \frac{1}{n} \sum_{i=1}^{n} \left|\acute{Y}_i - y_i\right|$$

$$\mathrm{RMSE} = \frac{1}{n} \sum_{i=1}^{n} \sqrt{\left(\acute{Y}_i - y_i\right)^2}$$

$$\mathrm{RMSSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left|\acute{Y}_i - y_i\right|^2}$$

where; n = is the number of soil sample points, $\acute{Y}_i$ = is the predicted SOC or TN, y_i = is the observed SOC or TN, $\overline{y_i}$ = the

Table 2. Descriptive Statistics of Soil Properties in Exclosures and Open Grazing Land.

VARIABLES	MIN	MAX	MEAN	*SD*	SKEWNESS	KURTOSIS	CV (%)
Bulk density (g cm^{-3})	1.02	1.31	1.16	0.08	−0.01	−0.37	6.64
Rock fragments (%)	31.55	82.61	53.27	10.53	0.54	0.66	19.77
MWD (mm)	2.20	3.87	2.81	0.40	0.70	0.51	14.06
WSA (%)	60.67	90.16	78.63	6.34	−0.87	1.12	8.06
SOC (%)	1.88	3.69	3.07	0.51	−0.81	−0.03	16.57
TN (%)	0.17	0.52	0.32	0.08	0.46	0.42	23.87
SOC stock (Mg ha^{-1})	11.39	24.08	15.75	2.92	1.00	0.77	18.54
TN stock (Mg ha^{-1})	0.62	3.10	1.69	0.48	0.53	1.21	28.35
Macroaggregate SOC (%)	1.70	3.69	2.77	0.61	−0.25	−0.87	21.98
Microaggregate SOC (%)	1.72	3.63	3.10	0.50	−1.21	0.83	16.09

Note. CV = coefficient of variance; MWD = mean weight diameter; SOC = soil organic carbon; TN = total nitrogen; WSA = water stable aggregates.

mean value of the observed SOC or TN and $\overline{\acute{Y}_i}$ = the mean value of the predicted SOC or TN.

Data analysis

Before pursuing any statistical analysis, the raw data from the soil laboratory was subjected to Normal Quantile-Quantile (Q-Q) analysis using Microsoft Excel 2019 for the identification of probability and obvious outliers (extreme values). Outliers affect the performance of spatial interpolation methods (Thomson et al., 2008; Yao et al., 2020). Following cleaning of the raw data from obvious outliers, descriptive statistics, skewness, and kurtosis tests were performed.

The first stage in the geostatistical analysis is to analyze data for descriptive statistics to check whether the SOC and TN data conformed to the necessary assumptions required for ordinary kriging (Chabala et al., 2017). For skewed distribution of soil properties, log transformation was applied. If soil properties showed a trend, the first order of trend analysis tool of ArcGIS 10.5 was applied to remove it. A one-way analysis of variance (ANOVA) following the general linear model (GLM) procedure was applied to test whether the age of exclosure and slope position affect soil properties. If the analysis of variance showed statistically significant differences ($p < .05$), a post hoc test of Tukey's honest significant difference (HSD) test was used for mean separation. Pearson correlation analysis was performed to evaluate whether some selected soil properties are correlated with each other. Other than geostatistical analysis, all other statistical analyses of soil properties were done using SAS 9.2 statistical software (SAS Institute Inc, 2009).

Results

Statistical characteristics of soil properties

Soil properties in the exclosures and adjacent open grazing land had both negative and positive skewness (Table 2). Water stable aggregates, SOC content, and micro, and macroaggregates' SOC were negatively skewed and the rest were positively skewed. Bulk density and macroaggregates' SOC were not skewed. In contrast to other soil properties, the skewness of SOC and TN stock was moderate (1.00) and low (0.53), respectively (Table 2). The kurtosis was also moderate (0.77) for SOC stock and nearly normally distributed (1.21) for TN stock. Except for WSA (1.12), the kurtosis value for all the soil properties ranged from −0.03 for SOC to 0.83 for microaggregate SOC. Descriptive statistical analysis of the skewness and kurtosis of the dataset showed that the soil properties were relatively normally distributed across the exclosures and adjacent open grazing land. The maximum coefficient of variation (CV) was documented for TN stock (28.35%), and the smallest CV was for bulk density (6.64%).

In Q-Q plot, if the data is normally distributed, the points will fall along the straight reference line. Thus, the Q–Q plot of this study showed that SOC and TN stock exhibited a normal distribution between the actual and predictive values (Figure 2) and it is confident to use methods such as kriging that rely on normality. Because of the relatively skewed distribution of SOC and TN stocks, log transformation was applied to the data to decrease the effect of extreme values. Transforming to logarithms makes the histogram more nearly symmetric (McGrath & Zhang, 2003).

Trend analysis showed that SOC and TN stock had a relatively small trend (Figure 3). The green line (upward curve for SOC stock and downward curve for TN stock) shows the trend in the East-West direction, and the blue line (upward curve) depicts the trend in the North-South direction. The existence of the trend indicates that trend removal is necessary to create more accurate prediction maps to justify an assumption of normality. Thus, the first order of trend analysis tool was applied to remove the trend in the SOC and TN data set. Accordingly,

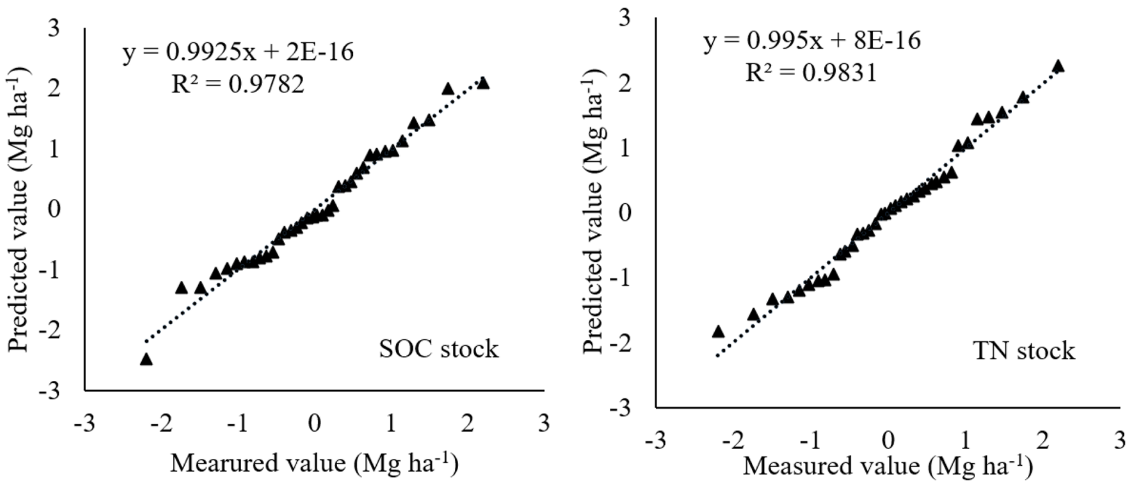

Figure 2. Q-Q Plots for SOC and TN stock at exclosures and open grazing land in Kewet district, central dry lowlands of Ethiopia.

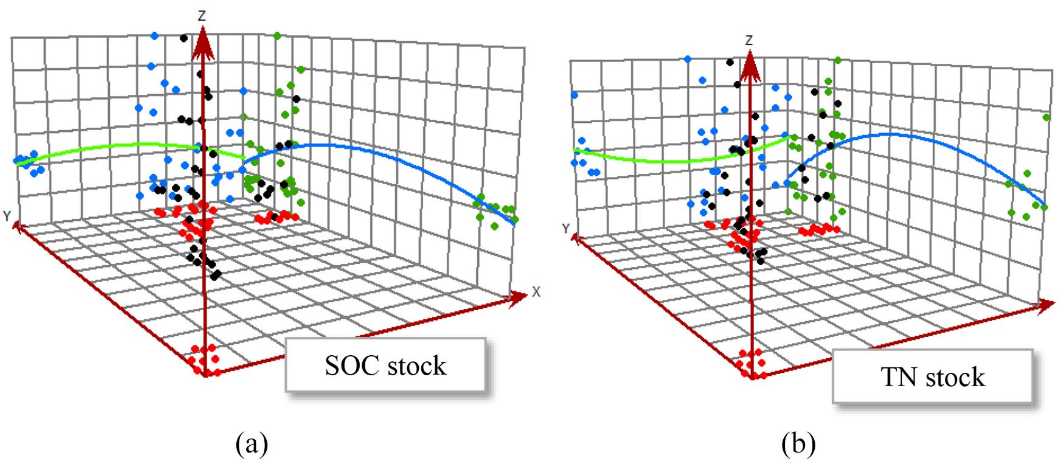

Figure 3. Trend analysis demonstrating the (a) SOC and (b) TN stock at exclosures and open grazing land.

this indicates that the dataset follows a normal distribution and the ordinary kriging interpolation can be applied.

Predicted versus measured plots shows how well is kriging predicting. With decreasing autocorrelation, the fitted line (blue line) will be close to horizontal. Accordingly, Figure 4 fitted plots showed that TN stock exhibited low spatial autocorrelation to SOC stock and SOC stock showed a moderate spatial autocorrelation. A similar study by Göl et al. (2017) in the Black Sea backward region of Turkey showed that SOC presented moderate spatial autocorrelation.

Aggregate size distribution and water-stable aggregates

Analysis of aggregate size destitution indicated that the proportion of macroaggregate (>0.25 mm) in both the exclosures and adjacent open grazing land was over 93% (Figure 5). Soil bulk density, rock-fragments, MWD, and WSA also did not show any significant ($p > .05$) variation among the different ages of the exclosure, slope position, and their interaction (Table 3). All ages of exclosures and adjacent open grazing lands also had higher WSA, which was greater than 78%.

SOC and TN stocks

Soil organic carbon showed significant interaction ($p < .05$) effect of age of exclosure and slope position. Soil organic carbon stock was significantly higher ($p < .05$) in the 15-year-old exclosure (18.43 Mg ha^{-1}) than in the other age of exclosures and adjacent open grazing land (Table 4). Statistical analysis showed that the interaction effect among exclosures age and slope position was significant ($p < .05$) for TN stock.

SOC associated with soil aggregates

SOC content of macroaggregates showed a significant ($p < .05$) interaction effect among exclosures and open grazing land and slope position. Analysis of organic carbon content of soil aggregates showed that microaggregates (<250 μm) had higher mean SOC than macroaggregates (>250 μm) (Table 5). Soil organic carbon content of both micro- and macroaggregates was significantly ($p < .05$) affected by the land use types. Accordingly, significantly ($p < .05$) lower SOC content of microaggregates was recorded in the 15-year-old exclosure as compared to that in the other age exclosures and adjacent open grazing land.

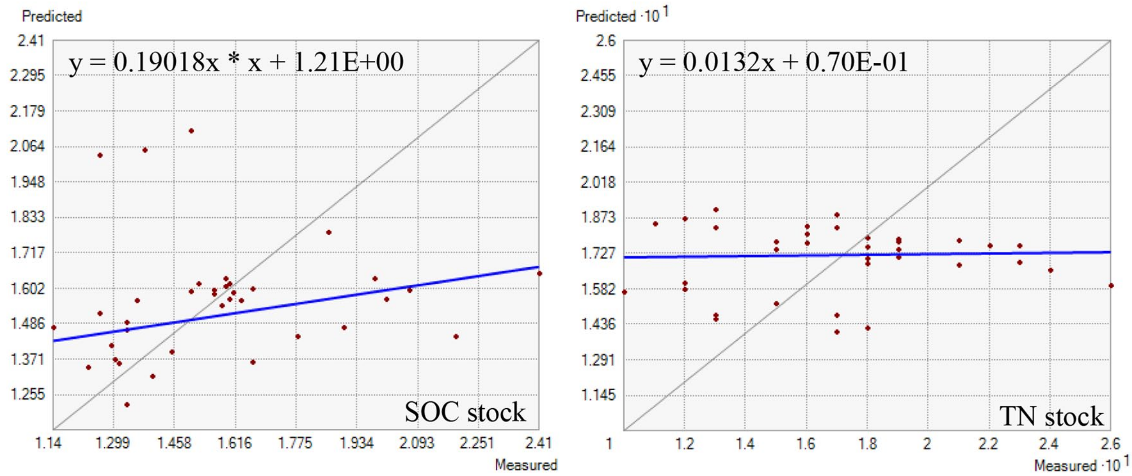

Figure 4. Plots of measured (observed) and predicted values of SOC and TN stock for validation of the results by the semivariogram model.

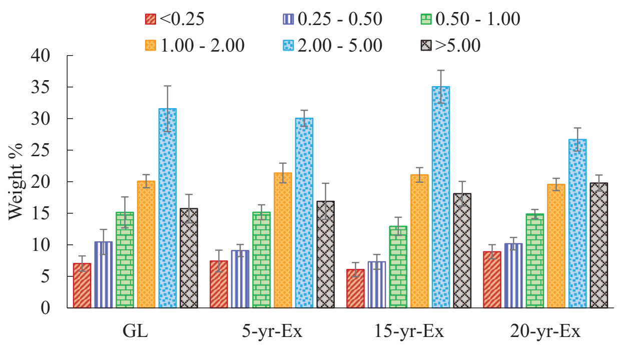

Figure 5. Aggregate size distribution (%) by dry sieving at exclosures and open grazing land.
Note. GL = open grazing land; 5-yr-Ex = 5-year-old exclosure; 15-yr-Ex = 15-year-old exclosure; 20-yr-Ex = 20-year-old exclosure.

Spatial variability of SOC and TN stocks

Nugget/sill ratio of SOC and TN stock were 0.25 and 0.57 (Table 6), respectively. Semivariogram analysis of this study indicated that the range of spatial dependency for spatial SOC and TN stocks was up to a distance of 885 and 2,446 m, respectively. The RMSE values of SOC and TN were 0.30 and 0.04, respectively which are approximately near Zero. Mean absolute estimation error and RMSSE of SOC and TN stock were also close to 0 and 1, respectively (Table 6). The cross-validation analysis result with the lowest RMSE, MAEE values, and RMSSE close to 1 shows that the Gaussian ordinary kriging model fits the data set of SOC and TN stock very well and is relatively unbiased. The best results of cross-validation were achieved by ordinary kriging which gave the lowest MAEE, RMSE, and RMSSE (Bhunia, Shit, & Maiti, 2018). Thus, for this study, the Gaussian ordinary kriging interpolation model is a reliable method to predict the spatial distribution of SOC and TN stocks in the exclosures and adjacent open grazing land. Spatial variability of SOC and TN stocks analysis in Southern China by Yao et al. (2020) showed a Gaussian model superiority over the other models.

The semivariogram model (Figure 6) described how SOC and TN stock varied with distance among the sampling locations.

The spatial distribution map of the SOC stock shows high variability in the 15-year-old exclosure which ranged from 12.1 Mg ha^{-1} in the Southwest to 23.1 Mg ha^{-1} in the Northwest direction (Figure 7). Conversely, SOC stock was uniformly spatially distributed in the 20-year-old exclosure, which ranged from 14.5 to 16.4 kg Mg ha^{-1}. It shows a moderate variability in the 5-year-old exclosure and adjacent open grazing land. The Northwest part (majority area) of the young exclosure and open grazing land showed a very low SOC stock which varied from 12.1 to 16.4 Mg ha^{-1}. Five and 15-year-old exclosures showed relatively higher SOC stock on the lower slope position than on the upper, whereas the 15-year-old and adjacent open grazing land shows relatively higher SOC stock on the upper slope position than on the lower slope position. Some portion of the 15-year-old exclosure showed very high SOC stock (20–20.31 Mg ha^{-1}).

From the spatial distribution map of TN, it was observed that almost all parts of the 15 and 20-year-old exclosures and adjacent open grazing land had >1.7 Mg ha^{-1} TN stock (Figure 7). A major part of the 5-year-old exclosure, some parts in the Northern part of the old exclosure, and the Southern of the 15-year-old exclosure had lower (<1.6 Mg ha^{-1}) TN stock. Except in the 5-year-old exclosure, relatively all sites showed a higher stock of TN in the lower slope position than the upper slope position.

Discussion

Aggregate size distribution and water-stable aggregates

Analysis of aggregate size destitution indicated that the share macroaggregate (>0.25 mm) was very high than microaggregate (<0.25 mm) in both the exclosures and adjacent open grazing land. The reason for the high proportion of macroaggregate in both the exclosures and adjacent open grazing land (Figure 5)

Table 3. Mean ± *SE* Values of ρb, Rock Fragments, MWD, and WSA at Exclosures and Open Grazing Land.

FACTORS	ATTRIBUTE OF FACTORS	PB (G CM-3)	ROCK FRAGMENTS (%)	MWD (MM)	WSA (%)
Age	Grazing land	1.19 ± 0.03	57.75 ± 5.13	2.79 ± 0.05	79.73 ± 2.52
	5-years-old exclosure	1.16 ± 0.03	47.58 ± 2.95	2.57 ± 0.10	74.58 ± 2.53
	15-years-old exclosure	1.14 ± 0.02	53.10 ± 10	3.03 ± 0.20	81.35 ± 1.29
	20-years-old exclosure	1.16 ± 0.02	54.67 ± 1.45	2.87 ± 0.10	78.84 ± 1.42
	p-value	0.584	0.242	0.151	0.148
Slope position	Upper slope	1.16 ± 0.02	50.49 ± 3.10	2.83 ± 0.13	79.36 ± 1.47
	Middle slope	1.18 ± 0.03	57.55 ± 3.42	2.74 ± 0.10	77.37 ± 2.47
	Lower slope	1.15 ± 0.02	51.78 ± 2.35	2.87 ± 0.12	79.15 ± 1.50
	p-Value	.619	.233	.750	.693
	Age*SP	0.01[ns]	70.40[ns]	0.05[ns]	37.65[ns]
	CV %	6.38	19.65	14.67	7.90
	Error	0.01	0.02	0.17	38.56

Note. Means ± *SE* with different letters within a column are significantly different ($p < .05$) (Tukey's test HSD). ρ*b* = bulk density; MWD = mean weight diameter; SP = slope position; WAS = water-stable aggregates. Age*SP mean square [ns] is non-significant.

Table 4. Mean ± *SE* Values of pH, SOC, TN, SOC Stock, and TN Stock at Exclosures and Open Grazing Land.

FACTORS	ATTRIBUTE OF FACTORS	PH (H_2O)	SOC (%)	TN (%)	SOC STOCK (MG HA-1)	TN STOCK (MG HA-1)
Age	Grazing Land	6.78 ± 0.03[a]	3.17 ± 0.13[b]	0.36 ± 0.03[a]	14.62 ± 0.86[b]	1.76 ± 0.13[ab]
	5-yr-Ex	6.58 ± 0.09[b]	2.58 ± 0.14[b]	0.24 ± 0.01[b]	14.22 ± 0.62[b]	1.41 ± 0.09[b]
	15-yr-Ex	6.81 ± 0.15[a]	3.37 ± 0.09[a]	0.34 ± 0.02[a]	18.43 ± 1.29[a]	1.81 ± 0.17[a]
	20-yr-Ex	6.60 ± 0.11[b]	3.15 ± 0.09[b]	0.34 ± 0.01[a]	15.76 ± 0.14[b]	1.79 ± 0.08[a]
	p-Value	.001	.003	.000	.000	.01
Slope position	Upper slope	6.62 ± 0.03	3.20 ± 0.14[a]	0.34 ± 0.03	16.99 ± 0.88[a]	1.79 ± 0.09
	Middle slope	6.74 ± 0.14	2.91 ± 0.05[b]	0.30 ± 0.02	14.59 ± 0.50[b]	1.56 ± 0.10
	Lower slope	6.71 ± 0.11	3.09 ± 0.15[ab]	0.32 ± 0.02	15.69 ± 0.99[ab]	1.72 ± 0.13
	p-Value	.06	.211	.33	.009	.11
	Age*SP	0.03[ns]	0.23[ns]	0.01[ns]	15.78**	0.34**
	CV %	1.91	17.00	16.38	11.01	16.16
	Error	0.02	0.17	0.00	3.01	0.07

Note. [a,b] Means ± *SE* with different letters within a column are significantly different ($p < .05$) (Tukey's test HSD). SOC = soil organic carbon; TN = total nitrogen; SP = slope position; yr = year; Ex = exclosure. Age*SP mean square. ** is significant at $p < .01$ level and [ns] is non-significant.

could be the result of binding agents that contributes to the formation of macroaggregates. Macroaggregates are formed by ephemeral binding agents, such as roots, fungal hyphae, and microbial (Gao, Wang et al., 2019). As a result of this, land use types with higher vegetation (grasses and woody species) will have a higher proportion of macroaggregates. A study by Zhao et al. (2017) in the Loess Plateau of China showed an increase in aggregates size in the order of forest > grassland >arable land. Safadoust et al. (2016) also reported the highest amount of aggregates between 2 and 4 mm sieves in a no-till method in the

Table 5. Mean ± *SE* Values of Macro and Microaggregates SOC at Exclosures and Open Grazing Land.

FACTORS	ATTRIBUTE OF FACTORS	SOC (%)	
		MACROAGGREGATES	MICROAGGREGATES
Age	Grazing Land	2.85 ± 0.18[a,b]	3.18 ± 0.11[a]
	5-years-old exclosure	2.96 ± 0.17[a]	3.25 ± 0.12[a]
	15-years-old exclosure	2.40 ± 0.29[b]	2.61 ± 0.22[b]
	20-years-old exclosure	2.85 ± 0.10[a,b]	3.36 ± 0.06[a]
	P-value	0.036	0.005
Slope position	Upper slope	3.05 ± 0.15[a]	3.28 ± 0.14
	Middle slope	2.61 ± 0.19[b]	3.07 ± 0.14
	Lower slope	2.64 ± 0.18[a,b]	2.95 ± 0.15
	p-value	0.023	0.174
	Age*SP	0.97**	0.08[ns]
	CV%	14.74	13.92
	Error	0.17	0.19

Table 6. Summary of Semivariogram Model Parameters and Cross-Validation Statistics for SOC and TN Stocks Prediction at Exclosures and Open Grazing Land.

PARAMETERS	C_0	C_1	SILL ($C_0 + C_1$)	NUGGET/SILL	RANGE (M)	MAEE	RMSE	RMSSE
SOC stock	0.01	0.03	0.04	0.25	885.45	−0.01	0.30	1.21
TN stock	0.04	0.03	0.07	0.57	2,446.37	0.00	0.04	1.03

Note. C_0 = the nugget; C_1 = the partial sill; MAEE = mean absolute estimation error; RMSE = root mean square error; RMSSE = root mean square standardized error.

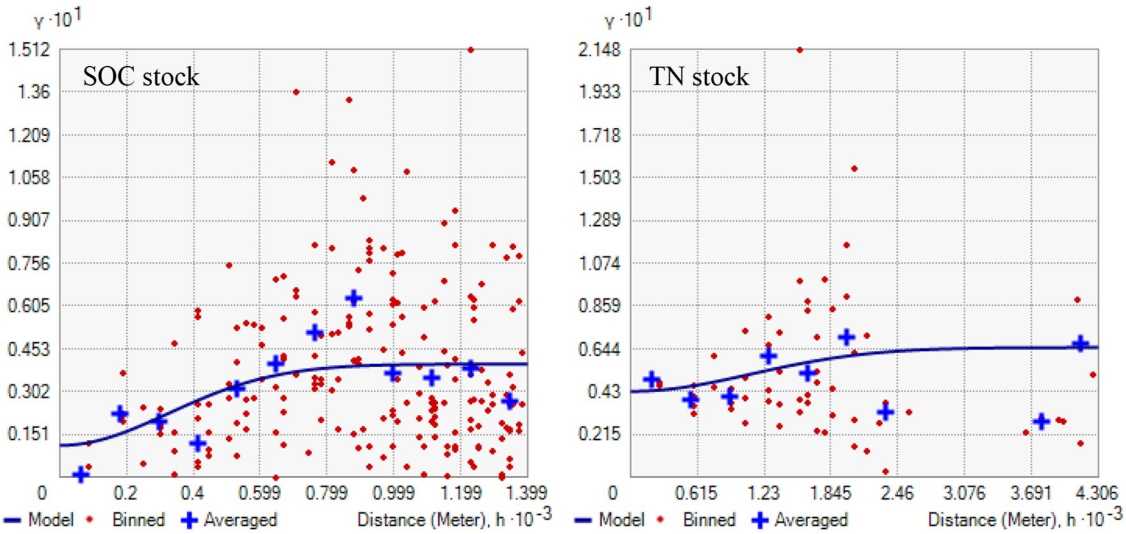

Figure 6. Semivariogram map for SOC and TN stock at exclosures and open grazing land.

semi-arid region of Iran. Gelaw et al. (2015) in Tigray, North Ethiopia reported a high proportion of macroaggregates (~70%, and ~60%) in *Faidherbia albida* based silvopasture and open grazing land, respectively. Dry aggregates showed an increase in proportion toward the agronomically most valuable aggregates (0.25–5.00 mm) (Iticha & Debele, 2017).

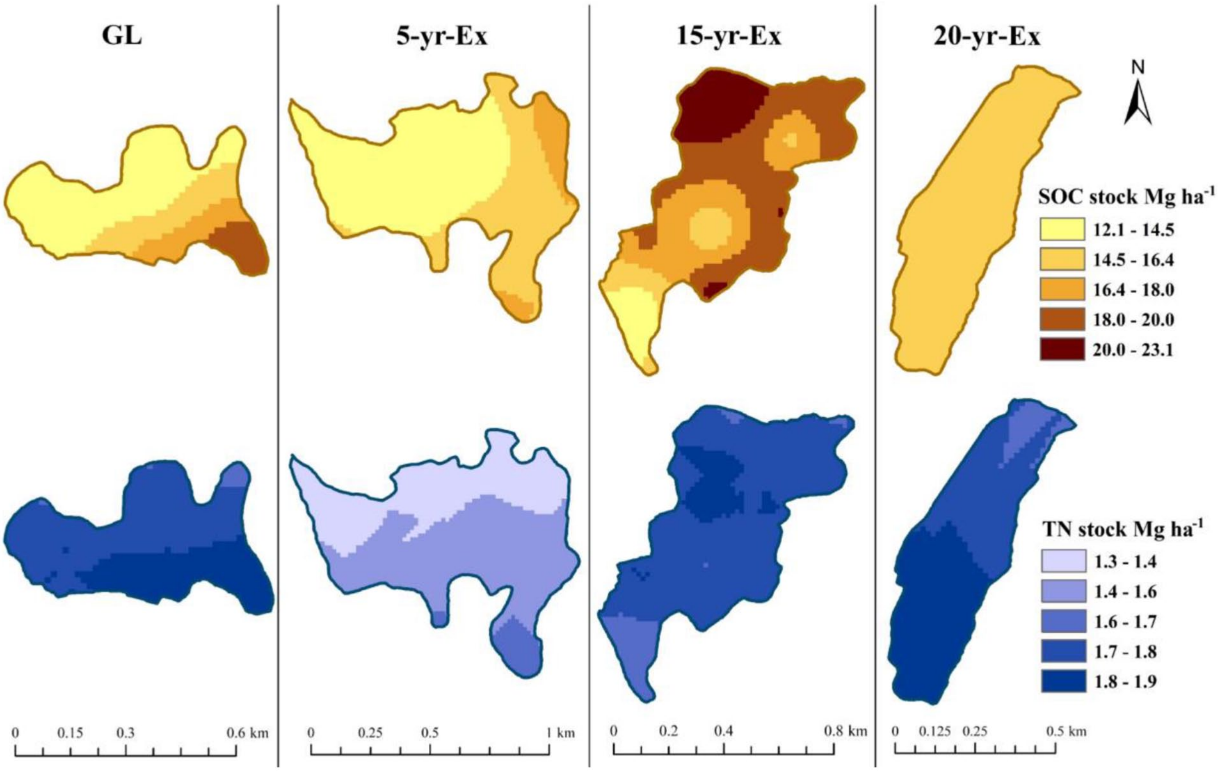

Figure 7. Spatial distribution of SOC and TN stock at exclosures and open grazing land.
Note. GL = open grazing land; 5-yr-Ex = 5 years old exclosure; 15-yr-Ex = 15 years old exclosure; 20-yr-Ex = 20 years old exclosure.

Regardless of the insignificant difference in MWD between exclosures and open grazing land, the mean value of MWD showed that both the exclosures and adjacent open grazing land were dominated by macroaggregates (Table 3). In Tigray, North Ethiopia, Mesfin et al. (2018) from an acacia tree-dominated area and Gelaw et al. (2015) from open grazing land reported a higher MWD value of 2.28 and 1.93 mm, respectively. Kalhoro et al. (2017) in Northern China also found a higher MWD in grassland and shrubland. WSA was relatively higher in all ages of exclosures and adjacent open grazing lands. A study from Tigray in North Ethiopia indicated that open grazing land had higher WSA than *Faidherbia albida* based agroforestry and dryland crop production (Gelaw et al., 2015). The higher MWD and WSA in all ages of exclosures and adjacent open grazing land could be due to the presence of higher SOC. Increased SOC content can enhance the soil's macroaggregate content (Kalhoro et al., 2017; Stavi et al., 2008). The stabilization of macroaggregates is controlled by management and declines when arable cropping is practiced (Tisdall & Oades, 1982).

SOC and TN stocks

SOC and TN stock have shown variability between age of exclosures and slope position. Because of that land use (age of exclosure) and slope (topography) are some of the soils forming factors, the SOC stock variability in this study could be due to the interaction of these two factors. This indicates that age of exclosure and slope position are important factors in controlling SOC stock in exclosures and open grazing land (Table 4). Thus, in this study, significant interaction ($p < .05$) effect of age of exclosure and slope position was observed for SOC (Table 4). Despite its significant difference, the 15 and 20-year-old exclosure had a higher SOC stock than the 5-year-old exclosure and adjacent open grazing land. This indicates that the exclosure age had significantly affected SOC stock. Other similar studies had also shown that exclosure significantly affected SOC content over time. For example, an experiment in Borana rangelands of Southern Ethiopia showed that 20 years old exclosure had significantly higher SOC stock than adjacent communally grazed areas (Bikila et al., 2016). Another study conducted around Yabello town in Borana rangelands, Southern Ethiopia, also showed that exclosures greater than 20 years old had a higher accumulation of SOC stock than the open grazed areas (Feyisa et al., 2017). Gebremedihin et al. (2018) found significantly higher SOC stock in 10 years and greater than 20 years old exclosure than open grazing land in the highlands of Tigray, Northern Ethiopia. In a similar region, Shimelse (2017) reported higher SOC stock in 15 and 20 years old exclosure than free grazing lands. On the contrary, Mekuria et al. (2017) in Gondar, Northwest Ethiopia, and Aynekulu et al. (2017) in Borana rangelands, Southern Ethiopia did not detect any significant differences in SOC content between exclosure and the adjacent communal grazing land.

The significant ($p < .05$) interaction effect of TN stock indicates that the difference in TN stock among the exclosures and the open grazing land, in addition to the exclosure effects, is also due to topographic features like slope position (Table 4). The slope is one of the key factors that control the spatial distribution of soil properties. Soil TN stock was significantly ($p < .05$) varied from 1.41 Mg ha^{-1} at 5-year-old exclosure to 1.81 Mg ha^{-1} at 15-year-old exclosure (Table 4). Compared with the open grazing land and 5-year-old exclosure, TN stock was significantly higher in the 15 and 20-year-old exclosures. However, TN stock did not show any significant variation along a slope gradient. In line with this study, (Mekuria et al., 2011) reported significantly higher TN stock in 15 and 20 years old exclosure than in 5-year-old exclosure and adjacent communal grazing land in the Northernmost region of Ethiopia. Compared to adjacent open grazing land, a significantly higher TN was reported in 30 years old exclosure in Borana rangelands, Southern Ethiopia (Feyisa et al., 2017).

Enhanced vegetation cover, litterfall input, exudates from plant roots, and residue of microorganisms over a longer period in the 15 and 20-year-old exclosures might have favored the accumulation of high SOC and TN in the soil. Findings from North Ethiopia indicated that litter production (Descheemaeker, Muys et al., 2006) and arbuscular mycorrhiza fungi (AMF) spore density and root colonization (Birhane et al., 2017) significantly rise after exclosure establishment. It is also well documented that exclosures displayed higher woody species diversity than adjacent grazing lands (Gebremedihin et al., 2018; Mekuria et al., 2018). During field observation, it was also observed that the 15 and 20-year-old exclosure had dense vegetation coverage. This indicates that the total biomass production increase with the increase in age of exclosure. Mekuria et al. (2019) also observed increased biomass production with an increase in exclosure age in Douga Tembien, North Ethiopia.

Furthermore, the minimal soil erosion in the 15 and 20-year-old exclosures might have contributed to the significantly higher SOC and TN stock in older (20-year-old) exclosures. The significantly ($p < .05$) higher SOC stock in the upper slope position of this study (Table 4) is a good indicator that exclosure is playing role in controlling soil erosion and traps a considerable amount of sediment. Field experiments from Tigray, North Ethiopia, indicated that exclosures have high sediment trapping capacity and are very efficient soil and water conservation measures. They accelerate fertile soil buildup and prevent important sediment loads from leaving the catchment (Descheemaeker, Nyssen et al., 2006). A study by Mekuria et al. (2018) suggested that the improvement of herbaceous layer cover through exclosure is a key strategy for reducing SOC and TN losses. The same study further underscored that restoration of native vegetation through exclosure can enhance ecosystem services that can be obtained from degraded lands.

Conversely, 5-year-old exclosure and adjacent open grazing land had significantly lower SOC and TN stock than the 15 and 20-year-old exclosures (Table 4). This might be attributed to the lower biomass (plant litter) input in the 5-year-old exclosure and the open grazing land. Overgrazing and eroded landscape were the features observed on the grazing lands. Unmanaged grazing can severely affect aboveground vegetation biomass and SOM content (Qasim et al., 2017). Generally, this study suggested that restoration of degraded lands through exclosure can enhance ecosystem services, such as SOM accumulation that may improve soil aggregation, and SOC and TN stocks. The higher stocks of SOC and TN in the exclosures are indicating that such restoration efforts of degraded lands can be used as a potential land-use type to sequester atmospheric CO_2.

SOC associated with soil aggregates

Slope and aspect can influence the rate of weathering and erodibility of soils and thus soil aggregate stability (Besalatpour et al., 2013). Furthermore, due to the reduced physical accessibility of organic compounds from microorganisms, extracellular enzymes, and oxygen, soil aggregation protects SOM from mineralizing (Zhao et al., 2017). Thus, the significant interaction effect among exclosures and open grazing land and slope position indicates the central role of exclosure age and slope position interaction on variability macroaggregated associated SOC (Table 5).

In addition, significantly ($p < .05$) affected by the land use types, Accordingly, SOC content of microaggregates was significantly ($p < .05$) lower in the 15-year-old exclosure as compared to that in the other age exclosures and adjacent open grazing land (Table 5). Findings from studies conducted in West Beijing, China, by Dameni and Wang (2012) and in Northern China by Yan et al. (2018) indicated that SOC was highly concentrated in microaggregates than in macroaggregates. Conversely, Gelaw et al. (2015) reported higher SOC in macroaggregates than microaggregates in the open communal grazing land of Tigray in North Ethiopia.

Even if there was an insignificant difference in MWD and WSA between different ages of exclosure and adjacent open grazing land, both land-use types had relatively larger MWD and WSA, which is an indicator of good soil structure. Microaggregates are formed within macroaggregates (Six et al., 2000). A large proportion of SOC is stabilized in soils by physical protection within aggregates (Wiesmeier et al., 2012). Soil organic carbon could be protected from microbial decomposition through sorption to clay minerals and encapsulation within soil aggregates (Chai et al., 2019). Soil carbon contained in free microaggregates has a slower turnover than soil carbon in macroaggregates, which is an important factor contributing to CO_2 sequestration (Six et al., 2000).

The lower SOC content in macroaggregates than microaggregates could be due to the high turnover rate of fresh plant residue and the activity of microorganisms. Macroaggregates consist of complexes of clay-polyvalent metal-organic matter where clay is bonded to humified organic matter through polyvalent metals (Tisdall & Oades, 1982). They are formed around fresh residue which then becomes coarse intra-aggregate particulate organic matter (Six et al., 2000). Macroaggregates have greater porosity than smaller aggregates (Oades & Waters, 1991). The fresh residue and roots and hyphae are temporary binding agents that are decomposed relatively quickly, resulting in a further decrease in macroaggregate stability (Tisdall & Oades, 1982). Thus, macroaggregates are generally less stable than microaggregates. When the macroaggregates are disrupted, the SOC will be released. Chai et al. (2019) found that the SOC in macroaggregates was younger and less persistent than that in microaggregates.

The inconsistent effect of age of exclosure and adjacent open grazing land on the SOC content of macroaggregates could be associated with the difference in biomass input and site factor. Soil organic carbon content of macroaggregates also varied significantly ($p < .05$) along slope position, whereas the effect of slope position on SOC content of microaggregates was not significant ($p > .05$) (Table 5). The SOC content of macroaggregates was the highest in the upper slope position (3.05%) as compared to the middle and lower slope positions. Mechanical dispersion of macroaggregates due to soil erosion could be the reason for the lower SOC content registered in the middle and lower slope positions. When the large aggregates are mechanically disrupted, the SOC contained in them can be released, exposing them to further decomposition by reducing their stability (Chai et al., 2019). Except for SOC stock and macroaggregated associated SOC, most soil properties did not show significant variation along slope position. This could due to the similarity of slope gradient which ranges from 15% to 30% (Figure 1) on all sites and vegetation coverage along slope position in each exclosure.

Spatial variability of SOC and TN stocks

According to Cambardella et al. (1994), the nugget/sill ratio falls on the scale of strong (SOC stock) and moderate (TN stock) spatial autocorrelation that is, spatial dependence (Table 6). The lower nugget/sill ratio of SOC stock shows that the strong spatial autocorrelation in all exclosures and adjacent open grazing land was primarily caused by intrinsic soil characteristics. On the other hand, the medium nugget/sill ratio of TN stock suggests that both the intrinsic and extrinsic factors may play a significant role in its moderate spatial autocorrelation (Behera & Shukla, 2015; Laekemariam et al., 2018; Shit et al., 2016). If the nugget/sill ratio is high, spatial autocorrelation in soil properties is primarily caused by stochastic factors such as anthropogenic activities and if low, it is caused by intrinsic factors such as parent material, topography, climate, soil properties, and other natural factors (Akbas et al., 2017; Cambardella et al., 1994; Shit et al., 2016).

In this study, the natural ecological succession in the area of exclosure might contribute to the strong and moderate spatial autocorrelation of SOC and TN stock, respectively. Area exclosure is a practice of land management whereby severely degraded lands are excluded from unmanaged accesses to promote vegetation rehabilitation and foster natural ecological succession. The current finding is in line with the study of Chabala et al. (2017) on soil organic carbon in Zambia which reported strong spatial autocorrelation of SOC. A study conducted in Southern Ethiopia by Laekemariam et al. (2018) had shown a moderate spatial autocorrelation of TN. Contrary to this study, Bhunia, Shit, and Chattopadhyay (2018) in West Bengal, India, and Birhane et al. (2017) in Northern Ethiopia reported moderate and strong spatial dependency of SOC and TN, respectively. Furthermore, Mousavifard et al. (2013) in the Aqade region, Iran, Shit et al. (2016) in West Bengal, India, and Kumar et al. (2012) in Pennsylvania state, USA reported a moderate spatial autocorrelation for SOC.

Semivariogram analysis of this study shows that TN stock is influenced by intrinsic factors and other random factors over a longer distance than SOC stock (Table 6). A large range value indicates that the value of measured soil property is influenced by factors over greater distances (Behera & Shukla, 2015). Overall, the range suggests that SOC stock shows strong spatial autocorrelation than TN stock in all the exclosures and adjacent open grazing. The slightly higher nugget of TN than SOC stock implies a random and inherent variability of TN stock (Husein et al., 2019).

Generally, except for SOC stock in the 20-year-old exclosure, both SOC and TN stocks showed high spatial variability across all ages of exclosure and adjacent open grazing land. The spatial variability of SOC and TN stocks in these areas might be due to the variation in vegetation cover and density and topography of the area. Understanding geographical distribution and precise mapping of soil properties are very important for environmental modeling (Bhunia, Shit, & Chattopadhyay, 2018).

Conclusions

This study quantified and investigated SOC and TN stocks, soil aggregate stability, and aggregates associated SOC under different ages of exclosure and adjacent open grazing land. The MWD average showed that both the exclosures and adjacent open grazing land were dominated by agronomically most valuable aggregates (macroaggregates ie, >0.25 mm). Higher SOC and TN stock were observed within the 15 and 20-years old exclosure. Macro- and microaggregates associated SOC were also significantly affected by age of exclosure. This indicates that such restoration efforts of degraded lands can be used as a potential land-use type to sequester atmospheric CO_2 through soil organic matter accumulation that may improve soil aggregation. Soil organic carbon stock was significantly influenced by the slope position and show a strong and moderate, respectively spatial autocorrelation along all ages of exclosures and adjacent open grazing land. It is suggested that further studies on litterfall associated with C and N and soil organisms are needed to better understand the dynamics of SOC and TN dynamics in these exclosures.

Declaration of Conflicting Interests

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