Effect of degraded land rehabilitation on carbon stocks and biodiversity in semi-arid region of Northern Ethiopia

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ABSTRACT
This study evaluated the effects of exclosures (EXs) on restoring woody species diversity and carbon stocks over the adjacent degraded open grazing land (DOGL). Two proximate sites were purposively selected. Then, systematic sampling method was employed. A total of sixty plots were surveyed for both tree/shrub inventory and soil sampling purposes. Overall, 49 woody species belonging to 45 genera and 28 families were identified, comprising 46 woody species in the EX and 26 woody species in the DOGL. Species richness, Shannon and Simpson diversity indices were significantly higher in the EXs than DOGL. The total carbon stock was significantly higher in EXs (61.3 Mg C ha\textsuperscript{–1}, it ranged from 54.3 to 68.3 Mg C ha\textsuperscript{–1}) than DOGL (40.4 Mg C ha\textsuperscript{–1}, it ranged from 35.1 to 45.7 Mg C ha\textsuperscript{–1}). The conversion of the DOGL to EXs enhanced soil organic carbon and aboveground biomass carbon stock by 38 and 197% at the age of 12 years, respectively. Woody species diversity, abundance and richness were positively correlated with biomass and soil organic carbon stocks. This study revealed that EXs assisted with enrichment planting can be considered as a viable woody species recovery and carbon sequestration strategy.

Abbreviations: EXs: Exclosures; DOGL: Degraded open grazing land; REDD\textsuperscript{+}: Reduce Emissions from Deforestation and Forest degradation plus; SOC: Soil organic carbon; dbh: Diameter at breast height; AGB: Aboveground biomass; BGB: Belowground biomass.

Introduction
Worldwide, semi-arid dryland areas cover 15.2% of the land surface and an estimate of 4.8% are degraded (Yirdaw et al. 2017). Land degradation is triggered by population pressure and over-exploitation of the natural resources (Mganga et al. 2015; Yirdaw et al. 2017). Livestock free grazing is one of the major anthropogenic activities resulting in land degradation and causing significant negative impacts on woody species diversity and carbon storage of the arid and semi-arid lands (Giese et al. 2013; Raiesi and Riahi, 2014; Wu et al. 2014; Austrheim et al. 2016). This is because of the arid and semi-arid rangelands are ecologically fragile and have been degraded by mismanagement which could be restored by establishing exlosures (Qi et al. 2011; Li et al. 2012; Mureithi et al. 2014).

Combating of land degradation is crucial to ensure the long-term productivity of semi-arid environments. In any environmental policy, an understanding of potential trade-offs and interactions between carbon sequestration and biodiversity is essential (Witt et al. 2011; Rana et al. 2017; Reside et al. 2017). Successful restoration includes improvement of land productivity, soil organic C stock, biodiversity and other ecosystem services (Mureithi et al. 2014; Mekuria et al. 2017; Reside et al. 2017). About three decades ago, EXs was initiated as one of the restoration practices to avert the degraded semi-arid lands of Ethiopia (Yayneshet 2011). So far, several studies have been conducted in the semi-arid area focused on species composition, soil properties and socio-economic importance of EXs (Mengistu et al. 2005; Birhane et al. 2007; Mekuria and Yami, 2013; Yami et al. 2013). However, these studies overlooked the importance of co-benefits of establishing EXs for biodiversity conservation and carbon sequestration and synergy between them. This undermines its significance for both carbon emission reduction and biodiversity conservation strategy in the arid and semi-arid land of the tropics. Moreover, the existing sole studied on the effectiveness of established EXs to improve soil carbon stock potential was inconsistent and variable (Pinheiro et al. 2010; Raiesi and Riahi 2014; Aynekulu et al. 2017). For instance, in some studies reported that EXs improves the carbon stock potential (e.g., Shrestha and Stahl 2008; Mureithi et al. 2014; Yimer et al. 2015) and several other observes decreases (e.g., Reid et al. 2004; Mekuria et al. 2017, Tang et al. 2016) while Aynekulu et al. (2017) and Mekuria et al. (2014) reported that EXs did not influence soil organic carbon. SOC increased in the EXs, because grazing is one of the critical factors in species composition and grassland degradation that have a significant effect on carbon storage...
Grazing affected SOC content by changing the magnitude of net primary production returning to soil. This also affects nitrogen pathway and altering soil organic matter decomposition (Mekuria and Yami 2013; Shang et al. 2017). In contrast, in other region shrub encroachment enhanced abundance of highly productive species which can enhance NPP and due to animal manure to soil improves C input to the soil under grazing (Pinheiro et al. 2010; Steinere et al. 2014). This difference was due to the variation on soil texture and structure, rainfall, temperature, an age of the exclosure and soil management factors (Parras-Alcantara et al. 2015; Aynekulu et al. 2017).

Thus, the present study has investigated the effects of degraded land rehabilitation on carbon stocks and biodiversity in the semi-arid climatic region of Northern Ethiopia. Based on the stated goals of restoration by EXs, we hypothesize that: (1) EXs assisted enrichment planting would increase woody species diversity and carbon stocks inference to the adjacent open degraded land, and (2) biomass carbon stocks could be positively related to woody species diversity in Semi-arid region of Northern Ethiopia DOGL.

**Material and methods**

**The study sites**

The study sites were situated in Endamekoni District, Southern Zone of Tigray, Northern, Ethiopia. Geographically, the area is bound between 12°37' and 12°51' North and 39°16' and 39°37' East, with altitude ranges from 1800 to 3250 m a.s.l. The site is located on the dry highlands of the district (Figure 1).

The mean total annual rainfall of the study district is 703 mm with average monthly temperature ranges from 10.4 to 22.6 °C. The area has mainly semi-arid climate with bimodal rainfall, locally called "Kiremt" from June to September and follows the pre-monsoon rainy season, February to May, (locally called Belg) that adds a small amount of rain to the area.

Based on the various geological formations, soil types are variable but the dominant soil type of the study site is Cambisols. The soil texture analysis of both EXs and adjacent DOGL is sandy loam. The forest type found in Southern Tigray is broadly categorized as dry single-dominant Afromontane dry forests. The mesic Tigray highlands support species like Erica arborea (Aynekulu et al. 2011). Currently, *Carissa edulis* (Forssk), *Euclea racemosa* subsp, schimperi and *Maytenus arbutifolia* (A.Rich.) are frequent woody plant species in the district.

**Data collection and sampling**

**Selection of specific study sites**

Twelve years old exclosures with their adjacent DOGL as control were selected purposively. The study sites had two replications (Tesfaye and Negash 2018), with an area of 26.3 ha EXs for May Chilchalo and 12.5 ha for MekabirFenih) and adjacent DOGL (36.5 ha and 16.9 ha, respectively).
Based on local informants, the study sites had existed under similar soil type, vegetation type, and topography before the establishment of EXs. Stone bunds and enrichment planting using five exotic plants were being conducted in the study sites (Table 1). Exotic tree planting is done by the community during the establishment of the exclosure in 2003. Enrichment planting was done only on selected plots found on the lower slope with an overall average density of 132 seedlings ha\(^{-1}\) (Table 1).

In the degraded open grazing land, unlimited access for free grazing is experienced while illegal tree cutting is not allowed.

### Sampling layout

A systematic random sampling technique was employed to lay out the sample plot and collect data from the EXs and adjacent DOGL. In each of the land use types, transect lines were placed at 200 m interval. Then, sampling plot of 20 m\(^{2}\) was laid down at 50 m intervals among the plots. A total of 60 nested plots (15 plots \(\times\) 2 site replications \(\times\) 2 land uses) were laid down along the transect lines. Inside each of the larger plot, 5 subplots sized, 4 m \(\times\) 4 m each were randomly established to count sapling and seedlings, and 1 m \(\times\) 1 m sub-plots were laid down within 4 m \(\times\) 4 m nested plot to soil sampling.

### Data collection and laboratory analysis

Inventory of all woody species were done in the main sample plots (20 m \(\times\) 20 m). For all tree’s diameter at breast height (dbh \(\geq\) 2.5 cm and height \(\geq\) 1.5 m) and to total height were measured and recorded. All woody species saplings (dbh < 2.5 cm and total height 50–150 cm) and seedlings (height < 50 cm) were counted in subplots. In the case of multi-stemmed species, each stem was measured separately and the equivalent diameter of tree/shrubs were calculated following Snowdon et al. (2001). Woody species identification was done in the field and using available literature.

Overall, 120 composite soil samples from two soil depth of 0–15 cm and 15–30 cm were collected from both studied land uses using soil augered method for determination of SOC. In a similar way, 120 soil samples were collected using soil core sampler for analysis of bulk density. Then, samples were transported to Mekele Soil Research Center, Tigray Agricultural Research Institute, Ethiopia for chemical analysis. The soil samples used for SOC analysis were air-dried, ground, homogenized and sieved with a 2-mm mesh size sieve. The carbon content of soil samples was determined using the Walkley-Black method (Rosell et al. 2001). Bulk density was determined using oven dry method (Blake and Hartge 1986).

### Data analysis

Species diversity in EXs and adjacent DOGL were determined using species richness, Shannon index of diversity (H\(^{\prime}\)), Simpson diversity index and Shannon equitability or evenness (E) (Magurran 1988). The similarity in woody species composition of the two-land use types was computed using S\(\ddot{o}\)rensen’s similarity coefficient (Magurran 1988). The important value index (IVI) of each species with DBH < 2.5 cm was following (Kent and Coker 1992) procedure. The equations for estimating aboveground biomass for trees and shrubs are shown in Table 2.

To convert the aboveground biomass to carbon, the generic value of 50% C content was used for all trees and shrubs (MacDicken 1997) and for C. lusitanica 48% C content was used (Berhe et al. 2013). Belowground biomass for trees and shrubs was estimated using root to shoot ratio. We used 27% of above ground dry biomass as recommended in IPCC (2003). SOC stocks (Mg C ha\(^{-1}\)) were primarily estimated by multiplying the concentrations (%) of soil carbon, the bulk density (g cm\(^{-3}\)) and depth of the sampled soil (Equation 2). The Ecosystem carbon stocks were calculated with the summation of biomass and soil C stocks.

\[
\text{SOC (Mg C ha}^{-1}\) = \left\{ \left( \text{soil bulk density,} \frac{\text{g (cm}^3\text{)}}{} \right) \times \text{Soil depth (cm)} \times \%C \right\}
\]

(1)

In this equation %C was expressed as a decimal fraction

Bulk density was also calculated using the formula of Pearson et al. (2007)

\[
\rho = \frac{\text{ODW}}{(\text{CV} - (\text{RF/PD}))}
\]

(2)

Where, \(\rho\) = Bulk density of the <2 mm fraction, (g/cm\(^3\))

\(\text{CV}\) = Core volume (cm\(^3\))

\(\text{ODW}\) = Oven-dry mass of fine fraction (<2 mm) in g

\(\text{RF}\) = Mass of coarse fragments (>2 mm) in g

\(\text{PD}\) = Density of rock fragments (g/cm\(^3\)). This often is given as 2.65 g/cm\(^3\).

### Statistical analysis

Prior to further statistical analysis, normality and equality variance of the data was checked using Kolmogorov- Smirnov and Levene’s test, respectively (Mekuria et al. 2015). The variation in species richness,
Woody species abundance, richness, diversity, and evenness

The species richness, abundance, Shannon diversity, Simpson diversity indices were significantly varied among EXs and adjacent DOGL (p < .05) (Table 3). The average abundance and species richness in the EXs were almost twice that of adjacent open grazing lands. The conversion of DOGL to EXs enhanced the Shannon diversity and Simpson diversity indices by 33% and 16%, respectively.

The contribution of exotic tree species for the EXs in abundance, richness, Shannon diversity and Simpson diversity indices were about 5%, 9%, 6%, and 18%, respectively.

Importance values of woody species and stand structure

J. procera, Acacia abyssinica Hochst.ex. Benth, Acacia decurrens Willd. var. decurrens, Acacia saligna, Erica arborea L. and D. angustifolia were the top six most important woody species in the exclosure, altogether accounted for 23% of planted species abundance (Appendices 1a).

Results

Woody species composition and similarity

A total of 49 species, belonging to 45 genera and 28 families were recorded in both EXs and adjacent DOGL. Of these, 46 of them were representing about 26 families with 44 genera in the EXs whereas, in the adjacent DOGL, only 26 woody species representing 18 families and 26 genera were recorded (Appendices 1a). Native woody species represented 90% of the total woody species in the EXs. The Sørensen’s coefficient of similarity for the EXs and adjacent DOGL was calculated to 84%, showing that high woody species similarity between the two studied ecosystems. The three most abundant species in the exclosures were Clusia abyssinica Jaub. & Spach, Becium grandiflorum (Lam.) Pichi-serm and Dodonaea angustifolia L.f., altogether accounted for 40% of the species abundance. While Myrsine africana L, Clusia abyssinica and Maytenus undata (Thunb.) Blakelock (altogether accounted for 40%) were the most abundant woody species in the adjacent DOGL. The most frequent planted exotic species in exclosures were M. undata, D. angustifolia, and Juniperus procera Hochst.ex. Endl. altogether accounted for 23% of planted species abundance (Appendices 1a).

Table 2. Allometric equations used to estimate aboveground biomass of naturally grown and planted woody species in the studied ecosystems of Endamekoni District, Northern Ethiopia.

| Species | Equation | D, cm | Source |
|---------|----------|-------|--------|
| All naturally grown trees/shrubs | \( AGB = 0.00673 \times D^{0.3762} \times H^{0.9794} \times 2 \) | 5–158 | Chave et al. (2014) |
| Cupressus lusitanica | \( AGB = 0.0319 \times D^{0.5823} \times H^{0.9196} \times 2 \) | 2–45 | Berhe et al. (2013) |
| Eucalyptus camaldulensis | \( AGB = 0.0155 \times D^{0.802} \times H^{0.41} \times 2 \) | 1–200 | Hallu (2002) |
| Eucalyptus globules | \( AGB = 0.45 \times D^{0.37} \times H^{0.41} \times (Dexp2.6) \times 2 \) | <20 | Zewdie et al. (2009) |
| Acacia saligna | \( AGB = (0.3197D^{0.41} + 0.0383) \times (Dexp2.6) \times 2 \) | <20 | WBISP (2000) |
| Acacia decurrens | \( AGB = 3.1582 \times 0.0337D^{2} \times H \times 2 \) | <20 | Tandon et al. (1989) |

*Trees and shrubs planted in the exclosures and the equations developed in Ethiopia. For estimating aboveground biomass of Acacia decurrens, the equation developed for Acacia meeru was used (Tandon et al. 1989) as specific equation for Acacia decurrens was not found. Besides, the two species are closely related to each other in their growth and morphological characteristics (Bekele 2007). AGB refers Aboveground biomass, kg tree\(^{-1}\), \( \mu \) Wood density, g cm\(^{-3}\), D Diameter at breast height, cm, H Height, m.

Table 3. Mean abundances, richness, Shannon diversity index (H), Simpson diversity index (D) and evenness of woody species grown in exclosures (EXs) and adjacent degraded open grazing land (DOGL) within 20 m × 20 m in Endamekoni District, Northern Ethiopia.

| Land use type | Abundance | Richness | H | D | Evenness |
|---------------|-----------|----------|---|---|---------|
| EXs (n = 30)  | 134 ± 53\(^a\) | 11 ± 4\(^b\) | 1.86 ± 0.3\(^b\) | 0.79 ± 0.09\(^b\) | 0.79 ± 0.07\(^b\) |
| DOGL (n = 30) | 64 ± 25\(^a\) | 7 ± 2\(^a\) | 1.40 ± 0.32\(^a\) | 0.68 ± 0.12\(^a\) | 0.76 ± 0.1\(^a\) |
| p-value       | <.001     | <.001    | <.001 | <.001 | .081    |

Different letters indicate significant differences and similar letters show not significant at \( p < .05 \).
Soil organic carbon stocks (Mg C ha$^{-1}$) in exclosures (EXs) and adjacent degraded open grazing land (DOGL) in Endamekoni District, Northern Ethiopia.

| Land use type | DBH (cm) | Height (m) | Basal area (m$^{2}$ha$^{-1}$) | Stem density (stems ha$^{-1}$) |
|--------------|----------|------------|-------------------------------|-------------------------------|
| EXs (n = 30) | 10.52 ± 4.20$^a$ | 4.75 ± 1.94$^a$ | 4.97 ± 2.85$^b$ | 528 ± 283$^b$ |
| DOGL (n = 30) | 13.21 ± 4.07$^b$ | 4.30 ± 1.30$^b$ | 1.94 ± 1.20$^a$ | 147 ± 111$^a$ |
| $p$-value | .036 | .574 | <.001 | <.001 |

DBH refers to diameter at breast height. Different letters indicate significant differences between EXs and DOGL and similar letters show not significant at p < .05.

### Biomass carbon stocks

The total above and belowground woody biomass carbon stocks including the planted tree species were significantly different between EXs and adjacent DOGL (p < .05). Though, without enrichment, the difference in biomass carbon stock was insignificant. Forty percent of the biomass carbon stock in the EXs was contributed by planted exotic tree species. The total biomass carbon stock recorded in EXs was nearly two-fold higher than adjacent DOGL. The total biomass C stocks were significantly correlated with species abundance and richness (Spearman $r = 0.42$–0.55, p < .05) (Table 7). SOC stock of the soil depth one (0–15 cm) was significantly correlated with species abundance and richness (Spearman $r = 0.27$ & 0.28, p < .05) but not with diversity. Likewise, the total SOC (0–30 cm, depth) stock was significantly correlated with species richness (Spearman $r = 0.27$, p < .05).

### Soil organic carbon stock

Soil organic carbon stocks (Mg C ha$^{-1}$) within 0–30 cm soil layer was significantly different between the EXs and adjacent DOGL (p < 0.05) (Table 6). The top layer (0–15 cm) contributed 57% of the total soil organic C stock for the EXs and 55% for DOGL. As expected, EXs with enrichment by selected tree species enhanced the soil organic carbon stocks by 38% over the adjacent open grazing land. The impact of EXs on SOC was higher in the surface layer (31%) than sub-surface soil layer (24%) over DOGL.

### Discussion

**Woody species composition, diversity, and structures**

Based on the reference of degraded open grazing land, our study showed that establishment of exclosures enhanced naturally regeneration and growth of woody species under degraded open grazing land at the age of 12 years. This illustrates that rehabilitation of the degraded free grazing land can occur in a relatively short period of time after the establishment of EXs (Mengistu et al. 2005; Mekuria and Yami 2013; Neelo et al. 2015). Moreover, most of the remaining woody species found in the degraded open grazing lands were unpalatable to livestock. Restoration of the degraded vegetation were due to improving microhabitat and emerging potential of woody species in the EXs. In addition, long period of protection from free grazing and human interface allow regeneration of tree and shrubs (Mekuria and Yami 2013). This result is in line with a study done under EXs of dry woodlands in the Northeastern Botswana (Neelo et al. 2015). The two dominant plant families such as Fabaceae and Lamiaceae in our study area are also inline with study.
The mean dbh was higher in degraded open grazing land than EXs this attributed to the availability of more spacing and less competition for nutrients, water, and light. While trees with lower diameter classes were absent because of human and livestock disturbance and trees in degraded open grazing land.

**Carbon stock potential**

The higher biomass carbon stock in the study EXs indicates that establishing EXs supported by enrichment of planting in the degraded land enhances biomass carbon stock. This is due to a higher number of stem density and basal area. Several studies in Ethiopia and elsewhere in the tropics reported similar findings (Mekuria et al. 2009; Mureithi 2012; Mekuria 2013; Mekuria et al. 2015). The aboveground biomass carbon stocks of our study EXs was comparable with the studies conducted by Mekuria (2013) in semi-arid lowlands of Northern Ethiopia (2.0–7.0 Mg C ha⁻¹), Mekuria et al. (2015) in Nile Basin Ethiopia (0.6–4.2 Mg C ha⁻¹) and in another place of the tropics (Cheng et al. 2011; Witt et al. 2011). The impact of EXs supported by enrichment planting to enhance carbon stocks was higher in the biomass than soil. This is due to the accumulation of carbon in soil from organic matter takes more time as compared to plant carbon sequestration. The increased of SOC due to EXs established on DOGL were also reported in other studies in the tropics (Verdoodt et al. 2009; Mekuria and Aynekulu 2011; Yimer et al. 2015). This might be due to increased vegetation composition associated with litterfall input and reduced erosion loss. For instance, in ours EXs the presence of woody species such as *J. procera*, *A. abyssinica*, *A. decurrens*, *A. saligna* and *E. arborea* could contribute more addition of litters to the soil. This is also well asserted by the significant positive correlation of naturally regenerated woody species richness and abundance with SOC stock in the EXs. The total SOC stock (0–30 cm) of the present study EXs was higher than those reported for tropical dry forest (33–48.82 Mg C ha⁻¹) (Sundarapandian et al. 2015) and central Mozambique woodlands (40.1 ± 2.5 Mg C ha⁻¹) (Woollen et al. 2012) and within the average range of African savannahs and woodlands (30–140 Mg C ha⁻¹) (Williams et al. 2008) for the same soil depth. Maintaining higher SOC levels ensures the productivity of degraded land and long-term C reserve in the soil. However, our result was lower than the findings of Mekuria (2013) in the highlands of Tigray and in contrast, to Mekuria et al. (2014) and Aynekulu et al. (2017) reported that EXs did not influence soil organic carbon. Such differences could be due to variation in soil properties, climate condition, vegetation type, and management practices.

The total carbon stock of our study EXs was lower than the studies made in Northern Ethiopia (Mekuria et al. 2009). This is due to variations in the equations used to estimate the biomass carbon, variation in soil type, management of EXs and topography.

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**Table 7.** Spearman correlations between total biomass and soil carbon stocks, and abundance, richness, Shannon diversity index (H'), Simpson diversity index (D) in Endamekoni District, Northern Ethiopia.

| Carbon stock components | Abundance | Richness | H' | D |
|--------------------------|-----------|----------|----|---|
| Total biomass            | 0.42**    | 0.52**   | 0.45** | 0.553** |
| SOC (0–15 cm)            | 0.27*     | 0.28**   | 0.22** | 0.18** |
| SOC (15–30 cm)           | 0.12**    | 0.21     | 0.11  | 0.04 |
| SOC (0–30 cm)            | 0.20      | 0.27**   | 0.18  | 0.12 |
| Ecosystem (biomass plus SOC) | 0.29*     | 0.37**   | 0.29* | 0.23 |

**p < .01, *p < .05, Total biomass include both aboveground and belowground biomass carbon stocks.**

reported from dry Afremontane forest of Tigray (Aynekulu et al. 2011). Establishment of EXs on the degraded land is also promising for restoring the endemic threatened woody species. The higher species similarity recorded between EXs and the adjacent DOGL was similar to other study conducted in Ethiopia (Kasim et al. 2015). This is due to the presence of similar edaphic, climatic condition and altitudinal ranges of the existing land use and vegetation types in the past. The higher Shannon diversity indices of EXs (33%) than DOGL is due to the presence of higher species richness and evenness. Similar results have also been reported by other authors (Yayneshet 2011; Mekuria and Yami 2013; Kasim et al. 2015; Neelo et al. 2015).

The higher IVI value in EXs of the present study was also related to the presence of higher basal area, abundance, and frequency. Among the recorded species, *J. procera* had the highest IVI, this showed that EXs are serving as a suitable ecological niche for the recovery and maintenance of the native woody species.

In this study, EXs had a higher number of individuals at seedling and sapling stages than adjacent DOGL, showing that better regeneration potential under EXs.
The relationship between woody species diversity and biomass carbon

The positive relationship between woody species diversity and carbon stock potential in study site shows that carbon stock largely depends on woody species diversity, abundance, and species richness. In addition, our findings are in consistent with study conducted at grassland biodiversity experiment by Lange et al. (2015) showed that positive plant diversity effects on soil carbon storage, Dayamba et al. (2016) at Western Africa showed positive relationships between diversity and biomass C pools and Mekuria et al. (2009) at Tigray regional state reported positive correlation between naturally regenerated plant species diversity and soil carbon concentration. The positive and significant association in our study upper layer soil with species abundance and richness were related to the presence of a higher accumulation of organic matter. However, the results of our study on woody species diversity and biomass carbon stock was in contrast with Zhang et al. (2011) found a negative relation in sub-afro-alpine coniferous forest. This difference was due to species diversity and biomass C storage depends on management practices, species, age and site factors.

Conclusions

Exclosures assisted with enrichment planting on previously degraded open free grazed lands of the studied region has enhanced the recovery of naturally regenerated woody species diversity, composition, and structure. Besides, exclosures enhanced to recover and maintain native woody species which are previously listed as threatened species in Ethiopia. The total biomass and soil carbon stock significantly increased following the establishment of EXs supported by enrichment of the selected exotic tree species, implying that enclosures are a potential land use intervention to enhance climate change mitigation and biodiversity conservation of degraded grazing lands in the semi-arid region of the tropics. Furthermore, EXs serve in climate change mitigation strategies such as REDD+ schemes as it has been put in place in national REDD+ strategy of Ethiopia and by IPCC for boosting up climate change mitigation contribution of tropical countries.

Authors’ contributions

AM, planned the study, collected data, and prepared the first manuscript, MN, MA commented the study plan, data analysis and commented and revised the draft manuscript.

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Disclosure statement

The authors declare that they have no competing interests.

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References

Austrheim G, Speed JDM, Eivju M, Hester A, Holand Ø, Loe LE, Martinsen V, Mobaek R, Mulder J, Steen H, et al. 2016. Synergies and trade-offs between ecosystem services in an alpine ecosystem grazed by sheep – an experimental approach. Basic Appl Ecol. 17(7):596–608.

Aynekulu E, Denich M, Tsegaye D, Aerts R, Neuwirth B, Boehmer HJ. 2011. Dieback affects forest structure in a dry Afromontane forest in northern Ethiopia. J Arid Environ. 75(5):499–503.

Aynekulu E, Mekuria W, Tsegaye D, Feyissa K, Angassa A, de Leeuw J, Shepherd K. 2017. Long-term livestock exclosure did not affect soil carbon in southern Ethiopian rangelands. Geoderma. 307:1–7.

Berhe L, Assefa G, Teklay T. 2013. Models for estimation of carbon sequestered by Cupressus lusitanica plantation stands at Wondo Genet, Ethiopia. South Forest J Sci. 75(3):113–122.

Birhanne E, Teketay D, Barklund P. 2007. Enclosures to enhance woody species diversity in the dry lands of Eastern Tigray, Ethiopia. Eas Afr J Sci. 1(2):136–147.

Blake GR, Hartge KH. 1986. Bulk density. In: Klute A, editor. Methods of soil analysis. Part 1. 2nd ed. Agronomy Monograph 9. Madison (WI): American Society of Agronomy; p. 363–375.

Chave J, Rejon-Meouch M, Bünzke A, Chidumayo E, Colgan MS, Delitti WBC, Duque A, Eid T, Fearnside PM, Goodman RC, et al. 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Change Biol. 20(10):3177–3190.

Cheng J, Wu GL, Zhao LP, Li Y, Li W, Cheng JM. 2011. Cumulative effects of 20-year exclusion of livestock grazing on above\-and belowground biomass of typical steppe communities in arid areas of the Loess Plateau, China. Plant Soil Environment. 57(No. 1):40–44.

Dayamba SD, Djoudi H, Zida M, Sawadogo L, Verchot L. 2016. Biodiversity and carbon stocks in different land use types in the Sudanian Zone of Burkina Faso, West Africa. Agric Ecosyst Environ. 216:61–72.

Giese M, Brueck H, Gao YZ, Lin S, Steffens M, Kögel-Knabner I, Blume T, Seneseth M, Steen H, et al. 2013. N balance and cycling of Inner Mongolia typical steppe: a comprehensive case study of grazing effects. Ecol Monogr. 83(2):195–219.

Hailu Z. 2002. Ecological impact evaluation of Eucalyptus plantations in comparison with agricultural and grazing land-use types in the Highlands of Ethiopia. PhD dissertation, Vienna University of Agricultural Sciences, Vienna, 271.

IBM Corp Released. 2012. IBM SPSS Statistics for Windows, Version 21.0.IPCC. 2003. Good practice guidance for land use. Land-use change and forestry. Hayama: Institute for Global Environmental Strategies (IGES). ISBN: 4-88788-003-0, 675 pp. Available at: http://www.ipcc-nggip.iges.or.jp/public/gppglulucf/gppglulucf.html [Verified 27/02/2019]

Kasim K, Assfaw Z, Derero A, Mekello M, Mamo Y. 2015. The role of area closure on the recovery of woody species composition on degraded lands and its socio-economic importance in central Rift valley area, Ethiopia. Int J Dev Res. 5:3348–3358.

Kent M, Coker P. 1992. Vegetation description and analysis: a practical approach. London: British Library; p. 363.

Lange M, Eisenhauer N, Sierra CA, Bessler H, Engels C, Griffiths RJ, Mellado-Vazquez PG, Malik AA, Roy J, Scheu S,
Steinbeiss S. 2015. Plant diversity increases soil microbial activity and soil carbon storage. Nat Commun. 6:670.

Li Y, Zhou X, Brandle JR, Zhang T, Chen Y, Han J. 2012. Temporal progress in improving carbon and nitrogen storage by grazing exclusion practice in a degraded land area of China’s Horqin Sandy Grassland. Agric Ecosyst Environ. 159: 55–61.

MacDicken K. 1997. A guide to monitoring carbon storage in forestry and agroforestry projects. Forest carbon Monitoring Program. Arlington (VA): Winrock International Institute for Agricultural Development: p. 87.

Magauran AE. 1988. Ecological diversity and its measurement. Princeton (NJ): Princeton University Press: p. 93.

Mekuria W. 2013. Changes in regulating ecosystem services following establishing exclusions on communal grazing lands in Ethiopia: a synthesis. J Ecosyst. 2013:1–12.

Mekuria W, Aynekulu E. 2011. Exclosure land management for the reestablishment of hte soils in degraded communal grazing lands in Northern Ethiopia. J Degrad Dev. 24(6):528–538.

Mekuria W, Langan S, Noble A, Johnston R. 2014. Soil Organic Carbon and Nutrient Contents are not influenced by Exclosures established in communal grazing land in Nile basin, Northern Ethiopia. In International Conference on Advances in Agricultural, Biological & Environmental Sciences (AABES-2014) 10 Oct 15-16, 2014 Dubai (UAE): 16-21. http://dx.doi.org/10.15242/IICBE.C1014045

Mekuria W, Langan S, Noble A, Johnston R. 2017. Soil restoration after seven years of exclusion management in Northwestern Ethiopia. Land Degrad Develop. 28(4): 1287–1297.

Mekuria W, Veldkamp E, Haile M, Gebrehiwot K, Muys B, Nyssen J. 2009. Effectiveness of exclusions to control soil erosion and local community perception on soil erosion in Tigray, Ethiopia. Afr J Agric Res. 4(4):365–377.

Mekuria W, Yami M. 2013. Changes in woody species composition following establishing exclusions on grazing lands in the lowlands of Northern Ethiopia. Afr J Environ Sci Technol. 7(1): 30–40.

Mengistu T, Teketay D, Hulten H, Yemshaw Y. 2011. Changes in woody species composition following establishing exclusions on communal grazing lands in Ethiopia: a synthesis. J Ecosyst. 2013:1–12.

Piñeiro G, Paruelo JM, Oesterheld M, Jobbágy EG. 2010. Pathways of grazing effects on soil organic carbon and nitrogen. Rangeland Ecol Manag. 63(1):109–119.

QI S, Zheng H, Lin Q, Li G, Xi Z, Zhao X. 2011. Effects of livestock grazing intensity on soil biota in a semiarid steppe of Inner Mongolia. Plant Soil. 340(1-2):117–126.

Raij F, Rahi M. 2014. The influence of grazing exclusion on soil C stocks and dynamics, and ecological indicators in upland arid and semi-arid rangelands. Ecol. Indicators. 41: 145–154.

Rana E, Thwaites R, Luck G. 2017. Trade-offs and synergies between carbon, forest diversity and forest products in Nepal community forests. Environ Conserv. 44(01):5–13.

Reid RS, Thornton PK, Crabb G, Kruka RL, Atieno F, Jones PG. 2004. Is it possible to mitigate Greenhouse Gas Emissions in pastoral ecosystems of the tropics? Environ Dev Sustain. 6(1/2):91–109.

Reside AE, VanDerWal J, Moran C. 2017. Trade-offs in carbon storage and biodiversity conservation under climate change reveal risk to endemic species. Biol Conserv. 207:9–16.

Rosell RA, Gasparoni JC, Galantini JA. 2001. Soil organic matter evaluation. In: Lal R, et al., editor. Assessment methods for soil carbon. Boca Raton (FL): Lewis Publishers. p. 311–322.

Shang Z, Cao J, Guo R, Henkin Z, Ding L, Long R, Deng B. 2017. Effect of exclusion on soil carbon, nitrogen and phosphorus of Alpine desert rangeland. Land Degrad Dev. 28(4): 1166–1177.

Shrestha G, Stahl PD. 2008. Carbon accumulation and storage in semi-arid sagebrush steppe: effects of long-term grazing exclusion. Agriculture Ecosystem Environ. 125(1-4):173–181.

Snowdon P, Keith H, Raison RJ. 2001. Protocol for sampling tree and stand biomass. Canberra (Australia): Australian Greenhouse Office.

Steiner JL, Franzluebbers AJ, Neely C, Ellis T, Aynekulu E. 2014. Enhancing soil and landscape quality in smallholder grazing systems. In: Lal R, Stewart BA, editors. Soil management of smallholder agriculture. Advances in soil science. Boca Raton (FL): CRC Press. p. 63–112.

Sundarapandian SM, Amirtha S, Gowshalya L, Kayathi P, Thamizharasi M, Dar JA, Srinivas K, Gandhi DS, Subashree K. 2015. Soil organic carbon stocks in different land uses at Puthupet, Tamil Nadu, India. Res Rev J Ecol. 4(3):6–14.

Tandon VN, Pande MC, Singh R. 1989. Organic matter production and distribution of nutrients in plantations of Acacia mearnsii in Nilgiris, Tamilnadu. Indian Forester. 115 (5): 286–295.

Tang J, Davy AJ, Jiang D, Musa A, Wu D, Wang Y, Miao C. 2016. Effects of excluding grazing on the vegetation and soils of degraded sparse-elm grassland in the Horqin Sandy Land, China. Agric Ecosystem Environ. 235:340–348.

Tesfaye M, Negash M. 2018. Combretum-Terminalia vegetation accumulates more carbon stocks in the soil than the biomass along the elevation ranges of dryland ecosystem in Southern Ethiopia. J Arid Environ. 155: 59–64.

Verdoodt A, Mureithi SM, Ye L, Van Ranst E. 2009. Chronosequence analysis of two enclosure management strategies in degraded rangeland of semi-arid Kenya. Agric Ecosystem Environ. 129(1-3):332–339.

WBISPP. (Woody Biomass Inventory and Strategic Planning Project). 2000. Manual for woody biomass inventory. Woody biomass inventory and strategic planning project. Addis Ababa (Ethiopia): Ministry of Agriculture.

Williams M, Ryan CM, Rees RM, Sambane E, Fernando J, Grace J. 2008. Carbon sequestration and biodiversity of re-growing miombo woodlands in Mozambique. For Ecol Manage. 254(2):145–155.

Witt GB, Noël MV, Bird MJ, Beeton RJG, Menzies NJ. 2011. Carbon sequestration and biodiversity restoration potential of semi-arid mulga lands of Australia interpreted from long-term grazing exclusions. Agric Ecosystem Environ. 141(12):108–118.
Appendix

Appendix 1a. List of woody species identified from the EXs and adjacent DOGL of Endamehoni district, Northern Ethiopia

| No | Species Name | Family | Local name | EX | DOGL | Life form |
|----|--------------|--------|------------|----|------|-----------|
| 1  | Acacia abyssinicaHochst.Ex Benth. | Fabaceae | Chia | +  | +  | T         |
| 2  | Acacia decurrens Willd. var. decurrens | Fabaceae | -   | +  | -   | T         |
| 3  | Acacia saligna (Labill) H.L.Wendl | Fabaceae | Akacha | +  | -   | S/T       |
| 4  | Acokanthera schimperi (A.DC.) Benth | Apocynaceae | Meroz | +  | -   | S/T       |
| 5  | Asparagus racemosusWilld. | Asparagusaceae | Kertstenio | +  | +  | C/S       |
| 6  | Astragalus atomosus (Hochst.) Bunge | Fabaceae | Tetem-agazen | +  | +  | S         |
| 7  | Becium grandiforum (Lam.) Pichi-serr. | Lamiaceae | Tebebe | +  | +  | S         |
| 8  | Bersama abyssinica Fresen. | Melianthaceae | Mirkuz-zibe | +  | -   | S/T       |
| 9  | Buddleja polychacthyaFresen. | Loganiaceae | Metere | +  | -   | S         |
| 10 | Cadia purpurea (Pic) Ait. | Fabaceae | Pichilen | +  | -   | -         |
| 11 | Calpurnia aurea (A.DC.) Benth. | Fabaceae | Hittawits | +  | -   | S/T       |
| 12 | Carissa edulis (Forsk) | Apocynaceae | Agam | +  | +  | S         |
| 13 | Chamaerops humilis (L.f.) | Fabaceae | Tree lucern | +  | -   | T/S       |
| 14 | Clerodendron myricoides (Hochst.) Vatke | Lamiaceae | Shewha | +  | +  | S         |
| 15 | Clusia abyssinica | Ebenaceae | Keyih | +  | +  | S         |
| 16 | Colutea abyssinica | Ebenaceae | Keyih | +  | +  | S         |
| 17 | Conyza abyssinica A.Rich. | Asteraceae | Tsaeda-kotsilo | +  | +  | T         |
| 18 | Cupressus lusitana Miller | Cupressaceae | Tshidi-fereni | +  | +  | T         |
| 19 | Discopodium peninervium | Sterculiaceae | Buyak | +  | +  | S/T       |
| 20 | Dovyalis abyssinica (A.Rich.) Warb. | Flacourtiaceae | Mengoli-hats | +  | +  | S/T       |
| 21 | Echinops hirtus | Asteraceae | Dender | +  | +  | S         |
| 22 | Erbaella auberti Engl. | Berberidaceae | Mucha-eff | +  | +  | S         |
| 23 | Erbaella auberti Engl. | Berberidaceae | Mucha-eff | +  | +  | S         |
| 24 | Etrobus auberti Engl. | Berberidaceae | Mucha-eff | +  | +  | S         |
| 25 | Eucalyptus camaldulensis Dehnh | Myrtaceae | KeyihKenamintos | +  | +  | T         |
| 26 | Eucalyptus globulus Labill | Myrtaceae | Tsaeda-kenamintos | +  | +  | T         |
| 27 | Euclea racemosa subsp. schimperi(A.DC.) Dandy | Ebenaceae | Kulo | +  | +  | S         |
| 28 | Eucalyptus globulus Labill | Myrtaceae | Tsaeda-kenamintos | +  | +  | T         |
| 29 | Flacourtiopsis hypophylla (Forssk) Vatke | Lamiaceae | Rewa | +  | -   | S/T       |
| 30 | Hypericum revolutumHvalh. | Hypericaceae | Abed | +  | +  | T/S       |
| 31 | Jasminum grandiforum (R.Br.Ex.Fresen.) P.S.Green | Oleaceae | Teslim-habi | +  | +  | C/S       |
| 32 | Juniperus procera Hochst.Ex.Endl. | Cupressaceae | Tshidi-habesha | +  | +  | T         |
| 33 | Lippia abdoensis Hochst.Ex.Walp. | Verbanaceae | Kushe | +  | -   | S         |
| 34 | Maytenus undata (Thunb.) Blakelock | Celastraceae | Ats-at | +  | +  | S         |
| 35 | Merandranalen galensis (Konig Ex. Roxb.) | Lamiaceae | Mesaguh | +  | +  | S         |
| 36 | Myristica africana L. | Myristicaceae | Kechemo | +  | +  | S         |
| 37 | Nuxia congesta R.Br.Ex.Fresen. | Loganiaceae | Tekariej | +  | -   | T         |
| 38 | Osteosperum integrifolium Bentham | Lamiaceae | Chi-end | +  | +  | S         |
| 39 | Olea europea subsp. Cupidata (Wall. Ex DC.) Cifferri | Oleaceae | Awile | +  | +  | S         |
| 40 | Osyris quadripartitaDecne | Sanalaceae | Kerets | +  | +  | T         |
| 41 | Otostegia fruticosa (Forssk) Schweinf.Ex Penzing | Lamiaceae | Chamo | +  | +  | S         |
| 42 | Rhus glutinosa A.Rich. | Anacardiaceae | Tetaelo | +  | +  | S/T       |
| 43 | Rosa abyssinica Lindely | Rosaceae | Kaga | +  | +  | S         |
| 44 | Rumex nivellus Vahl. | Polygonaceae | Bahot | +  | +  | S         |
| 45 | Solanum schimperi Hochst. | Solanaceae | Berbereaewald | +  | +  | S         |
| 46 | Sphenoclea zeylanica (L.) DC | Anacardiaceae | Tselimerberere | +  | +  | T         |
| 47 | Sphenoclea zeylanica (L.) DC | Anacardiaceae | Tselimerberere | +  | +  | T         |
| 48 | Syzygium guineense Wall. | Myrtaceae | Tselim Om | +  | +  | S         |
| 49 | Withania somnifera (L.) Dalzal | Solanaceae | Agol | +  | +  | S         |

Note: *+* Present; *-* absent
| No | Species name                        | EXs (n = 30) | OGL (n = 30) |
|----|-------------------------------------|--------------|--------------|
| 1  | Acacia abyssinica Hochst.ex Benth.  | 69.98        | 106.73       |
| 2  | Acacia decurrens Willd. var. decurrens | 42.09      | –            |
| 3  | Acacia saligna                      | 17.39        | –            |
| 4  | Acokanthera schimperi (A.DC.) Benth | 1.17         | –            |
| 5  | Astragalus atropilosus (Hochst.) Bunge | 6.20       | –            |
| 6  | Carissa edulis                      | 6.98         | 8.43         |
| 7  | Chamaecytisus prolferus             | 5.09         | –            |
| 8  | Clutia abyssinica Jaub. & Spach.    | 1.36         | –            |
| 9  | Cupressus lusitanica Miller         | 7.35         | –            |
| 10 | Dodonaea angustifolia L.f.          | 13.93        | –            |
| 11 | Dovyalis abyssinica (A.Rich.) Warb. | 1.17         | –            |
| 12 | Erica arborea L.                    | 16.53        | –            |
| 13 | Eucalyptus camaldulensis Dehn.      | 2.47         | –            |
| 14 | Eucalyptus globules                 | –            | 7.39         |
| 15 | Hypericum revolutum Vahl.           | 1.52         | –            |
| 16 | Juniperus procera Hochst.ex.Endl.   | 82.62        | 177.41       |
| 17 | M. undata (Thunb.) Blakelock        | 3.86         | –            |
| 18 | Olea europaea subsp cuspidate       | 5.56         | –            |
| 19 | Osyris quadpartita Decn             | 7.26         | –            |
| 20 | Rhus glutinosa A.Rich.              | 1.21         | –            |
| 21 | Rosa abyssinica Lindely             | 2.34         | –            |
| 22 | Rumex nervosus                      | 1.18         | –            |
| 23 | Schinus molle*                      | 1.17         | –            |
| 24 | Syzygium guineense                  | 1.56         | –            |
|    | Total                               | 300          | 300          |