Article

Carbon sequestration and soil restoration potential of grazing lands under exclosure management in a semi-arid environment of northern Ethiopia

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Abstract: Exclosures are used to regenerate native vegetation as a way to reduce soil erosion, increase rain water infiltration and provide fodder and woody biomass in degraded grazing lands. Therefore, this study assessed the impact of grazing exclosure on vegetation biomass, carbon sequestration and soil nutrients under five and ten years of grazing exclosures and freely grazed areas in Tigray, northern Ethiopia. Vegetation biomass, carbon stocks and soil nutrients increased with increasing grazing exclusion. However, open grazing lands and five years of grazing exclosure did not differ in aboveground biomass, above-and-belowground carbon stocks. Moreover, ten years of grazing exclosure had a higher ($P<0.01$) grass, herb and litter carbon stocks compared to five years exclosure and open grazing lands. The total carbon stock was higher for ten years exclosure (193.3 t C ha^{-1}) than the five years exclosure (154.0 t C ha^{-1}) and in open grazing areas (146.6 t C ha^{-1}). Grazing lands closed for ten years had a higher SOC, organic matter, total N, available P, and exchangeable K+ and Na+ compared to five year's exclosure and open grazing lands. Therefore, establishment of grazing exclosures had a positive effect in restoring degraded grazing lands, thus improving vegetation biomass, carbon sequestration potentials and soil nutrients under the changing climate and global warming.

Keywords: Above-ground carbon stock; Below-ground carbon stock; soil nutrients; exclosure

1. Introduction

Grazing land resources are facing challenges like intense degradation as a consequence of deforestation, agricultural land expansion and continuous heavy grazing [1,2]. In arid and semi-arid grazing lands, overgrazing is one of the most important destructive factors, which causes to the increase of unpalatable species by destroying the most palatable species in the sward and reduce plant cover and biomass, thereby increase erosion hazard and reduce the overall productivity of the land [3,4].

The direct effect of livestock grazing includes consumption of the important plant species and soil trampling, which destroy the structure and composition of plant communities [5]. Determination of herbivore density and proper distribution of livestock in grazing land are the most important issues in grazing land management [6] since vegetation biomass, vegetation height and percentage of plant cover reduced with increasing grazing intensity [7-9]. Accordingly, increasing

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grazing changes the species composition and endangered the stability of the grazing lands through reducing soil nutrients [10]. Light grazing increases aboveground biomass, canopy cover and height of the species, but from a long-term perspective, moderate grazing would balance the production of different species and livestock production [11]. Vegetation response to different grazing land management practices has been investigated in several studies [5,9,12-14] in which the results indicated that overgrazing of communal grazing lands causes a change in vegetation structure through decreasing the vegetation density and biomass. However, continuous heavy grazing can also affect the carbon sequestration potentials of grazing lands through reduction of carbon accumulation in the soil systems [15-17]. According to Mekuria, *et al.* [18] soils in areas excluded from gazing had a higher soil organic matter (SOM) contents compared to open grazed areas. Thus, uncontrolled (open) grazing could result in severe degradation of both native vegetation and soil fertility in communal grazing lands in arid and semi-arid environments [13].

Restoration of degraded lands in arid and semi-arid environments often involves excluding livestock from degraded sites [2,13,18,19]. According to Aerts, *et al.* [20] and [21] exclosures are areas protected from human and domestic animal disturbances with the purpose of regenerating native vegetation and reducing land degradation of the formerly degraded communal grazing lands. Yayneshet, *et al.* [13] reported that exclosures can be effective in enhancing the composition, diversity, and density of vegetation on degraded grazing lands. Moreover, exclosures can be effective in restoring degraded soils and increase soil carbon in the highlands of Tigray [19]. Accordingly, rehabilitation of degraded communal grazing lands through establishing exclosures has become increasingly important in Tigray region, northern Ethiopia. Hence, approximately 1.5 million hectares of land has been excluded from grazing in the last three decades in the highlands of Tigray region [21]. However, information on carbon sequestration and soil restoration potentials of degraded grazing lands after grazing exclusion in semi-arid environments of Tigray region of Ethiopia is lacking under the ever-changing climate and global warming. In the study area, the grazing exclosures were established in 2005 and 2010 in the lowlands of northern Ethiopia. Therefore, we investigated vegetation biomass, above-and-belowground carbon stocks and soil nutrients under five and ten years of grazing exclosures compared to freely (open) grazing areas and along soil depths in semi-arid environment in northern Ethiopia.

2. Materials and Methods

2.1. Study Area

The study site was located in the semi-arid areas of Tselemti district in the northwestern Tigray region of Ethiopia (Figure 1), which is located at 13°05′N Latitude and 38°08′E Longitude. The landscape of the district is characterized with flat plain plateau, mountainous valley and some immediate break of slope with an altitude ranged between 800 to 2870 m above sea levels.

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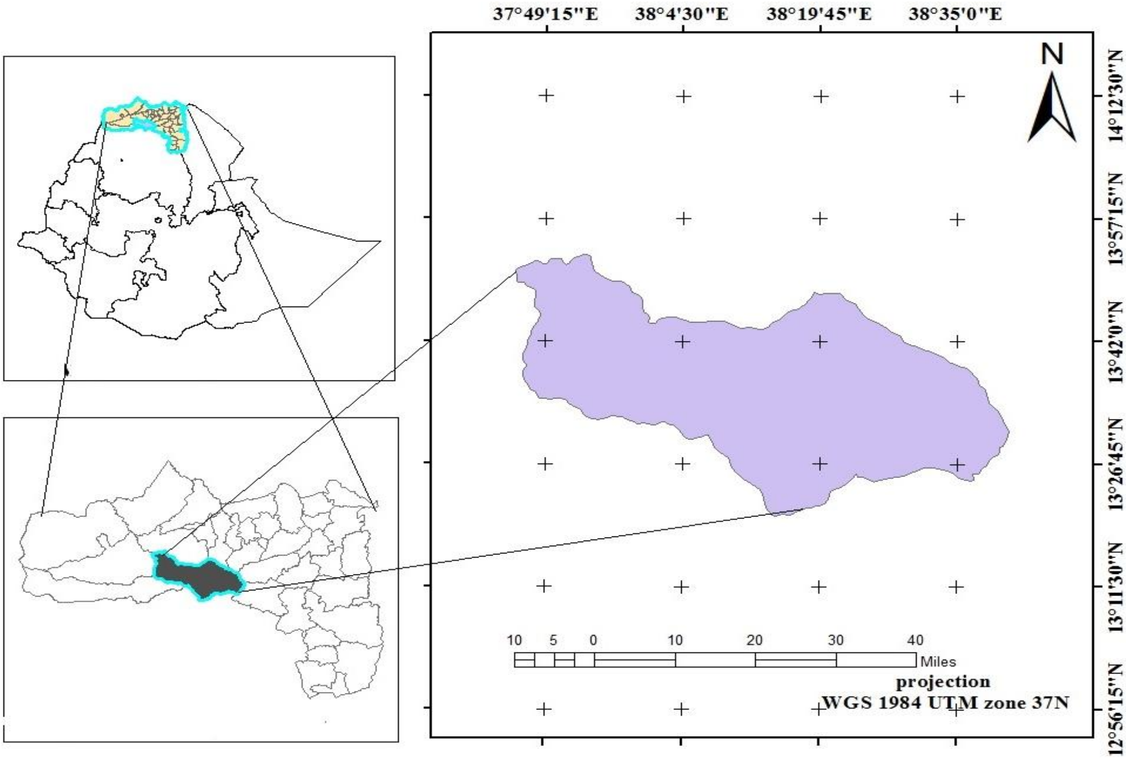

Figure 1: Map of the study area, Tselemti district, in Tigray region, northern Ethiopia

The mean maximum temperature varied between 33 °C in April to 41.7 °C in May, while the mean minimum temperature is between 15.8 °C in December to 21.7 °C in May. The dry season occurs from November to May, whereas, the main rainy season occurs between June to September. The vegetation cover in the district includes Combretum-Terminalia and Acacia-Commiphora Woodlands which are characterized by small to moderate-sized drought-resistant trees and shrubs with fairly large deciduous leaves. *Anogeissus leiocarpus* (DC) Guill & Perri, *Dichrostachys cinerea* (L.) Wight & Am, *Dovyalis abyssinica* (A. Rich) Warb, *Oxythenanthera abyssinica* (A. Rich) Munro, *Boswellia papyrifera* (Del). Hochst, *Erytherina abyssinica* (DC) and *Balanites aegyptiaca* (L) Del are some of the dominant woody species in the study area [14].

2.2. Study site selection and field layout

A field observation was made throughout the areas to be sampled prior to the field layout for vegetation and soil sampling. Accordingly, sampling sites within five years old exclosures, ten years old exclosures and open grazing lands were selected for data collection. The size/area of the selected sites varied from 60 to 105 ha for open grazing lands and from 72 to 98 ha for grazing exclosures. The exclosures and open grazing lands were assumed to have been on similar conditions before the establishment of the exclosures. To cover the variability in soil and topography, we selected three replicates for each exclosure age and open grazing land throughout the study area. The same site was divided into both exclosure and open grazing land due to the presence of high number of livestock and shortage of grazing land. Hence, the exclosure and the grazing lands were homogenous. To reduce variability as a result of distance, the design for data collection was systematic. We used systematic transect sampling technique to collect the vegetation and soil data within the three sampling sites (Figure 2) under each grazing land management. The first and the last transect lines were laid at least 100 m inside from the edge of the nearest adjacent grazing lands to avoid edge effects. The first sample plot was laid randomly and the others systematically at 100m interval for larger plots (100 m^2) and 70m interval for smaller plots(1 m^2) along the transect line. At each site, six parallel line transects each with 1000 m long at 200 m intervals from each other was established in each management practice. Plots measuring 10mx10m were systematically taken for woody vegetation data collection according to previous studies [22-24] and 1 m^2 were established for

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grass, herbs and litter (GHL), as well as soil sampling in each transect line, a total of 270 sample quadrats were taken for sampling woody vegetation and 405 sample quadrats for measuring GHL and soil sampling during the study (Figure 2).

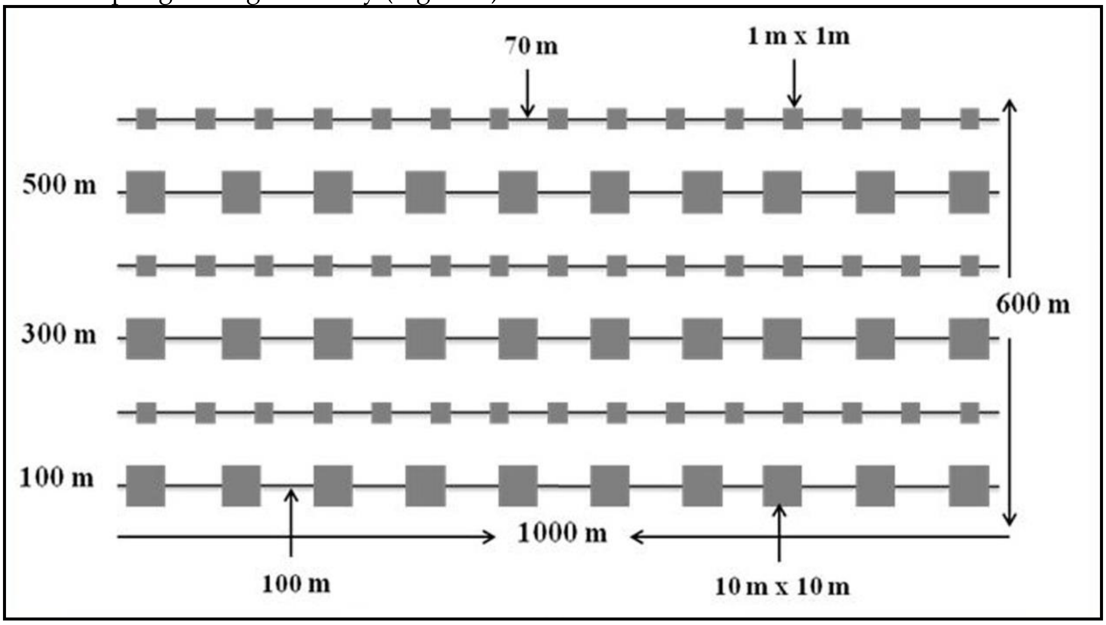

Figure 2: Sampling design and plot layout of the experimental site (Key: The small quadrats in the Figure have 1m x 1m size and are allocated for herbaceous species as well as soil sampling. The larger squares in the Figure have 10 m x 10 m size and are allocated for woody species sampling).

2.3. Sampling of woody vegetation and carbon stock determination

Data on woody vegetation were collected during September to October 2015. In each plot, every tree and shrub having a diameter of ≥2.5 cm at stump height (30 cm from the ground) and breast height (1.30 cm above the ground) circumference were measured with a meter tape and converted to diameter at breast height (DBH). The diameter was measured separately and considered as individual trees when the bole was branched at breast height or below. Moreover, in cases where tree/shrub boles buttressed, DBH was measured from the point just 5 cm above the buttresses. The diameters of multi-stemmed shrubs were measured the same way as single-stemmed trees according to Eshete and Ståhl [25]. The height of woody species was measured using calibrated bamboo stick having 7 m height graduated with 10 cm markings. Trees greater than 7 m in height were measured using clinometers.

The biomass and carbon stock of dominant tree/shrub was estimated through allometric equations developed for each tree/shrub species according to previous studies [26,27]. The general allometric equation developed by WBISSP [28] for all woody species were also used for estimating the aboveground woody biomass carbon stocks when species-specific allometric equation is absent. Then, the above-ground woody biomass carbon is calculated from the aboveground biomass using a biomass-carbon conversion factor of 0.5 [29]. Moreover, the below-ground biomass for trees and shrubs was estimated from root-shoot ratios by taking in to account the 27% of above-ground biomass of woody species [30].

2.4. Sampling of herbaceous vegetationand carbon stock determination

The aboveground biomass of herbaceous vegetation was measured in a 1 m^2 quadrat .from September to October 2015. Destructive sampling method was used for measuring the biomass of grasses and herbs by harvesting the whole fresh vegetation within each quadrat using hand shears. Clipped fresh samples together with litters were well-mixed and weighed in the field using sensitive balance. Sub-sample of the total weight was separated and placed in a marked bag and taken to the

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laboratory to determine an oven-dry-to-wet mass ratio that is used to convert the total wet mass to oven dry mass. The sub-sampled was air dried and latter oven-dried at Mekelle Soil Laboratory at 80°C for 24hr according to Rau, *et al.* [31] until constant weight was obtained and finally re-weighed for their dry weight using a sensitive balance with a precision of 0.1g. Herbaceous vegetation carbon stocks were calculated as 50% of oven-dried herbaceous biomass [32].

2.4. Sampling of soil parameters and laboratory analyses

Soil samples were collected in each plot at three soil depths (0-10, 11-20 and 21-30 cm).One soil core sample was also taken from the center of each transect line for soil bulk density (SBD) determination. Equal weights of each sample from a given transect line were pooled and mixed together according to their depth, air dried and passed through a 2 mm sieve to separate debris and gravel. Finally, composite samples were divided into four equal parts, of which one was randomly chosen and stored in plastic bags, labelled, sealed and transported to the soil laboratory for physical and chemical analyses. In the laboratory, soil samples were dried in an oven at 105°C for 24 hours for bulk density analysis. Bulk density was measured using the core method [33] and soil organic carbon was determined by Walkley–black method [34]. Soil texture was analyzed by hydrometer method, pH using a pH-meter in a 1:2.5 soils: water ratio. The percent soil organic matter (SOM) was calculated by multiplying the percent organic carbon by a factor of 1.724 [35]. Total nitrogen was determined by the Kjeldahl method [36], Available K and P were analyzed using ammonium acetate method and Olsen method [37], respectively. Mg and Ca were determined using Atomic Absorption Spectrophotometer and Flame Photometer was used for K and Na [38]. EC was determined using the sodium saturation ratio [39] and cation exchange capacity (CEC) was determined using ammonium acetate method [40]. Soil organic carbon stocks (t C ha^{-1}) in the 0 -10, 11 - 20 and 21 - 30 cm depths were calculated according to Pearson, *et al.* [41].

2.5. Estimation of total carbon stocks

The total carbon stock from various carbon pools was calculated by aggregating the carbon stock densities of the individual carbon pools using the equation given by Subedi, *et al.* [42]. The total carbon stock is then converted to tons of CO_2 equivalent by multiplying it by 44/12, or 3.67 [32].

2.5. Estimation of total carbon stocks

A General Linear Model (GLM) was applied, to test for differences in all data recorded, with exclosure land management, soil depth and their interactions, as independent factors, and replications, as a random factor. Data were analyzed using SAS Software (SAS Inc., 2002), and results are presented as mean ± S.E. Tukey HSD test was employed to investigate significant differences between means at $P \leq 0.05$. However, mean comparison of the interaction effects between exclosure land management and soil depths were not performed for vegetation biomass, above-and-belowground carbon stocks due to the lack of significant effects. Dependent proportional data were arcsine transformed to meet the assumptions of normality and homogeneity of variance.

3. Results

3.1. Vegetation biomass across grazing land management practices

The mean aboveground herbaceous biomass was significantly higher (P<0.001) in the ten years of grazing exclosure than the five years exclosure and the open grazing lands (Table 1). The mean herbaceous dry biomass yield in area exclosures was four times higher than the open grazing lands. However, the lowest GHL biomass was recorded from open grazing land (0.56 dry matter (DM) t ha^{-1}), while the highest biomass (3.08 DM t ha^{-1}) was from the ten years of grazing exclosure (Table 1). Age of grazing exclosure had significantly (P<0.001) affected aboveground vegetation biomass as grazing lands excluded from the interference for five years had a lower mean vegetation biomass compared to grazing lands excluded for ten years in the present study.

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Woody biomass production varied between 37.2 t ha^{-1} of DM under ten years of grazing exclosure and 17.6 DM t ha^{-1} in open grazing lands (Table 1).The mean aboveground woody biomass (AGB) significantly (P<0.001) varied across exclosure land management practices, for instance, the ten years of grazing exclosure had a higher woody biomass (P<0.001) compared to the five years of grazing exclosure and open grazing lands. Belowground biomass significantly differ (P<0.05) between the grazing land management practices being the ten years of grazing exclosure had the highest (10.1 t ha^{-1}) belowground biomass, whereas, the open grazing land had the lowest mean belowground biomass (4.74 t ha^{-1}) in our study. However, belowground biomass did not significantly vary (P>0.05) between the five years grazing exclosure and the open grazing lands in the present study.

Table 1: Least square mean of vegetation biomass (DM t ha^{-1}; mean ±SE)under the five and ten years of grazing exclosures and open grazing lands in Tselemti district of Tigray region, northern Ethiopia(n = 270 for woody vegetation aboveground biomass and belowground biomass and n = 405 for grasses, herbs and litter biomass).

Management practices	AGB	BGB	GHLB	TAGB
Open grazing land	17.57±2.46^{b}	4.74±0.67^{b}	0.56±0.38^{c}	18.13±2.22^{b}
Five years exclosure	17.83±1.49^{b}	4.82±0.41^{b}	2.67±0.07^{b}	20.50±1.35^{b}
Ten years exclosure	37.23±2.40^{a}	10.10±0.65^{a}	3.08±0.06^{a}	40.31±1.93^{a}
P value	<0.0001	<0.0001	<0.0001	<0.0001

Means with the same superscripts along columns are not significantly different at P≤0.05. DM = Dry matter; AGB = Aboveground biomass; BGB = Belowground biomass; GHLB = Grasses, herbs and litter biomass; TAGB = Total aboveground biomass; t ha^{-1} = tone per hectare; SE = Standard error

3.2. Aboveground carbon stocks

Aboveground carbon stocks increased with duration of grazing exclusion; however, the open grazing lands and five year exclosures did not differ significantly (P>0.05) while the grazing lands closed for ten years differs significantly (P<0.05) with both the five years exclosure and open grazing land (Table 2). The mean aboveground carbon stock under the open grazing lands, five and ten years grazing exclosures were 8.78, 8.92 and 18.62 t C ha^{-1}, respectively.

3.3. Belowground carbon stocks

The estimated mean belowground carbon stocks for the ten years grazing exclosure (5.05 t C ha^{-1}) was significantly higher (P<0.001) than five year gazing exclosure (2.41 t C ha^{-1}) and open grazing lands (2.37 t C ha^{-1}). However, the mean belowground carbon stocks between the five years grazing exclosure and the open grazing lands did not significantly (P>0.05) differ in the present study (Table 2).

3.4. Grasses, herbs and litters carbon stocks

Grass, herb and litter (GHL) carbon stocks significantly vary (P<0.001) between open grazing lands, five and ten years grazing exclosures (Table 2). Accordingly, the highest GHL carbon stocks were obtained under the ten years grazing exclosure (1.54 t C ha^{-1}), whereas the lowest GHL carbon stock (0.28 t C ha^{-1}) was recorded under the open grazing lands.

3.5. Soil organic carbon stocks

Soil organic carbon (SOC) stocks showed a significant variation (P<0.01) between the three grazing land management practices in our study. The highest SOC (168.1 t C ha^{-1}) was obtained under the ten years of grazing exclosure and the lowest SOC stocks (135.2 t C ha^{-1}) under the open

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grazing lands (Table 2). However, there was no significant (P>0.05) difference in SOC between the five years grazing exclosure and the open grazing lands in our study.

3.6. Total carbon stocks across the grazing land management practices

The total carbon stock was significantly higher (P<0.001) under the grazing exclosures compared to the open grazing lands. Accordingly, the total carbon stocks for open grazing lands, five and ten years of grazing exclosures were 146.6, 154.0 and 193.3 t C ha^{-1}, respectively (Table 2). A higher total carbon stocks were stored in the soil than in the aboveground vegetation across all management practices. Accordingly, soil carbon stock of open grazing areas, five and ten years of grazing exclosures accounted for 92.2%, 91.8% and 87% of the total carbon stocks, respectively. Hence, the estimated ratios between the mean SOC and aboveground biomass carbon stocks were 11.8, 11.2 and 6.7 for open grazing areas, five and ten years of grazing exclosures, respectively.

Table 2: Carbon stocks in ton per hectare(mean ±SE) under the five and ten years of grazing exclosures and open grazing lands in Tselemti district of Tigray region, northern Ethiopia(n= 270 for woody vegetation aboveground and belowground woody carbon stocks, n =405 for grasses, herbs and litter carbon stocks as well as for soil carbon stock).

Management practices	AGWCS	BGCS	GHLCS	SOC	TCS
Open grazing land	8.78±1.23[b]	2.37±0.34[b]	0.28±0.19[c]	135.18±5.98[b]	146.6±1.42[c]
Five years exclosure	8.92±0.75[b]	2.41±0.20[b]	1.34±0.35[b]	141.31±5.95[b]	154±0.85[b]
Tenyears exclosure	18.62±1.20[a]	5.05±0.33[a]	1.54±0.03[a]	168.12±9.98[a]	193.33±1.22[a]
P value	0.0001	0.0001	0.0001	0.0075	0.0001

Means with the same superscripts along columns are not significantly different at P≤0.05. AGWCS = Aboveground woody carbon stocks; BGCS = Belowground carbon stocks; GHLCS = Grasses, herbs and litter carbon stocks; SOC = soil carbon stocks; TCS= total carbon stock; SE = Standard error

3.7. Soil organic carbon stocks along soil depths

The SOC significantly differ (P<0.05) between the three soil depths in each grazing land management practices, as the SOC significantly reduced with increasing soil depths in our study. Accordingly, the higher soil depth (0-10 cm) had a higher SOC compared to the other soil depths (11 –20 and 21 –30 cm) across the grazing land management practices (Figure 3).

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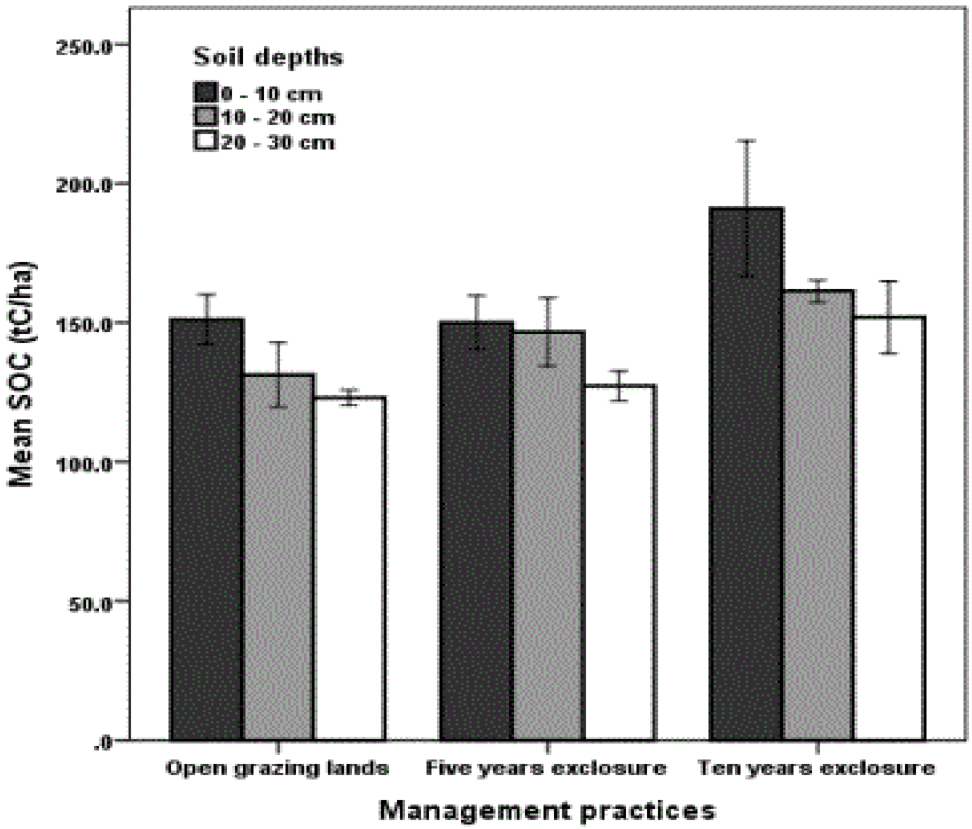

Figure 3: Soil organic carbon stocks (t C ha^{-1}) across grazing land management practices and three soil depths (0 -10, 10 – 20and 20-30 cm) in Tselemti district of Tigray region, northern Ethiopia.

3.7. Soil nutrients between land management practices and soil depths

The soil textural class for the five and ten years of grazing exclosures was clay loam, while open grazing lands had a sandy clay loam textural classes (Table S1). The mean percentage of sand recorded in open grazing lands, five and ten years of grazing exclosures were 49.1, 41.3 and 41.3, respectively, while their corresponding mean clay and silt values were 25.2, 24.9, 30.3 and 25.7, 33.8, 28.3, respectively. The silt and sand particle size fractions were higher in the topsoil layer than in the middle and lower soil depths across the grazing land management practices. In contrast, the clay particle was slightly higher in the middle soil depth compared to the top and lower soil depths across the grazing land management practices (Table S1).

Age of exclosure, soil depth and their interactions had no significant ($P>0.05$) effect on the sand and clay contents of the soil in our study. The silt content was not significantly ($P >0.05$) affected by the soil depth and its interaction with grazing land management practices, whereas, the silt content in the five years of grazing exclosure had significantly ($P<0.05$) higher percentage of silt content compared to the ten years of grazing exclosure and open grazing lands (Table S1). Moreover, bulk density had significantly varied ($P<0.001$) across the soil depths and grazing land management practices in the present study.

Available P showed significant variations ($P<0.001$) with grazing land management practices, soil depths and their interaction (Table S1). Available P across soil depth ranged from 4.69 ppm for the topsoil depth (0-10 cm) to 2.7 ppm for the lower soil depth (21-30cm). Available P varied significantly across management practices from 3.03 ppm in the open grazing lands to 4.68 ppm in the ten years of grazing exclosure. Soil organic carbon and exchangeable K+ were significantly ($P<0.001$) affected by soil depth and exclosure land management practices. Total nitrogen (TN) highly significantly varied (P<0.001) between the grazing management practices, as low as to 0.06% in the open grazing lands to as high as 0.15% for the ten years of grazing exclosure (Table S1). Soil pH and EC did not significantly vary (P<0.05) across the soil depths, grazing land management practices and their interactions.

However, cation exchange capacity and exchangeable bases varied significantly (P<0.01) across soil depths and management practices in our study (Table S1). Open grazing lands had a lower exchangeable Ca++, Mg++and K+ compared with the five and ten years of grazing exclosures (Table 3). Moreover, the ten years of grazing exclosure had a higher exchangeable Na+ (0.41 C mol (+)/kg) compared with five years grazing exclosure (0.31 C mol (+)/kg) and the open grazing lands (0.29 Cmol (+)/kg). In terms of soil depth, OC, OM, TN%, AP, exchangeable K+ and Na+ reduced with increasing soil depths, whereas, pH, EC, Ca++, Mg++ and CEC increased with increasing soil depth in the present study (Table S1).

4. Discussion

4.1. Biomass yield of aboveground vegetation

The lowest vegetation biomass in open grazing lands compared to the five and ten years of grazing exclosures in our study could be due to continuous heavy grazing, which negatively affects the growth of plant species. This finding is in line with Yayneshet, *et al.* [13] who reported that more than double aboveground biomass has been produced under grazing exclosures than open grazing lands in the highlands of Tigray region of Ethiopia. Besides, Snyman [43] and Li, *et al.* [44] also reported that accumulation of aboveground vegetation biomass declined with grazing land degradation, reduction in basal cover and root biomass, and change in species composition, leading to a less aboveground biomass production at higher grazing pressure compared to a lower grazing pressure.

The extent of woody vegetation biomass variation across grazing land management practices in our study could be due to the variation in the size of tree species, as the interference herbivores (both grazers and browsers), as well as human disturbances in the open grazing lands could lead to a significant reduction of total woody plant density. Five years of grazing exclosure had lower woody biomass than the ten years of grazing exclosure due to the difference in the size of trees. Hence, higher distribution and proportion of sapling and seedling stages in the five years of grazing exclosure had a lower contribution for aboveground woody biomass reported in our study [14]. According to Witt, *et al.* [45], aboveground woody biomass increases with grazing exclusion due to the regeneration potentials of tree and shrub species. Likewise, some studies in semi-arid Kenya [46], in semi-arid Azerbaijan [47], and in southern Mongolian desert steppes [48] showed that aboveground biomass increased following the establishment of grazing exclosure on communal grazing lands, which might be due to the higher abundance and density of woody vegetation, which had more potential to produce larger quantities of above-and-belowground biomass compared to the open grazing lands.

4.2. Carbon stocks

The highest aboveground carbon stock in ten years exclosures might be due to the availability of higher aboveground biomass in ten year exclosures as compared with five years exclosure and open grazing lands. The lowest aboveground carbon stocks in open grazing lands could be due to loss of carbon stocks as a result overcutting and trimming of trees/shrubs by local people for fences, charcoal production and other purposes. The mean aboveground carbon stocks for the ten years of grazing exclosure recorded in our study is similar within the tropical forests [49] and deciduous woodlands in the north-western lowlands of Ethiopia [15]. However, the aboveground carbon stocks found in this study was lower compared to the aboveground carbon stocks reported from

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rangelands enclosed for about 20 years in the southern parts of Ethiopia [12]. Moreover, the mean carbon stock in our study was higher than the carbon stocks reported in the Nile basin [5], in highlands of Tigray region of Ethiopia [17] and in the shrublands of northern Kenya [24].

The mean belowground carbon stocks of the ten years of grazing exclosure were higher than the five years of grazing exclosure and open grazing lands, which might be due to the higher biomass of woody species in grazing exclosures. The belowground carbon stock in our study is similar to belowground root carbon stocks reported from the deciduous woodlands in the lowlands of Ethiopia [15]. However, the belowground carbon stocks found in this study was higher compared to the belowground carbon stocks reported in the semi-arid pastoral areas of northern Kenya [24].

A higher grass, herbs and litters (GHL) carbon stocks were found in the ten years of grazing exclosure compared to the five years of grazing exclosures and open grazing lands in our study. This might be due to the fact that continuous heavy grazing in open grazing lands inhibits the growth of herbaceous layers and decrease aboveground herbaceous biomass through direct removal, leading to the depletion of GHL carbon stocks and soil nutrients. Our result is in agreement with previous studies [12,16,17] who reported a significant difference in herbaceous carbon stocks between gazing land exclosures and open grazing lands. Moreover, the herbaceous carbon stocks reported in our study under the open grazing lands is almost similar to herbaceous carbon stocks in the untapped Boswellia woodlands in the north-western lowlands of Ethiopia [15]. Our result indicated that exclusion of eroded and degraded grazing lands from animal interferences had a positive effect on the accumulation of herbaceous vegetation and litter carbon stocks.

The ten years of grazing exclosures had the highest SOC, whereas, the lowest SOC was recorded in the open grazing lands (135.2 t C ha^{-1}) in our study. The differences in SOC stocks between the ten years of grazing exclosure and open grazing lands could be as a result of the increased vegetation biomass and the subsequent production and decomposition of litterfall from this vegetation that would add OM into the soil systems. Thus, grazing lands with more aboveground vegetation biomass contribute more to the soil carbon sequestration potential as compared to grazing lands having less aboveground vegetation biomass. This finding is in agreement with Bikila, *et al.* [12] and Mekuria [17] who reported that SOC was markedly higher for exclosures than the open grazing areas. Sheikh, *et al.* [50] and Fynn, *et al.* [51] also reported that high SOC mass was recorded in the protected areas.

The contribution of area exclosures to SOC improvement is controlled by several factors that include level of land degradation, composition of plants, climatic factors, duration of grazing exclosures, as well as land use type and management practices of the areas. In our study, the overall belowground carbon pool was greater than the corresponding overall aboveground carbon pool in each grazing land management practice.

The total carbon stocks were highest in the ten years of grazing exclosure compared to the five years of grazing exclosure and open grazing lands in this study. Moreover, across the grazing land management practices, a higher total carbon stock was stored in soil than in the aboveground vegetation. According to Girmay, *et al.* [52] more than 90% of the total carbon stocks were contributed from SOC in wooded grassland of northern Ethiopia. In our study, the ratio between the mean SOC and aboveground carbon stock were 11.81, 11.15 and 6.66 for open grazing areas, five and ten years of grazing exclosure, respectively. This is in agreement with Sheikh, *et al.* [50] and Fynn, *et al.* [51] who reported that the soil contains about three times more organic carbon than the aboveground vegetation. The decrease in SOC with increasing soil depths in our study was in line with Bikila, *et al.* [12].

4.3. Soil nutrients between land management practices and soil depths

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The lowest silt percentage in the open grazing lands might be due to wind and water erosion as a result of higher bare-ground and low basal cover due to the low aboveground biomass through continuous heavy grazing. However, exclusion of grazing lands from grazing and trampling for five years had a positive effect on silt percentage but not for sand and clay percentage. Areas excluded from grazing had a lower soil bulk density than open grazing lands while there is no significant variation between young and old exclosures in our study, indicating that excluding of livestock from degraded grazing areas had a significant effect on soil bulk density.

The higher available P and TN% recorded from the ten years of grazing exclusion could be due to the higher accumulation and decomposition of litters into the soil. The results for the OC, TN% and AP was in agreement with the reports of Yimer, *et al.* [53] who stated that the relative increase in the soil parameters in exclosures is due to the management establishment and subsequent increased organic matter accumulation derived from litterfall from the trees/shrubs and herbaceous species biomass and from reduced soil erosion through effective ground cover. Besides, the increases in canopy cover with the increase in exclosure duration could decrease soil nutrient losses by reducing the erosive impact of raindrops and soil erosion [54,55].

5. Conclusions

The establishment of area exclosures on degraded communal grazing lands had positive effect in restoring vegetation biomass, carbon sequestration potentials and soil nutrients of eroded communal grazing lands. The aboveground biomass and carbon stocks increased with duration of grazing exclusion; however, the open grazing lands and five years of grazing exclosure did not differ significantly in our study. A similar pattern was observed for belowground carbon stocks and soil organic carbon stocks that the grazing lands excluded for ten years from grazing differed significantly with both the five years closed area and the open grazing lands. The grass, herbs and litter carbon stocks were the highest in the ten years of grazing exclosure, amounting almost more than five times the value recorded in the open grazing lands. Similarly, the overall total carbon stock was highest for the ten years of grazing exclosure followed by the five years of grazing exclosure and open grazing areas. In the present study, higher total carbon stock was stored in soil than in the aboveground vegetation across all grazing land management practices. Therefore, establishment of area exclosures needs to be widely practised in the semi-arid areas of the region to enhance vegetation biomass, carbon sequestration potentials and soil nutrient contents. Moreover, further studies on temporal and spatial vegetation biomass and carbon stocks need to be thoroughly investigated to capture the whole dynamics of the grazing land ecosystems under various regimes of grazing exclusions in arid and semi-arid environments.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, **Table S1**: Physical and chemical soil properties under the five and ten years of grazing exclosures and open grazing lands (n = 405) in Tselemti district of Tigray region, northern Ethiopia, with statistical results of GLM (F, P values).

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