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Modelling long-term attainable soil organic carbon sequestration across the highlands of Ethiopia

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Response to Reviewers:	08 July 2021 Prof. Dr. Luc Hens,

Editor-in-Chief, Journal of Environment, Development and Sustainability

Subject: Revised Manuscript ENVI-D-20-03177R2 – Abegaz et al. “Modelling long-term attainable soil organic carbon sequestration across the highlands of Ethiopia”, after minor revision, i.e., English language corrections.

Dear Prof. Dr. Luc Hens,

Thank you very much for your positive decision to accept our manuscript for publication after we have carried out English language corrections by a native English Language speaker.

We also would like to extend our thanks to the reviewers for reviewing our revised manuscript and their recommendation for publication.

Dear Prof. Dr. Luc,

Based on your advice, we hereby resubmitted the paper with language corrections by a native English speaker (the Co-author of the paper, Jo U Smith is a native English Speaker). We have highlighted using blue font the changes and added texts, while deleted texts are removed from the revised manuscript.

Yours sincerely,

Assefa Abegaz (on behalf of all co-authors)

Modelling long-term attainable soil organic carbon sequestration across the highlands of Ethiopia

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Modeling long-term attainable soil organic carbon sequestration across the highlands of Ethiopia

Abstract

The objectives of this study across the highlands of Ethiopia were (i) to characterize the association between soil organic carbon (SOC) stocks and biophysical variables, and (ii) to model and map attainable SOC sequestration associated with five improved land management practices. The spatial distribution of the SOC stock was studied using a multiple linear regression model driven by eight biophysical predictors. A widely used SOC model (RothC) was then used to model changes in SOC over the next 20 to 50 years of improved land management. Simulations were driven by the derived SOC stocks, pH and clay contents that are available in the ISRIC soils database at 250 m resolution and climate data from the "Enhancing National Climate Services Initiative" database. Organic carbon inputs to the model were estimated from the "Improved Crop Varieties Yield Register" of the Ministry of Agriculture and Livestock Resource and the Central Statistics Authority. After 50 years of conservation tillage with 80% of available manure applied to cultivated land, the total SOC stock increased by 169,182,174 t, which is 2.8 times higher than the stock increase with only 50% of available manure applied. Introduction of improved pasture species and measures to control soil erosion was an important source of net carbon sequestration in grasslands. Afforestation and reforestation of degraded landscapes and protection of natural ecosystems further increased soil carbon. This highlights the importance of improved land management practices to SOC sequestration, which in turn could enhance agricultural productivity, food security and sustainable development.

Keywords: SOC stock, improved land management, long-term simulated SOC sequestration, biophysical variables affecting SOC sequestration, RothC model.

1. Introduction

The soil carbon (C) pool holds 3 times the amount of C stored in the atmosphere and 4 times that in the biotic pools (Lal 2004). The soil serves as the link between C pools in the atmosphere, biota and oceans, acting as either a sink or a source of carbon dioxide (CO_2) and other greenhouse gases (World Bank 2012). Therefore, since land-use change is a major global source of CO_2, methane (CH_4) and nitrous oxide (N_2O) emissions (Xiao 2015), small changes in this large pool can have significant effects on the concentration of atmospheric CO_2 and hence climate change (Xiao 2015; Lal 2008).

Carbon sequestration in the soil requires the rate of accumulation of soil organic carbon (SOC) to be increased through sustainable land management practices while controlling practices that result in losses (Abera et al. 2020; Namirembe et al. 2020; Fusaro et al. 2019; Ramesh et al. 2019; Adimassu et al. 2018; Blanco-Canqui et al. 2018; Bass et al. 2000). Three measures exist for SOC sequestration; potential, attainable and actual, as defined by a physiochemical maximum limit for storage of C in the soil, the socioeconomic factors that limit the input of C to the soil system, and the current land management practices that reduce SOC, respectively (World Bank 2012).

Soil C sequestration depends on a number of soil forming factors, including soil physiochemical parameters, land-use, management, climate, topography, agroclimatic zone and time (Wiesmeier et al. 2019; Begum et al. 2017; FAO 2001). Soil C increases significantly with increasing percentage soil clay (Follett et al. 2012) because physical protection of organic matter by clays reduces the rate of decomposition (Xiao 2015; Dalal and Chan 2001). Soil pH controls the efficiency of decomposition of SOC by microbial enzymes, with optimum decomposition observed at a pH of about 6.7 (Xiao 2015; Dalal and Chan 2001). Increasing soil moisture to field capacity increases annual biomass production and net plant-derived C input to the soil, so potentially increasing the rate of C sequestration (Cotrufo et al. 2011; Zhou et al. 2008). However, increased soil moisture also increases microbial activity, so accelerating the rate of decomposition (Jobbagy and Jackson 2000). Increased mean annual temperature can result in higher plant biomass and so higher inputs of organic C to the soil (Xiao 2015), but increased soil temperature also facilitates faster microbial decomposition and greater loss of C through respiration (Follett et al. 2012; Canadell et al. 2007). Altitude and agroclimatic zone control the temperature and rainfall distribution in tropical highland regions, such as in Ethiopia, which in turn impact vegetation and crop growth, land-use options and human activities (IFPR and CSA 2006), so determining attainable SOC sequestration.

A range of improved land management practices have been suggested to increase attainable SOC sequestration in agricultural and natural ecosystems, and consequently to enhance soil health, food production and the resilience of ecosystem services to climate change (Fig.1A; Xiao 2015; World Bank 2012; Lal 2011; Feller et al. 2001). Forest and alpine vegetation ecosystems in the Ethiopian highlands contain more C stock per unit area than any other land-use (Abegaz et al. 2020). Therefore, protection of existing natural forest, alpine vegetation, closed bush-shrub-woodlands and swamps (Fig. 1A) is the least-cost and most recommended management option for conserving SOC stocks (World Bank 2012). Ethiopia has become a partner of the REDD + network, which aims to conserve existing forest carbon stocks (MEFCC 2018). Afforestation of barren lands and reforestation of degraded forest and bush-shrub-woodlands provide further methods for achieving long-term sequestration of C (FAO 2001). In 2019, with the “Green Legacy” initiative, Ethiopia has planted 4 billion seedlings (Abegaz et al. 2020), with the program continuing in 2020 and planting a further 5 billion seedlings.

FIGURE 1 HERE

Different options for grassland management can be adopted to increase attainable SOC sequestration (Fig. 1A). Controlled grazing could reduce land degradation, SOC depletion and ammonia (NH_3) emissions (World Bank 2012).

Introduction of more productive and deep-rooted grass species could support the restoration of degraded vegetation and increase above- and below-ground biomass production, which consequently can reintroduce large amounts of soil organic matter into the soil resulting in C sequestration (FAO 2017; World Bank 2012).

Different cropland management practices could be used to enhance rates of SOC sequestration (Namirembe et al. 2020; Fusaro et al. 2019). These include conservation tillage (with incorporation of more than 30% of crop residues into the soil (World Bank 2012)), application of manures and composts, use of crop rotations, adoption of improved crop varieties and controlled soil erosion (Fig. 1A). A meta-analysis by Abera et al. (2020) reported that implementation of conservation agriculture practices in Ethiopia showed significant increases of SOC (24%) and agricultural productivity (18%), and a significant decrease of soil erosion (45%). Application of animal manure to croplands is an age-old practice that has been commonly used in the highlands of Ethiopia to increase or maintain agricultural productivity. Use of organic manures as fertilizers has potential to maintain crop yields, while also increasing C inputs to the soil and avoiding potential adverse environmental impacts of chemical fertilizers (Lu et al. 2015; Reeve et al. 2012).

Finally, accelerated soil erosion due to misuse of agricultural land poses a serious challenge in both cultivated and grazing land in the highlands of Ethiopia (Shiferaw et al. 2013). Adoption of effective conservation measures to combat accelerated soil erosion could reverse soil degradation trends and increase attainable SOC sequestration (Chen et al. 2020; Adimassu et al. 2018; Hishe et al. 2017). Adoption of these practices also has multiple benefits to hydrological and nutrient cycling, soil quality, climate change mitigation and improved resilience of agricultural systems (Fig. 1B). Since the 1980s, a large-scale initiative in soil and water conservation practices has been underway in the highlands of Ethiopia (Kosmowski 2018; Engdawork and Bork 2014). Indigenous agricultural terraces are well-developed practices that are used in different parts of Ethiopia (Kosmowski 2018; Gebreslassie 2014), and so these have been included in the package of the Sustainable Land Management Program of Ethiopia (Abera et al. 2021). A study by Wei et al. (2016) reported that terraced plots were on average 11.5 times more effective at controlling erosion than non-terraced plots, which in turn enhanced SOC sequestration. A study by Chen et al. (2020) suggested that the increase in SOC sequestration attributable to terracing was on average 32.4%.

Many previous studies in different areas of the Ethiopian highlands have focused on changes in SOC associated with land use change. Local changes have been measured by Vågen et al. (2013), Chibsa and Ta' (2009), Freier et al. (2009), Girmay et al. (2008), Lemma et al. (2006), and Yimer et al. (2006). Regional scale losses were calculated by Abegaz et al. (2020), and Niles et al. (2010). Long-term dynamics have been investigated by Abegaz et al. (2016) and Abegaz and van Keulen (2009).

Most of modeling of SOC sequestration has been carried out at global scale, or in Europe and the USA (e.g. Husniev et al. 2020; Cagnarini et al. 2019; FAO 2019; Gomes et al. 2019; Morais et al. 2019; Begum et al. 2017; Wang et al. 2017a; Wang et al. 2016; Gottschalk et al. 2012; Liu et al. 2011; Barančíková et al. 2010; Smith et al. 2005). Application of modelling at regional and national scales in Africa is missing, in part because the spatial distribution of SOC is poorly defined and knowledge gaps remain in many regions of Africa. Specifically, to date, there has been no agroclimatic or land-use based modeling and mapping of attainable SOC sequestration associated with improved land management across the highlands of Ethiopia. Therefore, the objectives of this study were (i) to characterize the variation of SOC stocks as related to the variation of biophysical variables, and (ii) to model and map SOC sequestration attainable following 20 (2021-2041) and 50 (2021-2071) years of improved land management across the highlands of Ethiopia. The results of this study will help to inform stakeholders in environmental and agricultural development planning on how to enhance SOC sequestration, mitigate climate change, and increase agricultural productivity and food security across the highlands of Ethiopia.

2. Materials and methods

2.1. The study area

The Ethiopian highlands are situated in the Horn of Africa between 3.10 °N and 14.65 °N, and 34.52 °E and 43.36 °E. They are defined by elevations ranging from 1,500 to 4,620 m above sea level (asl) (IFPRI and CSA 2006). The area under this zone covers 37,710,846 ha, which is about 33% of the total land area of Ethiopia (Fig. 2). In Ethiopia, 33 different agroclimatic zones are defined (Dinku et al. 2014a,b; MoARD 2005), by overlaying elevation, length of growing period and thermal zones, following the FAO (1996) guidelines for agroecological zoning. The length of growing period and thermal zones were defined based on gridded mean monthly temperature, rainfall and evapotranspiration data at 4km resolution from 1983 to 2017, using data from nearly 300 meteorological stations and the MODIS land surface satellite data (Dinku et al. 2018). Elevation, length of growing period and thermal class layers were overlayed and combined spatially in a geographical information system environment to establish the agroclimatic zones at elevations over 1,500 m asl. Based on this operation, 26 agroclimatic zones were defined in the highlands of Ethiopia. We reclassified them into 15 zones (Fig.2A) by merging 11 zones (each zone with less than 0.3% area of the highlands of Ethiopia) with zones which do not have significant differences in annual rainfall and temperature distribution. While each of the cool, cold and very cold agroclimatic zones were subdivided into four subzones of moist, submoist, sub-humid and humid (MoARD 2005), we merged the subzones of each zone and defined them as cool submoist-humid, cold submoist-humid and very cold submoist-humid zones, respectively. The cool semi-arid zone was merged with the tepid semi-arid zone, and the warm per-humid zone was merged with the warm sub-humid zone. The three major agroclimatic zones were tepid moist (28.06%), tepid subhumid (14.48%) and warm moist (10.13%). Minor agroclimatic zones were very cold submoist-humid (0.18%), tepid per-humid (0.63%) and cold submoist-humid (0.75%).

FIGURE 2 HERE

The land cover of the highlands of Ethiopia was classified by Kassawmar et al. (2016; 2018a,b) using Landsat 30 m satellite image analyses for the period between 1986 and 2016, following the approach used by Anderson et al. (1976) and Loveland et al. (2000), adjusted for the Ethiopian highlands. The classification scheme produced 12 major classes based on a total 4380 validation points (Kassawmar et al. 2016). We reclassified them into seven land-use/cover classes (Fig. 2B) by merging shrubland, woodland and bush lands into a single “shrub-wood-bush land” class, natural forest and plantation forest into a single “forest” class, and private and state cultivated lands into a single “cultivation” class. Water bodies were excluded from the analysis. The largest land cover is cultivation (55.15%) followed by shrub-wood-bush land (19.72%), forest (12.35%) and grassland (11.32%), while the smallest land cover is barren land (0.24%) followed by swamps (0.28%) (Fig. 2B). Land use was differently distributed amongst agroclimatic zones, with cultivation dominating the cool moist, tepid moist and tepid per-humid zones (over 61% of the total area of each), forests dominating the tepid subhumid (70.59%) and tepid humid (58.50%) zones, and shrub-wood-bush lands dominating the warm submoist zones (43.98%). Cultivated and forest lands occurred in all agroclimatic zones.

2.2. Characterization of the variation of soil organic carbon stocks as related to the variation of biophysical variables

Because direct survey measurements of SOC stocks at regional scale do not exist in the highlands of Ethiopia, eight biophysical predictors (clay content, soil pH, soil moisture, rainfall, temperature, potential evapotranspiration (PET), land-use and altitude) were used to characterize the current spatial distribution of SOC stocks. Each of these biophysical predictors were classified into five to ten classes. The mean SOC stock for each class of each biophysical variable along with the agroclimatic zone classes was calculated and assigned to the corresponding land-use classes and the spatial distribution of the current SOC stock in the top 0-20 cm of soil was mapped. The total SOC stock, SOC_{tot} (t), was calculated using equation 1.

$$SOC_{\mathrm{tot}} = \sum_{k=i}^{N} \sum_{i=1}^{n} A_{\mathrm{i,k}} \times SOC_{\mathrm{i,k}} \qquad (1)$$

where N is the total number of agroclimatic zones, n is the total number of land-use types in each agroclimatic zone, and $A_{\mathrm{i,k}}$ is the area (ha) and $SOC_{\mathrm{i,k}}$ is the SOC stock (t ha^{-1}) of land-use type i (ha) in agroclimatic zone k. Inferential statistics were analyzed using statistical package for social sciences (SPSS) version 20. A one-way ANOVA was used to test whether the differences in the mean SOC stocks of the biophysical variables were significant or not at $P<0.05$ level. In order to quantitatively understand the factors that control the spatial variability of SOC stocks, we used multiple linear regression model (John et al. 2020; Wang et al. 2018; Abegaz et al. 2016; Meersmans et al. 2008) using the eight biophysical predictors listed above as

$$SOC_{\mathrm{i,k}} = \partial + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n) \qquad (2)$$

where, $SOC_{\mathrm{i,k}}$ is the predicted SOC stock, X_1, X_2, ... X_n, are predictor variables, β_1, β_2, ... β_n are the coefficients of predictor variables X_1, X_2, ... X_n, respectively, and ∂ is a constant. An F-test was used to test whether the coefficients of the multiple linear regression model were significantly different from zero or not at $P<0.05$ level.

2.3. Modeling and mapping soil organic carbon sequestration attainable following 20 and 50 years of improved land management

2.3.1. Model selection

There are several types of process-based SOC models that can be used to estimate the SOC stock (a list of about 30 models can be found in Falloon and Smith (2009)). Table 1 presents the comparative features, advantages and disadvantages of some of the widely used process-based models, including RothC. Since our study focuses specifically on SOC dynamics, the RothC model was selected as it is able to do these simulations with lower data requirements (Table 1).

TABLE 1 HERE

The RothC model was developed using experimentally derived biophysical variables, and has been widely used over the last 20 years using field measurements in a wide range of countries, including Ethiopia (e.g. Shahzad et al. 2017; Abegaz et al. 2016; Setia et al. 2011a,b; Smith et al. 1997). It has also been applied at catchment, regional and global scale using data obtained from digital databases (e.g. Setia et al. 2013, 2012; Gottschalk et al. 2012, 2010; Smith et al. 2005; Schröter et al. 2005; Smith et al. 2000a,b, 1998).

The performance of RothC has also been evaluated and its robustness has been confirmed by comparing modeled and long-term measured changes in SOC (e.g. Husniev et al. 2020; Cagnarini et al. 2019; Gomes et al. 2019; Morais et al. 2019; Begum et al. 2017; Wang et al. 2017a; Wang et al. 2016; Gottschalk et al. 2012; Barančíková et al. 2010; Guo et al. 2007; Smith et al. 2005; and Falloon and Smith 2002). Abegaz et al. (2016) also evaluated the RothC model in the highlands of Ethiopia by comparing its outputs with those produced by the Wolf model (Wolf et al. 1989). The evaluations presented in these studies suggest that RothC is suitable for prediction of SOC dynamics under a wide range of soil and agricultural management systems. Therefore, in this study we used the existing tested RothC model, without modification, for scenario prediction across the highlands of Ethiopia.

2.3.2. Data used for model initialization

The RothC model was initialized for each of the seven land-uses and 15 agroclimatic zones across the highlands of Ethiopia using (i) measured SOC stock and soil physical parameters (percent clay content, pH, salinity, volumetric moisture at field capacity (FC) and permanent wilting point (PWP)) for the top 0-20 cm of soil from the ISRIC SoilGrids250 m database (Hengl et al. 2017); and ii) gridded weather data at 4km resolution from 1983 to 2017 (mean monthly and mean annual rainfall, air temperature and PET) provided by the ENACTS tool of Ethiopia's National Meteorological Agency (NMA) (Dinku et al. 2018). These gridded data were prepared by blending data from nearly 300 meteorological stations and the MODIS land surface temperature satellite (Dinku et al. 2018). The study was restricted to the top 0-20 cm soil depth (Aberal et al. 2021; Abegaz et al. 2020, 2016; Vågen et al. 2013).

2.3.3. Description of soil organic matter pools and determination of initial pool sizes

RothC is a simple five-pool model, of which four pools are active compartments that are assumed to decompose by first-order processes (Jenkinson et al. 1987, 1992). These active pools are described as fresh plant material that is decomposable (DPM) or resistant (RPM) to decomposition, and decomposed organic matter that is active microbial biomass (BIO) or stabilized humus (HUM) (Jenkinson et al. 1987; 1992). The fifth pool is assumed to be resistant to decomposition and is referred to as inert organic matter (IOM) (Falloon and Smith 2009). The rate constants of the active pools, k, are 10.0 y^{-1} (DPM), 0.3 y^{-1} (RPM), 0.66 y^{-1} (BIO), and 0.02 y^{-1} (HUM) (Jenkinson et al., 1987, 1992). The size of IOM pool, C_{IOM} (t ha^{-1}), was estimated from the measured total SOC using the Falloon equation (Falloon et al. 1998) as

$$C_{\mathrm{IOM}} = 0.049 \times {C_{\mathrm{meas}}}^{1.139} \qquad (3)$$

where C_{meas} is the measured SOC (t ha^{-1}).

Computational procedures for the active pools, their relative proportions, and the distribution of the annual plant C inputs through the year can be found in Abegaz et al. (2016), Smith et al. (2014, 2005). The size of C inputs as DPM and RPM for arable lands, grasslands, forests/alpine vegetation, bush-wood-shrub lands and swamps are defined based on the default values provided by Coleman et al. (1997). The C inputs of extra organic amendments (cattle manure and compost) as DPM and HUM are defined as given by Smith et al. (2014) using a DPM: HUM ratio of 31.45; this estimates a minimum rate of C sequestration because the decomposable component of the organic inputs is high. The DPM and RPM decompose to produce BIO, HUM and CO_2 and then the BIO and HUM pools further decompose to BIO, HUM and CO_2 (Smith et al. 2014). The monthly rate of decomposition in each pool is modified by the rate modifying factors of temperature (a), moisture content

(b), pH (c) and salinity (d) of the soil, plant cover (e) and the decomposition rate constant ($k/12$) (equation 4). Computational details for each rate modifier can be found in Smith et al. (2014) and Falloon and Smith (2009). The amount of SOC (t ha^{-1}) of each of the four active pools (DPM, RPM, BIO, and HUM) at the end of the month is estimated as described by Coleman and Jenkinson (1996) as

$$C_{\text{end}} = C_{\text{start}} \times e^{-abcdek/12} \quad (4)$$

where C_{end} is SOC in the pool at the end of the month and C_{start} is SOC in the pool at the beginning of a month, both in t ha^{-1}. The sum of these pools gives the total active SOC.

2.3.4. Contextual improved land management and organic inputs

In this study five improved land management practices were considered (Fig. 3 and Table 2). These practices were derived from Fig. 2B and the National Atlas of the Forest Sector Development Program of Ethiopia (MEFCC 2018, 2016). The first improved land management practice was conservation tillage; this was used for two scenarios. Scenario 1 involves use of 50% crop residues in combination with the use of improved crop varieties, crop rotation, controlled soil erosion and 50% of the available manure applied on all currently cultivated lands; this was defined as “conservation tillage-50”. Scenario 2 involves use of 50% crop residues in combination with the use of improved crop varieties, crop rotation, controlled soil erosion and 80% of the available manure; this was defined as “conservation tillage-80”. The annual dry matter manure production in the highlands of Ethiopia was estimated from the livestock database of Ethiopian Central Statistical Agency (CSA, [CSA 2018]) and organic C inputs to the soil from manure were estimated by assuming annual dry matter manure production of 1.8 t per year per head of cattle, and 55% C content of the dry matter content of the manure (Snijders et al. 2013).

FIGURE 3 HERE

Data on improved crop varieties and grain yields in the highlands of Ethiopia were collected from the Crop Varieties Register of the Ministry of Agriculture and Livestock Resources (MALR, [MALR 2017]). It was estimated from the harvest index and shoot/root ratio that on average 50% of the plant dry matter was input to the soil as crop residues, roots and root exudates (Poeplau 2016; Gelaw et al. 2014; Dubey and Lal 2009), respectively. About 50% of the crop residues were assumed to be collected from the fields for use as livestock feed and for other household uses. In crop rotation, three to six improved crop varieties were considered based on their agroclimatic growth requirements (MALR 2017) (see Table 2 footnote). Descriptions of the current land-use management practices and improved practices are presented in Table 2.

TABLE 2 HERE

2.3.5. Prediction of long-term attainable soil organic carbon sequestration

There were 79 land cover / agroclimatic zone combinations (barren lands in 6 zones, swamps in 7 zones, alpine vegetation in 10 zones, grasslands in 13 zones, shrub-wood-bushlands in 13 zones, cultivated lands in 15 zones, and forests in 15 zones). Out of these 24 land cover types (forests, shrub-wood-bushlands, alpine vegetation, and swamps in agroclimatic zones 8, 5, 7, and 4) were set for protection and so remained unchanged. The RothC model was used to explore the long-term dynamics of SOC sequestration for 55 land cover types under the proposed improved management options (Fig. 3; Table 2). Two simulation periods were used: (i) 20 years (2021-2041), and (ii) 50 years (2021 – 2071). For each land use along with agroclimatic zone, net change in SOC stock ($\Delta SOC_{\text{stock}}$) with application of improved land management was calculated using equation 5, and mapped for 2041 and 2071.

$$\Delta SOC_{\text{stock}} = SOC_{\text{end}} - SOC_{\text{start}} \tag{5}$$

where SOC_{end} is total SOC stock at the end of 2041 or 2071 and SOC_{start} is the total SOC stock at the beginning of 2021, both in t ha^{-1}. Finally, the results were cumulated for the whole of the highlands of Ethiopia to estimate net gain or loss of SOC for the two periods.

3. Results and discussion

3.1. Current soil organic carbon stocks as related to variation in biophysical factors

3.1.1. Soil organic carbon stock variation as related to variation of clay content, pH and soil moisture

Fig. 4 shows the variation in the mean stock of SOC as related to biophysical factors across the highlands of Ethiopia. Clay content ranged from 10 to 60% (Fig. 4A). The stock in soils of 10-15% clay content was the lowest (44.2 (± standard error of 0.43) t ha^{-1}), and it increased to 93.4 (± 0.05) t ha^{-1} with increasing clay content up to 35%, and then it gradually declined to 68.7 (± 0. 47) t ha^{-1} at 55-60% clay contents. The variation in C stock along classes of clay fraction was significant ($P<0.001$). This implies that in soils with higher clay content, the decomposition rates of SOC are lower and so they have the capacity to accumulate more soil C than soils with lower clay contents (Zhong et al. 2018; Xiao 2015; Feng et al. 2013; Follett et al. 2012; Giardina et al. 2001). The decline in soil C above 35% clay may be due to the dominance of Nitosols in the highlands of Ethiopia which contain >30% clay content (Elias 2016) but with weak binding to organic matter (Wattel-Koekkoek 2002). Consistent with our result, Wang et al. (2017b) have reported a negative association between soil C accumulation and soil clay fraction in soils with higher SOC content.

The SOC stock in soils of pH 4-5 was the highest (110.5 (± 0.34) t ha^{-1}), and gradually declined to 47.0 (± 0.14) t ha^{-1} with increasing pH up to 9 (Fig. 4B). The variation in C stock with soil pH class was significant ($P<0.001$). Similarly, Zhou et al. (2019) and Dan et al. (2016), reported an inverse relationship between soil C accumulation and soil pH. This inverse relationship is due to the reduced activity of soil micro-organisms at low pH as well as the increased solubility of soil organic matter with reduced bonding between the organic constituents and clays at above pH 6 (Neina 2019; Curtin et al. 2016; Andersson et al. 2000).

The C stock was lowest in soils with soil moisture content at field capacity (FC) of 25-29% (C stock 50.8 (± 0.04) t ha^{-1}). This increased to 91.1 (± 0.03) t ha^{-1} with increasing FC up to 40%, and then declined to 88.4 (± 0.13) t ha^{-1} as FC increased to 40-45% (Fig. 4C). The variation in C stock with soil moisture at FC was significant ($P<0.05$). This is in agreement with the findings of Manns et al. (2016) and Franzluebbers (2002) who reported a direct positive linear relationship between soil water holding capacity and SOC stock for a wide range of locations. The decline in soil C stock above 40% FC may be due to increased rate of soil C decomposition because of increased soil moisture accompanied by high temperatures that facilitate increased microbial activity (Jobbagy and Jackson 2000).

3.1.2. Change in soil organic carbon stock with rainfall, temperature, potential evapotranspiration and altitude

Annual rainfall in the study area ranged from 400 to 2300 mm (Fig. 4D). The mean C stock in soils with 400-700 mm rainfall was the lowest (54.3 (± 0.04) t ha^{-1}), and showed a significant ($P<0.01$) linear increase to 110.0 (± 0.16) t ha^{-1} with increasing annual rainfall. The wide range of annual rainfall greatly influenced the soil moisture and hydrological processes (Heisler and Weltzin 2006), which in turn governed the dynamics of SOC stocks (Gomes et al. 2019; Chen et al. 2016). Rainfall influences SOC stocks in two ways; firstly, high rainfall increases the quantity of C inputs from plants to soils and secondly higher soil moisture content increases the decomposition rates of those C inputs and SOC.

The mean C stock was highest in areas with a mean annual temperature of 8-11 °C (122.1 (± 0.11) t ha^{-1}), and decreased linearly to 72.0 (± 0.05) t ha^{-1} with increasing annual temperature up to a temperature class of 20-23 °C. Mean C stock then increased to 90.8 (± 1.15) t ha^{-1} at temperatures between 26-29 °C (Fig. 4E). The variation in C stock with annual temperature was significant ($P<0.001$). The trend below 23 °C is consistent with other studies that suggest SOC stock decreases with increasing temperatures (Gomes et al. 2019; Sheikh et al. 2009; Jobbagy and Jackson 2000) due to increased microbial activity with increasing temperature (Dan et al. 2016), with a rate of decomposition that approximately doubles with every 10 °C increase in temperature (Schlesinger 2000). Above 26 °C, the rate of decomposition may slow due to it being too hot and/or dry for the micro-organisms to function (Moyano et al. 2013).

The mean C stock was the highest in areas with 1000 – 1200 mm PET (121.8 (± 0.14) t ha^{-1}), decreasing approximately linearly to 73.4 (± 0.09) t ha^{-1} with increasing annual PET up to 1800-2000 mm class (Fig. 4F). There was a significant relationship between C stock along and annual PET ($P<0.001$). Some studies have reported that in semi-arid environments, water loss is dominated by evapotranspiration, which subsequently limits biomass productivity (Lu et al. 2011; Kurc and Small 2004) and microbial function (Moyano et al. 2013). Therefore, since rainfall events in many parts of the highlands of Ethiopia are erratic and concentrated in only three to four months each year, higher rates of PET in barren lands, grasslands and cultivated lands (Fig. 2B), that prevail in warm and tepid zones (Fig. 2A), might limit biomass productivity and the functioning of micro-organisms, and hence reduce the stock of SOC.

The mean C stock was lowest in soils at 1500-1900 m asl (71.8 (± 0.02) t ha^{-1}), increasing approximately linearly to 131.0 (± 0.18) t ha^{-1} with increasing altitude up to 3900 m asl (Fig. 4G). This is in agreement with the findings of Garten et al. (1999), Tate (1992) and Sims and Nielsen (1986). The variation in C stock along classes of altitude was significant ($P<0.001$).

FIGURE 4 HERE

3.2. Soil organic carbon stock variation as related to agroclimatic zones and land-uses

The spatial variation in mean C stock in the top 0–20 cm soil depth ranges from 44 to 142 t ha^{-1}, generally increasing from the north to south and southwest, and from east to the southwest (Fig. 5); this follows the rainfall gradient and perhaps also the vegetation cover (Fig. 2B). Only ~0.36% of the highlands of Ethiopia had C stocks between 132 and 142 t ha^{-1}, while 26, 22 and 18% of the area had C stocks between 77 and 87, 88 and 98, and 66 and 76 t ha^{-1}, respectively (Fig. 5). The total SOC stock in the top 0-20 cm soil was ~3,089,867,050 t (which is equivalent to ~82.94 t ha^{-1}).

The mean C stock in the 0–20 cm soil depth showed significant variation with agroclimatic zone ($P < 0.001$), ranging from 47.1 (± 0.08) t ha^{-1} in warm semiarid-arid to 137.5 (± 0.25) t ha^{-1} in cold submoist-humid (Fig. 5). The C stock per unit area in the cold submoist-humid zone was 2.9 times higher than that in the warm semiarid-arid zone. The high stock in the cold submoist-humid zone may be due to lower soil pH, higher FC, lower PET (data not shown), more recalcitrant organic inputs and very cold temperatures that limit the decomposition rate of organic inputs.

The mean C stock varied with land use from 48.7 (± 0.31) t ha^{-1} in barren lands to 102.3 (± 0.23) t ha^{-1} in alpine vegetation, and the difference between land-uses was significant ($P < 0.001$). The mean SOC stock per unit area in alpine vegetation and forest soils were 2.1 and 1.9 times higher than in barren lands, respectively. The mean C stock was highest in alpine vegetation, probably due to the cool climate and the more recalcitrant organic inputs of alpine vegetation. Similarly, the higher mean C stocks in forest soils may be due to the higher FC and annual rainfall (data not shown), lower soil pH and the dense vegetation cover that results in higher inputs of litter C to the soil (Sheikh et al. 2009).

FIGURE 5 HERE

3.3. Determinants of dynamics of SOC stock

Among the eight explanatory variables used, land-use, agroclimatic zone/elevation, percent clay, annual rainfall and moisture content at FC had a significant positive impact on the SOC stock ($P<0.001$), while soil pH, mean annual temperature and annual PET had a significant negative impact (Table 3). Of the variables with a positive impact, the effect of land-use was the strongest with a change in SOC stock of 2.80 (± 0.01) t ha^{-1} (unstandardized coefficient) per unit change in the explanatory variable, followed by agroclimatic zone (1.71 ± 0.009 t ha^{-1}). Of the variables with a negative impact, the effect of soil pH was the strongest with an unstandardized coefficient of -15.5 (± 0.05) t ha^{-1}. The coefficient of determination of the model indicates that 60.6% of the C stock variation was explained by these eight variables; the 39.4% unexplained variation is due to other biophysical and socio-economic factors that are not considered in this analysis. The multiple linear regression model that describes the mean SOC stock across the highlands of Ethiopia, SOC_{stock} (t ha^{-1}), is as given by

$$C_{\text{stock}} = 169.6 + 2.80LU + 1.72AC + 1.22FC + 0.321Cl + 0.004R - 15.5pH - 0.43T - 0.029PET \quad (6)$$

where LU is the land use class (barren land = 1; grassland = 2; cultivated land = 3; shrub-wood-bush land = 4; swamps = 5; forest = 6; and alpine vegetation = 7); AC is the agroclimatic zone (see Table 3 footnote); FC is the field capacity (vol%); Cl is the clay content (%); R is the mean annual rainfall (mm); pH is the soil pH; T is the mean annual temperature (°C); and PET is the annual PET (mm).

TABLE 3 HERE

3.4. Long-term dynamics of attainable soil organic carbon sequestration under improved land managements

3.4.1. Dynamics of attainable soil organic carbon sequestration by agroclimatic zone

Predicted long-term dynamics of SOC stocks are discussed here according to improved land-use management categories and agroclimatic zones (Fig. 6). The change in SOC after 20-years of improved land-use management ranged from -20 t ha^{-1} with conservation tillage-50 in the tepid perhumid zone to +24 t ha^{-1} in grassland soils in the cool submoist-perhumid zone (Fig. 6A). Loss of SOC was observed in soils with higher C stocks and higher annual rainfall and temperature (data not shown) due to higher rates of C mineralization, associated with the high soil moisture contents and temperatures. Similar results have been documented by Wang et al. (2017a), with higher inputs of C required in these zones to reverse the loss of SOC

(Wang et al. 2017a). In the first 20 years of conservation tillage in cultivated land, the loss in the tepid perhumid zone was reduced from -20 t ha^{-1} (for conservation tillage-50) to -15 t ha^{-1} (for conservation tillage-80) (Fig. 6C); increasing manure input from 50% to 80% resulted in a 25% reduction in the rate of C loss. The change in C stocks after 50-years of improved management ranged from -30 t ha^{-1} for conservation tillage-50 in the tepid perhumid zone to +39 t ha^{-1} for grassland in the cool submoist-perhumid zone (Fig. 6B). For the same period, with conservation tillage, SOC loss was reduced from -30 t ha^{-1} (for conservation tillage-50) to -25 t ha^{-1} (for conservation-tillage-80) in the tepid perhumid zone (Fig. 6D).

The changes in SOC stocks remained negative under both conservation tillage-50 and -80 in cultivated lands of tepid perhumid, tepid humid, tepid subhumid and warm subhumid zones, as well as in the grasslands of the tepid humid, tepid subhumid and warm subhumid zones (Table 4). The loss in these zones is again likely to be due to the low rates of C inputs compared to the high C losses associated with the high annual rainfall and temperatures (Follett et al. 2012). In other zones, 50 years of improved land management with conservation tillage-80 increased C stocks by between 1.7 t ha^{-1} in warm moist zone and 22.4 t ha^{-1} in the very cold submoist-humid zone (Table 4). This is similar to the estimation of Wang et al. (2017a) who reported that the annual rate of SOC sequestration in croplands with 60% crop residue retention was 0.45 t ha^{-1} y^{-1}.

FIGURE 6 HERE

3.4.3. Dynamics of attainable soil organic carbon sequestration by improved land management

The total afforested area of barren land was 90,919 ha. The initial mean SOC stock in barren lands ranged from 44 t ha^{-1} in tepid semiarid to 55 t ha^{-1} in tepid moist zones. After 20 years of afforestation, increased C stocks ranged from 1.14 t ha^{-1} (2%) in warm moist zone to 11.94 t ha^{-1} (27%) in tepid semiarid zone. After 50 years, the stock increase ranged from 7.5 t ha^{-1} (14%) in warm moist zone to 17.54 t ha^{-1} (40%) in tepid semiarid zone. The rate of increase was highest in the first 20 years; ranging from 0.06 t ha^{-1} y^{-1} in warm moist zone to 0.60 t ha^{-1} y^{-1} in tepid semiarid zone, compared to the rates ranging from 0.04 to 0.20 t ha^{-1} y^{-1}, and 0.03 to 0.16 for the period between 20 and 40, and 40 and 50 years, respectively (Fig. 7A). After 20 and 50 years of afforested land, the total amounts of SOC sequestered were 553,989 t (6.09 t ha^{-1}) and 911,722 t (10.03 t ha^{-1}; Table 4), respectively.

TABLE 4 HERE

While the total land area of cultivation in the highlands of Ethiopia was 20,796,518 ha, the initial SOC stocks of 62% of this land were relatively low, ranging from 51 t ha^{-1} in warm semiarid-arid to 81 t ha^{-1} in tepid moist zone. This low rate of C stock is due to use of over 80% of crop residues and cattle dung for household energy in the highlands of Ethiopia at the expense of crop residue and manure application to farmlands (Negash et al. 2017; Gudina and Nonhebel 2015; Gwavuya et al. 2012). From these results, we concluded that the business-as-usual system should not continue. The availability of crop residues and manures for soil amendment could be increased by using alternative energy sources that do not burn dung and crop residues, such as biogas digesters, solar, wind energy and electrification; electrification will be provided by the Ethiopian Grand Renaissances Dam that will soon start supplying hydroelectric power to both the rural and urban population of Ethiopia.

After 20-years of conservation tillage-50, SOC continued to decline in six zones (Fig. 7C), ranging from a total of 0.80 t ha-1 (0.9%) in cool moist to 17.49 t ha-1 (16%) in tepid perhumid. In nine zones, C sequestered ranged from 0.17 (0.2%) in tepid moist zone to 5.79 t ha^{-1} (7%) in warm moist zone (Fig. 7C). After 50-years of conservation tillage-50, SOC declined in only five zones, ranging from a total of 2.46 t ha-1 (3.7%) in warm moist zone to 27.45 t ha-1 (24.36%) in tepid perhumid zone. In ten zones, the C sequestered ranged from 0.89 t ha-1 (0.97%) in cool moist to 11.20 t ha-1 (20.63%) in warm submoist zone.

For conservation tillage-80, SOC continued to decline after 20 years only in four zones (Fig. 7D), ranging from a total of 2.32 t ha^{-1} (2.5%) in tepid subhumid zone to 15.06 t ha^{-1} (13.36%) in tepid perhumid zone. In 11 zones, SOC increased, ranging from 0.11 t ha^{-1} (0.15%) in warm moist to 8.33 t ha^{-1} (15.35%) in warm submoist zone. After 50 years, the decline in the three zones ranged from 1.15 t ha^{-1} (1.25%) in warm subhumid to 22.67 t ha^{-1} (20.11%) in tepid perhumid zone, whereas in the other 11 zones, C sequestration ranged from 6.78 t ha^{-1} (7.43%) in cool moist to 16.36 t ha^{-1} (31.13%) in warm submoist zone.

FIGURE 7 HERE

Over the whole area of cultivated lands, after 20-years of conservation tillage-50, SOC stocks declined by 20,382,891 t (0.98 t ha^{-1}) from the initial stock, but after the longer 50 year period the initial C stocks increased by 3,753,524 t (0.18 t ha^{-1}, Table 4). This result is consistent with a result of Husniev et al. (2020), who reported a decline SOC stocks in a 60-year period with an annual input of 1.9 t C ha^{-1}. For conservation tillage-80, SOC stocks were already increasing after 20 years by 32,040,507 t (1.54 t ha^{-1}), and increasing to 112,349,160 t (5.40 t ha^{-1}) after 50 years (Table 4). For both conservation tillage-50 and -80, the annual rates of change were highest in the first 20 years compared to the period between 20 and 40, and 40 and 50 years (Figs. 7 C&D).

The total land area of grassland was 4,270,034 ha. The initial SOC stocks were much higher than in the cultivated land, ranging from 48 t ha^{-1} in warm semiarid-arid to 107 t ha^{-1} in tepid perhumid zone. After 20 years of improved grassland management, the SOC stocks declined in only three zones; 6.98 t ha^{-1} (9%) in warm subhumid, 12.22 t ha^{-1} (12%) in tepid humid and 15.05 t ha^{-1} (14%) in tepid perhumid zones (Fig. 7E). After 50 years, loss of SOC continued in the same zones; 10.92 t ha^{-1} (14%) in warm subhumid, 19.18 t ha^{-1} (19%) in tepid humid, and 23.63 t ha^{-1} (22%) in tepid perhumid zones. In the remaining eight zones with grasslands, improved grassland management resulted in an increased C stock. After 20 years, the increases ranged from 1.30 t ha^{-1} (1%) in warm humid to 20.49 t ha^{-1} (20%) in cool submoist-perhumid. After 50 years, the increases were between 2.03 t ha^{-1} (2%) in the warm humid to 34.49 t ha^{-1} (34%) in the cool submoist-perhumid zones. Over the whole area of grasslands, the amount of SOC sequestrated was 7,786,302 t (1.82 t ha^{-1}) after 20 years and 12,446,337 t (2.91 t ha^{-1} after 50 years of improved management (Table 4).

The total reforested area of degraded forests, alpine vegetation, shrub-wood-bush land and swamps was 6,380,380 ha. After 20 years of reforestation of this area, the rate of soil C stock increase ranged from 1.80 t ha^{-1} in tepid moist to 12.40 t ha^{-1} in cold submoist-humid zones (Fig. 7B). The rates of increase after 50 years ranged from 2.70 (4%) in tepid moist to 21.68 (21%) t ha^{-1} in cold submoist-humid zones. After 20 and 50 years of reforestation, the absolute rates of soil C sequestration were 26,094,121 t (4.09 t ha^{-1}) and 43,474,955 t (6.81 t ha^{-1}; Table 4), respectively. Similarly to afforested and cultivated lands, the rates of change in SOC stocks were higher in the first 20 years compared to the period between 20 and 40, and 40 and 50 years in soils of improved grasslands (Fig. 7E) and reforested lands (Fig. 7B).

In six agroclimatic zones (in tepid subhumid, tepid humid, tepid perhumid, warm moist, warm subhumid, and warm humid), areas under forest, shrub-wood-bush, alpine vegetation and swamps, with a total area of 6,172,995 ha are recommended for protection and conservation, because they are natural ecosystems and are identified as least priority for tree-based landscape restoration by MEFCC (MEFCC 2018). Therefore, soil C stocks in these areas were assumed to remain unchanged.

Over the whole area and all land uses, after 20 years of improved land management, the regional SOC sequestration was 14,051,321 t using conservation tillage-50 and 32,040,507 t using conservation tillage-80 on the cultivated land. After 50 years, this increased to 60,586,539 t and 169,182,174 t (Table 4), equivalent to an increase from current stocks by 2.9% (0.06% y^{-1}) and 5.5% (0.11% y^{-1}), respectively. Total SOC sequestration after 50 years of improved land management was 2.8 times higher with conservation tillage-80 than with conservation tillage-50. This information is important for communicating the value of different management practices to stakeholders and for planning management for soil C conservation and sequestration, and greenhouse gas emission reduction (World Bank 2012).

3.4.4. **Uncertainties and limitations**

In this study at least four uncertainties and limitations may arise around the model inputs, parameters, and subsequently model predictions (Barančíková et al. 2010). The first uncertainty is associated with the climatic change. We used the current climatic data for SOC prediction. However, increasing temperatures will speed up the decomposition of SOC in the future (Smith et al. 2005). The second uncertainty is the estimated C inputs from plant residues and manures. While increased SOC stocks and adoption of crop rotations are expected to increase soil fertility and agricultural biomass, model C input is estimated from yield of the current improved crop varieties and manures are estimated from the current livestock numbers. This may underestimate future C inputs to the soil and rates of C sequestration. The third uncertainty is in the DPM and HUM ratio used for cattle manure in the model. While recommended ratios for DPM : HUM in cattle manure ranged from 0.07 to 31.45 (Smith et al. 2014), we used the highest value (31.45) in order to estimate the minimum likely rate of C sequestration. The fourth uncertainty is the use of mean initial SOC stock from heterogeneity of local landforms from which heterogeneity of SOC can be observed.

4. Conclusion and recommendation

This study characterized the association between the spatial distribution of the SOC stock and eight biophysical predictors (clay content, soil pH, soil moisture, rainfall, temperature, PET, land-use and altitude). The study also modeled and mapped SOC sequestration attainable following 20 (2021-2041) and 50 (2021-2071) years of five improved land management practices. The results of this study revealed that, over the whole area and all land-uses of the highlands of Ethiopia, the total SOC stock in the top 0-20 cm soil was ~3,089,867,050 t (~82.94 t ha^{-1}). The difference in SOC stocks with biophysical variables, agroclimatic zones and land-uses was significant ($P<0.001$) (Fig. 4). Multiple linear regression revealed that the impact of changes in land-use, agroclimatic zone, rainfall, clay content and FC on SOC stock change was positive and significant (Table 3, $P<0.001$). Land-use had the strongest positive impact, followed by agroclimatic zone/elevation and FC. This implies that adoption of improved land management practices should be used to increase rates of C sequestration.

Initial SOC stocks of barren lands, grasslands, cultivated lands and other degraded land-uses were smaller than stocks of forest and alpine vegetation, suggesting that improved land management practices in the former land-uses are needed for sustainable agricultural and ecosystem services. This further indicates the need for afforestation in barren lands and reforestation in degraded forest, shrub-wood-bush land and alpine vegetation. The simulated results of this study indicate that rate of SOC sequestration is the interplay between initial SOC stocks, the biophysical environment, the rate of organic inputs and length of management.

After 50 years of conservation tillage-50 in cultivated land, the initial stock declined in five zones (warm subhumid, warm humid, tepid subhumid, tepid humid and tepid perhumid) due to the high annual rainfall and temperature, which results in higher rates of SOC decomposition. Therefore, in order to counter these losses, organic inputs should be increased. Our simulations revealed that, after 50 years of conservation tillage-80, SOC sequestration increased by 179% compared to conservation tillage-50. Therefore, in croplands, effective soil C sequestration can be achieved by adopting conservation tillage-80.

Introduction of improved pasture species and controlling soil erosion can lead to net benefits of C sequestration and mitigation of greenhouse gas emission from grasslands of the region. Protection of natural ecosystems of the alpine vegetation, forests, shrub-wood-bush and swamp should also be included in C loss mitigation measures. The simulated results of this study indicate the need to adopt improved land management in the highlands of Ethiopia that lead to increased attainable SOC sequestration and simultaneously reduced CO_2 and greenhouse gas emissions, providing more sustainable agricultural production and environmental management systems. The results could help to guide management of carbon inputs across the highlands of Ethiopia to effectively mitigate climate change. However, we would like to indicate that modeled results are for aggregated land-use or land cover classes, which may be too coarse to produce land unit specific results, as the highlands of Ethiopia are characterized by highly variable topographic features in each land-use within the same agroclimatic zone. Therefore, a further study that considers topographic variability is required.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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FIGURES

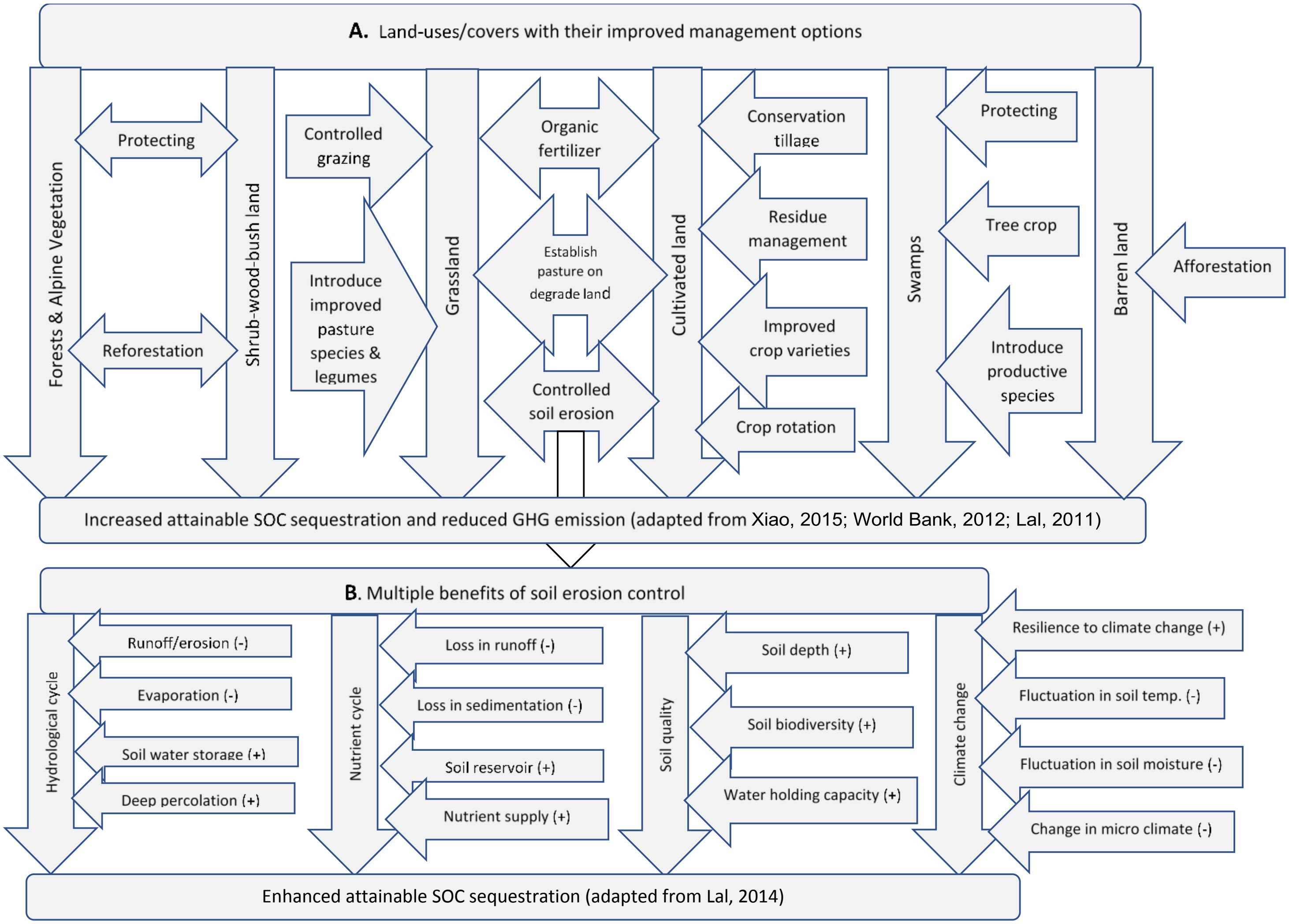

Figure 1. Land-uses/covers with their improved management options (A) and multiple benefits of controlled soil erosion (B).

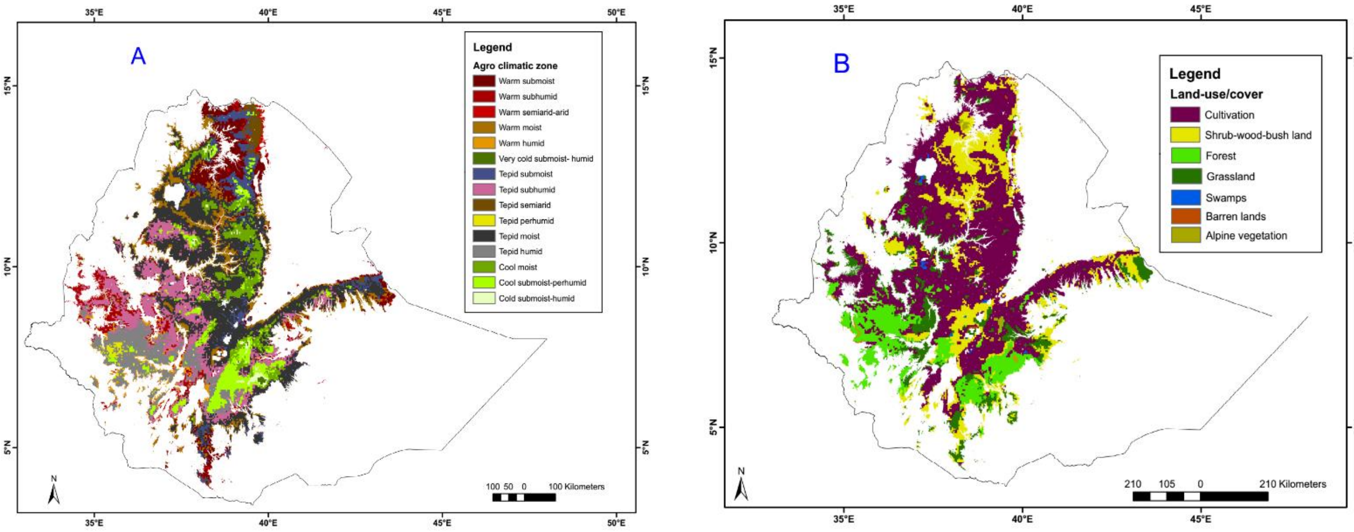

Figure 2. Agroclimatic zones (A) and land-uses/covers (B) across the highlands of Ethiopia.

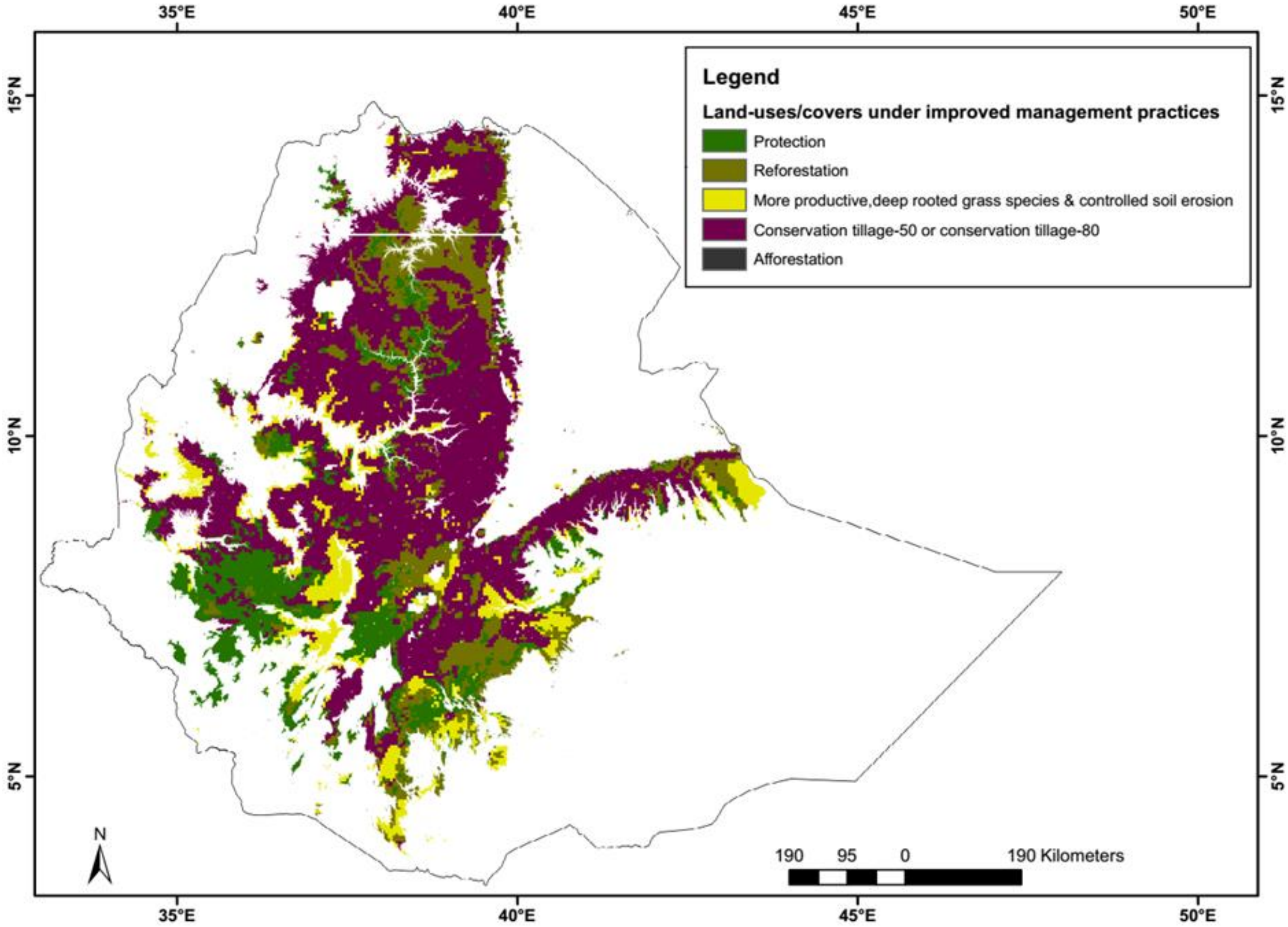

Figure 3. Improved land managements used in the long-term simulation of SOC stock sequestration across the highlands of Ethiopia.

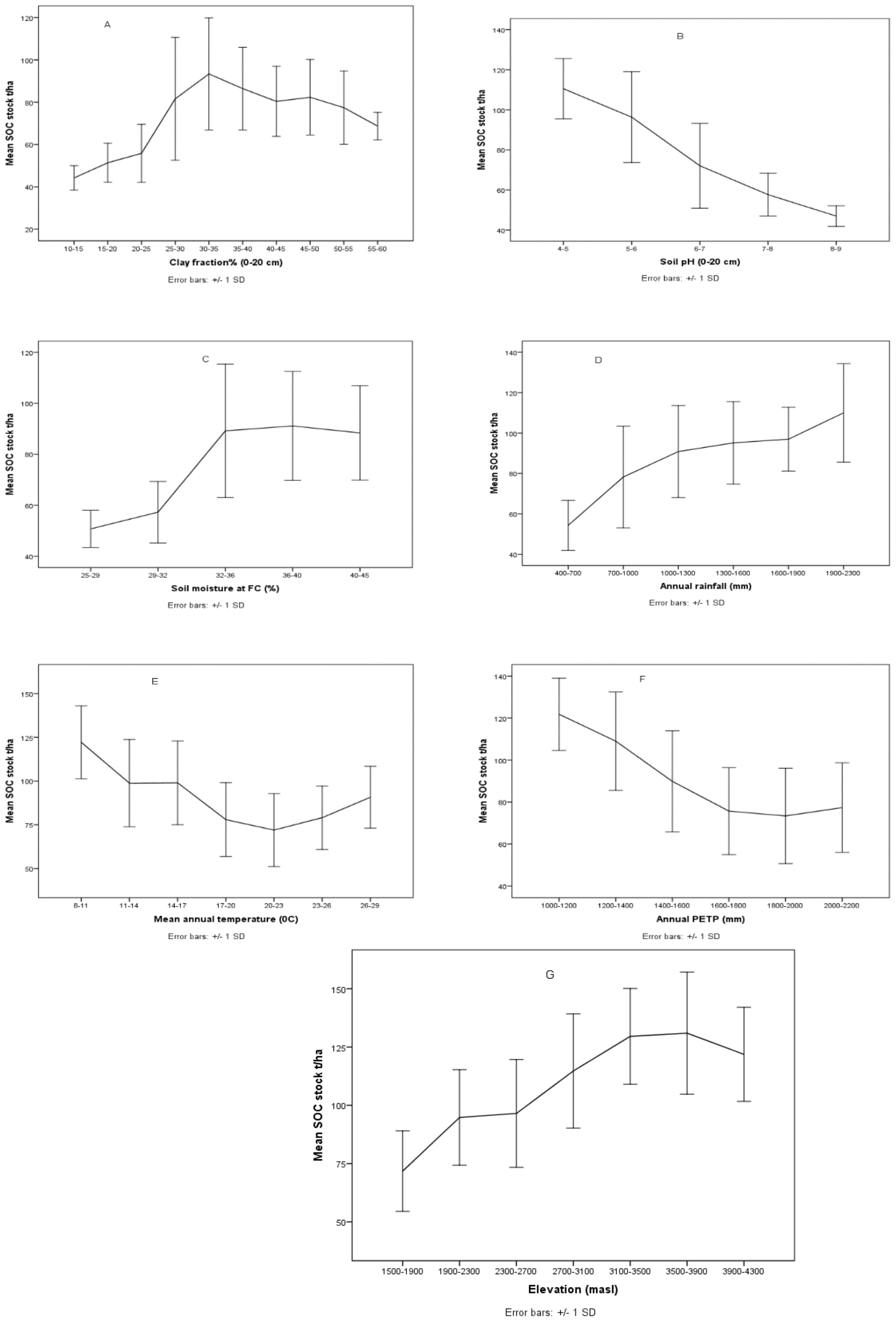

Figure 4. Variation of SOC stock as related to clay fraction% (A), soil pH (B), soil moisture at FC% (C), annual rainfall (mm) (D), mean annual temperature (^{0}C) (E), annual potential evapotranspiration (mm) (F), and altitude (masl) (G) across the highlands of Ethiopia.

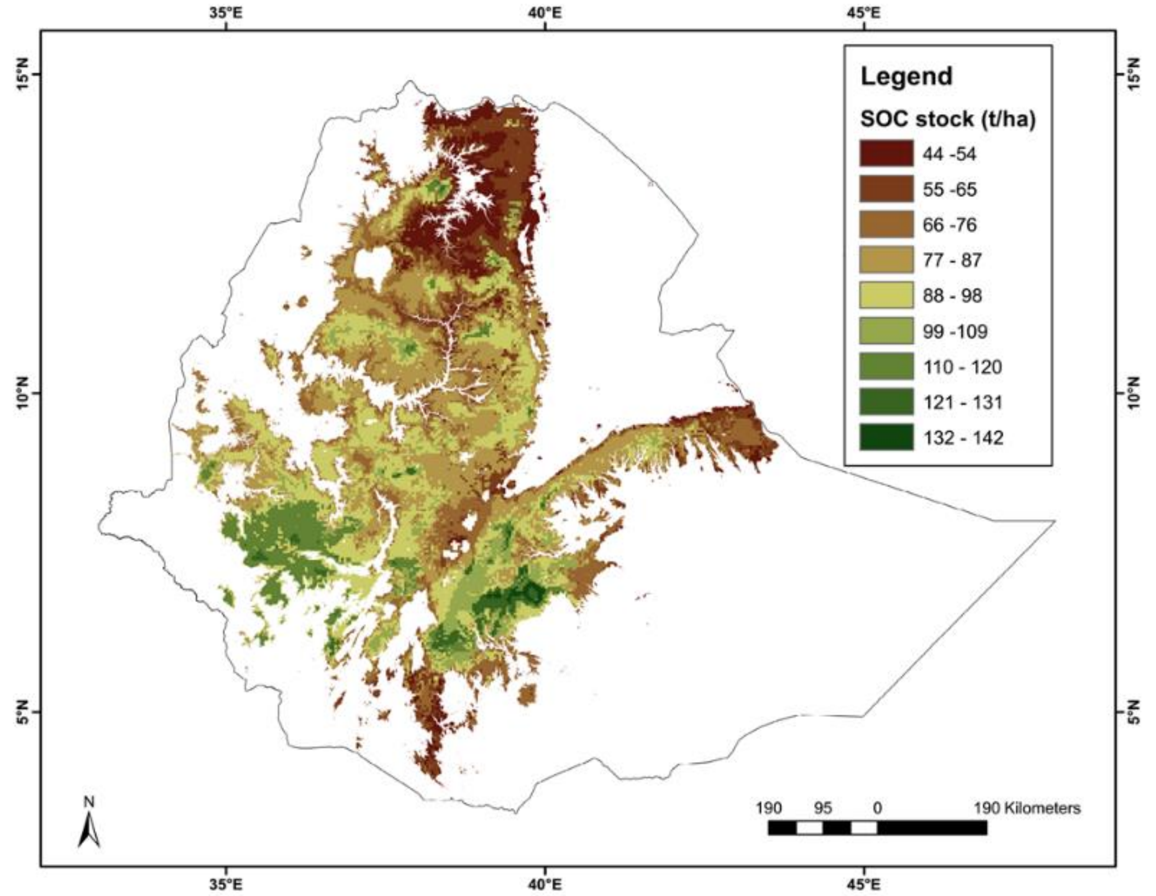

Figure 5. Spatial distribution of SOC stock t ha^{-1} in the top 0-20 cm soil depth across the highlands of Ethiopia.

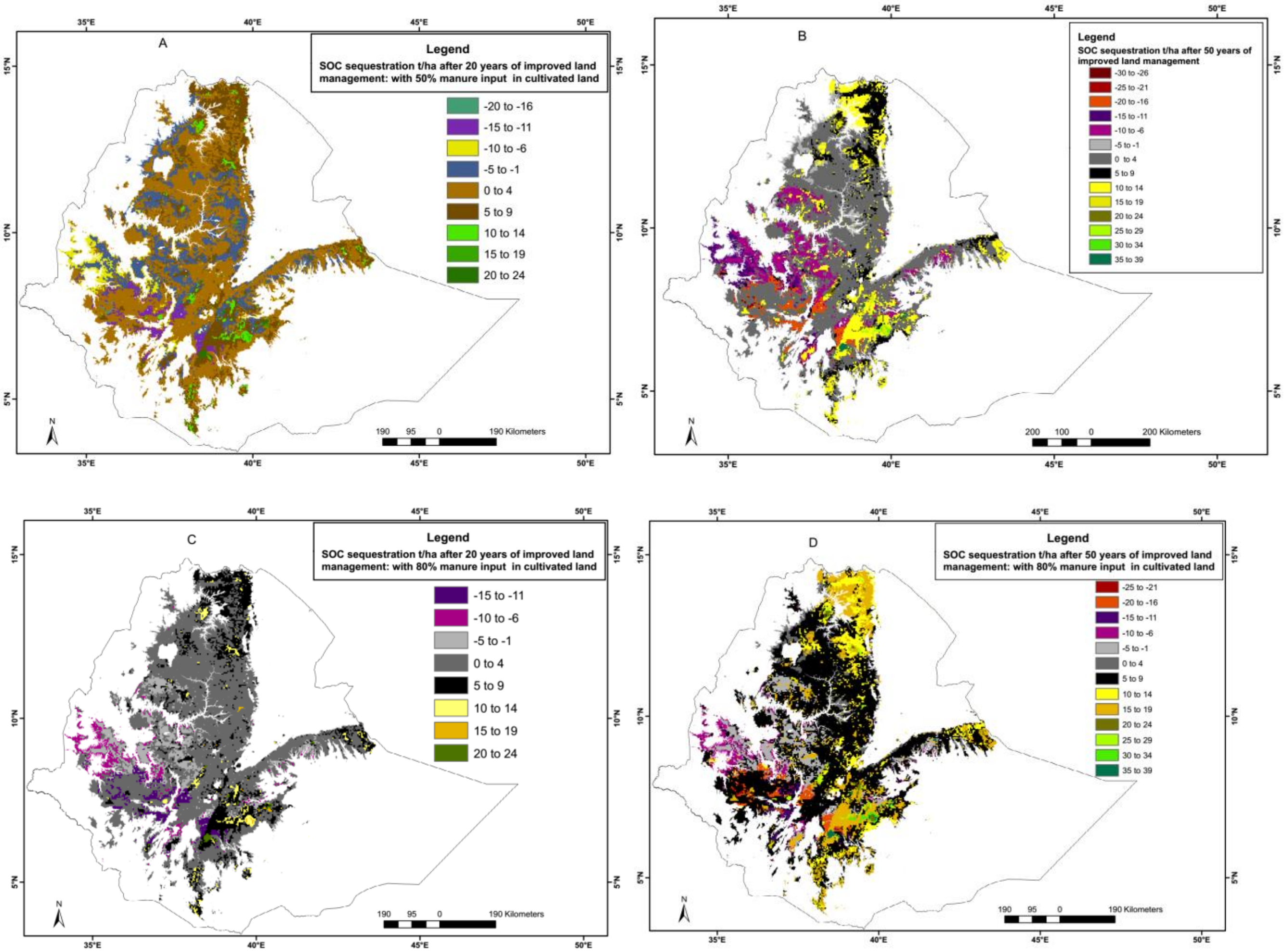

Figure 6. Rates of SOC sequestration after 20 years (A) and 50 years (B) of improved land management (with 50% manure input in cultivated lands), and after 20 years (C) and 50 years (D) of improved land management (with 80% manure input in cultivated lands) across the highlands of Ethiopia.

Figure 7. Annual rate of SOC sequestration t ha^{-1} in the top 0-20 cm soil depth by adapting improved land-use management: aforestation (A); reforestation (B); conservation tillage-50 (C); conservation tillage-80 (D); and introduced productive and deep-rooted grass (E) across the highlands of Ethiopia.

Table 1. Comparative features of key inputs and outputs, advantages and disadvantages/limiting factors of some process-based SOC models

Model	Key inputs	Key outputs	Advantages	Disadvantage/limiting factor
RothC (Coleman et al. 1997)	Clay, MR, MPET, MAT, initial SOC, organic input.	Total carbon	Simulates only C dynamics. It has lower data requirements than many other models, using data that can easily be obtained from databases, and has a relatively low computational time.	RothC includes only the C cycle. It does not account for other processes, such as nutrient and water limitation. However, this is not a limitation in our case, because our interest is to simulate only soil carbon dynamics.
CENTURY (Parton et al. 1996)	DMMiT and DMMaT, TP; plant N, P, and S content; soil texture; atmospheric and soil nitrogen inputs; and initial soil carbon, nitrogen, phosphorus, and sulfur levels.	TSC, SWD, CCY, TDM, and CPR.	Has a broader scope than RothC, because it simulates not only soil C, but also N, phosphorous and sulphur dynamics (Morais et al. 2019)	Requires a higher number of input values and fixed parameters (some of which are difficult to obtain) and has a higher computational time than RothC (Morais et al. 2019).
DNDC (Li et al. 1996)	Plant growth data, soil clay, BD, pH, AT, rainfall, ANDR, CRTT, IFTAT, ITA, RITA, and TTA.	TSC, TN=total nitrogen, SWD, biomass C, CO2, crop yield, C input into soil, fluxes N2O, NO, NH3, and CH4.	Simulates both C and N cycling in the soil.	Requires a higher number of input values and fixed parameters (some of which are difficult to obtain) and has a higher computational time than RothC (Morais et al. 2019).
APSIM (Holzworth et al. 2014)	DMMiT and DMMaT; soil texture, soil depth, BD, SMFC, FC, HC, WFPS, SD, HD, PE, IFTAT, ITA, RR, PP (Begum et al. 2017).	SOM decomposition, nitrification, denitrification, plant production and SWD (Begum et al. 2017).	Includes SOM decomposition, nitrification and denitrification, plant production and soil water dynamics (Begum et al. 2017).	Requires a higher number of input values and fixed parameters (some of which are difficult to obtain), and has a higher computational time than RothC (Begum et al. 2017).

Note: MR= monthly rainfall, MPET=monthly potential evapotranspiration, MAT=monthly air temperature, DMMiT=daily mean minimum temperature, DMMaT=daily mean maximum temperature, TP=total precipitation, BD=bulk density, AT=air temperature, ANDR=atmospheric nitrogen decomposition rate, CRTT=crop rotation timing and type; IFTAT=inorganic fertilizer timing, amount and type, ITA=irrigation timing and amount, RITA=residue incorporation timing and amount, TTA=tillage timing and type, SMFC=soil moisture at field capacity (FC), HC=hydraulic conductivity, WFPS=water filled pore space, SD=sowing date, HD=harvesting date, PE=ploughing events, RR=residue removal, PP=phenological parameters, TSC=total soil carbon, SWD=soil water dynamics, CCY=commercial crop yield, TDM=total dry matter, CPR=carbon in plant residue, TN=total nitrogen, SOM=soil organic matter.

Table 2. Description of current and improved land managements, and plant and manure organic carbon inputs (t ha^{-1} y^{-1}) used in the long-term simulation of attainable SOC sequestration across the highlands of Ethiopia

Current land-use/cover	**Description of current land-use/cover**	**Description of improved management**	**Area (ha)**	**Plant OC input in the soil (t ha^{-1} y^{-1})**	**Manure OC input in the soil (t ha^{-1} y^{-1})**
Currently cultivated land	The farming system is characterized by intensive continuous mono-cropping. The majority of animal manure is used for household fuel and almost all crop residues are collected from the field for livestock feed and household fuel (Abegaz et al. 2016).	***Scenario 1*, conservation tillage-50***. Involves use of 50% crop residues directly incorporated after harvest, improved crop varieties, crop rotations, controlled soil erosion and addition of 50% manure in soils of cultivated lands one-to-two months before the cropping period.	20,796,518	2.59, 2.62, 3.86[a]	1.3
		Scenario 2*, conservation tillage-80. This scenario is different from scenario 1 only in the amount of manure input. In this scenario addition of manure in soils of cultivated lands was increased to 80%.	The same above	2.59, 2.62, 3.86[a]	2.08
Currently grazed land	Free grazing is practiced and cattle dung is collected from the field for household energy (Abegaz et al. 2020).	***Adopting more productive deep-rooted grass species & controlled soil erosion.*** Involves introduction of more productive, deep rooted grass species with a cut-and-carry system of 50% above ground grass and controlled soil erosion. In this management, Napier grass is grown. This is a fast-growing perennial grass native to Sub-Saharan Africa that is widely grown across the tropical and subtropical regions of the world, also currently is being adopted in different parts of the highlands of Ethiopia, however only at local scale (Negawo et al. 2017). Soil erosion is also assumed to be controlled (Lal 2014).	4,270,034	5.00	---------
Barren land	This land-use/cover includes areas that have been extensively used for cultivation for a long period of time. It is characterized by thin soil, sparse and stunted plant growth and limited biodiversity.	***Afforestation.*** Involves establishment of new forests on non-forested degraded land (FAO 2010). This system increases SOC stocks through the increase of organic materials input into the soil system.	90,919	3.60[b]	----------
Degraded natural ecosystem	This land-use/cover is degraded because of forest clearing for cultivation and exploitation of forests and shrub-wood-bushes for fuelwood and charcoal without replanting.	***Reforestation.*** Involves reforestation and plantation on degraded forest, alpine vegetation, shrub-wood-bushland, and swamps that are found in areas identified as region of priority 1 for tree-based landscape restoration by the Ministry of Environment, Forest and Climate Change (MEFCC, [MEFCC 2018; 2016]).	6,380,380	3.60[b]	------------
Natural ecosystem	This land cover is protected by the Government (MEFCC 2018; Bekele 2011). It has not been altered by human interference (Abegaz et al. 2020).	***Protection.*** Involves protection of natural ecosystems (dense forest, alpine vegetation, closed shrub-wood-bushlands and swamps) that are found in areas identified as region of least priority for tree-based landscape restoration by MEFCC (MEFCC 2018; 2016).	6,172,995	---------	-----------

Note: [a] 2.59, 2.62, and 3.86 are average plant organic carbon inputs (t ha^{-1} y^{-1}) from crops used in rotation of (i) wheat, barley and faba bean; (ii) teff, sorghum, wheat, maize, barley and faba bean; and (iii) wheat, barley and maize, respectively. Input of 2.59 was used in cool submoist-perhumid, cold submoist-humid, and very cold submoist-humid; 2.62 was used in tepid semiarid, tepid submoist, cool moist, and warm semiarid-arid; and 3.86 was used in tepid moist, tepid subhumid, tepid humid, tepid perhumid, warm submoist, warm moist, warm subhumid, and warm humid agroclimatic zones. [b] is estimates given by Medina and Zelwer (1972, cited in Brown and Lugo, 1982)). * 50 and 80% annual dry matter manure production was estimated from the livestock database of Ethiopian Central Statistical Agency (CSA, [CSA 2018]) and organic C input to the soil from manure was estimated by considering annual dry matter manure production of 1.8 t per cattle, and 55% C content of organic matter of dry manure (Snijders et al. 2013).

Table 3. Explanatory variables and coefficients of multiple linear regression model of soil organic carbon stock dynamics in 0–20 cm soil depth across the highlands of Ethiopia.

No.	Constant & explanatory variables (x)	Unstand. (B)	Standard error	Stand. Beta	Coefficient of r	Adjusted R^2 (%)	ANOVA (F)
1	Constant	169.6***	0.5		0.78***	60.6***	201817***
2	Land-use[a]	2.80***	0.01	0.173***			
3	Agroclimatic zone[b]	1.71***	0.009	0.237***			
4	Mean moisture at field capacity (vol%)	1.22***	0.008	0.148***			
5	Mean annual rainfall (mm)	0.004***	0.001	0.052***			
6	Clay (%)	0.321***	0.004	0.072***			
7	Soil pH	-15.5***	0.05	-0.299***			
8	Mean annual temp. (°C)	-0.43***	0.01	-0.51***			
9	Annual potential evapotranspiration (mm)	-0.029***	0.001	-0.052***			

***coefficient is significant at the 0.001 level (2-tailed). Notes: a an interval scale was used for land-uses as barren land = 1; grassland = 2; cultivated land = 3; shrub-wood-bush land = 4; swamps = 5; forest = 6; and alpine vegetation = 7. b an interval scale was used for agroclimatic zones as Warm semiarid-arid = 1; Warm submoist = 2; Tepid semiarid = 3; Tepid submoist = 4; Warm moist = 5; Tepid moist = 6; Warm subhumid = 7; Warm humid = 8; Tepid subhumid = 9; Tepid humid = 10; Tepid perhumid = 11; Cool moist = 12; Cool submoist-humid = 13; Cold submoist-humid =14; and very cold submoist-humid = 15 (as per increasing order of their mean altitude m asl).

Table 4. Absolute SOC sequestration t by agroclimatic zone and land-use after 50 years of improved land management across the highlands of Ethiopia.

Agroclimatic zone	**Absolute rate of SOC sequestration t after 50 years**							**Total land area (ha)**	**Absolute rate of SOC sequestration t ha^{-1}**	
	Afforested	**Conservation tillage-50**	**Conservation tillage-80**	**Grassland (adopting more productive grass)**	**Reforestation & plantation**	**Total with conservation tillage-50**	**Total with conservation tillage-80**		**Conservation tillage-50**	**Conservation tillage-80**
Tepid semiarid	268,252	4,100,371	6,611,150	107,663	1,484,854	5,961,141	8,471,920	592,945	10.05	14.29
Tepid submoist	90,830	5,500,741	12,261,391	2,543,363	6,324,876	14,459,811	21,220,460	2,238,239	6.46	9.48
Tepid moist	70,508	14,845,852	52,893,547	9,694,877	8,718,276	33,329,512	71,377,207	10,541,023	3.16	6.77
Tepid subhumid	---	-21,128,664	-3,853,750	0[a]	0[b]	-21,128,664	-3,853,750	4,033,841	-5.24	-0.96
Tepid humid	---	-14,553,798	-13,251,763	-6,464,261	0[b]	-21,018,059	-19,716,024	1,180,882	-17.80	-16.70
Tepid perhumid	---	-1,298,052	-1,071,652	-255,795	0[b]	-1,553,847	-1,327,447	58,100	-26.74	-22.85
Warm semiarid-arid	179,652	322,372	925,953	1,020,200	958,721	2,480,945	3,084,526	341,744	7.26	9.03
Warm submoist	189,933	13,959,931	20,394,072	5,007,240	5,385,214	24,542,317	30,976,459	2,992,108	8.20	10.35
Warm moist	112,547	-4,336,061	4,114,277	0[a]	0[b]	-4,223,514	4,226,825	2,479,909	-1.70	1.70
Warm subhumid	---	-10,689,496	-6,679,240	-5,709,121	0[b]	-16,398,617	-12,388,361	1,398,707	-11.72	-8.86
Warm humid	---	672,589	1,395,086	405,276	0[b]	1,077,865	1,800,362	345,806	3.12	5.21
Cool moist	---	1,953,665	14,960,751	1,182,498	1,501,357	4,637,520	17,644,605	2,477,352	1.87	7.12
Cool submoist-perhumid	---	13,796,669	22,565,362	4,914,397	13,000,989	31,712,056	40,480,748	2,505,795	12.66	16.15
Cold submoist-humid	---	578,822	1,032,649	---	4,619,966	5,198,789	5,652,616	282,857	18.38	19.98
Very cold submoist-humid	---	28,583	51,327	---	1,480,702	1,509,285	1,532,029	68,544	22.02	22.35
Total sequestrated SOC t	911,722	3,753,524	112,349,160	12,446,337	43,474,955	60,586,539	169,182,174			
Total land area (ha)	90,919	20,796,518	20,796,518	4,270,034	6,380,380	31,537,851	31,537,851	31,537,851		
Absolute rate of SOC sequestration (t ha^{-1})	10.03	0.18	5.40	2.91	6.81	1.92	5.36		1.92	5.36

Note: ---- land-use/cover is unavailable; [a] SOC stock is at equilibrium/steady state; [b] land-use/cover exists but recommended for protection or conservation of existing stock, therefore, excluded from simulation, and rate sets at 0 (zero).