Dondo G *et al.* (2024)
Nova Geodesia 4(4):210
Research Article

Carbon stocks under different land cover types in the Hallaydeghe wildlife reserve, northeastern Ethiopia

Grace DONDO[1], Sintayehu Workeneh DEJENE[1], Agnes UWIMBABAZI[1,2,3], Petros CHAVULA[1,4*], Desta ANTENEH[1]

[1]Haramaya University, Africa Center of Excellency for Climate Smart Agriculture and Biodiversity Conservation, College of Agriculture and Environmental Sciences, P.O. BOX 138, Dire Dawa, Ethiopia; gdondo80@yahoo.co.uk; sintekal@gmail.com; anthil2005@gmail.com
[2]Rwanda Polytechnic - College of Kitabi, Department of Nature Conservation, Rwanda, PoBox 330 Huye, Rwanda; auwimbabazi@iprckitabi.rp.ac.rw
[3]School of Natural Resources, The Copperbelt University, PO Box 21692, Kitwe, Zambia
[4]World Agroforestry Centre, St Eugene Office Park 39P Lake Road, P.O. Box 50977, Kabulonga, Lusaka, Zambia; chavulapetros@outlook.com (*corresponding author)

Abstract

The Hallaydeghe Wildlife Reserve, with its semi-arid to desert climate, features diverse land cover classifications. This study examined land cover changes and total carbon stocks from 1999 to 2019, focusing on forest, woodland, grassland, and bushland vegetation types. Land cover classes were created using 1999, 2003, and 2019 Landsat images. ArcGIS 10.4.1 and ERDAS IMAGINE were used for map creation, while future land use changes were simulated using the CA-Markov model. Carbon stock assessment involved five pools: soil, dead wood, aboveground, belowground, and litter carbon. Soil samples were collected at three depths, and data on woody plant species, soils, and litter were gathered through random systematic sampling. From 1999 to 2019, woodland grew by 57.94%, while grassland and bushland decreased by 6.86% and 10.51%, respectively. Projections for 2035 indicate a 40.68% increase in bushland, decreases in forest and grassland, and the emergence of bareland. Total carbon stocks varied among vegetation types: forest (35.94±6.63 tC ha^{-1}), grassland (22.55±3.35 tC ha^{-1}), and bushland (23.65±3.25 tC ha^{-1}). The soil organic carbon pool contributed the most across all land cover categories. The shift from grassland to forest may impact the Grevy's zebra's habitat. Effective land use management is crucial for preserving carbon stores and ecosystem health. Implementing climate-smart policies, including community-based conservation and sustainable management practices, is essential to mitigate the impacts of land cover changes on wildlife and carbon stocks in the reserve.

Keywords: carbon stock; climate change; land cover; nature reserve

Introduction

Arid and semi-arid regions may be considered unsuitable for cultivation and face challenges like lower economic growth and high poverty levels. However, they still play an important role in global environmental

Received: 18 May 2024. Received in revised form: 02 Oct 2024. Accepted: 03 Oct 2024. Published online: 03 Oct 2024.

sustainability and crop production (Hussein, 2022; Tilahun *et al.*, 2022). These regions have significant potential for carbon sequestration through their high soil organic carbon stocks, which can contribute to climate change mitigation if properly managed. They also harbour unique biodiversity that requires conservation efforts, whilst cultivation may be more challenging, these areas can still support sustainable grazing systems and adapted crop varieties, providing livelihoods and food security. Pastoralism predominantly utilizes the primary production in these regions, where highly resilient vegetation types flourish under varying climate conditions (Girmay *et al.*, 2008; Taddese et al., 2019). As climate change intensifies, these regions may become increasingly valuable for developing adaptation strategies. By recognizing their worth and implementing holistic management approaches, we can harness the potential of arid and semi-arid areas to support environmental sustainability, food production, and climate resilience globally.

Land use and land cover (LULC) change affects the carbon sequestration potential of these fragile ecosystems. Most carbon fluxes between the atmosphere and Earth's surface are attributed to anthropogenic factors, primarily land use/land cover changes (Tumushabe *et al.*, 2023). LULC changes are the second largest source of anthropogenic greenhouse gases, accounting for 12-20% of carbon emissions. In Ethiopia, arid and semi-arid lands (ASALs) are affected by climate change (Kendie *et al.*, 2021), including the conversion of natural lands to agricultural production and population growth. Dry forests, essential natural resources, provide carbon sequestration services, but land degradation and poor management practices lead to extensive desertification (Taddese *et al.*, 2019). Land use changes and increased Indigenous population growth, higher relative earnings to work, and land in crop production contribute to nearly 12.5% of the total global anthropogenic carbon emitted (Sintayehu *et al.,* 2020).

Studies on carbon dynamics at the landscape level are still lacking, and this is even evident in mountain areas, arid and semi-arid areas where evaluation of carbon vertical pools and horizontal landscape dynamics are currently insufficient. Ecosystem conditions affect carbon sequestration; hence, changes in land use including forest clearance for agriculture settlement, and industrial expansion have contributed about 136 (+/-55) Gt carbon or one-third of total anthropogenic emissions of $CO2$ to the atmosphere over the past 50 years.

In 1995, the LULC research program, jointly proposed by the International Geosphere-Biosphere Program (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP), made land use changes a focus of global climate change studies (Mulat *et al.*, 2021). Studying the impact of LULC on carbon stocks in arid and semi-arid environments is of critical importance for addressing climate change on both regional and global scales. These environments, which cover over 40% of the Earth's land surface, play a vital role in the global carbon cycle yet are often overlooked in carbon accounting and climate mitigation efforts. Several studies in Ethiopia have highlighted the carbon sequestration potential of arid and semi-arid ecosystems when managed sustainably (Taddese *et al.*, 2019; Toru and Kibret, 2019; Sintayehu *et al.,* 2020). Through evaluating the impacts of land use change on carbon stocks in this representative semi-arid environment, this study provides vital insights that can inform land management policies and climate change adaptation strategies across semi-arid and arid regions since these areas are more vulnerable to climate change and prone to soil organic carbon losses. Its findings contribute to the growing body of research emphasizing the importance of sustainable land use for global climate change mitigation through carbon sequestration.

Materials and Methods

Description of the study area

Hallaydeghe Wildlife Reserve, one of Ethiopia's eight wildlife reserves, is in northeastern Ethiopia. Established in 1965, it covers 1832 km^2 with elevations ranging from 700-945 m above sea level. The reserve's semi-arid climate features annual rainfall of 400-700 mm and temperatures averaging 25-30 °C. The landscape consists primarily of grassland plains with woodland and shrubland habitats. Common grasses include *Bothriocloa radicans* and *Chrosopogon plumulosus*, while Acacia species are prevalent among trees and shrubs. The reserve is crucial for protecting endangered species, particularly the Grevy's zebra (*Equus grevyi*). Other notable wildlife consists of *Beisa oryx*, Soemmerring's gazelle, ostrich, warthog, and lesser kudu. However, the reserve faces challenges from pastoralists using the area for grazing, leading to soil erosion and bare land. Overgrazing has contributed to the invasion of *Prosopis juliflora*, threatening wild animal habitats. Some pastoralists have even established permanent residences within the reserve, further complicating conservation efforts.

Land cover analysis

This study analyzed land cover change using Landsat images from 1999, 2003, and 2019, obtained from the U.S. Geological Survey. Images from December to March were selected to minimize cloud cover and seasonal variation effects, as this winter period in Ethiopia is free of crop cover, facilitating easier image classification. Field data on existing LULC types, historical trends, and potential drivers were collected through FGDs and field observations. These methods provided crucial information about the current LULC situation, its historical patterns, and possible causes of changes in the study area. The research combined remote sensing data with on-the-ground observations to comprehensively assess LULC changes and their underlying regional factors over the three-decade period.

Table 1. Satellite data acquisition

Acquisition Date	Sensor	Path/Row	Resolution	Source
30/01/1999	Landsat ETM+	167/54	30 m	USGS
10/03/2003	Landsat TM	167/54	30 m	USGS
25/01/2019	Landsat 8 OLI	167/54	30 m	USGS

Image classification

This study employed hybrid classification methods, combining unsupervised and supervised techniques for LULC analysis. Unsupervised classification was initially used to identify general LULC classes and select training sites. Subsequently, maximum likelihood supervised classification categorized images using training sample points. Unsupervised classification groups pixels with similar spectral properties automatically, while supervised classification requires user-defined training sites. The study area's LULC classes were identified using supervised classification, followed by field visits for verification. Random sampling collected training points using GPS; considering less than 5m accuracy. The Maximum Likelihood Classifier, which uses probability density distribution functions, was employed. Ground truth data was processed in ArcGIS 10.4.1, while classification was performed in ERDAS IMAGINE 2015. The process involved resampling, band stacking for false-colour composites, and supervised classification. The Maximum Likelihood method considers cluster centres, shape, size, and orientation, calculating statistical distances based on mean values and covariance matrices.

Accuracy assessment of image classification

Image classification is based on samples of the classes; hence, the accuracy of the classification should be checked and quantified. Classification results and the reference data (ground truth points) on LULC brought from the field were compared. Historical aerial photographs and Landsat images (panchromatic-5 m resolution) were obtained from the Ethiopian Mapping Agency (EMA) for use as reference data to evaluate the accuracy of 1999, 2003 and 2019 Landsat image classifications, respectively.

LULC change analysis and prediction

Land cover change analysis

The change rate of single land use as a dynamic degree can be quantitatively measured by the change of a certain land use type and this index is recognized as one of the most widely used indices for detecting the land use change rate. Land cover change patterns and processes were described by the land use change rate equation:

$$K = \frac{(U_b - U_a)}{U_a} \times \frac{1}{T} \times 100\% \qquad \text{Equation 1}$$

where K is the land use change rate (%) for a single land use type, U_a and U_b are the area of land at the beginning and the end of the study area respectively, and T is the study period in years.

Land cover prediction and focus group discussion

The CA-Markov model, utilizing IDRIS 17.0 software, was used to analyze LULC changes in this study, enhancing spatiotemporal dynamic modelling and forecasting (Dayamba *et al.*, 2016). To simulate future LULC changes, vector data were converted to a raster format, and LULC maps from 1999, 2003, and 2019 provided transition matrices based on the first-order Markov model (Seyum *et al.*, 2019; Toru and Kibret, 2019). Transition suitability maps, generated for 1999-2019 (Pellikka *et al.*, 2018), defined transition rules and identified factors and constraints, leading to a predicted LULC map for 2035.

FGDs were conducted to document observations and perceptions of land cover change and its drivers. Participants included residents, workers, tourist guides, herders, and park officers, with three to five members per group, selected based on age, area knowledge, and residency duration. These discussions provided qualitative data, complementing the quantitative findings from the CA-Markov model, and offered a comprehensive understanding of land cover changes and impacts.

Stratification of the Study Area and sampling design

The study area was stratified by land cover type. In each type, three 20 × 20 m plots were established, totalling nine main plots. Each main plot contained five 5 × 5 m sub-plots for shrubs and one 1 × 1 m sub-plot for soil sampling, totalling 15 sub-plots per land cover type. Soil samples were taken at depths of 0-10 cm, 10-20 cm, and 20-30 cm from each sub-plot, totalling 27 samples. Organic carbon, bulk density, and soil organic matter were calculated.

Vegetation data collection

Litter sampling

The litter samples were collected from a sub-plot of 1 m × 1 m in each main plot, from each plot at each corner and centre of the sub-plot. All litter samples in each subplot were collected manually. A 100 g composite sample was prepared for field wet weight and taken for laboratory analysis. The litter samples were oven-dried at 105 °C for 48 hrs using dry ashing method (Fryer and Williams, 2021). Oven-dried samples were taken in pre-weighed crucibles. Then the samples were ignited at 550 °C for one hour in a muffle furnace. After cooling, the crucibles with ash were weighed and the percentage of organic carbon was calculated. Finally, carbon in litter t ha^{-1} for each sample was determined.

Soil carbon stock assessment

A 100 g soil sample from each of the three depths was collected from five pits in the main plot (one at the centre and four at the corners). These samples were properly mixed within their respective layers to prepare a composite sample. The soil samples were placed in plastic bags, labelled separately, and taken to the Haramaya University laboratory for analysis. At the laboratory, the samples were air-dried and passed through a 2mm sieve to remove soil moisture and determine the percentage of organic carbon.

Data Analysis

Vegetation data analysis

Relative Density (RD)

Relative Density (RD) is the total number of individuals of all species on a particular area.

$$RD = \frac{\text{Number of individuals of species}}{\text{Number of individuals of all the species}} \times 100 \qquad \text{Equation 2}$$

Relative Frequency (RF)

Relative frequency is the degree to which individual species are distributed in an area in relation to the number of all the species found in that area.

$$RF = \frac{\text{Number of occurrences of individual species}}{\text{Number of occurrence of all species}} \times 100 \qquad \text{Equation 3}$$

Relative Dominance (RDO)

Relative dominance is the basal coverage value of an individual species with reference to the sum of coverage of all the species in that area.

$$RDO = \frac{\text{Total basal area of the individual species}}{\text{Total basal area of all the species}} \times 100 \qquad \text{Equation 4}$$

$$BA = \pi \times r^2 \qquad \text{Equation 5}$$

where BA = basal area, π = 3.142 and r = radius of tree or shrub

Importance value index (IVI)

This is a sum of three parameters i.e. RD, RD, and RDO. Its purpose is to measure the importance of a certain species in an ecosystem. The summation of the percentages of the three parameters is then designated as the Importance Value Index of that particular species (Olorunfemi *et al.,* 2020). This index is regarded as important because it gives a summary of the distinctiveness and position of the species for conservation purposes (Olorunfemi *et al.*, 2022).

$$IVI = RF + RD + RDO \qquad \text{Equation 6}$$

where, RF = Relative frequency, RD = Relative density, RDO = Relative dominance.

Carbon stock analysis

Aboveground

All trees/shrubs (live and dead) within the plot were recorded and their diameter at breast height (1.30 m above ground) for trees and diameter at stump height (0.3 m above the ground) for shrubs were measured using a calliper. Whereas, in cases where there were multi-stemmed small trees and shrubs (>1 stem on a sample shrub or small tree) prone to multi-stem below 1.3 m diameter, the measurement of the diameter was calculated by the diameter equivalent (de) as follows:

$$de = \sqrt{\sum_{i=1}^{n} di2} \qquad \text{Equation 7}$$

where, de = diameter equivalent, di = diameter of the i^{th} stem at 1.30 cm height.

The allometric equation was used to estimate the aboveground biomass of trees and shrubs in the study area. The equations are as follows:

$$Trees: Y = 0.1975 \times DCH \times 1.1859 \qquad \text{Equation 8}$$

$$Shrubs: Y = 0.1936 \times BD \times 1.1654 \qquad \text{Equation 9}$$

where, Y = fresh weight of trees/shrubs biomass (kg)

The results of the allometric equation only provide fresh biomass estimates therefore, to measure dry biomass, the results were multiplied by 60% (Toru and Kibret, 2019). To convert the aboveground biomass to kilograms per hectare, scaling factors of 7.96 and 127.31 for trees and shrubs respectively, were used, according to the calculation of scaling factors (Mengist *et al.*, 2023; Wola, 2023). To convert the above-ground biomass to aboveground carbon, a conversion factor of 0.47 was used according to REDD and IPCC defaults.

$$Tree\ AGB \times 7.96 = Aboveground\ biomass\ kg/ha \qquad \text{Equation 10}$$

$$Shrub\ AGB \times 127.31 = Aboveground\ biomass\ kg/ha \qquad \text{Equation 11}$$

$$AGB \times 0.47 = Aboveground\ carbon\ (REDD+, IPCC\ default) \qquad \text{Equation 12}$$

Belowground

Roots play an important role in the carbon cycle as they transfer considerable amounts of carbon to the ground, where it may be stored for a relatively long period. As indicated by Tesfaye *et al.* (2019) and Shiferaw *et al.* (2022), the standard method for estimation of below-ground carbon can be obtained as 20% of above-ground tree carbon. That is root to shoot ratio value of 1:5 is used.

The equation is given below:

$$BGC = AGC \times 0.2 \qquad \text{Equation 13}$$

where BGC is belowground carbon; AGC is aboveground carbon; and 0.2 is the conversion factor (or 20% of AGC).

Deadwood biomass

For standing dead wood, carbon stocks were estimated in a similar manner using the allometric equation of aboveground biomass. As the standing deadwood does not have leaves, therefore, there was the need to subtract 5-6% for conifer species while 2-3% for broad-leaved species.

Litter Biomass

The estimation of the amount of biomass in the leaf litter was calculated by:

$$LB = \frac{Wfield}{A} \times \frac{Wsub\ sample\ (dry)}{Wsub\ sample\ (fresh)} \times 0.001 \qquad \text{Equation 14}$$

where, LB = Litter biomass (ha^{-1}); W field = weight of wet field sample of litter sampled within an area of size 1 m^2 (g); A = size of the area in which litter were collected (ha^{-1}); W sub-sample, dry = weight of the oven-dry sub-sample of litter taken to the laboratory to determine moisture content (g); W sub-sample, fresh = weight of the fresh sub-sample of litter taken to the laboratory to determine moisture content (g). Marelign (2022) noted that the carbon content of biomass is almost always found to be between 45 and 50% (by oven dry mass). Therefore, carbon stored in litter was calculated as:

$$C\ stored\ \left(\frac{t}{ha}\right) = LB \times C\ content \qquad \text{Equation 15}$$

The carbon content used for this study was 47%.

Soil organic carbon

Collected composite soil samples were examined for soil organic carbon estimation for all the land uses using the Walkley-Black method. The soils were sieved through a 2 mm sieve mesh and mixed to a uniform consistency, and then a sub-sample of soil was taken and carbon analysis was done at Haramaya University laboratory. Therefore, SOC was calculated as follows:

$$SOC = (pb(\frac{g}{cm^3} \times D(cm) \times \%C) \quad \text{Equation 16}$$

where, SOC = soil organic carbon; ρ = bulk density (gcm^{-3}) = Oven dry mass (g)/volume (cm^3); D= soil depth (cm), % Carbon = carbon concentration (%) determined in the laboratory following the Walkley and Black method. Bulk density (ρb): soil bulk density was determined after oven drying from the soil samples that were taken with a core sampler as follows: formula as recommended.

$$V = h \times \pi \times r^2 \quad \text{Equation 18}$$

Where: V = volume of the soil in the core sampler in cm^3, h = height of the core sampler in cm, = 3.14, r = the radius of the core sampler in cm. Moreover, the bulk density of a soil sample was calculated as follows: where ρb is the bulk density of the soil sample per quadrat (gcm^{-3}), Wav, dry is the average air-dry weight of the soil sample per quadrat, V is the volume of the soil sample in the core sampler auger in cm^3.

Total Carbon Stocks Estimation

The total carbon stock was calculated by adding the carbon stock densities of the individual carbon pools of the stratum using the formula below:

$$CT = AGC + BGC + DWC + LC + SOC \quad \text{Equation 19}$$

where, CT = Total Carbon stock for all pools ($t\ ha^{-1}$); AGC=above ground carbon stock ($t\ ha^{-1}$); BGC= below ground carbon stock ($t\ ha^{-1}$); DWC=dead wood carbon ($t\ ha^{-1}$); LC=litter carbon stock ($t\ ha^{-1}$); SOC= soil organic carbon ($t\ ha^{-1}$). The total carbon stock was then converted to tons of CO_2 equivalent by multiplying it by 44/12, or 3.67 as indicated.

Impacts of land use/land cover change on carbon stocks

Standard methods deployed by previous empirical studies were used to estimate the impact of LULC change on an ecosystem service (carbon) during the study period 1999 to 2019, mathematically expressed in the following equation:

$$ESV = \sum(A_K \times VC_k \quad \text{Equation 20}$$

Where ESV is the ecosystem service impact, A_K is the area in ha of each land cover type in each year and, VC_k is the value coefficient of each land cover class; in this case, it is taken as the amount of carbon stocks for each land cover type per hectare. To estimate the impact of LULC change on carbon socks for each LULC class, it was attempted to manipulate individual ecosystem services.

Statistical analysis

Statistical R-software version 3.4.4 was employed to test the significant differences in carbon stock pools of the different land use systems using Analysis of variance (ANOVA). Analysis of variance was used to analyze the mean of soil organic carbon across the soil depths and land cover types and to analyze the mean of change in carbon stocks with change in time. The least significant difference (LSD) was also used to separate the means at a significant level of $p<0.05$. The correlation among carbon pools was tested using the Pearson correlation matrix.

Results and Discussion

Land Cover Classes, Changes, and Prediction

Land cover classes

As a result of the reconnaissance survey, Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS), and focus group discussion in the study area, three major land cover types were identified. These three major land cover types were woodland, bushland, and grassland (Table 2).

Table 2. Description of land cover classes identified

LULC Class	Description
Woodland	Land with woody species covers>20% of tree species, height ranges from 5-20 m
Bushland	Bush-dominated land with isolated trees and a lower range of grasses
Grassland	Land predominantly covered with grasses and herbs with scattered trees or shrubs

Meshesha *et al.,* 2013

Accuracy assessment

An overall accuracy of 95.83%, 93.33 and 97.50% was computed for 1999, 2003 and 2019 respectively, and thus deemed acceptable for further data analysis (Table 3). An accuracy assessment was conducted using GPS points that were randomly collected during a field survey. Error matrices were used to calculate the user's and producer's accuracies for all land cover classes, overall accuracies, and the Kappa coefficient of each image individually as well as collectively as shown in Table 3. The results of the classification met the accuracy requirements to be used for the subsequent post-classification operations.

Table 3. Summary of LULC (1999-2019) classification accuracy (%)

LC change	1999		2003		2019	
	Producer	User	Producer	User	Producer	User
Woodland	96.55	93.33	93.33	100	96.77	100
Grassland	93.33	93.33	80.00	96.00	96.55	93.33
Bushland	93.55	96.67	100	81.08	96.67	96.67
Kappa Analysis	0.94		0.91		0.97	
Overall accuracy	95.83		93.33		97.50	

Land cover change analysis

Woodland, grassland, and bushland were the dominant land cover types during the study period (Figure 1, Table 4). Numerous land cover changes occurred throughout the period in question. During the whole period (1999-2019), woodland increased by 57.94% whereas grassland and bushland decreased by 6.86 and 10.51% respectively (Table 4). This change shows a percentage change in the component. It means that for example, in 1999, woodland covered 13.74% of the total area and by the year 2019 it increased by 57.94% to cover 40.16% of the total area. In the year 1999, woodland accounted for 13.97% which increased to 29.39% and 40.16% in 2003 and 2019 respectively. During the same year, grassland covered 29.36% which increased to 29.94% and decreased to 22.72% in the years 2003 and 2019 respectively whereas bushland was accounting 56.85% and decreased to 40.67% and 37.13% in 2003 and 2019 respectively. The LULC change rate for grassland shows that it increased by 1.15% during the period 1999-2003, and it decreased by 15.08% and 6.86% during the period 2003-2019 and 1999-2019 respectively. The decrease in grassland area might be due to succession from other land cover types. Bushland also decreased by 16.74%, 5.44% and 10.51% during the period 1999-2003, 2003-2019 and 1999-2019 respectively. The decrease in bushland can also be due to management measures being done by the surrounding communities and might be the transformation of bushland into woodland.

Table 4. LULC status for the period 1999-2019 in HWR

LC change	1999		2003		2019		LULC (%)		
	ha	%	ha	%	ha	%	1999-2003	2003-2019	1999-2019
Woodland	20 197.7	13.79	43 053.9	29.39	58 817.9	40.16	66.57	22.88	57.94
Grassland	43 007.5	29.36	43 849.6	29.94	33 270.4	22.72	1.15	-15.08	-6.86
Bushland	83 263.2	56.85	59 564.9	40.67	54 380.1	37.13	-16.74	-5.44	-10.51
Total	146468.4	100.00	1 46468.4	100.00	146468.4	100.00			

NB. The negative values indicate the magnitude of decline in that land cover type

Several studies related to LULC changes in Ethiopia have indicated that the country has experienced rapid and increasingly pronounced LULC changes since the second half of the 20th century. Most of the studies have documented a significant increase in cropland at the expense of other LULC types in the country. reported the expansion of cropland at the expense of forest, woodlands, grasslands, and water in the Central Rift Valley but this is somewhat contrary to the results of this study which show an expansion of woodland at the expense of grassland and bushland. Likewise (Toru and Kibret, 2019), reported a decline of forest, shrubland, and grassland between 1985 and 2015 in the Andassa watershed in the Blue Nile Basin as a result of the development of cultivated land in the area but in this study, results show that there was an increase in woodland between 1999 and 2019 in the Hallaydeghi Wildlife Reserve.

However, other studies have documented a different trend of LULC changes in the country. For example, Dissanayake *et al.* (2018) reported natural forest regrowth in the uplands of the Bela-Welleh catchment in northern Ethiopia. The results from this study support the results obtained in Hallaydeghe Wildlife Reserve which shows the increase around the natural woodland of Hallaydeghe Wildlife Reserve. Inappropriate agricultural practices, drought-induced migration, high human and livestock populations, and government land policies have been frequently reported as the main drivers of LULC changes in the country (Olorunfemi *et al.*, 2020). This is also supported by the results obtained from the FGDs which were conducted in the area during the data collection period. Resettlement programs played an important role in reducing grassland. Policy shifts and regime change also contributed to the expansion of woodland in the reserve since it became a protected area, earlier before the study was conducted during the 1960s.

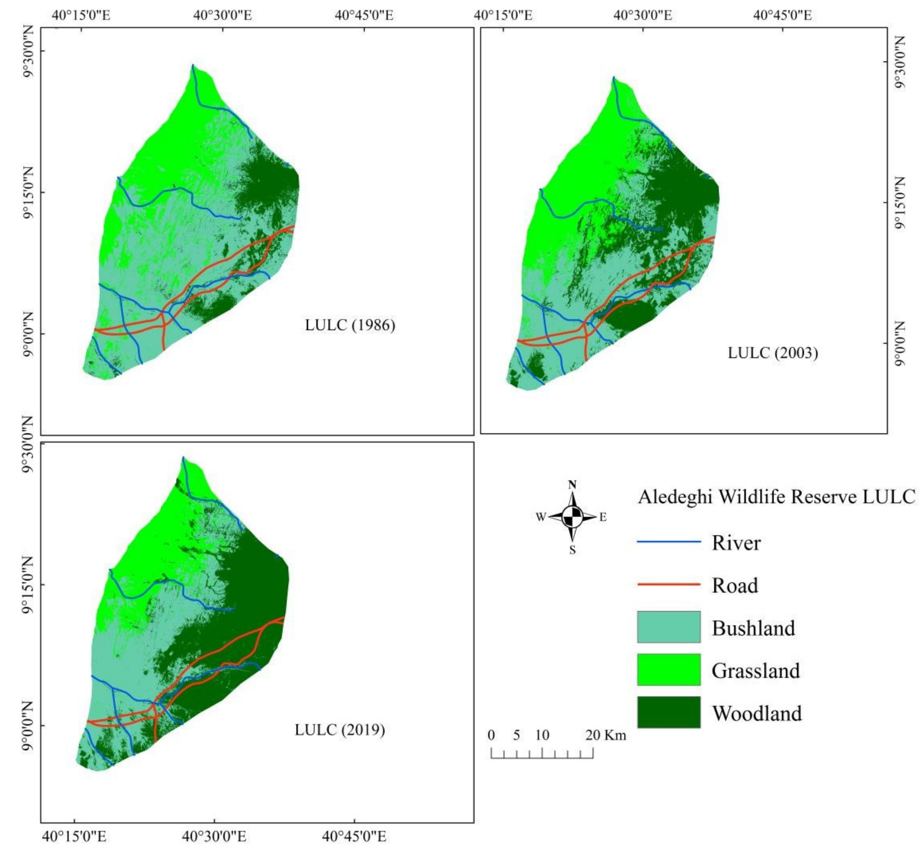

Figure 1. LULC maps of Hallaydeghi Wildlife Reserve in 1999, 2003 and 2019

Other studies have noted the occurrence of bush encroachment in areas where there is shallow soil depth and grazing is infrequent (Girma *et al.*, 2020), especially with Prosopis spp. Before the introduction of other land uses such as agriculture, traditional institutions of the Afar communities were strongly organized to serve the needs of the members living within specified physical boundaries. Although land is legally owned by the state, grazing lands are communal properties accessible to all members of a clan or groups of clans within the boundary (Hussein, 2022). However, land under cultivation by agro-pastoral communities is private property. Although not fully implemented, the 1994 constitution declares (in Article 40) – that Ethiopian pastoralists have a right to free land for grazing and cultivation as well as the right not to be displaced from their lands.

Various studies done in African drylands have recognized a decline in woodland vegetation cover (Kendie *et al.*, 2021; Lahtinen, 2022). Woodland loss is usually attributed to land clearing for crop production, but this is contrary to the results obtained from the study area since the woodland cover type is dominating amongst the other two land cover types while bush encroachment is attributed to overgrazing and absence of fire (Dube and Chatterjee, 2022). Frequent droughts and rainfall variability are among the causes of land cover change in the study area. A slight increase in bushland indicates partial recovery from drought which was experienced a season before the study was conducted during the 1984/85 season. Most of the pastoralists shifted to small stock (goat) and camel production to utilize the bush-encroached areas and increase the demand for meat from the growing population in nearby towns in recent years, this is also an opportunity to increase the goat population that can browse on the bush cover. For this reason, it is observed that the bushland is now being overused thereby leading to its decline due to pressure from the small livestock stocking densities. The general trend observed in the study area implies a loss of grassland and an increase in bushland.

Table 5. Conversion matrix for LULC change (1999-2019)

1999/2019	Woodland	Bushland	Grassland	Total
	19555.5	882.271	36.545	20474.32
Woodland		42821.8	4182.52	82984.12
Bushland	35979.8		29033.6	43009.93
Grassland	3311.43	10664.9		
Total	58846.73	54368.97	33252.67	146468.4

Table 5 above shows the transformation of one land cover type to the other for the whole study period, 1999-2019. Woodland converted to bushland and grassland by 882.27 ha and 36.55 ha respectively. Bushland was transformed to woodland and grassland by 35979.8 and 4182.53 ha respectively and grassland was changed to woodland and bushland by 58846.73 and 10664.9 ha respectively. The study emphasizes that bushland is being transformed into woodland and grassland is being transformed into bushland. The reason for grassland being transformed into bushland is that there is bush encroachment by the invasive alien species *Prosopis juliflora.*

Land cover prediction

Prediction of land cover shows that in the year 2035 woodland will decrease by 52.61%, grassland by 43.78%, and bushland will increase by 40.68% (Table 6, Figure 1). There will also be the emergence of a new land cover type which is bareland.

Table 6. LULCprediction for the year 2035

LC type	2019		2035		LULC (%)
	ha	%	ha	%	
Woodland	58817.9	40.16	9307.18	6.35	-52.61
Grassland	33270.4	22.72	9966.24	6.80	-43.78
Bushland	54380.1	37.13	89779.2	61.29	40.68
Bareland			37415.8	25.54	155.71
Total	146468.4	100	146468.4		

The potential distribution of land cover classes by 2035 shows the emergence of a new land cover class, bare land, probably because of overgrazing of the study area and the effects of climate change like soil erosion from wind and water and soil compaction from the grazing livestock and wildlife. It also showed that woodland will decrease drastically due to anthropogenic activities such as charcoal production, construction deforestation and other effects of climate change (Figure 2). Another reason could be the increase in population growth thereby a higher demand for construction material and demand for firewood and charcoal as a source of livelihood. The results also showed the increase in bushland because of bush encroachment by the invasive species *Prosopis juliflora* thereby resulting in the decrease of grassland and encroachment into other land cover types. The area is experiencing a lot of pressure since it is now failing to sustain grazing pressure from local communities' livestock. It is also surrounded by human settlements mainly pastoralists who use wood for construction and different household purposes and therefore it fails to sustain the pressure. According to Mulat *et al.* (2018), the availability of habitats of important species is influenced due to these changes. Reduction and fragmentation of habitats lead to the decline of species and their ecological niches. Future effects of land cover changes on natural land cover can be understood by simulated maps of future land cover.

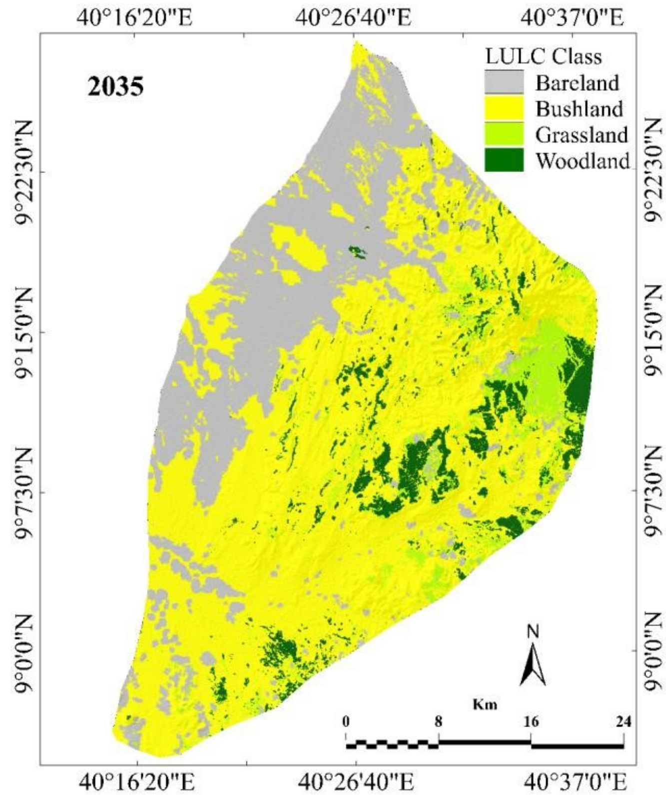

Figure 2. Prediction land cover map for the year 2035

Vegetation composition

Species composition provides essential information that values and recognizes the flora and ecosystem health of the study area. A total of 25 plant species which include 10 (40%) trees, 8 (32%) shrubs, and 7 (28%) herbaceous that belonged to 13 families were identified.

Tree species

The tree species that dominated the three land cover types were *Acacia Senegal* (L.) Wild, *Acacia tortilis* (Forssk.) Hayne, *Acacia abyssinica* (Hochst) Benth, *Acacia oerfota* (Forssk) Schweinf, and *Acacia mellifera* (Vahl) Benth. This is supported by previous studies, which observed that the top six dominant woody species in the Hallaydeghi Wildlife Reserve were *Acacia senegal, Acacia tortilis, Acacia mellifera, Acacia oerfota, Balanites Aegyptiaca* (L.) Del and *Dobera glabra* (Forssk.) Juss. ex Poir. A total of nine *Acacia* species were identified in this study therefore, it shows that *Acacia* species is the dominant tree and shrub species found in the study area. According to empirical studies, such dominant species can be viewed as ecologically important and most booming species in their regeneration and/or the least favoured by animals. Some plant species like *Acacia* species have a wide range of dispersal mechanisms and/or rapid reproduction strategies, which has contributed to their dominance favoured with the climatic suitability for this genus. In general, in the study area, stochastic processes most likely determine the dominance of acacia species. *Acacia tortilis* showed the highest density (116.67 individuals ha^{-1}) in woodland followed by *A. abyssinica* which had a density of 75 individuals ha^{-1} (Table 7). *Ziziphus mucronata* showed the highest density in the grassland cover type. *A. tortilis* showed the highest abundance and relative dominance in woodland. The tree species abundance, frequency and relative dominance were higher in woodland than in grassland. The reason might be the key species of this wildlife reserve, the Grevy's zebras, depend on grasses as grazing animals rather than trees thus reducing impacts on such tree species. The Importance Value Index (IVI) is useful to compare the ecological significance of species (Olorunfemi *et al.*, 2020). Trees and shrubs with IVI > 10 could be considered important species in the ecosystem to the ecological management plan for intervention. *A. tortilis* had the highest IVI in the study area. IVI is a very essential parameter for measuring the ecological significance of a given species in a certain environment. The species with high IVI values are regarded as more important than those with low IVI values for preservation programs and management by local societies and other stakeholders before the disappearance.

Table 7. Tree Species composition

Land cover type/Species	Frequency	RF	Abundance	D	RD	BA	RDO	IVI
Woodland								
Acacia abyssinica (Hochst) Benth	2	18.18	9	75.00	27.27	4.45	36.72	82.17
Acacia tortilis (Forssk.) Hayne	3	27.27	14	116.67	42.42	4.47	36.88	106.57
Acacia seyal (Del.)	1	9.09	2	16.67	6.06	0.54	4.46	19.61
Balanites aegyptiaca (L.) Del.	3	27.27	6	50.00	18.18	2.36	19.47	64.92
Dobera glabra (Forssk.) Juss. ex Poir.	1	9.09	1	8.33	3.03	0.1	0.83	12.95
Cordia species (Johnst.)	1	9.09	1	8.33	3.03	0.2	1.65	13.77
Total	11	100	33		100		100	300
Grassland								
Acacia nilotica (L.) Willd. ex Del.	2	28.57	2	16.67	20.00	0.86	19.15	67.72
Boswellia papyrifera (Del.) Hochst	2	28.57	3	25.00	30.00	1.5	33.41	91.98
Ziziphus mucronata (Wild.)	1	14.29	4	33.33	40.00	1.43	31.85	86.14
Commiphora erythraea (Ehrenb.)	2	28.57	1	8.33	10.00	0.70	15.59	54.16
Total	7	100.00	10		100.00		100.00	300.00

NB: RF (%) = relative frequency, D (individuals per ha) = density, RD (%) = relative density, BA (m^2) = basal area, RDO (%) = relative dominance, IVI = importance value index

Shrub species composition

The most dominant shrub type in the three land cover types was *Prosopis juliflora* (Table 8). It had the highest abundance, RF, BA, RDO and IVI in the bushland cover type. The bushland cover type exhibited the highest abundance of shrubs and bushes as compared to the other two land cover types. *Prosopis juliflora* was also seen invading the grassland (RDO and IVI of 36.48 and 95.32, respectively), (Table 8). This might be due to seed dispersal by livestock since the reserve is a major communal livestock grazing area for Afar and Somali pastoral communities. *Prosopis juliflora* showed the highest abundance and dominance because it is not palatable to livestock and the seed dispersal is due to wind, water, and livestock. Therefore, its regeneration is high. Woodland had the lowest IVI values as compared to the other two land cover types but it had a higher abundance comparing it with the grassland. The reason is that grassland is mainly dominated by grasses. Woodland exhibited the highest number of shrub species as compared to the other two land cover types.

Table 8. Shrub species composition

Land Cover Type/Species	Frequency	RF	Abundance	D	RD	BA	RDO	IVI
Woodland								
Acacia senegal (L.) Wild	3	23.08	8	66.67	36.36	46.60	38.96	98.40
Ricinus communis (L.)	1	7.70	2	16.67	9.09	6.26	5.23	22.02
Dichrostachys cinerea (L.) Wight & Arn	2	15.38	2	16.67	9.09	12.00	10.03	34.50
Acacia oerfota (Forssk.) Schwenf	3	23.08	4	33.33	18.18	17.90	14.96	56.22
Prosopis juliflora (Swartz)	2	15.38	4	33.33	18.18	24.65	20.61	54.17
Ziziphus pubescens (Oliv.)	2	15.38	2	16.67	9.09	12.21	10.21	34.68
Total	13	100.0	22		100.0		100.0	300.0
Grassland								
Acacia senegal (L.) Wild	2	28.57	4	33.33	36.36	10.14	26.14	91.07
Prosopis juliflora (Swartz)	2	28.57	3	25.00	27.27	14.15	36.48	95.32
Entada abyssinica (Forssk.) Schwenf	1	14.29	1	8.33	9.09	2.93	7.55	30.93
Acacia oerfota (Forssk.) Schwenf	1	14.29	2	16.67	18.18	7.38	19.03	51.50
Acacia mellifera (Vahl) Benth	1	14.29	1	8.33	9.09	4.19	10.80	34.18
Total	7	100.00	11				100.0	300.0
Bushland								
Acacia mellifera (Vahl) Benth	3	37.50	18	150.00	31.58	77.96	34.09	103.17
Prosopis juliflora (Swartz)	3	37.50	30	250.00	52.63	118.23	51.70	141.83
Acacia senegal (L.) Wild	2	25.00	9	75.00	15.79	32.49	14.21	55.00
Total	8	100.0	57		100.0		100.00	300.00

NB: RF (%) = relative frequency, D (individuals per ha) = density, RD (%) = relative density, BA (m^2) = basal area, RDO (%) = relative dominance, IVI = importance value index.

Estimation of Carbon Stocks in different carbon pools

The mean total carbon stocks stored in woodland, bushland and grassland were 35.94, 22.55 and 23.66 t ha^{-1} respectively (Table 9).

Aboveground carbon

The AGC for woodland and bushland did not show any significant difference but these two land cover types showed a significant difference with that of grassland, $p<0.0455$ (Table 9). The reason for low AGC in grassland might be that trees and bushes in this land cover type are sparsely distributed and its grass species are exposed to overgrazing which reduces its primary production. The reason for high AGC stocks for woodland and bushland is that there is a high tree and shrub composition in the two land cover types respectively. The other reason for a variation in the amount of AGC stocks amongst the three land cover types might be due to the variation of presence and densities of trees and shrubs found in each one of them. The AGC for all three land covers were 3.297±0.280, 1.186±0.245, and 3.385±0.112 tC ha^{-1} for woodland, grassland, and bushland, respectively.

Bushland had the highest amount of AGC in this study. This is supported by Girma *et al.* (2020) who stated that the introduced *Prosopis juliflora* species had the highest average contribution of 3.47 tC ha^{-1} in a similar environment. The total AGC (7.87 t ha^{-1}) of the three land cover types was found to be far below that of the tropical (45.45 tC ha^{-1}) and regional (58.9 tC ha^{-1}) estimates of similar land cover types in semi-arid ecosystems. Generally, the AGC pool (7.868±0.637 tC ha^{-1}) contributed a much higher carbon stock as compared to DWC, LC, and BGC pools. AGC and SOC contributed more to the overall carbon stocks across land uses in the Wujig Mahigo Waren forest of Ethiopia. The aboveground carbon stocks of this study, when compared to other studies done in the country showed a similarity e.g. a study conducted by Hussein, (2022) in the semi-arid lowlands of Northern Ethiopia showed 2.0-7.0 MgC ha^{-1}.

Table 9. Mean carbon stocks in different pools across land cover types

Carbon pools	Land Cover Type			*p*-value
	Woodland	Grassland	Bushland	
AGC	3.297±0.280^{b}	1.186±0.245^{a}	3.385±0.112^{b}	0.0455
BGC	0.659±0.056^{a}	0.237±0.049^{a}	0.677±0.022^{a}	0.4295
DWC	1.236±0.021^{a}	0.334±0.232^{a}	1.201±0.538^{a}	0.4290
SOC	30.258±6.208^{a}	20.510±2.68^{b}	17.991±2.460^{b}	0.0101
LC	0.450±0.061^{a}	0.282±0.144^{b}	0.404±0.118^{a}	0.0390
Total	35.94±6.626	22.549±3.35	23.658±3.25	

The values are in mean and standard deviation. Different letters in the row indicate that there is a significant difference between means at $p < 0.05$.

Belowground carbon

The BGC for all three land cover types did not show any significant difference and the estimated mean of BGC stocks were as follows, 0.659±0.056, 0.237±0.049, and 0.677±0.022 tC ha^{-1} for woodland, grassland, and bushland respectively with an estimated p-value of 0.4295 (Table 9). In the findings, the estimated BGC for bushland (0.677±0.022 tC ha^{-1}) was slightly higher than that of woodland (0.659±0.056 tC ha^{-1}). This is in contrast with the results of Kan *et al.* (2022), Mugabowindekwe *et al.* (2023) and Wola (2023) who stated that trees have much more potential to produce a larger quantity of BGC as compared to shrubs. Onrizal and Kusmana (2020) also revealed that more biomass production increased aboveground litter and belowground root production thereby making trees an important factor for SOC. Roots are a very vital parameter for belowground activities, which makes them the key foundation of SOM, which affects soil microbial activity thereby affecting the decomposition processes.

Deadwood carbon

Deadwood carbon stocks across the land cover types did not show any significant difference (p=0.4290; Table 9). The mean DWC stocks for the different land cover types were 1.236±0.021, 0.334±0.232 and 1.201±0.538 tC ha^{-1} for woodland, grassland, and bushland. The total DWC stock for the study site was 2.771±0.791 tC ha^{-1}, which shows that it lies within the range of the reported results of the drier ecosystem zones of the tropics pegged at 1.2-3.3 MgC ha^{-1}. Grassland showed the lowest amount of DWC stock and this might be due to the reason that trees and shrubs are sparsely distributed in this land cover type and thus, therefore, a low contribution to the DWC pool. Woodland contributed the highest amount of carbon to the DWC pool probably because it has more tree species and grass cover. These results indicate that deadwood carbon stock is smaller than the other carbon pools, suggesting that warm and humid climates quicken the decomposition of dead wood. This might be the result of the low accumulation of dead wood in the semi-arid ecosystems of Ethiopia.

Litter carbon stock

Litter carbon in woodland and bushland did not show any significant difference but showed a significant difference with that of grassland (p=0.0390; Table 9). The total mean carbon stock for LC was 1.136±0.323 tC ha^{-1}. The lower litter carbon in the study area may be because of the collection of twigs and branches for fuel wood and charcoal making by the local communities. The amount of litter carbon is controlled by many factors like age and density of trees, soil nutrient levels, species composition, quantity and quality of annual litter input, decomposition rate, human disturbances, and management history. Litter decomposition rates are commonly measured from regulation by soil organisms, ecological conditions and chemical characteristics of the litter (Gedefaw *et al.,* 2014). The physical atmosphere, especially soil moisture, temperature, and relative humidity are significant in litter decay as they adjust the biological activity in soil. The climatic condition of the study area is extremely hot and humid during the rainy season leading to a high rate of decomposition and in turn low litter accumulation beneath the tree cover.

Soil organic carbon stock

The soil organic content was determined using the Walkley-Black wet oxidation method. This method involves oxidizing organic matter with a potassium dichromate and sulfuric acid mixture, followed by titration of the excess dichromate with ferrous ammonium sulfate. The mean soil organic carbon (SOC) stocks for woodland, grassland, and bushland were 30.26, 20.51, and 17.99 t ha^{-1}, respectively (Table 9, Table 10).

Table 10. Distribution of carbon with depth across land cover types

Land cover type	Carbon stocks at different depths (tC/ha)			Pooled mean
	0-10 cm	10-20 cm	20-30 cm	
Woodland	19.027±3.060^{Ab}	28.571±11.800^{Ab}	43.174±5.885^{Aa}	30.258±6.208
Grassland	9.139±1.477^{Bb}	25.190±3.769^{Aa}	27.200±8.511^{Aa}	20.510±2.68
Bushland	8.159±1.387^{Bb}	17.326±1.790^{Ab}	28.488±10.441^{Aa}	17.991±2.460

Means shown by similar superscripts (Capital letters) within a column (Land Cover) or across the rows ((small letters) depth) is not significantly different at a 5% level of significance. The values in the table are means of triplicate samples.

The results indicated that the SOC stock at a 0-10 cm depth in woodland was significantly higher than in grassland and bushland. However, the SOC stocks in grassland and bushland at the same depth were not significantly different from each other. There were no significant differences in SOC stock at 10-20 cm and 20-30 cm depths for all land cover types (Table 10). Woodland had the highest SOC content across all three depths, likely due to the type of plant species and vegetation types present. The higher SOC stock in woodland may be attributed to the frequent addition of plant litter. Toru and Kibret (2019) noted that natural forests have higher SOC stocks due to frequent litter addition, extensive root networks, and a modified microclimate that enhances organic matter decomposition. This study showed variation in SOC stock among land cover types, with minimal differences in lower soil layers compared to surface layers, indicating the influence of different management practices on surface soil layers. The study found an increase in SOC content with depth across all three land cover types, with the highest carbon content at the 21-30 cm depth (43.174 ± 5.885 tC ha^{-1} in woodland, 27.200 ± 8.511 tC ha^{-1} in grassland, and 28.488 ± 10.441 tC ha^{-1} in bushland). These findings align with Lasco and Pulhin (2003), who reported that in dry climate zones, most carbon stock in the top meter is stored in subsoil (30-100 cm), while in wet climates, a lower proportion is in the upper soil (0-30 cm). This study supports the idea that subsoils contribute significantly to total SOC stocks despite their lower SOC concentration. Karouach *et al.* (2022) found that the percentage of SOC below 20 cm relative to the first meter averaged 67% for shrublands, 58% for grasslands, and 50% for forests, varying from 71% in cold arid shrublands to 43% in cold humid forests. These studies support the findings of this study, showing higher relative SOC storage levels in lower depths in dry climates compared to moist climates.

The results reported by Bayle *et al.* (2023) suggested that there is a higher relative proportion of SOC storage in subsoils in the drier regions of eastern Australia compared to the moister States for equivalent soil types. This supports the results of the current study where organic carbon stocks increased with depth. Toru and Kibret (2019) stated that the presence of 68-60% of the organic carbon in the lower soil layers (0.2-0.4 m and 0.4-0.6 m) indicated that the deeper layers of the soil are important pools for preserving soil organic carbon in drier regions. Wolka *et al.* (2021) predicted that the impact of climate change on SOC content will be larger in surface soils than in-depth. However, several studies have reported higher organic carbon values in the upper layers of soils compared with the lower or deeper layers. The presence of SOC in lower soil depths indicates the importance of these layers in preserving soil organic carbon over the long term. These findings support the Hallaydeghe Wildlife Reserve's potential for soil carbon sequestration, contributing to current climate change mitigation in semi-arid conditions.

Tilahun *et al.* (2022) reported that climate change influences organic matter production and mineralization, with organic matter levels being highest under cool moist conditions. Long-term improvements in soil carbon stocks can only be anticipated after several years and will contribute to considerable long-term carbon storage in rangelands under grazing. Additionally, higher soil organic carbon can lead to higher above- and below-ground organic carbon in plants. Conversely, the removal of grass vegetation due to overgrazing and deforestation contributes to low soil organic carbon stocks. This might explain the low soil organic carbon in both grassland and bushland in this study area. Soil compaction due to overgrazing increases bulk density, potentially facilitating further loss of soil organic carbon by runoff. Like many global arid and semi-arid lands, Hallaydeghe Wildlife Reserve has been deteriorating. However, ASALs have the potential to sequester more carbon if properly managed. Proper management of drylands can facilitate carbon sequestration, mitigating CO2 emissions. Management aimed at increasing carbon sequestration should be of paramount importance in the face of climate change (Demie *et al.*, 2024). Suitable management practices can significantly increase carbon stocks or reduce carbon losses.

Total carbon stock

The total carbon stock from various carbon pools was calculated by aggregating the carbon stock densities of the individual carbon pools (Fryer and Williams, 2021). The total carbon stocks for woodland, grassland, and bushland were 35.94±6.63, 22.55±3.35, and 23.65±3.25 tC ha^{-1} respectively. These results are consistent with carbon stocks for grazing areas of sub-Saharan Africa (Dibaba *et al.*, 2019). Differences in carbon stock among land cover types may be due to species composition, climatic, and edaphic factors. Woodland sequestered the most carbon (35.94±6.63 tC ha^{-1}), likely due to its plant species composition. Bushland, dominated by *Prosopis juliflora*, also contributed significantly to carbon sequestration. Studies suggest *Prosopis juliflora*, despite its invasive nature, can effectively re-vegetate marginal lands and sequester carbon (Raihan *et al.*, 2021). Deforestation is increasing in the study area, particularly in woodland and bushland, where local communities cut down trees for construction, charcoal, and firewood, reducing the number of plant species contributing to carbon pools. Grassland had the lowest carbon stocks (22.55±3.35 tC ha^{-1}), likely due to higher grazing pressure and exposure to soil erosion and wildfires. Overgrazing, competition between livestock and wildlife, and low herbaceous cover reduce carbon sequestration in grasslands (Aryal *et al.*, 2018). The study found that grasslands contributed less to carbon stocks than bushland, contrary to some findings that grasslands can store more carbon than forests. However, grasses have been found to sequester similar amounts of soil carbon compared to native forests in subtropical or semi-arid climates. The largest carbon pool in all land cover types was the soil organic carbon (SOC) pool, contributing about 68.76±11.35 tC ha^{-1}. This supports findings that soil has higher carbon stock compared with aboveground biomass, even under poor management (Toru and Kibret, 2019). The second highest pool was aboveground carbon (AGC), followed by dead wood carbon (DWC), belowground carbon (BGC), and litter carbon (LC). These results are consistent with a study in Marsabit Central grazing lands in Kenya, which showed that 98.39% of carbon is stored in soils. Anthropogenic activities impacting soils will significantly reduce carbon stocks in grazing lands. The contribution of pastoral ecosystems in offsetting atmospheric greenhouse gases (GHGs) through carbon storage is often overlooked, while livestock production in rangelands is criticized for emitting GHGs. The role of rangelands in livestock production and ecosystem services, maintaining significant carbon stocks in soils and vegetation, should be considered to balance the potential adverse effects of GHG emissions (Tifafi *et al.*, 2018). Studies in Ethiopia have shown that rangelands and grazing areas store carbon above and below ground. In Europe, converting cropland to grassland increased carbon stock. Although information on the carbon stock of Ethiopian highland grazing lands is scarce, communal semi-arid rangelands in southern Ethiopia reported 28.39 t ha^{-1} belowground and 13.11 t ha^{-1} aboveground organic carbon. Understanding the relationship between land use systems and carbon stock is crucial, as each system impacts the carbon balance. Semiarid areas with Prosopis and Acacia can sequester significant carbon. Thus, with proper management, the study area has the potential for increased carbon sequestration.

Correlation analysis among different carbon pools

In the present study, the results show that all the carbon pools have a positive correlation (Table 11). There is a very strong positive correlation between AGC and BGC (0.95). This means that any destruction of the aboveground plant species will affect the belowground carbon. There is also a positive correlation between AGC and DWC and BGC and DWC (0.708 for both respectively). However, there was a weak relationship between AGC and SOC, BGC and SOC, DWC and LC and SOC and LC. The results therefore show that each carbon pool influences another.

Table 11. Pearson correlation analysis of carbon pools

	AGC	BGC	DWC	SOC	LC
AGC	1.00				
BGC	0.950**	1.00			
DWC	0.708*	0.708*	1.00		
SOC	0.252	0.252	0.581	1.00	
LC	0.665	0.665	0.389	0.246	1.00

*Correlation is significant at α=0.05; **Correlation is significant at α=0.01

Impact of land cover change on carbon stocks

The carbon stocks for 1999 and 2003 were obtained by assuming that individual cover class carbon values did not change. In 1999, 2003 and 2019, the carbon stocks found in the Hallaydeghe Wildlife Reserve were 3.6, 3.9 and 4.1 million tones C respectively, Figure 3. Carbon stocks slightly increased throughout the study period (1999-2019) (Figure 3). The total carbon stock in 2019 was higher than both in 1999 and 2003; however, the total carbon stock in 1999 was slightly lower than that of 2003. In 1999, woodland recorded the least amount of carbon stocks. This might be due to the emigration of migrants from the Tigray region following an outbreak of famine in the 1980s, whilst bushland recorded the highest and grassland recorded the intermediate carbon stocks. However, in 2003 and 2019 woodland increased in carbon volumes whilst grassland slightly increased in 2003 and then decreased in 2019, the reason for the decrease might be an encroachment of both bushland and woodland, and bushland recorded a decrease in both years and this might have been caused by anthropogenic activities e.g. charcoal making, wood construction, etc. The difference in carbon stocks across land cover types may be due to the species composition of each land cover type. This is in line with Ouyang and Lee (2020), who stated that the variation of carbon stocks in land cover types might be due to the variation in the number of stems, density and size of trees in each land cover type. This is also supported by Dibaba *et al.* (2019), who reported that density and diameter contribute to the carbon biomass of northern Ethiopian landscapes.

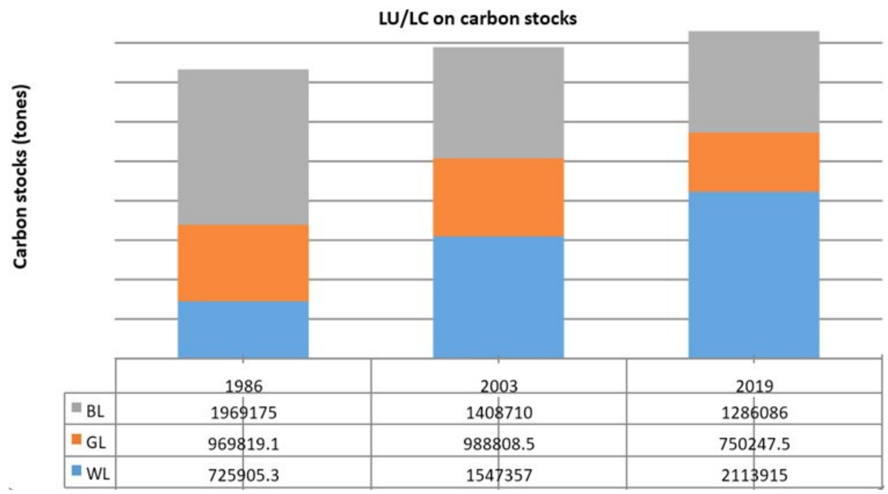

Figure 3. Estimated carbon stocks for each land cover type in different years

There was an increase in carbon stocks in the Hallaydeghe Wildlife Reserve between 1999 and 2019 following its establishment in 1965 for the protection of the endangered gravy's zebra species. Therefore, due to it being protected from human encroachment, thus saved from being degraded. This study shows that carbon stock was slightly affected by land cover change. Many of the previous studies agreed that land cover change affects carbon stocks. For example, in a study conducted in Nepal in 1976-1989, it was observed that there was a net gain in carbon stocks in most parts of the mountain watershed whilst a net loss was recorded from 1989 to 2003 due to LULC change.

Many authors have proved that LULC change has an effect mainly in the SOC pool. Since this study shows that the SOC pool was the one which contributed most of the carbon as compared to the other carbon pools, it then means land use and land cover changes should strictly be monitored because a change in land use means an effect on the SOC pool. In arid and semi-arid areas, it was found that the main predictor variable of SOC is land use and land cover, therefore conversion of one land use type to another will alter the carbon stocks by reducing carbon biomass in the soil. The decrease in carbon stocks observed in this study might be due to human interference and the effects of climate change.

Conclusion

The study examined carbon stocks across different land cover types in a semi-arid environment, finding significant variability. Woodland had the highest carbon stocks due to plant species composition and density, while grassland had low stocks requiring attention to manage overgrazing. Bushland with the invasive *Prosopis juliflora* showed intermediate carbon stocks, requiring management to protect native species. Notably, the soil organic carbon (SOC) pool contained the highest amount of carbon compared to aboveground, belowground, deadwood, and litter carbon pools. This contrasts with many studies emphasizing the importance of aboveground carbon. The results suggest both SOC and aboveground carbon pools should be conserved and properly managed to realize the area's carbon sequestration potential. Significant land cover changes occurred from 1999 to 2019, with woodland expansion at the expense of grassland and bushland. This could challenge the habitat of the Grevy's zebra, a key wildlife species. Balancing carbon sequestration with habitat protection for endangered species is crucial. The findings demonstrate the carbon sequestration potential of semi-arid areas, contrary to their perceived unimportance. This information is valuable for researchers, managers, and policymakers in developing policies for arid and semi-arid ecosystems. Proper conservation techniques are needed to protect these ecosystems from disturbances like deforestation, overgrazing, and burning, which can reduce biomass and carbon sequestration potential. Overgrazing and deforestation particularly impact SOC, requiring strategies like controlled livestock stocking and grazing calendars. Without proper management, the study area is likely to continue suffering from land degradation due to human factors and climate change. Policies should be implemented to take advantage of the carbon sequestration potential for carbon marketing and overall reserve management. Awareness programs for local communities on sustainable resource use are also important. In conclusion, this study highlights the need for careful land use and cover management in arid and semi-arid environments to balance carbon sequestration, biodiversity conservation, and climate change mitigation objectives through adaptive strategies and community engagement.

Author contributions

The authors made the following contributions to this paper: Conceptualization (DG); methodology (DG, AD, DSW); software (CP); validation (CP, UA, AD); formal analysis (UA, DG, DSW); investigation (DG); resources (DG); data curation (DG); writing—original draft preparation (UA, DG); writing—review and editing (CP, UA); supervision (UA, DSW, AD). All authors have read and agreed to the published version of the manuscript.

Acknowledgement

The World Bank provided funding through the African Centre of Excellence for Climate-Smart Agriculture and Biodiversity Conservation, Haramaya University, Ethiopia

Conflict of interests

The authors declare no conflict of interest

References

Aryal S, Shrestha S, Maraseni T, Wagle PC, Gaire NP (2018). Carbon stock and its relationships with tree diversity and density in community forests in Nepal. International Forestry Review 20(3):263-273. *https://doi.org/10.1505/146554818824063069*

Bayle D, Feyissa S, Tamiru S (2023). Effects of land use and slope position on selected soil physicochemical properties in Tekorsh sub-watershed, east Gojjam zone, Ethiopia. Open Agriculture 8(1):20220147. *https://doi.org/10.1515/opag-2022-0147*

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. Agriculture, Ecosystems and Environment 216:61-72. *https://doi.org/10.1016/j.agee.2015.09.023*

Demie G, Negash M, Asrat Z, Bohdan L (2024). Carbon stocks vary in reference to the models used, socioecological factors and agroforestry practices in Central Ethiopia. Agroforestry Systems 98(6):1905-1925. *https://doi.org/10.1007/s10457-024-00998-5*

Dibaba A, Soromessa T, Workineh B (2019). Carbon stock of the various carbon pools in Gerba-Dima moist afromontane forest, south-western Ethiopia. Carbon Balance and Management 14(1):1-10. *https://doi.org/10.1186/s13021-019-0116-x*

Dissanayake STM, Beyene AD, Bluffstone R, Gebreegziabher Z, Kiggundu G, Kooser SH, Martinsson P, Mekonnen A, Toman M (2018). Improved biomass cook stoves for climate change mitigation? Evidence of preferences, willingness to pay, and carbon savings. World Bank, Washington, DC. *https://doi.org/10.1596/1813-9450-8499*

Dube LC, Chatterjee S (2022). Assessing livelihood impact of forest carbon projects using sustainable livelihood framework. Mitigation and Adaptation Strategies for Global Change 27(8):49. *https://doi.org/10.1007/s11027-022-10022-9*

Fryer J, Williams ID (2021). Regional carbon stock assessment and the potential effects of land cover change. Science of the Total Environment 775:145815. *https://doi.org/10.1016/j.scitotenv.2021.145815*

Gedefaw M, Soromessa T, Belliethathan S (2014). Forest carbon stocks in woody plants of Tara Gedam Forest: Implication for climate change mitigation. Science, Technology and Arts Research Journal 3(1):101-107. *https://doi.org/10.4314/star.v3i1.16*

Girma D, Wogi L, Feyissa S (2020). Effect of land use types on soil organic carbon stock at Sire Morose sub watershed, Hidabu Abote district of North Shoa Zone, central highland of Ethiopia. Science Research 8(1):1-6. *https://doi.org/10.11648/j.sr.20200801.11*

Girmay G, Singh BR, Mitiku H, Borresen T, Lal R (2008). Carbon stocks in Ethiopian soils in relation to land use and soil management. Land Degradation and Development 19(4):351-367. *https://doi.org/10.1002/ldr.844*

Hussein A (2022). Carbon stock potential across different land covers in tropical ecosystems of Damota natural vegetation, eastern Ethiopia. Applied and Environmental Soil Science 2022(1):414027. *https://doi.org/10.1155/2022/8414027*

Kan ZR, Chen Z, Wei YX, Virk AL, Bohoussou YN, Lal R, Zhao X, Zhang HL (2022). Contribution of wheat and maize to soil organic carbon in a wheat-maize cropping system: A field and laboratory study. Journal of Applied Ecology 59(11):2716-2729. *https://doi.org/10.1111/1365-2664.14265*

Karouach F, Ben Bakrim W, Ezzariai A, Sobeh M, Kibret M, Yasri A, Hafidi M, Kouisni L (2022). A comprehensive evaluation of the existing approaches for controlling and managing the proliferation of water hyacinth (*Eichhornia crassipes*): Review. Frontiers in Environmental Science 9:767871. *https://doi.org/10.3389/fenvs.2021.767871*

Kendie G, Addisu S, Abiyu A (2019). Biomass and soil carbon stocks in different forest types, northwestern Ethiopia. International Journal of River Basin Management 19(1):123-129. *https://doi.org/10.1080/15715124.2019.1593183*

Lahtinen O (2022). Comparing carbon footprint of maize production in low-input, high-input, and agroforestry systems in Zambia. *http://urn.fi/URN:NBN:fi:hulib-202202221336*

Marelign MA (2022). Estimating and mapping woodland biomass and carbon using Landsat 8 vegetation index: A case study in Dirmaga Watershed, Ethiopia. Computational Ecology and Software 12(2):67. *https://doi.org/10.3997/2214-4609.20215521130*

Mengist W, Soromessa T, Feyisa GL (2023). Responses of carbon sequestration service for landscape dynamics in the Kaffa biosphere reserve, southwest Ethiopia. Environmental Impact Assessment Review 98:106960. *https://doi.org/10.1016/j.eiar.2022.106960*

Mugabowindekwe M, Brandt M, Chave J, Reiner F, Skole DL, Kariryaa A, Igel C, Hiernaux P, Ciais P, Mertz O, Tong X, Li S, Rwanyiziri G, Dushimiyimana T, Ndoli A, Uwizeyimana V, Lillesø JPB, Gieseke F, Tucker CJ, … Fensholt R (2022). Nation-wide mapping of tree-level aboveground carbon stocks in Rwanda. Nature Climate Change 13(1):91-97. *https://doi.org/10.1038/s41558-022-01544-w*

Mulat Y, Kibret K, Bedadi B, Mohammed M (2021). Soil quality evaluation under different land use types in Kersa sub-watershed, eastern Ethiopia. Environmental Systems Research 10:1-11. *https://doi.org/10.1186/s40068-021-00224-6*

Muñoz-Rojas M, Jordán A, Zavala LM, De la Rosa D, Abd-Elmabod SK, Anaya-Romero M (2012). Organic carbon stocks in Mediterranean soil types under different land uses (Southern Spain). Solid Earth 3(2):375-386. *https://doi.org/10.5194/se-3-375-2012*

Olorunfemi IE, Fasinmirin JT, Olufayo AA, Komolafe AA (2020). Total carbon and nitrogen stocks under different land use/land cover types in the Southwestern region of Nigeria. Geoderma Regional 22:e00320. *https://doi.org/10.1016/j.geodrs.2020.e00320*

Olorunfemi IE, Olufayo AA, Fasinmirin JT, Komolafe AA (2021). Dynamics of land use land cover and its impact on carbon stocks in Sub-Saharan Africa: an overview. Environment, Development and Sustainability 24(1):40-76. *https://doi.org/10.1007/s10668-021-01484-z*

Onrizal RH, Kusuma C (2020). Allometry of biomass and carbon stock of planted *Eucalyptus grandis* forest in Toba highland. Proceedings of the International Conference of Science, Technology, Engineering, Environmental and Ramification Researches 1:129-131. *https://doi.org/10.5220/0010102401290131*

Ouyang X, Lee SY (2020). Improved estimates on global carbon stock and carbon pools in tidal wetlands. Nature Communications 11:317. *https://doi.org/10.1038/s41467-019-14120-2*

Pellikka PKE, Heikinheimo V, Hietanen J, Schäfer E, Siljander M, Heiskanen J (2018). Impact of land cover change on aboveground carbon stocks in Afromontane landscape in Kenya. Applied Geography 94:178-189. *https://doi.org/10.1016/j.apgeog.2018.03.017*

Raihan A, Ara Begum R, Mohd Said MN (2021). A meta-analysis of the economic value of forest carbon stock. Malaysian Journal of Society and Space 17(4):321-338. *https://doi.org/10.17576/geo-2021-1704-22*

Shiferaw H, Kassawmar T, Zeleke G (2022). Above and belowground woody-biomass and carbon stock estimations at Kunzila watershed, Northwest Ethiopia. Trees, Forests and People 7:100204. *https://doi.org/10.1016/j.tfp.2022.100204*

Sintayehu DW, Belayneh A, Dechassa N (2020). Aboveground carbon stock is related to land cover and woody species diversity in tropical ecosystems of Eastern Ethiopia. Ecological Processes 9(1):1-10. *https://doi.org/10.1186/s13717-020-00237-6*

Taddese G, Seyum S, Mebrate T (2019). Land use land cover changes on soil carbon stock in the Weshem Watershed, Ethiopia. Forestry Research and Engineering: International Journal 3(1):24-30. *https://doi.org/10.15406/freij.2019.03.00074*

Tesfaye MA, Gardi O, Bekele T, Blaser J (2019). Temporal variation of ecosystem carbon pools along altitudinal gradient and slope: the case of Chilimo dry afromontane natural forest, Central Highlands of Ethiopia. Journal of Ecology and Environment 43(1):17. *https://doi.org/10.1186/s41610-019-0112-9*

Tifafi M, Guenet B, Hatté C (2018). Large differences in global and regional total soil carbon stock estimates based on soil grids, hwsd, and NCSCD: intercomparison and evaluation based on field data from USA, England, Wales, and France. Global Biogeochemical Cycles 32(1):42-56. *https://doi.org/10.1002/2017gb005678*

Tilahun E, Haile M, Gebresamuel G, Zeleke G (2022). Spatial and temporal dynamics of soil organic carbon stock and carbon sequestration affected by major land-use conversions in Northwestern highlands of Ethiopia. Geoderma 406:115506. *https://doi.org/10.1016/j.geoderma.2021.115506*

Toru T, Kibret K (2019). Carbon stock under major land use/land cover types of Hades sub-watershed, eastern Ethiopia. Carbon Balance and Management 14(1):7. *https://doi.org/10.1186/s13021-019-0122-z*

Tumushabe JT, Turyasingura B, Chavula P (2023). The sustainability of carbon markets for climate-smart agriculture among smallholder farmers in Uganda. Asian Journal of Research in Agriculture and Forestry 9(4):337-345. *https://doi.org/10.9734/ajraf/2023/v9i4263*

Ulsido MD, Alemu E (2014). Irrigation water management in small scale irrigation schemes: the case of the Ethiopian rift valley lake basin. Environmental Research, Engineering and Management 67(1):5-15. *https://doi.org/10.5755/j01.erem.67.1.6240*

Wola AW (2023). Review on the above and below ground biomass and carbon stock estimation options for trees and forest resources: within and around Mago national park, southern region of Ethiopia. Ethiopian Journal of Environmental Studies and Management 16(2):235-235. *https://ejesm.org/doi/v16i2.9*

Wolka K, Biazin B, Martinsen V, Mulder J (2021). Soil organic carbon and associated soil properties in Enset (*Ensete ventricosum* Welw. Cheesman) - based homegardens in Ethiopia. Soil and Tillage Research 205:104791. *https://doi.org/10.1016/j.still.2020.104791*