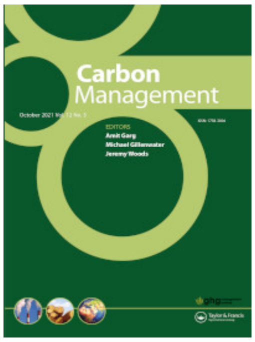

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REVIEW ARTICLE

Carbon sequestration and storage value of coffee forest in Southwestern Ethiopia

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ABSTRACT

The purpose of this research is to determine the amount and value of carbon stock in Southwestern Ethiopia's coffee forest from 1978 to 2050, as well as carbon sequestration from 1988 to 2050. Different time-series satellite data were acquired and classified into land-use categories using ArcGIS and ENVI 5:0, followed by IDRISI forecasts up to 2050, and finally modeling with INVEST. Data were collected within the plot constructed in a systematic random sampling manner using quadrates 20 m X 20 m. The social cost of carbon (US$12/ tCO_2e) used to estimate the monetary worth of the services. Forest conversion anticipated to reduce the carbon stock by 1.86 Mt by the end of 2050, from 65.8 Mt in 1978 to 7.01 Mt in 2018. The rate of Carbon sequestration was 2.1Mt/year at the end of 1998, and it will be reduced to 1.49Mt/year by the end of 2050. Overall, 121.1Mt of CO_2 is sequestered over 63 years, but there was also emission from deforestation and service loss (84.4Mt), resulting a net sequestered CO_2 of 36.6Mt by the end of 2050. The total elemental carbon stock value in 1978 was $2. 896 billion, this will be reached $2.5billion ($9.175 billion CO_2e) at the end of 2050. The value of sequestration will be estimated at $1.715 billion, but with a value loss of $1.153 billion, the net sink value from 1988 to 2050 will be $0.6 billion. In general, these findings show that the forest region will have a total storage and sequestration value (CO_2e) of $9.775 billion by the end of 2050. The carbon worth in this forest area is thus a good indicator of the importance, and thus the value estimate here may well persuade policymakers to revise their forest-related policy and provide site-specific information to preserve this remnant forest.

KEYWORDS
Carbon sequestration; carbon stock; coffee forest; value

Introduction

The earth's temperature is expected to rise by 1.5–5.88 °C [1] during the twenty-first century. This is due to greenhouse gas emissions caused by anthropogenic activity, including land-use change in the case of deforestation [2]. Terrestrial habitats, on the other hand, significantly contribute to climate change mitigation by sinking greenhouse gases [3,4], with forests playing a significant role in carbon storage in the given bio-network structure and carbon sinking in the given time series processes [5,6].

The moist evergreen forest of Southwestern Ethiopia has a long history; as a result, habitats accumulate more carbon per hectare [7] but traditionally converted to other land covers at an annual rate of 8% [8]. The forest, which is also a source of *Coffea arabica,* serves as a gene pool service and is regionally significant due to its location in the Baro-Akobo basin [9].

These have a great contribution to fauna and flora conservation, erosion protection, nutrient cycling, and climate change mitigation [10,11]. Forests in the Baro catchment are floristically richer which lie at lower to higher altitude (650–1900masl) the tree species are *Trichilia degeana, Trilepsium madagascerensis, Ficus exasperata, Cordia africana, Croton machrostachyus, Eugenia bukobensis, Strychnos mitis, Aningeria altissima, Anthocleista schweinfurthii, Celtis philippensis, Elaeodendron buchananii, Garcinia huillensis, Manikara butugi, Morus mesozygia*, and which belongs to highland forest [12] , similarly our identification also presented (Appendix A). The other forest found in this region is midland forest, which comprises, *Ficus spp*, and *Syzygium guineense* followed by small trees and bushes includes *Galinera coffeodes* and ground stratum includes local spices *Aframomum korarima*, turmeric's and long pepper. This biomass, has a vital role in carbon storage

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and sequestration, and preservatives of soil organic carbon, under the floor [13].

The dynamics of land cover, on the other hand, contribute significantly to greenhouse gas emissions into the atmosphere, primarily from farmed tropical soils [12]. The forest of southwest Ethiopia is a solution for reducing CO_2 emissions from forest ecosystems [14]. This is one of Ethiopia's remnant and buffer zones of moist evergreen Afromontane forests, which cover a large area [15]. Worldwide, research on Carbon stock conducted majority indicated that Carbon sequestration and storage in the terrestrial ecosystem was greatly reduced in the case of several factors [16].

Particularly in Ethiopia, the Carbon storage and sequestration quantity and values commonly estimated at the national level, rather than location-specific, this all does not bring changes to the mind of the local governance, policymakers and the local community, also not reduce the pressure on the natural forest [14] and [17]. Furthermore, previous studies revealed varying results, for example, Ethiopia's Forest Reference Level (EFRL) estimated aboveground biomass carbon 100 C tons/ha [18], global forest resource assessment technical report on Ethiopia (UNFCCC, 2020) stated 57–58.5 C ton/ha and Ethiopian Forest Resources Current Status 106 C t/ha reported [19] and in Kenya also very variable outcomes [20].

Similar studies were conducted in Southwestern Ethiopia by Oumer [21], but only at a higher elevation; however, this study differed because it included a lower elevation. The overall carbon value of the forest identified and assessed to close the variability gap, reduce CO_2 emissions through carbon sequestration, and stop deforestation. As a result, climate policy involvement implemented to reduce emissions and initiate policy incentives [22] and [16].

Previously, the community in and around the forest reflected a constructive approach that prioritized future benefits over immediate rewards. This is because their livelihood is based on honey, and the reachable forest area is divided by clan leaders, with each stratum of the forest having its illegal owner. They considered this forest to be sacred, and it was not deforested or destroyed like an Ethiopian church forest, but it used as a source of materials and for the placement of beehives (Dukehs personal communication, 2018 Guraferda).

The destruction began in 1988 when the Bebaka plantation started, according to clan leaders, during the Derg regime. Currently, over 100 licensed agri-business investors are beginning to work, all of which is reliant on the forest resource [23]. The investors are thinning or completely removing the forest, which has a significant impact on the local community, causing them to push and compute the forest and pledge to divert the natural forest, in which case the society's choice has been transformed [8]. This particular region is one of Ethiopia's forest priority areas (FPA), and its carbon value and quantity have never been evaluated previously [24].

We hypothesized that the ecosystem services value of carbon is very high and that mapping, quantification, and valuation of carbon in this virgin forest is critical for sustainable forest management. As a result, this study is very important for the area because it provides valuable site-specific information for forest conservation.

(1) Estimated carbon is creating an insurance buffer for reducing emissions in the event of deforestation and increasing sequestration as a result of concerned focus (2) Obtain certification for the area, after which carbon can be sold to generate funds for community benefit. (3) initiates a dialogue between scholars (on the available carbon value), policymakers (to revise forest-based investment policy), communities and associations (following the Protective and Productive approach), and then shifts society's preference to future benefits over immediate benefits.

(4) The amount of carbon stored (present and future) as well as the loss or sequestration in ton/ha will be mapped, and (5) the overall economic worth of the carbon stock will be determined (6) Importantly, the net flow of value ($/ha) of carbon sequestration between the present and the future, based on the social cost of carbon and land use land cover change, will be assessed from 1988 to 2050 projection scenarios.

Therefore, the objectives of this study are (i) to estimate the quantity and value of the carbon stock based on the land use land cover change category of different time serious (ii) to map and estimate the carbon sequestration quantity and value from 1988 to 2050 projection scenario, thereby determine the carbon sequestration value coefficient.

Methodology

Study area

The study was conducted in the moist evergreen Afromontane forests of Southwestern Ethiopia, which is the home of Arabica coffee [25]. The area is found in the Bench Maji zone of three districts (Guraferda, South bench, and Sheko) (Figure 1)

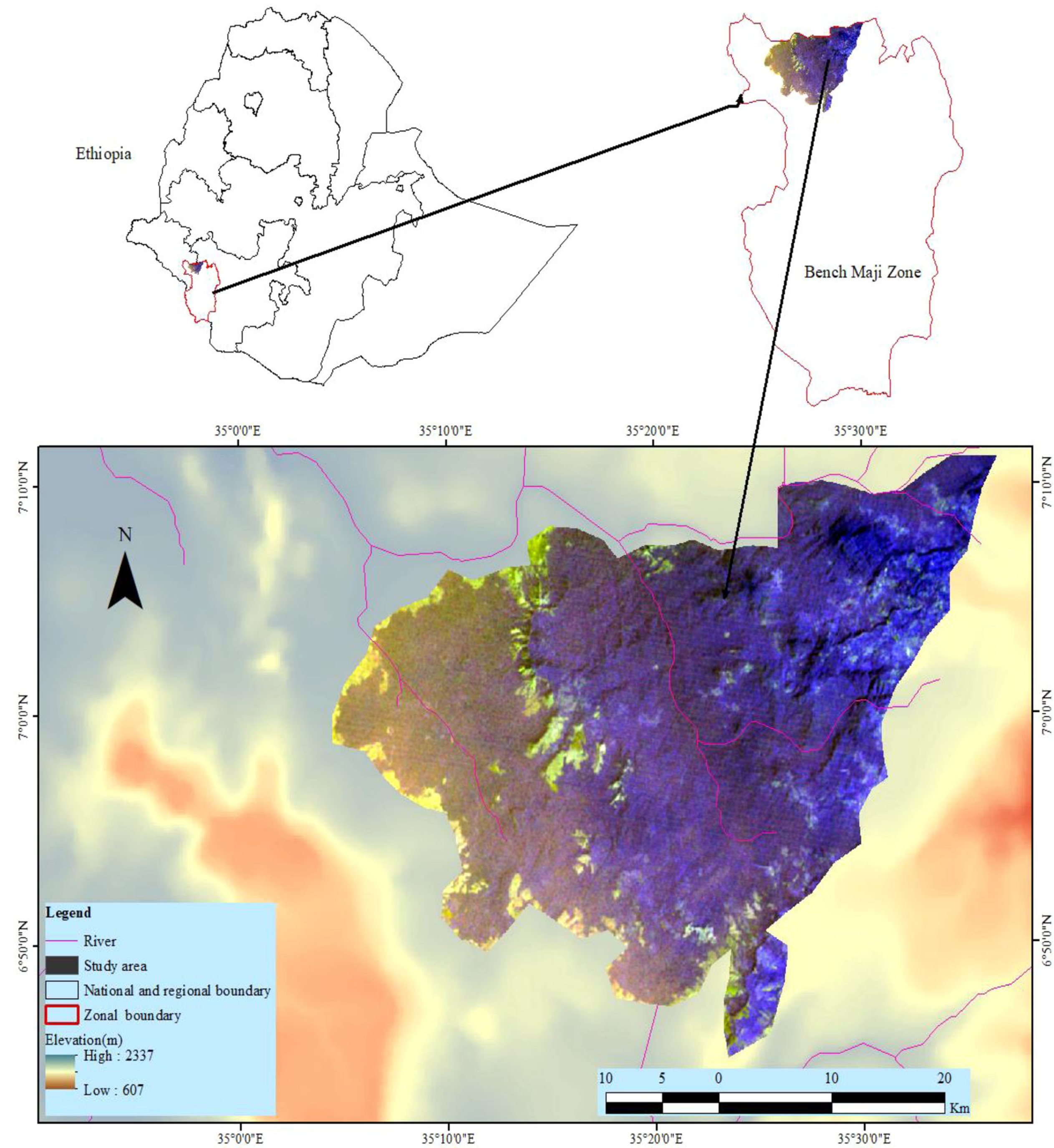

Figure 1. **Map of the study area.**

located from 5.33° to 7.26° latitude and longitudes from 34.88° to 36.14° with an elevation range from 690 to 2500 meters above sea level, which has 140000 ha of the natural forest [23]. It is far away 640 km from Addis Ababa and found under the Baro akobo basin and the buffer zone of the highland forests, besides that coffee forest Biosphere with spices is found in this area.

Land cover mapping and classification

A Set of different time-series satellite data in 1978, 1988, 1998, 2008, and 2018 were acquired from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov) of earth explorer with a different ID (Landsat 2,5,7and 8) and sensor (Multispectral scanner, Thematic mapper, Enhanced thematic mapper, and Operation Land Image) with a raw 055 and path 183 and 170 with a low cloud cover (0.5 to1%) with a spatial resolution of 30 × 30m. This was projected to the Universal Transverse Mercator (UTM), projection system zone 36 N. Forest map was collected from the regional and Zonal Forest conservation and natural resource office; this was Geo-referenced and developed a ship-fill using Arc GIs to clip the region of interest.

This study began with the classification of five land use categories after Quaic and Flash atmospheric correction of the Land-sat image. For this, the image was classified by pixel-based supervised image classification place in the year 2018 by ENVI 5:0 remote sensing software. Accuracy of the classification was made by collecting 450 ground-truth points using GPS.

This classification includes natural forest (which has less human intervention except for some resource collection and coffee is grown and regenerating naturally), semi-forest (which is similar to natural forest, but managed and thinned out at least once per year and coffee seedlings may be planted/regenerating naturally), and Coffee plantation (commercial coffee investment), grass/shrubs (primarily for wild animal grazing place, with some shrubs), and agricultural lands (covered by annual and perennial crop).

For the processes, ENVI 5:0 remote sensing software was employed and finalized by ArcGIS. We used IDRISI Land Change Modeler for the prediction of the 2050 future scenario (CA–Markov model), this all used for the input of INVEST for modeling the carbon storage and sequestration of the land use types.

Data collection

Transacts were laid out across the slope, in different length based on the forest extent, and the spacing between two transects along the slope varied from 2 to 4.5 km, and the distance between the two sampling plots was ranging, from 400 to 1000 **m**, this was depending on the slope and the land homogeneity of the forest.

We were setting the plot in a systematic random sampling method using quadrates of 20 m x 20 m that were distributed along the transect. All vegetation and soil data were collected in the entire place of the plot. Many researchers used similar sample sizes and shapes [26–33]. However, the number of sample plots varied in relation to the land use category that was included for forest and semi-forest 88, coffee investment 26, agriculture 19, grass and shrubs 17.

Carbon data

United Nations Framework Convention on Climate Change groupings carbon pools into five categories this was included aboveground biomass, belowground biomass, soil, dead wood, and dead organic matter [34]. This study designed to estimate this carbon pool based on the collected sample from the nested quadrat design approach for litter, herbs (non-woody with DBH $<$ 2 cm), and soil samples with inside 1 by 1 m frame (but all from different places in which the entire plot of tree measurements);10m $\times$ 10m for 2–10 cm DBH (shrubs) and dead wood, again DBH $\geq$10 cm counted in the entire sample plots of 20m $\times$ 20m. We measured the DBH at 1.3 but for multiple stems below the collar diameter or at 1.3 m, following the World Agroforestry Centre (ICRAF) irregular tree diameters measurement methods [35].

For growth abnormalities, we followed Rain for protocols [36,37], and for coffee, we used other methods [38]. The plant heights were estimated based on the observed angle on the top of the tree and the distance of the reader from the tree by using clinometers and this was computed by standard trigonometric relationships [39]. We used the appropriate revised non-destructive allometric equation recently developed for tropical vegetation for trees $\geq$5 cm diameter [40]. Based on this the aboveground live biomass (AGB, kg) were estimated as a function of DBH (cm), height (H, m), and wood-specific gravity (ρ, g/cm^3).

$$AGB = 0.0673x\left(pD^2H\right)\ 0.976 \tag{1}$$

Below ground biomass (BGB), estimated from root-shoot ratios (R/S) by taking 25% of above-ground biomass [41,42], and total carbon is 47% of the biomass [43]. However, for trees 2–5cm diameter, another allometric equation was used developed for the tropical area [44–47]. The estimation per 400 m^2 plots of each species and the summation of the above-ground mass of all the trees at the sample point was converted into hectare. Others also used the same plot area and procedures [26, 32,33, 48–50] and allometric formula [28, 44] for tropical forest and for Ethiopian Afromontane coffee forest [25].

Any live vegetation in this study below 2 cm DBH was considered as non-woody above-ground biomass [19]. We used the frame method (1m $\times$ 1m) placed at the four corners and the center of the sample plot, non-woody vegetation inside the frame was collected. The sub-sample was measured and taken into Mizan Plant regional laboratory and oven-dried at 75 °C. Based on dried mass, the wet to dry ratio of the sub-sample was estimated and this converted into plot and hectare bases.

We measured standing deadwood (with all parts except the leaves) similarly with live tree measurement steps. However, for measuring standing deadwood with big branches alone and other deadwood types, we were following the practice of others [50–52] 3% reduction.

We obtained Wood Specific gravity at the species level from the Ethiopian natural resource and the Global Wood Density Database [40]. We identified the species, but, for those unknown species we were taking to Addis Ababa University National Herbarium and identified to the species level using the Voucher specimens were deposited. We considered in this study the dead organic surface materials less than 10 cm diameter as a litter, and then this sample collected in the frame of 1m × 1m in the four corners and the center. The sub-sampled was taken to laboratories, for oven-dry, finally, the dry mass per plot and then per hectare was calculated. Soil sample (150) was collected from a 1 m^2 frames, from 0–20 cm, 20–40 cm, and 40–60 cm soil depth. The sub-sample was taken and this was air-dried, sieved, and ground and 100 g were taken into Tapi regional soil laboratory for carbon analysis. For soil bulk sampling, we used a core sampler with a similar depth of soil carbon sample. The bulk density of the composite sample was determined in the laboratory. This was oven-dried at 105 °C, and the dry weight and bulk density were calculated. To calculate the soil carbon stock, the volume of the soil was calculated (area by depth) and then multiplied by bulk density, followed by the fraction of carbon (%).

During transect sampling, we discovered cropland (including coffee), which we treated as woody, and thus the carbon stock was measured similarly to the forest woody and non-woody procedures described above.

The amount of carbon stored in annual cropland, on the other hand, is negligible because the gain is assumed to be equal to biomass losses from harvest and mortality [43], and then soil carbon and trash crop residue were estimated based on litter and soil attributes. Carbon in the grass and shrub categories were measured using the same procedure as for soil, litter, and herbal biomass [42], and for shrub biomass, we used a 5m × 5m plot to collect aboveground biomass using the same defined methodological specifications of others (49). Carbon accounted for 47% of aboveground biomass.

Modeling approach

We used the InVEST model to map carbon in the various poles of the forest area, based on the categorized image and the acquired carbon data. We then indicated the stored carbon, as well as mapped the sequestered or lost carbon over time. However, this model has also a limitation, since assumed that LULC types are fixed storage level equal to the average of measured storage levels within that LULC type, the only stock changes are due to changes from one LULC type to another (not change, have a sequestration value of 0), because incremental and regrowth is not considered. The valuation result of InVEST also only indicates the future value, not for current conditions [53]. Based on this the annual value flow of the sequestration and storage services were calculated with excel following the appropriate formula.

Climate regulation service and Dis-Service modeling

Accounting of carbon storage services

The most widely recognized ecosystem service is forest carbon sequestration and storage [43]. Climate change mitigation and a key ecosystem benefit provided by forests are the reductions of released carbon and the conservation of carbon in storage [54,55]. Human interventions influenced forest cover change [56], posing a significant challenge to carbon storage and biodiversity conservation [37].

The amount of carbon stored in each land use category over time was calculated using a comprehensive approach that included a sum of AGB, BGB, soil, and dead organic matter polls placed on currently collected data. This was related to the land use category classified map (Tabel2). A periodic accounting method was used to compute decadal stock variation with the assumption of net sequestered carbon increment based on the 2018 collected data scenario.

We assumed that the carbon stock of the previous decade had increased due to sequestration and that this leaner increment would continue on biomass until 2050, as many scholars suggested [57]. Finally, the carbon stock was calculated and mapped using the InVEST model based on land category.

Sequestration services

The carbon sequestration service is one type of regulating service provided by forests. In this study, the amount of carbon sequester by land-use class was estimated from 1988 to 2050 based on the gain and loss scenario. This determined by the increment of above-ground and below-ground biomass, resulting from natural growth (Table 1), and new plants regenerated. This method was the

Table 1. Annual increment and expansion parameter of land uses class.

Land use Class	Mean annual increment (m^3/ha/year)	Area expansion (regenerated) %	Biomass Conversion and expansion factor t/m^3
Natural forest	5.65	0.1	1.3
Semi forest	4	0	1.3
Grass /Shrubs	0.46	0.2	2.8
Coffee-plantation	1.5 coffee 3 for shade	0	1.3
Agriculture	0.22	0	

Source: [8,,58–60,90, 93-95].

most common approach used for Carbon uptake estimations [61–63].

However, during estimation, we did not include the sequestered carbon in soil and dead matter. We assumed that some of the soil pool also used to compensate for carbon outflow during soil heterotrophic respiration and stand consumption because litter is dynamic and cannot be considered a long-term carbon store [64, 92]. Many studies have found that stand respiration consumes a portion of carbon uptake in mature forests, influencing net yields in tropical forests [45]. Furthermore, increased plant inputs in tropical soil may alter the formation of organo-minerals, limiting the ability of tropical soils to sequestered additional carbon [65].

Carbon sequestration rates were computed based on the baseline year 1988 (Equation 2 to 6). The incremental coefficient, the expansion factor, and the regeneration ratio (Table 1) of the land category were collected from different sources [14, 59,60]. The naturally regenerated volume also calculated based on the expansion parameters for each land use category for forest (0.1%), shrub land (0.2%) [17, 66], however, we gave zero value for Semi forest, plantation, and agriculture because tinning, slashing and other management activity was taken and we considered no any plant was regenerated.

$$I_{Vt} = A(ha) \ * \ MAI\left(m^3/ha/year\right) \tag{2}$$

$$R_{at}(ha) \ = \ A(ha) \ * \ Rr \ (\%) \tag{3}$$

$$R_{vt} = \ Ra \ * IR\left(m^3/ha/year\right) \tag{4}$$

$$AGB \ (iv) \ = \ iv \ * \ BCEF \tag{5}$$

$$AGB \ (rv) \ = rv \ * \ BCEF \tag{6}$$

Ivt = total incremental volume, MAI = mean annual increment, Rat = total regenerated area,Rvt = total regenerated volume, IR = regeneration rate, BCEF = biomass conversion and expansion factor, AGB = above ground biomass. Below ground biomass is 25% of the AGB and 50% of the biomass is the total carbon and then total sequestered was calculated (Equation 7).

$$Total \ carbon \ sequestration = + \sum \ (CRvt) \tag{7}$$

Carbon dis-service modeling

The CO_2 release in to the atmosphere were computed based on emitted data using equation (8).

$$T_{CR} = \ (A_L * \ C_S) \ + (R \ * \ A_L * N_{sy}) \ + \ CLo \tag{8}$$

T_{CR}=Total Carbon Released, A_L= area Lost, C_s =Carbon Stock, R = Rate, N_{sy}= Number of Sequestration Years and Lo = loss from others.

The majority of the carbon emitted was from deforestation (we considered deforestation and good service loss all from natural forest), but there was also good service loss (Lo) from wood fuel, wood for house construction, and timber. This computed based on survey questionnaires from 250 respondents following “PEN” standards, guidelines, and procedures to make accurate, reliable, and valid results of the investigations, but with a certain modification that relevant to carbon similar to this author that did before [67,68]. Because these items are used, sold, and purchased on the market. We estimate the carbon loss due to full wood consumption based on daily consumption because one household (4.53 families) consumed an average of 1 women’s load/4 days.

This estimated 0.75 × 0.35 × 0.25 (0.066 m^3) ranged from 14 to 30 kg an average of 29.2 kg/ 4 days, 6.52 kg/days or 1.63 kg person/day (0.0037 m^3 person/day) 1.25565 m^3/capita/year or 594.95 kg, this multiplied by the total population directly benefited from the forest. Full wood transported to the nearby 11 towns also measured, weekly 3women’s (0.12 m^3) load/town (total 33) this converted into the year (1716 women’s load/ or 50107.2 kg). Similar, finding of annual per capita traditional fuel consumption of 601 kg [17] reported in Ethiopia.

The households on the forest edge did not use charcoal to meet their energy needs, but they used it as a source of income, transporting and selling it in the nearby 11 markets. According to their estimation, two women’s loads (40 kg/market/day) were sold to the local market, which multiplied by the number of towns and then converted into annual. We assumed that the conversion efficiency of fuel wood to charcoal is 5 to 1 by weight, and 47% of this is carbon. To calculate the decade consumption, we used a population incremental rate of 2.5% per year [69] and energy demand growth information 2.8% [70].

The carbon loss by construction materials computed based respondent's estimate there are 43 Kebles (local administrative) within the extent of the forest, minimally 3new-house constructed and 2old houses repaired per year. The total round wood needed for one new house construction was 1. 5 × 1. 5 × 3 m (6.75 m^3) and one-fourth of this is enough for old house repairing (1.6875 m^3). This multiplied by the number Keble's directly benefited from the forest and converted into total mass (1 m^3=600kg). Totally 8.4375 m^3 for one Keble's, or 362.8125 m^3/year for the total were required. This indicated that 217687.5 kg/year harvested around the forest, and 47% of this is carbon. The decadal consumption was estimated based on 2.5%/year, the demand increment of the Zonal min, and the energy office scenario [69,71].

Carbon also lost in timber wood that's used for furniture and others, consequently, we estimated the timber volume based on the known species *Cordia africana*. These species dominantly consumed in the area for timber production. However, transported timber wood to the central market was negligible but, there are 44 furniture and woodworking shop that, found in 11 cities which directly benefited timber from the forest. One shop bay and used 6 *Cordia africana,* which is an average estimated volume of each 0.016 m_3 (2 × 0.02 × 0.4 m^3) timber per week.

This was converted on a yearly basis and multiplied by the related wood density and the number of shops to calculate the total volume harvested from the forest. We used the conversion factor (a mean root/shoot) as specified above for below-ground biomass. A total of 0.848 kg ×6 of *Cordia africana* was required, which equates to 0.73 kg per day or 265.3 kg per year per shop. Currently, 11673.2 kg of timber is used per year in 44 shops, and the total weight of carbon has been calculated.

The total estimated shop was 3 in 1988, 11 in 1998, 21 in 2008 and now 44, this will be rise to 54 in 2050 [23], we used this scenario for a decade of consumption. The forest was, not subjected to fires, thus this loss was not included, however, insect attacks, diseases and pest infestation was expected, hence, we adapted the other method, 0.031% of damage and stand mortality 0.031% [14, 72]. For the loss of harvest damage (fuel wood and wood for charcoal) 5%, for timber, and for construction wood 12. 5% of the volume harvested was used [70, 72,73]. Finally, net carbon sequestration was computed (Equation 9).

$$\text{Net } CO_2 \text{ Sequestered} = \text{Sequestered} - \text{Releasedx}3.67 \tag{9}$$

Valuation of carbone storage and sequestration

The monetary valuation of regulation service in this study was done by the social cost of carbon (SCC) method, a commonly employed method grounded on the expected value of carbon-storing today by avoiding future damages, however, valuation based on the market price was difficult because prices were strongly dependent on the set-up of the market. The SCC was low before 2010 and also varies from 10 in 2010 to 26 for 2050.

For that reason, we used a SCC presented by the US government standard value (US\$12/tCO_2e or \$44 for C, in 2007 dollars unit at 5% discount rate), as adjusted in 2013(Interagency Working Group on Social Cost of 2013, updated in 2016). The monetary value was estimated based on two approaches. The first approach was estimating the carbon stored value in the forest at any given time. This was done directly without computing discounting rate (equation 10) similarly to the natural capital project computed approach (Sharp *et al.*, 2016).

$$Carbon\ density\ (5\ pools)\ (ton/ha)\ Area\ (ha)x\ (cost/ton) = Value \tag{10}$$

The second approach was to value sequestration (Beaumont *et al.*, 2013). Because InVEST can only estimate land conversion but not another uptake, we used the standard calculation procedure to calculate the total service flow from 1988 to 2050. Based on this, the net present value approach was used to estimate the value of the change in carbon uptake over time, and the coefficient value (\$/ha) was determined.

$$NPV^t = \sum\nolimits_t^1 Ct/(1+r)^t \tag{11}$$

C = Net benefits in year t, r = Discount rate

Results and discussion

The classification accuracy of the Landsat image based on the collected ground truth (450 points) by ENVI 5:0 remote sensing software (1978, 1988,

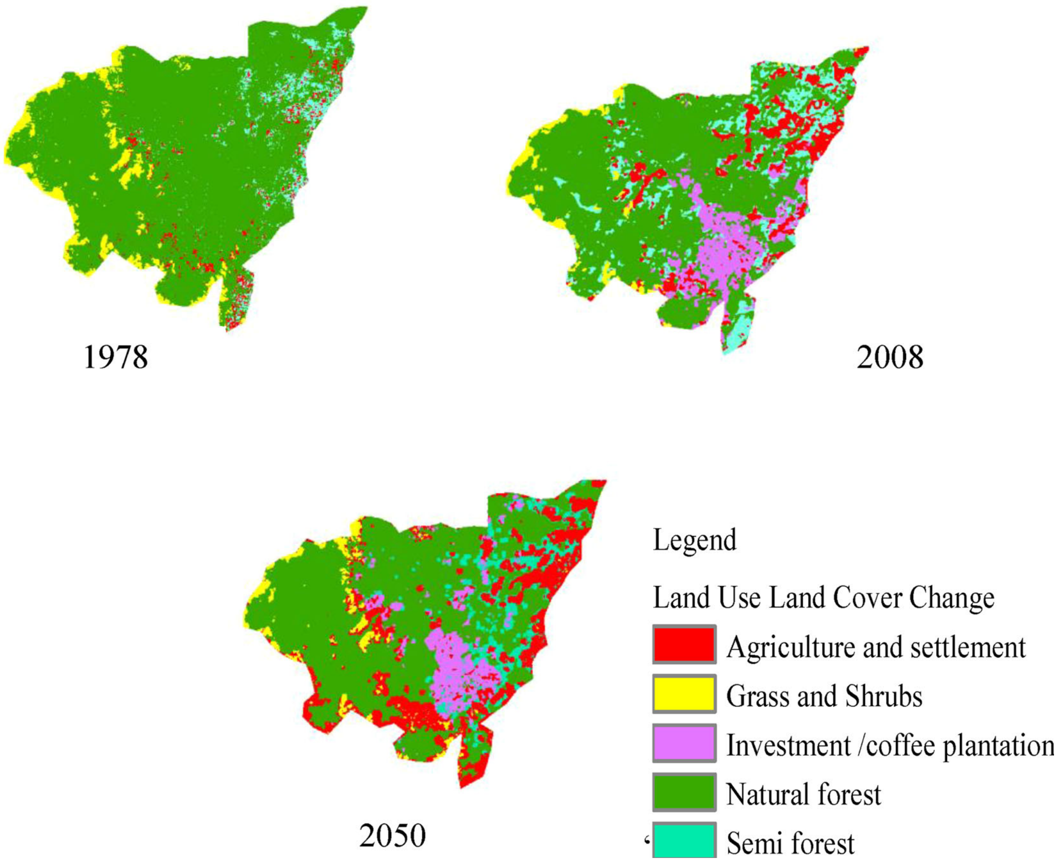

Figure 2. **Land use land cover change map in 1978, 2008 and predicted 2050.**

1998, 2008, and 2018) and IDRISI for prediction of the 2050 future scenario ranged from 89 to 92%, and the Kappa coefficient ranged from 0.87 to 0.95, indicating that the classification met the accuracy and nearly perfect agreement (Figure 2). Therefore, the estimated carbon quantity and value of the study area was accurate, thus, we hypothesized that the carbon stock and sequestration value of the southwestern Ethiopia coffee forest would be high,

Land cover change

The impact of land use/land cover change (LULC) from 1978 to 2050 (Table 2) affected the carbon stocks in the study area. This result showed a 35.1% decrease in natural forest coverage over the last three decades. This decreased by 11052.6 ha between 1978 and 1988, 22080.6 ha between 1988 and 1998, 3234.4 ha between 1998 and 2008, and 8728.58 ha between 2008 and 2018. This loss will be continued and reduced by 10992.53 ha from 2018 to 2050, which predicted an average of 779.01 ha/year (Figure 2). This result is similar to the earlier findings of 36% forest covers loss in Southwestern Ethiopia [74–76]. Conversely, agriculture and investment increased except for grassland, which reduced. This inter-period change had a significant impact on carbon uptake and, as a result, had a significant impact on global warming due to carbon emissions [77].

Carbon stock change

The highest carbon stock recorded in this study was from a natural forest (461 t/ha), followed by a semi (396 t/ha) and grassland (286 t/ha). Agriculture also had a higher carbon stock (246.5 t/ha) when compared to similar cropland that had recently been converted to cultivation due to deforestation. Many studies reported findings that were consistent with these findings on natural forest (496.26 t/ha) [78], 508.9 t/ha [79], in Ethiopia. The IPCC [42] also estimated 130–510 ton/ha of aboveground oven-dry biomass in Africa, with carbon accounting for 47%. The global carbon stock estimated to be in the range of 84–642 t/ha, and the carbon density of aboveground biomass for tropical moist forests estimated to be around 248 t/ha [30].

Similar to this area on natural forest [80], from 0 to 60 cm depth of soil, 365 Mg/ha of carbon on soil reported, likewise on the indigenous natural forest in Kenya on aboveground carbon (360), below ground carbon (90), and soil carbon (305) in tone/ha was informed [20]. But some also reported

Table 2. Carbon stock in 2018 (ton/ha) and area accounts (ha) from 1978 to 2050.

	Carbon ton/ha (2018)					Land cover change (ha)					
LULC Name	Above ground	below ground	Dead	soil	Total	1978	1988	1998	2008	2018	2050
Natural forest	176.3	44.0	14.7	233	461	128223	117170.4	97871.8	91855.2	83126.6	72134.1
Semi forest	124.9	31.2	9.5	236.7	396	7694.64	9847.81	22521.5	25303.7	25571.6	28443.0
Coffee plantation	53.63	13.4	3.2	191.6	259.4	0	3446	9289.31	12893.6	23456.1	31134.6
Grass and Shrubs	14.36	3.6	2.73	267.1	286.8	9190.0	7903.04	6005.14	4688.2	1234.3	444.7
Agriculture	6.73	1.6	0.16	238.1	246.5	4070.5	10810.89	13490.3	14437.2	15789.5	17021.5
					Total	149178.2	149178.1	149178.1	149177.7	149178.2	149178.1

Table 3. Carbon stock (tons) and Stock value ($) from 1978 to 2050 projection Scenario S = stock (tons) and V = value ($) in billions.

Land category		1978	1988	1998	2008	2018	2050
Natural forest	S	59117214.1	54021412.9	45123793.39	42349839.9	38325541.9	33257436.0
	V	2.6	2.4	2	1.9	1.7	1.5
Semi forest	S	3047539.1	4692447	8919865.2	10021783.42	10127899.7	11265134.5
	V	0.134	0.206	0.392	0.440	0.446	0.496
Coffee plantation	S	0	894099.16	2410204.3	3345373.4	6085925.6	8078201.4
	V		0.039	0.10	0.147	0.268	0.355
Grass and Shrubs	S	2635990.6	2266828.9	1722454.3	1343564.41	354041.1	127576.24
	V	0.12	0.099	0.075	0.059	0.016	0.006
Agriculture	S	1003708.8	2665749.2	3326438.1	3559924.7	3893374.9	4197173.7
	V	0.044	0.117	0.146	0.157	0.171	0.185
Total	S	65804452.6	64540537	61502755.3	60620485.89	58786783.2	56925521.8
	V	2.898	2.861	2.713	2.703	2.601	2.542

higher results, compared to these findings (614.72 t/ha), in which soil has a great share followed by aboveground biomass in Egdu forest [77]. Other also lower, 316 t/ha in Gara-Mukitar forest [81] in Ethiopia.

The carbon stock (Table 3) was directly affected by the land cover change (Table 2). The total forest carbon stock in 1978 (only forest) was 59117214.1 ton, which was greater than the current (2018) total LULC carbon stock (Figure 3). In the beginning, 65804452.6 tons of carbon were stored (1978) in all land, with the forest accounting for 90% of the stock. Totally, 7017669 tons of carbon have been released into the atmosphere in the last 40 years (175441.7 t/year), with an additional 1861261 tons expected in the next three decades. Similarly, many researchers indicated that changes in land cover had a significant impact on carbon stock [82,83].

According to our findings, converting this natural forest into a coffee plantation lost nearly 70% of the total biomass and thus carbon content (Tables 2 and 3), whereas Simi forest land converted into a coffee plantation lost 58% of the stock. The highest level of canopy cover found in wild and semi-forested areas provides a global benefit in terms of carbon storage [66, 84].

The amount of carbon loss from natural forest conversion into agriculture 96.2%, followed by Semi forest into agriculture 94.6%, thus agricultural expansion and investment growth at the expense of forest in this region were a great concern [31, 85] and affected the general bionetwork of this remnant forest [74].

Accounting of carbon sequestration and loss

Besides storing carbon, the forest provides regulating services; these services defined by the increment in growth and the carbon uptake by newly regenerated plants. The result of this computed based on (Tables 1 and 2) above, formulation on increment in volume and biomass expansion and conversion factor since 1988 using Equation (2 to 6) as indicated (Tables 4 and 5).

Our quantitative assessment indicated, the CO_2 sequestered at the end of 1998 were 21176043 ton (2117604 t/year) which had forest 86.3% share, however, the carbon sequestration quantity, affected through forest changes (Tables 2 and 4), carbon dioxide uptake from the atmosphere reduced and reach to 19967902tons at the end of 2008 (19967902 ton/year) and a rate of 1915934 t/year from the last eleven years to the present, recorded. This uptake will be significantly reduced in the future (31 years) and reach 58893126 tons (forest share71%) (Table 4 and Figure 4).

In total, 92411073tons of CO_2 sequestered and will be sequestered over the period from 1988 to 2050. This indicates a sequestration rate of 4.1 C t/ha/year (15.1 CO_2) for natural forest and 4 t/ha/year for semi-forest, which contributed more to remove CO_2 from the atmosphere. A similar

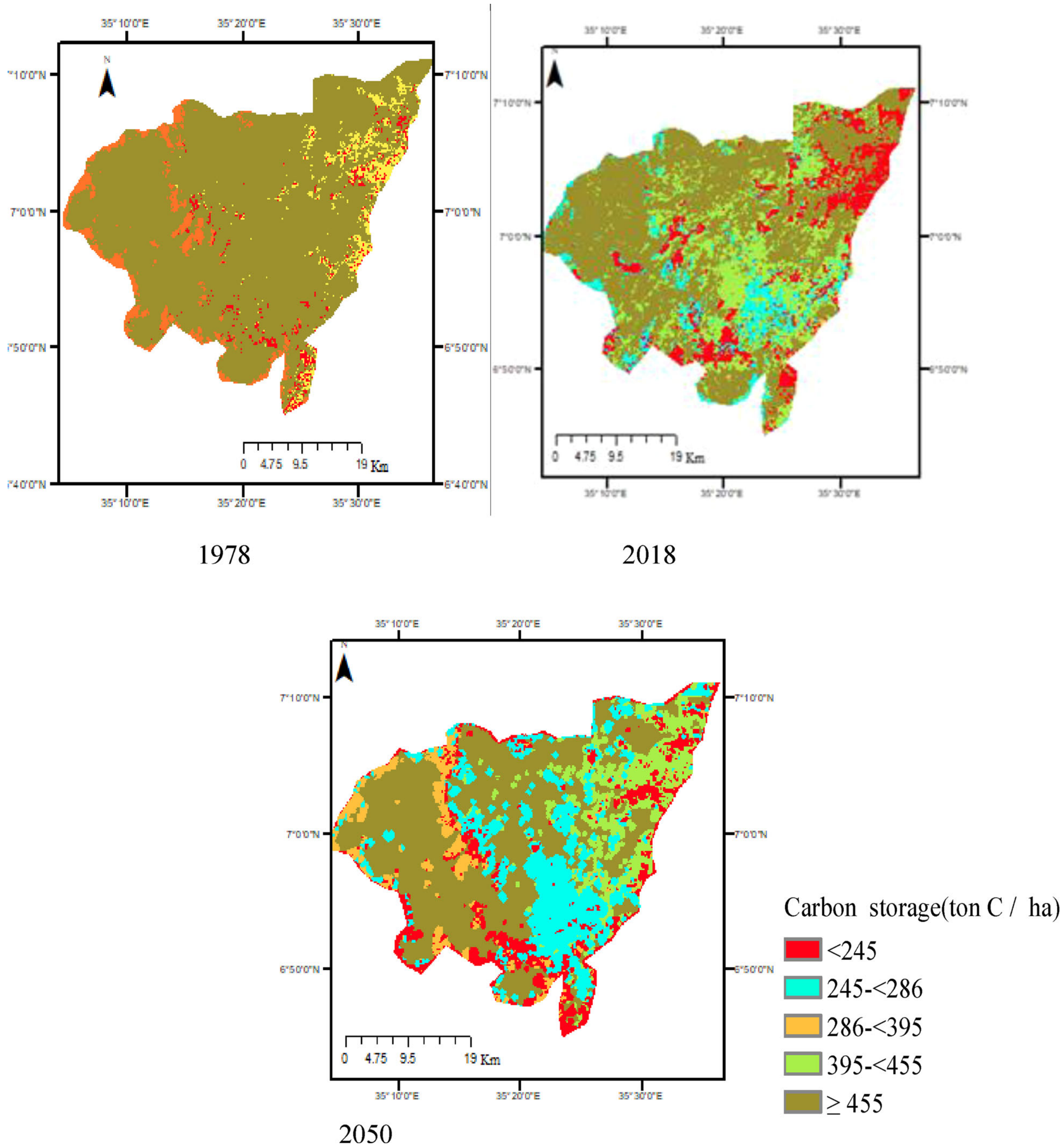

Figure 3. **Carbon storage change.**

estimate of above and below ground increment reported in southern Ethiopia [56, 86,87].

The major loss to the atmosphere in the last three decades and the future scenario were from area loss of the natural forest by deforestation (78072553 tons) followed by forest biomass reduction by other services (6366500 ton) (Table 5). Because this natural forest produced a large number of forest products each year (Sutcliffe, 2009), and deforestation in southwest Ethiopia had a significant impact on carbon loss [56,80, 88,89].

Our findings revealed that when natural forests converted into coffee plantations, their sequestration capacity reduced by 44%, but when natural forests converted into agriculture, it reduced by 90%. This was comparable to the reduction rate observed in this region over six years [87].

Valuation of carbon storage and sequestration

Our stock value estimation based on REDD reasoning [90] by direct valuation approach indicated that the total elemental carbon stock value in 1978 was $2.895 billion, with 94.5% forest share, so we considered this as the country National accounts [14]. However, due to deforestation in case of forest-based economic activity, this reached

Table 4. Decadal CO_2 sequestrations (tons).

LULC	Current scenario (31 years) 1988 to< 1998 10 years	1998 to $<$ 2008 10 years	2008 to $\leq$ 2018/11 year	Total	Future scenario (32 years) 2018 to $\leq$ 2050
Forest	18295559.2	16048928.7	16125712.2	50470199.6	41940874.1
Semi-forest	2123467.65	2835362.8	3337210.2	8296040.78	10322067.30
Coffee Planation	469935.7	818564.32	1341328.6	2629828.80	5809346.4
Grass	208250.6	173756.1	96235.14	478241.8	78208.213
Agriculture	78828.6	91290.8	174793.8	344913.4	742630.3
Total	21176043.1	19967902.6	21075280.2	62219227.5	58893126

Table 5. Long term CO_2 sequestration and release from, 1988 to 2050 and its monetary values by Net Present Value approach.

	C-sequestered	Lund use land cover: Forest 92411073.4	Simi forest 18618107.4	Coffee planation 8439174.9	Grass and Shrubs 556449.8	Agriculture 1087543.5	Total 121112352.4
Carbon loss	CO_2-released		–	–	–	–	
	Fuel wood	5417717.4	–	–	–	–	5417717.4
	Charcoal	86588.1	–	–	–	–	86588.1
	Construction wood	22208.2	–	–	–	–	22208.2
	timber	802.2	–	–	–	–	802.
	Charcoal harvest	176411.7	–	–	–	–	176411.7
	other harvest	661667.6	–	–	–	–	661667.6
	mortality	552.7	100.1	3.1	6.4	–	552.7
	diseases and pest	552.7	100.1	3.1	6.4	–	552.7
	Loss from deforestation	78072553	–	–	–	–	78072553
	Total-release	84439053	200.2	6.2	12.8		84439272.2
	Net CO_2 stored	7972020.4	18617907.4	8439168.7	556436.9	1087543.8	36673077.2
	CO_2 gain ton/ha/year)	15.1	14.9	10.1	1.82	1.39	
	NPV ($) gain	1.45 billion	0.220 billon	0.075billion	0.0013billion	0.001bilion	1.745 billion
	Loss values-deforestation ($)	1.066 billion	–	–	–	–	1.066 billion
	Loss values in others ($)	0.087 billion	4 thousand	0.044 thousand	0.485thousand	–	0.087 billion
	Net value ($)	0.293 billion	0.22 billion	0.075 billion	0.0013 billion	0.011 billion	0.60 billion
	Coefficient ($/ha/year) sequestration	817.01	583.41	213.2	166.17	44.5	–

$2.587 billion, an 11% decrease from the start in 2018 (Table 3). This will be continued and expected to reach $2.504 (9.175 CO_2e) billion at the end of 2050, a reduction of at least 4% from the present.

The net present value methodology used to assess the overall economic value Carbon sequestered by the land uses class (Tabel5). The total carbon value flows from 1988 to 2050 expected to be $1.766 billion, with forests being the largest contributor at $1.446 billion (81.5%) , followed by semi-forests at $0.22 billion (12.5%). However, when forest land converted into coffee plantations, the sequestration capacity of the biomass reduced, resulting in a $48 reduction in CO2 uptake value; however, when converted into agriculture, this was severe, resulting in a $164.52 loss per hectare conversion; a total 13.3% reduction in net sequestration value will be estimated at the end of 2050 as compared to the end of 1998.

The monetary value loss associated with forest conversion was $1.06 billion. The other natural loss (disease and mortality) and harvesting loss accounted for $0.086 billion dominantly from forests (98%). Based on this calculation, the net benefit after compensation of the loss will be $0.613 billion at the end of 2050. Comparable findings also reported for natural forests [14,22, 59, 91].

Conclusion

Forests help to mitigate climate change by storing carbon and removing CO_2 from the atmosphere. The southwest Ethiopian forest is one of the country's remaining forests and one solution to climate change. However, when engaging in various forest-based economic activities, policymakers undervalue the value of the forest. As a result, this study investigates the quantity and value of carbon stock (1978 to 2050) and sequestration (1988 to 2050) in this forest region.

The results show that the total land cover stored in 2018 is 58786783t of carbon (forest 90% share), with a monetary value of elemental carbon of $2.6 billion, which is less than the total land cover stored in 1978 by 7017669t (value $3.1 million) due to forest conversion.

This will be 56925521t by the end of 2050, worth $2.5 billion ($9.175 billion CO_2e), representing a $3.9 million decrease in stock value from 1978 to 2050. The total CO_2 uptake by the land

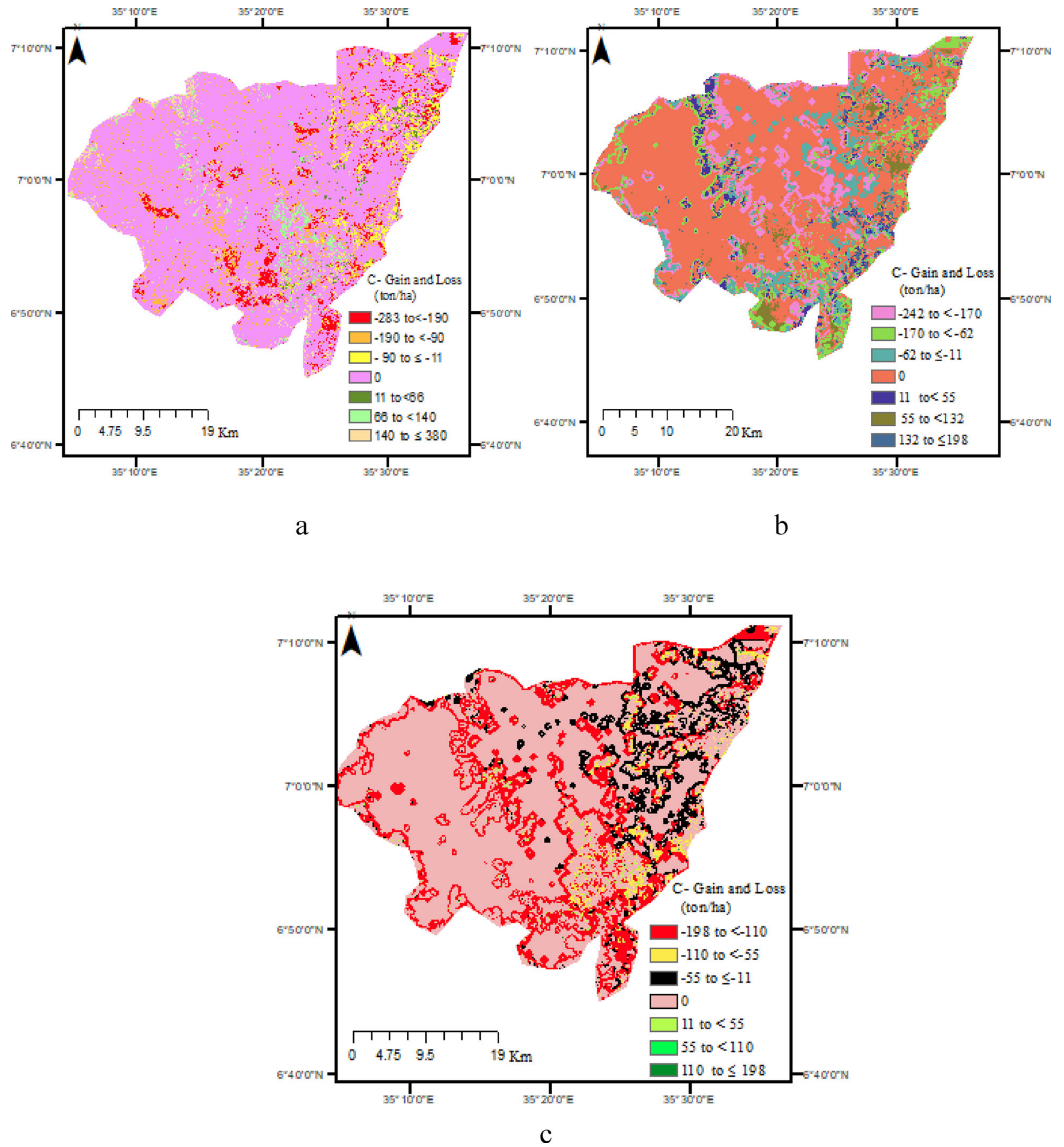

Figure 4. Carbon sequestrations rate based on LULC from 1988 to 1998 (a); 2008 to 2018 (b) and from 1988 to 2050 (c) 0 indicates not change its LULC type over time

cover from 1988 to 1998 is 21176043 tons (2117604 t/year), with the forest accounting for a large share of this, but the forest's sequestration capacity from 1988 to 2050 is 92411073t (1466842 t/year), with a \$1.745 billion gain but a \$1.153 billion loss due to deforestation and other factors, resulting in a net monetary value of \$0.6 billion. This demonstrates a 61% decrease in gain value as a result of long-term deforestation caused by agricultural expansion, forest-based investment, and other factors.

We conclude that the forest region will have a total of \$9.775 billion storage and sequestration value (CO_2e) at the end of 2050, but it is not only the carbon worth and also a home of many world economical crops like *Coffea arabica* with diverse fauna and flora. The estimated value here may then be used to persuade policymakers to revise their policies and develop site-specific conservation strategies to preserve Southwest Ethiopia's remnant evergreen forests.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix A. List of major (tree and shrubs) plant species obtained from the field data of the study area

No	Species name	Family	Habit of the Plant (Growth form)	Local name	
				name	language
1	*Coffee arabica (Linnaeus)*	Rubiaceae	shrub	Buno	Sheko
2	*Croton macrostachyus (Hochst.)*	Euphorbiaceae	tree	Wushe	Bench
3	*Millettia ferruginea (Hochst).*	Papilionaceae	tree	bibero	sheko
4	*Cordia africana (Lam)*	Boraginaceae	tree	Giqa	sheko
5	*Apodytes dimidiata (Mey.ex)*	Icacinaceae	Tree	Okam	sheko
6	*Dracaena steudneri (Schweinf*	Agavaceae	Tree	Banga	Bench
7	*Ekebergia capensis (Sparrman*	Meliaceae	Tree	Olanch	Mejenger
8	*Sapium ellipticum (Hochst.)*	Euphorbiaceae	Tree	Boska	Bench
9	*Grewia ferruginea (Rich)*	Tiliaceae	shrub	Grwa	sheko
10	*Trema guineensis (Schumum and Thonn)*	Combretaceae	Tree		
11	*Ekebergia capensis (Sparrm.)*	Meliaceae	Tree		
12	*Albizia grandibracteata (Taub)*	Mimosaceae	Tree	sat	Bench
13	*Acanthus eminens (Clarke)*	Acanthaceae	Tree	Ocha	Mejenger
14	*Albizia gummifera (Gmel)*	Acanthaceae			
15	*Albizia grandibracteata (Taub)*	Fabaceae	Tree	Zania	sheko
16	*Albizia lebbek (Linnaeus)*	Fabaceae	Tree	Zania	sheko
17	*Allophylus abyssinicus (Hochst)*	Sapindaceae	Tree	Shebebo	Bench
18	*Allophylus macrobotry (Rich)*	Sapindaceae	shrub	Gonu	Bench
19	*Prunes africana (Hook.f.) Kalkman*	R (osaceae	Tree	Ongaja	Bench
20	*Albizia anthelmintica (Rich)*	Fabaceae	Tree	Kerche	Bench
21	*'Manikara butjei (Chiov)*	Spotaceae	Tree	gayo	Bench
22	*Aspilia mosambicensis (Linnaeus)*	Asteraceae	Tree	Kirshu	Bench
23	*Bersama abyssinica (Fres)*	Melianthaceae	Tree	Toshka	sheko
24	*Bridelia micrantha (Hochst.) Baill.*	Euphorbiaceae	shrub	Ucham	Mejenger
25	*Carissa spinarum (Linnaeus)*	Apocynaceae	shrub	kwene	Mejenger
26	*Cassipourea malosana (Baker), Alston*	Rhizophoracea	tree	Gusha	sheko
27	*Celtis africana Burm. (Burm)*	Ulmaceae	tree	Dira	sheko
28	*Chionanthus mildbraedii (Gilg &. Schellenb).*	Oleaceae	tree	Maqua	Mjenger
29	*Trichilia emetic (Vahl.)*	Meliaceae	tree	Dapi	sheko
30	*Trilepisium madagascariense (De Candolle)*	Moraceae	tree	Guita	Mejenger
31	*Vepris dainellii (Pic. Serm.)*	Rutaceae	tree	Kaja	sheko
32	*Vernonia auriculifera (Hiern)*	Asteraceae	tree	Buzu	Mejenger
33	*Vernonia hochstetteri (Venho)*	Asteraceae	tree	Baytashu	Bench
34	*Teclea nobilis (Del)*	Rutaceae	tree	Gemu	Bench
35	*Syzygium guineense (Wall)*	Myrtaceae	tree	Mutku	Mejenger
36	*Solanum capsicoides (Allioni)*	Solanaceae	tree	Karue	Mejenger
37	*Solanecio gigas (Vatke)*	Asteraceae	tree	Deda	Bench
38	*Senna obtusifolia (Linnaeus)*	Fabaceae	tree	hanue	Mejenger
39	*Schefflera abyssinica (Hochst). ex A.Rich.*	Araliaceae	tree	Kabu	Bench
40	*Rytigynia neglecta (Hiern) Robyns*	Rubiaceae	tree	Mera	Bench

No	Species name	Family	Habit of the Plant (Growth form)	Local name	
				name	language
41	*Rothmannia urcelliformis* (*Thunb)*	Rubiaceae	Tree	Boko	
42	*Psydrax schimperiana (Rich)*	Rubiaceae	Tree	Qarcu	Bench
43	*Prunus africana (Hook)*	Rosaceae	Tree	Ota	sheko
44	*Polyscias fulva (Hiern)*	Araliaceae	Tree	Bata	sheko
45	*Pittosporium viridiflorum* (*Sims)*	Pittosporaceae	Tree	Deduninxi	Mejenger
46	*Phytolacca dodecandra* (*Linnaeus)*	Phytolacaeae	Tree	Gunja	Bench
47	*Phoenix reclinata* (*Jacq)*	Arecaceae	Shrub	Anco	Sheko
48	*Pavonia urens* (*Cav)*	Poaceae	Shrub		sheko
49	*Oxyanthus lepidus (Moore)*	Rubiaceae	Shrub	Bongu	sheko
50	*Ocotea kenyensis (Chiov.)*	Lauraceae	Tree	Hujuri	sheko
51	*Erythrococca trichogyne (Mull)*	Euphorbiaceae	Tree	Cicqa	sheko
52	*Ficues vasta* (*Forssk).*	Moraceae	Tree	Warka	sheko
53	*Ehretia cymosa (Thonn)*	Boraginaceae	Tree	Derma	sheko
54	*Ilex mitis (Linnaeus) Radlk.*	Aquifoliaceae	Tree	Disha	sheko
55	*Combretum paniculatum* (*Vent)*	Combretaceae		Nechoe	sheko
56	*Asparagus racemosus* (*Willd)*	Asparagaceae	Tree	Daro	sheko
57	*Hymenodictyon floribundum (Hochst. & Steud.).Rob.*	Rubiaceae	Shrub	Haygeni	Mejenger
58	*Artabotrys monteiroae (Oliv)*	Anonaceae	Tree	Caxu	sheko
59	*Grewia ferruginea (Rich)*	Tiliaceae	Shrub	Shorke	sheko
60	*Diospyros abyssinica (Hiern)*	Ebenaceae	Tree	Gbizit	Bench
61	*Dombeya torrida (Gmel.)*	Sterculiaceae	Tree	Bobco	sheko
62	*Maytenus gracilipes (Welw). ex Oliv.*	Celastraceae	Shrub	Shiku	Bench
63	*Harungana madagascariensis (Lam) ex Poir*	Clusiacea	Tree	Ashu	sheko
64	*Flacourtia Indica (Burm.) Merr.*	Bumo	Tree	Onge	Mejenger
65	*Dalbergia lacteal (Vatke)*	Fabac (eae	Shrub	kanju	Mejenger
66	*Isoglossa somalensis (Lindau)*	Acanthaceae	Shrub	kanju	sheko
67	*Traichilla dregerea (Sond)*	Meliaceae	Tree	Deshe	Bench
68	*Microglossa pyrifolia (Lam)*	Asteraceae	Shrub	kanju	Mjenger
69	*Rungia granndis* (*Anderson)*		Tree	Sekra	sheko
70	*Dracaena steudneri* (*Vand.) ex L*	Dracaenaceae	Tree	Osto	Mejenger
71	*Polycias ferruginea (Hiern)*	Araliaceae	Shrub	Wober	sheko
72	*Maesa lanceolata* (*Forssk.)*	Myrsinaceae	Tree	Tura	Mejenger
73	*Pouteria adolfi-friederici (Chiove)*	Sapotaceae	Tree	Kerero	Bench
74	*Lepidotrichilia volkensii (Gurke) J.-F.Leroy*	Meliaceae	Tree	Shahu	sheko
75	*Commiphora monoica* (Vollese)	Flacourtiaceae	Tree	Situ	Mejenger
76	*Ficussur forssk* (*Forssk.)*	Moraceae	Tree	Seeka	sheko
77	*Croton macrostachyus (Hochst). ex Delile*	Euphorbiaceae	Tree	Woshu	Mejenger
78	*Lepidotrichilia volkensii (Gürke) J.-F.Leroy*	Melastomataceae	Shrub		
79	*Mimusops kumme* (*Bruce)*	apotaceae	Tree		
80	*Solanecio gigas (Vatke)*	Asteraceae	Shrubs		
81	Pouteria altissima (Chev.)	Sapotaceae	Tree	gayo	Bench