DEPARTMENT OF BIOLOGY AND
ENVIRONMENTAL SCIENCES

SOIL ORGANIC CARBON STOCK DEVELOPMENTS IN RESPONSE TO LAND USE CHANGE AND CLIMATE CHANGE



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ABSTRACT

Soils play a significant role in carbon sequestration by storing large amount of organic carbon. This carbon storage can be affected by future changes in land use and climate, which would lead to further emission of greenhouse gases. The study was aimed to predict the impact of land use change (LUC) on soil organic carbon (SOC) dynamics under different climate scenarios in Birr watershed in Ethiopia. The Q model was employed to estimate the SOC stock changes. The model was driven by mean annual litterfall and mean yearly air temperature and these data were taken from literature. Natural forest, *Eucalyptus* plantation, bushland and cropland were the land uses included. Six LUC scenarios and three litter production scenarios (no change, 5% decrease and 22% increase) under climate change were studied. If litterfall remains unchanged, SOC stock would decrease by around 8% in all land use scenarios due to climate change. Conversely, SOC accumulation would increase by 13% in all land use scenarios if litterfall increases by 22% in response to changing climate. All LUC scenarios resulted in net loss of SOC under contemporary climate but not conversions to *Eucalyptus* planation. Climate change would result in SOC loss in all LUC scenarios except cropland to *Eucalyptus* conversion. Litter increase by 22% would not offset the impact of LUC scenarios from natural forest to other land uses. Preservation of natural forests appears to be the best option to maintain SOC. However, since much of the natural forest cover is already lost in the area, afforestation of croplands and bushlands with *Eucalyptus* plantation appears to be a better option to regain SOC.

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ANOVA	Analysis of Variance
C	Carbon
CC	Climate Change
FAO	Food and Agriculture Organization
GHG	Green House Gas
IPCC	Intergovernmental Panel on Climate Change
LUC	Land Use Change
LULUCF	Land Use, Land Use Change and Forestry
masl	meter above sea level
NPP	Net Primary Production
REDD	Reducing Emissions from Deforestation and Degradation
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
UNFCC	United Nations Framework Convention on Climate Change

1. INTRODUCTION

1.1 Soil organic carbon

The global carbon cycle is taking place in three main reservoirs. These are; the oceans, the atmosphere, and terrestrial systems, which store carbon in different forms and varying amounts. Oceans store large amount of reactive carbon (38,000 Pg. C) followed by terrestrial systems (2060 Pg. C). Although the atmosphere store the least amount of reactive carbon (750 Pg. C), its role in connecting the other two reservoirs is crucial in the planetary carbon cycle. In terrestrial systems, carbon is stored in soil and terrestrial plants. Soil store high amount of reactive carbon (1500 Pg. C in the first one meter of soil) as soil organic matter. This amount is estimated to be three times higher compared to carbon stored in terrestrial plants (500 Pg. C) and two times higher than the amount stored in atmospheric compartment. Because of this, small relative change in the soil reservoir may significantly influence the balance of global carbon, mainly atmospheric carbon dioxide concentration (Post *et al.*, 1990; Raich & Schlesinger, 1992 Schlesinger & Bernhardt, 2013).

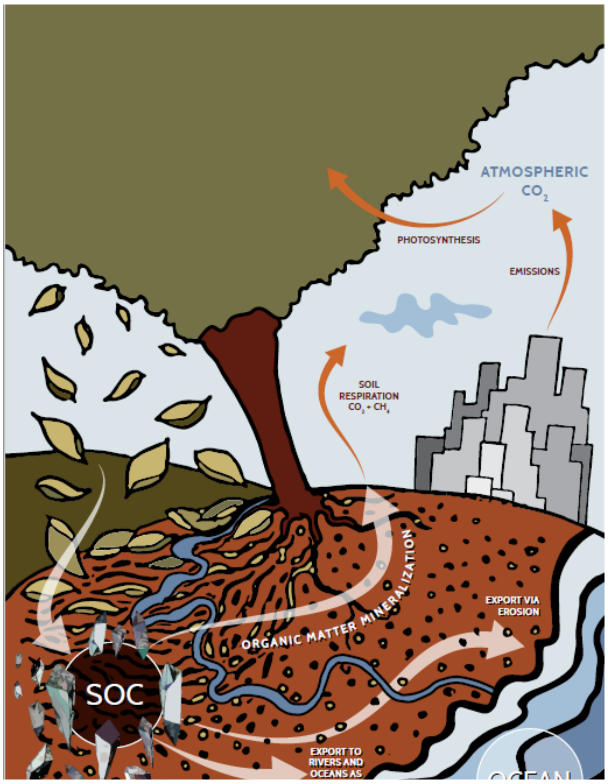


Figure 1 Schematic diagram showing SOC in the global carbon cycle (Lefèvre *et al.*, 2017)

Soil organic matter (SOM) is formed from different organic materials having different decomposition stages amalgamated together. These materials include dead biomass such as plant, animals, and microbial residues. SOM plays a vital role in functioning of soil ecosystem and global warming. It enhances agricultural productivity and environmental resilience by increasing soil fertility. This is because it maintains soil structure, preserves and releases of plant nutrients, and boosts water-holding capacity (Lefèvre et al., 2017).

Approximately 55-60% by mass of SOM is carbon. From this figure, the majority of the carbon is stored in organic form which is knows as soil organic carbon (SOC) (FAO, 2015). The net balance between the amount of C entering the soil and rate of mineralization of the inputs determines the amount of SOC that stores in the soil (Post & Kwon, 2000). From the different sources of carbon (C) input for SOC formation, plants take the biggest part. Plants facilitate accumulation of SOC by the input of new carbon sources to the soil, e.g., litter input from leaf, twig, branch, and root fractions, which gradually are transformed into humus through time (Schumacher, 2002).

Based on its physical and chemical stability, SOC can be categorized into fast pool (decomposes within 1-2 years), intermediate pool (partially stabilized organic carbon with turnover times in the range 10-100 years), and slow pool (highly stabilized soil carbon which takes 100 to 1000 or more years to decompose) (Lefèvre *et al*., 2017).

As mentioned earlier, a small relative change in SOC significantly affects the equilibrium of the global carbon cycle. This particularly affects the atmospheric carbon pool since many processes that influence the SOC take place at the land-atmosphere interface. This in turn has its own implication on global warming, as more greenhouse gases (GHG) might be emitted to the atmosphere when the SOC is affected (Raich, & Schlesinger, 1992). Many factors such as land use, soil type, climate, and vegetation affects soil organic carbon sequestration (Guo & Gifford, 2002). The amount of SOC can be significantly affected by land use change and climate change (Jones *et al*., 2005; Smith, 2008a; Smith, 2008b; Don *et al*., 2011; Munoz-Rojas *et al*., 2013).

1.2 SOC and climate change

Now days more emphasis is given to understand the dynamics of SOC as different SOC reserves are vulnerable to climate warming, which society has an increasing concern for (IPCC, 2001).

The relation between soil organic carbon and climate change seems interesting to study as they can influence each other. The impact of climate change (mainly temperature rise) on SOC pool is negative whereas soil can be either a source or sink of carbon based GHGs depending on the circumstances (Lefèvre *et al*., 2017).

Climate change affects the soil organic carbon dynamics as climatic variables regulate the different terrestrial carbon components and the processes that occur in this system. Change in the global climate mainly temperature rise would affect soil organic carbon dynamics by altering its decomposition rate and plant litter production. Temperature increase would facilitate soil respiration, which lead to release of more GHGs into the atmosphere (Raich, & Schlesinger, 1992). In addition, climate change affects the pattern of plant litter production (Melillo *et al*., 1993; Cao & Woodward, 1998) which is the prime source of new SOC. Changes in amount of litter would likely lead a significant impact on the soil organic carbon stock dynamics and bio-geological cycles (Sayer *et al*., 2007). However, it is difficult to predict the impact of climate change on SOC due to the reason that litter production under climate change may either decrease, increase or remain the same depending on the carbon dioxide concentration in the atmosphere (Cao & Woodward, 1998; Yurova *et al*., 2010; Cao *et al*., 2011). This implies under litter decrease and no change scenarios, the impact would be decrease in SOC stock as the temperature enhances SOC decomposition. However, the outcome is yet unknown under litter increase scenario since it depends on the magnitude of increase.

On the other side, SOC affects global climate by either being a source or sink of carbon based GHGs responsible for global warming. SOC serves as a sink to GHGs when atmospheric carbon dioxide is sequestrated by vegetation and the litter input from these plants ends up in the soil. This phenomenon reduces global warming. On the contrary, SOC can enhance global warming by emitting GHGs such as carbon dioxide and methane because of different processes and activities that facilitate mineralization such as land use change, erosion, etc (Lefèvre *et al.*, 2017). The exchange of GHGs between terrestrial ecosystems and the atmosphere is highly influenced by anthropogenic activities related to land use, which in turn lead to alteration of the global climate.

1.3 SOC and land use change

Population growth coupled with associated consequences such as urbanization, agricultural expansion, and industrialization are the main drivers of land use/cover changes in many parts of the world. Historically, the land demand for cultivation, pasturing, human settlements, forest products, and biofuels led to land use changes to occur. Particularly, expansion of cultivated land and pastures at the expense of forests has been happening to feed the growing population. This demand for land will likely to continue in the future, as the rapidly increasing commercialization of all types of food and bioenergy will likely increase the need of land (Knickel, 2012).

Land use change (LUC) changes the biotic and abiotic characteristics of an area, including the soil. It directly or indirectly affects the soil structure, which subsequently influences the biodiversity, balance of water and different gases. This is due to that LUC principally affects the soil organic matter, which regulates many processes taking place in the soil. Hence, it may lead to change in SOC stock. The outcome depends on the LUC scenario meaning it could lead to either a gain or loss in SOC stock. For instance, conversion of forest into arable land may lead to decline of SOC stock and would have the reverse impact if cropland converted to forest (Feller & Beare, 1997). In a meta-analysis study, Guo & Gifford (2002) indicted that land use change has a significant impact on soil C stock. Land use changes from forest or grassland to croplands led to significant loss of SOC.

Land use change has been one of the main sources of human induced emission of GHGs since preindustrial times. For instance, one-third of the anthropogenic generated GHGs was due to land use change between 1750 and 2011 (Pachauri *et al*., 2014).

1.4 Land use change in Blue Nile basin in Ethiopia

Similar to other sub-Saharan countries, land use conversions are common phenomena in Ethiopia. In particular, expansion of croplands at the expense of natural forest has been occurring in various parts of the country during the 20th century due to policy changes. A significant land use/land cover change in the form of deforestation has been taking place in the Blue Nile basin where the Birr watershed is situated (Gebrehiwot *et al*., 2014; Abebe, 2016; Gashaw *et al*., 2017).

This change in land use was mainly driven by population growth and associated consequences such as increased demand for food and shelter. Population increase, slope, livestock and distances from various infrastructures were the main factors predicted to be the drivers of land use change in the upper part of Blue Nile in Ethiopia (Yalew *et al*., 2016). Abebe (2016) investigated the drivers of LUC in the Birr watershed by conducting socio-economic surveys. Based on Abebe (2016) finding, population growth which escalated demand for cultivated /settlement land and fuel wood consumption, economic factors through market availability, market price, expansion of infrastructure like road and land tenure security and policy that increases the confidence of farmers to manage their plot of land were identified as the major driving forces of LUC in the watershed.

1.5 Estimation of SOC

To meet the Kyoto protocol objectives, it is necessary to establish methods for estimating changes in carbon stocks due to different process. This is also helpful for monitoring and reporting of changes in soil carbon stocks and associated GHG emissions. For this purpose, different methods have been suggested for estimating gases responsible for global warming (IPCC, 2003; Smith, 2004). The use of models and inventory measurement systems, which were categorized under tier 3 in the decision trees of IPCC good practice guidance for LULUCF, are among these methods. These methods estimate greenhouse gas emissions with higher certainty compared to the lower tiers (IPCC, 2003).

Estimating and understanding of how environmental changes affect trends and dynamics of SOC with time is essential for mitigation of climate change. Factors such as high cost and expensive effort requirement make soil inventories unrealistic though they are more accurate to estimate soil carbon changes. For this reason, the use of soil carbon models is preferable.

There is little knowledge to explain the changes in molecules in fresh litter undergo while converting to SOM (Chertov *et al*., 2007). This is because different process such as biochemical, chemical and physical involve in soil C decomposition. This makes modelling of SOC complex. However, this factor does not restrict us from the use of modelling method to estimate SOC dynamics. Different models developed with different assumptions have been applicable to estimate SOC dynamics. To mention some: RothC (Coleman & Jenkinson, 1996), Q (Ågren & Hyvönen,2003), ROMUL (Chertov *et al*., 2001), and the Yasso07 (Liski *et al*., 2005) models in which all are process based models.

The Q model is a process-oriented soil C modelling tool, which works based on continuous quality changing assumption. Soil organic matter is described by a distribution g (q, t) over a continuous variable quality, q, in which the quality changes with time. Detailed description of the model can be found in Ågren & Bosatta (1996) and Ågren & Hyvönen (2003). The model is previously used to estimate the national soil carbon stock balances (Ortiz *et al*., 2011; Eliasson *et al*., 2013) of Sweden and to determine impacts of intense forest biomass harvest on SOC (Ågren & Hyvönen, 2003; Ortiz *et al*., 2014). It was also applied in prediction of future climate impact on soil carbon (Yurova *et al*., 2010).

1.6 Research question

In this study, it is hypothesized that land use change and climate change would influence SOC stock dynamics in Birr watershed in Ethiopia. To test this, the following research questions have been formulated.

1) What would be the consequence of predicted climate change on SOC stock dynamics at the end of the 21^{th} century?
2) What is the impact of LUC on the SOC stock balance?
   a) Which LUC scenario could result to more SOC loss?
   b) Which LUC scenario would lead to SOC stock increase?
3) What would be the combined effect of predicted LUC and climate change on SOC stock dynamics at the end of the 21^{th} century?

2. METHODOLOGY

2.1 Study area

The impact of land use changes under different climate scenarios on soil organic carbon dynamics of the Birr watershed (Figure 2b) in the Blue Nile basin (Figure 2a) was investigated. The Blue Nile basin, one of the two sub-basins of the Nile River, is situated in the northwestern part of Ethiopia (Figure 2c). The basin covers an area of *Ca.* 2×10^5 Km^2 and contributes approximately 60% of the total water volume of Nile River at Aswan in Egypt (Gebrehiwot *et al*., 2014).

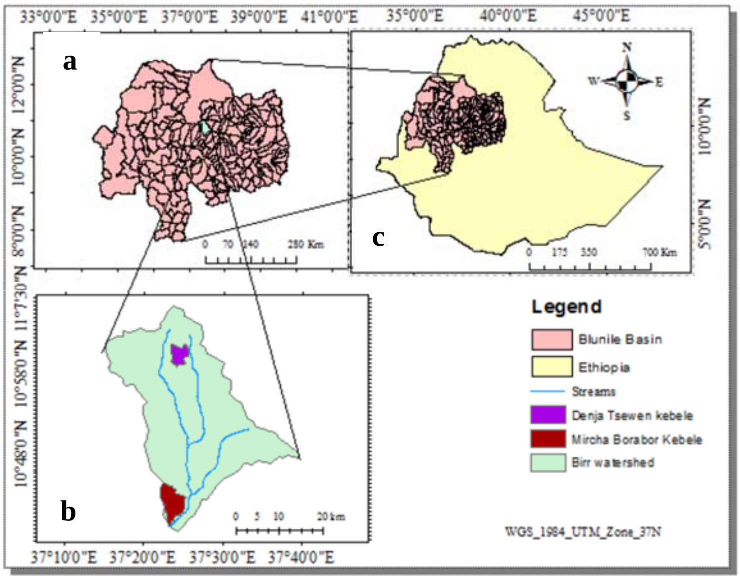


Figure 2 Location map of the study area (Adopted from Abebe, 2016)

The Birr watershed is delineated within the coordinates of 10°38´ & 11°17´ North, and 37°16´ & 37°45´ East on the geographic coordinate system. The watershed covers an area of 980 Km^2. The mean annual precipitation and mean daily temperature of Birr watershed are 1730 mm and 16°C, respectively (Gebrehiwot *et al*., 2014).

2.1.1 Soil and topography

According to Gebrehiwot *et al*., (2014), Haplic Luvisols and deep Alisols soil types dominated by tuff basalt rocks characterize the soil and geology of Birr watershed. The altitude of the watershed ranges from 1789 - 3290 *masl.* In general, the area is dominated by higher elevation. Mountains and highly dissected terrain with steep sloppy areas in the upper stream part and gentle slope and flat areas in the downstream parts are the main topographic features of the Birr watershed.

2.1.2 Vegetation and crop

Information on vegetation type is important for a more accurate estimation of litter input. According to Kebede (2016), the vegetation of the Birr watershed is diverse which includes tree and shrub/bush species. *Croton macrostachys, Cordia africana, Acacia abyssinica, Ficus sur, Albizia gummifera, Rosa abyssinica* and *Erythrina abbyssinica*, *Phoenix reclinatam* are some of the widely observed natural forest species in the watershed. Planted species such as the *Eucalyptus* species (*Eucalyptus camaldulensis*, *Eucalyptus globulus*, and *Eucalyptus saligna*), *Juniperus procera* and *Gravillea robusta* are also common in the area. The common shrub species that grow in the watershed are; *Vernina amygdalina, Calpurnea aurea, Carissa edulis*, and *Bersama abyssinica.*

The farmers in the area practice subsistence way of agriculture, which mostly carried out during the rainy season (June to October). Common crops cultivated include; Tef (*Eragrostis tef*), Finger millet (*Eleusine coracana*), Maize (*Zea mays*) and Wheat (*Triticum vulgare*) as indicated by Kebede (2016).

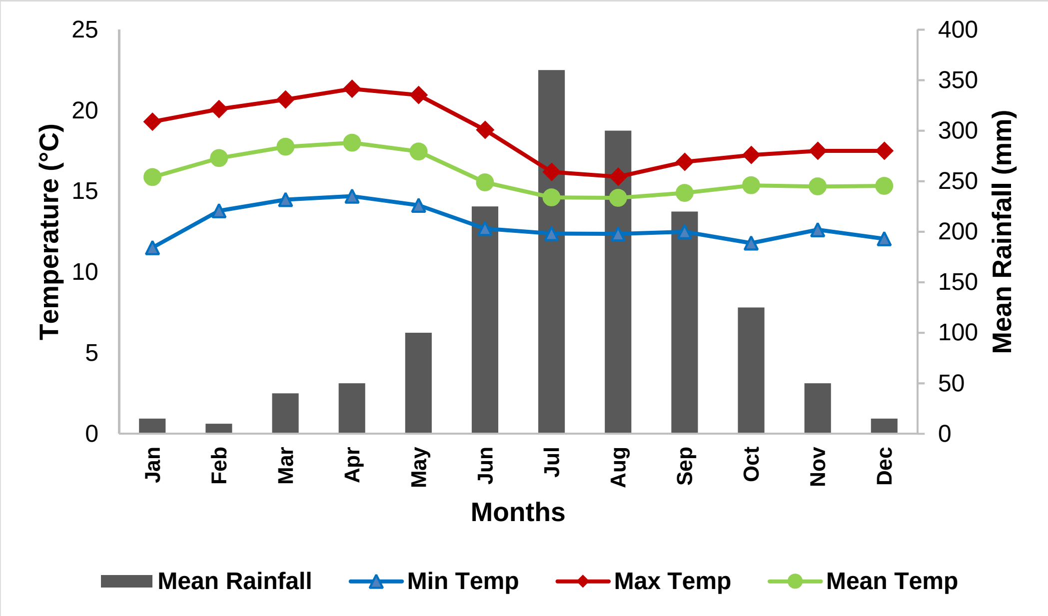


Figure 3 Monthly average rainfall and monthly maximum, minimum and mean temperature of Birr watershed for the period 1962-2004 (Mellander *et al*. 2013)

2.2 The soil C model

The model that was employed to estimate SOC stock change due to land use change and future climate is the Q soil carbon model. The model, which is used to estimate soil C developments over time, works based on the continuous quality theory, called Q theory (Ågren & Bosatta, 1996). The model calculates the remaining soil carbon while the soil carbon input material decomposes continuously with time. The concept behind the model is that decomposing microbes are carbon limited. Hence, litter input is their main source of carbon and energy. A litter cohort has its own initial quality 'q', which is better in quality than litter in the later stages of the decomposition process. As the litter quality decreases over time, it becomes more recalcitrant (Berg *et al*., 1995). This is because the litter loses carbon and changes its chemical characteristics. Due to this, the decomposition rate is faster in the initial stages of litter degradation and then slows down as the carbon quality declines.

The model calculates the remaining mass of litter by dividing into different fractions; such as, needle, fine root, branches, stems, course root, stump, and understory vegetation. The reason for this division is that the time required for complete invasion of these fractions is different as their surface area may vary. For instance, stumps and course roots need more time to be fully invaded by decomposers than leaves.

Taking into account quality decrease and C loss of the remaining litter mass, the remaining fraction of litter cohort, g, after time t, is estimated by the decomposition function:

$g(t) = (1+fc\beta\eta 11 u_0 q_0^{\beta} t)^{-(1-e0/\beta\eta 11e0)}$ -- eq. 1

Where: fc is the carbon concentration in decomposer biomass; q_0 is either the initial litter quality in needles (q_{0n}) or the initial litter quality in woody fractions (q_{0w}). e_0 is the decomposer growth efficiency which explains the portion of carbon assimilated into new decomposer biomass per unit of carbon utilized. η_{11}, is the parameter-describing rate of decrease in quality, whereas, β indicates the shape of decomposer quality in response to quality decrease depending on soil texture, especially clay. The parameter u_0 is decomposer growth rate, which is dependent on average air temperature (T) at the site. For woody fractions, the above equation has to be modified to incorporate the parameters *maxb* (yr) and *maxs* (yr). These parameters are added in the model to consider the time required for decomposers to invade branches, stems and stumps completely.

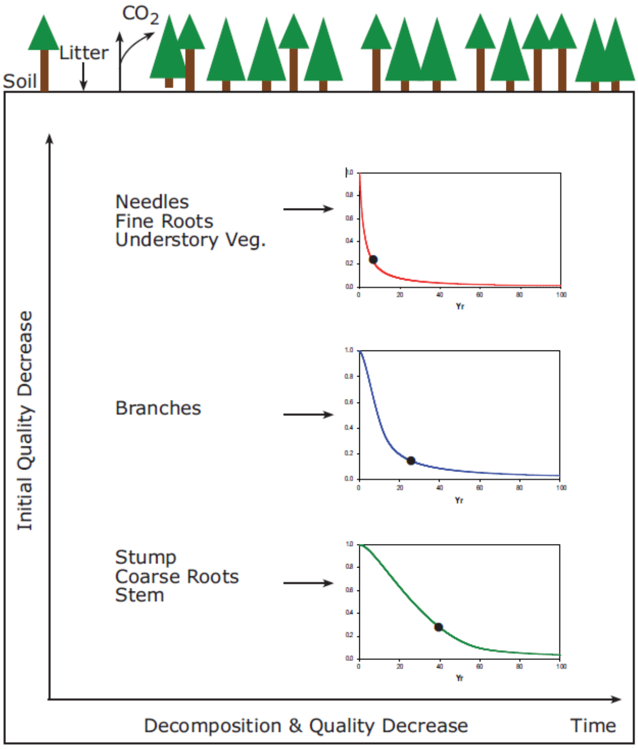


Figure 4 A schematic diagram of the Q model. The curves describe the mass of different litter fractions remaining as a function of time (Ortiz, 2012)

To simplify matters, the different parameters are lumped together and the model can be described by the formula:

$G(t)=(1-\alpha_n t)^{-z}$ -- eq. 2

Where; n in α_n represents the decomposition of needle litter and would be replaced by α_w for woody litter decomposition.

$\alpha = fc\beta\eta 11u0q^{\beta}{}_0$ -- eq. 3

$Z = \frac{1-e0}{\beta\eta 11e0}$ -- eq. 4

The detailed mathematical description and explanation of different parameters is clearly found in many publications (Ågren *et al*., 2007; Ågren & Hyvönen, 2003; Hyvönen & Ågren, 2001; Hyvönen *et al*., 1998).

2.3 Model input

The model is driven by annual mean litterfall production and mean annual air temperature.

2.3.1 Litterfall production

The Q model was developed based on the assumption that litterfall from surrounding vegetation is the main source of new carbon to the soil organic matter. Hence, the amount of new carbon added to the soil is dependent on the amount of annual litterfall produced.

Annual litter production data for each land use were collected from previously done studies in the Birr watershed, and where such reports were not found from the Blue Nile basin and Ethiopian highlands.

Dominant tree species mainly *Croton macrostachys, Cordia africana, Acacia abyssinica* and *Juniperus procera* were considered for the estimate of annual litter input data for natural forest land use. Therefore, result findings of different studies done at different times were compiled together and the average value was taken (Lisanework & Michelsen, 1994; Bernhard-Reversat & Loumeto, 2002; Demessie *et al*., 2012; Negash & Starr, 2013). Litterfall data for *Eucalyptus* plantations was estimated by taking the average values of common *Eucalyptus* species observed in the area (Lisanework & Michelsen, 1994; Demessie *et al*., 2012). Collection of firewood from the forest by residents to meet their energy need is a common practice in area. Hence, the amount of wood biomass removed from the forest based on Olsson (2005) study was considered for both forest types to get a more accurate estimate of yearly litter input. The annual litter production values measured by Abegaz *et al*. (2016) were used for bushland and cropland land uses. Proportions of different litter fractions (leaves, stem, branch, and stump & course roots) for different land uses were taken from the corresponding studies.

Table 1 Mean annual litterfall production for the different land uses used in the Q model

Land use	Mean litterfall (Mg C ha^{-1} $year^{-1}$)	Reference
Natural forest	7.3	Lisanework & Michelsen (1994) Bernhard-Reversat & Loumeto (2002) Demessie *et al*. (2012); Negash & Starr (2013)
Eucalyptus plantation	5.8	Lisanework & Michelsen (1994) Demessie *et al*. (2012)
Bushland	4.7	Abegaz *et al*. (2016)
Cropland	4.1	Abegaz *et al*. (2016)

2.3.2 Temperature

For the contemporary climate, the average temperature (16°C) for the years 1962-2004 recorded by the Ethiopia Metrology Agency and corrected by Mellander *et al*. (2013) was used. For climate change, the mean temperature increase predicted by the seven GMC's as locally downscaled in Mellander *et al*. (2013) based on Hulme *et al*. (2001) was used. It was predicted that the mean temperature between 2050 - 2100 would be 2.6°C higher compared to the mean temperature between 1961-1999 in Blue Nile Basin.

2.4 Model parameterization

The range values for model parameterization were adopted from Ortiz *et al*. (2011). These values were estimated for Swedish forests specifically for pine and spruce species. However, adjustments were made for some of the parameters, which could be more sensitive to circumstances. These parameters are related to litter chemical properties such as carbon to nitrogen ratio (C: N) and Lignin to nitrogen ratio (Lignin: N) and soil characteristics like clay content. This is because some of the parameters, for instance, initial litter quality (q_0), decomposer growth efficiency (e_0) and shape of decomposer-quality response (β) are dependent on these characteristics.

Table 2 Q model parameter estimates used in the simulations. Average, minimum, and maximum values of the parameter sets (n =231) based on Ortiz et al. (2011).

	Parameters								
Values	q_0n	q_0w	e_0	$\eta 11$	β	*maxb*	*maxs*	u_{00}	u_{01}
Min	1.080	0.901	0.202	0.300	5.067	1.004	10.373	0.040	0.010
Max	1.559	1.294	0.300	0.400	8.990	39.996	59.948	0.090	0.020
Mean	1.273	1.064	0.263	0.349	7.030	20.943	36.220	0.065	0.015

2.5 Model calibration

To reduce model output uncertainty and for better parametrization of the input parameters, the model was calibrated using measured data of the study area. To do this, the SOC stock values for different land uses measured by Wondimagegn (2015) were used to calibrate the model. The SOC values measured were for the top 20 cm soil depth. However, the majority of SOC would store in the first meter depth (Lefèvre *et al*., 2017). The Q model calculates the amount of SOC pool based on litter input, which most probably stores in the upper part of the soil. Hence, to estimate the amount of SOC to one meter depth, a model developed by Gale & Grigal (1987) used for vertical root distributions and later adopted for vertical distribution of SOC by Assefa *et al*. (2017) was used.

$$Y = 1- \beta^d \qquad \text{-- eq. 5}$$

where Y is the cumulative SOC fraction from the surface to soil depth d in centimeters, and β the estimated parameter used as a measure of index of vertical SOC distribution. The value of β depends on land use types and these values were adopted from Assefa *et al*. (2017) study in the Blue Nile basin.

2.6 Model scenarios

Six land use change scenarios under contemporary and future climates were considered. In addition, three litter production scenarios were considered under climate change.

As for the climate scenarios, the contemporary climate (1960 -2015) and climate change (2050 -2100) scenarios were studied. Although the mean yearly air temperature of these periods were used, the model was used to simulate for 100 years for both scenarios by inputting specific temperature for each year. Different studies have indicated different litter production possibilities for climate change. It has been predicted net primary and litter productions of tropical ecosystems would decrease, increase or remain as present under climate change scenario. This is because net primary production (NPP) depends on carbon dioxide concentration in the atmosphere and availability to plants. Hence, the model was run with no change in litterfall production, litterfall increase (by 22%) and litterfall decrease (by 5%) scenarios as predicted by Cao & Woodward (1998) and Yurova *et al*., (2010).

According to Gebrehiwot *et al.* (2014) classification, four types of land use/land cover have been existing since 1957 in Birr watershed. These are; forest (natural and plantation), bushland, wetlands, and cultivated lands. In addition, six land use change scenarios taking place at different times were observed in the study area. The LUC scenarios are from; i) natural forest to bushland, ii) natural forest to cropland, iii) bush land to cropland, iv) bushland to *Eucalyptus* plantation, v) cropland to *Eucalyptus* plantation and vi) wetland to cropland. However, LUC from wetland to cropland was not considered in this study as it was very small area and hence assumed the impact would be minimal. Instead, the LUC scenario from natural forest to *Eucalyptus* plantation was studied, even if it did not happen in the site during the study period by Gebrehiwot *et al*. (2014). This LUC scenario was considered because this study is a part of LULUCF and REDD+ project, hence to see the difference between natural forest and *Eucalyptus* plantation contributions to SOC accumulation.

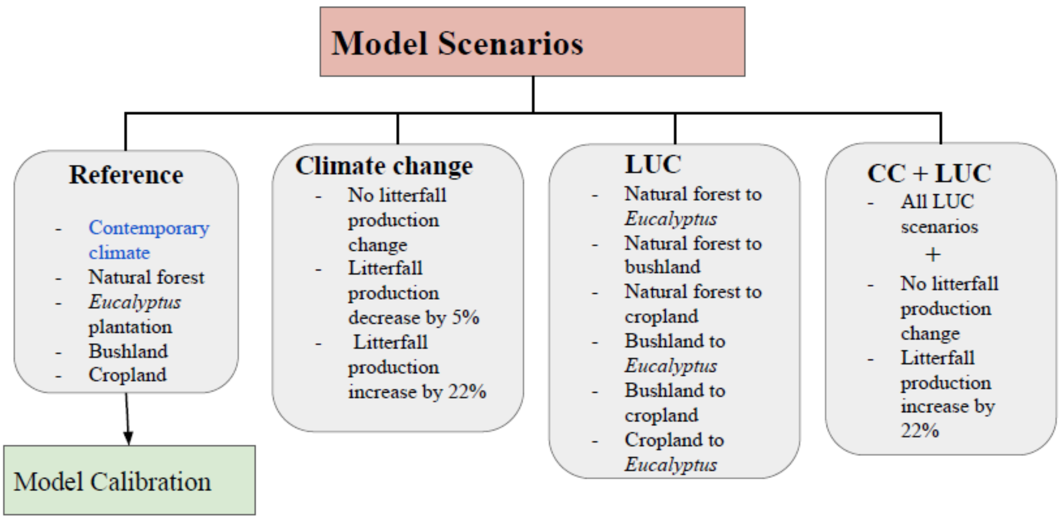


Figure 5 Schematic diagram showing tested model scenarios and calibration

The management practices specifically harvesting for *Eucalyptus* plantation was considered in the simulation. According to Olsson (2005) study, harvesting of *Eucalyptus* occurs every seven years on average in Ethiopia to generate a regular income for the farmers.

2.7 Statistical analysis

Prior to the analysis, the data were checked for normality. Based on this, the data were found not normally distributed. Hence, non-parametric tests were performed. To determine whether the mean values of measured and modelled SOC stocks are different among different land uses, Kruskal wallis test (one-way ANOVA) was performed. In addition, the mean measured and modelled SOC stock values under different climate scenarios were compared. The analysis was done in *R studio*.

3. RESULT

3.1 Model evaluation

Comparison of the distribution of the model estimates (grey line) and measured values (black line) of total SOC stocks representing different land use types in Birr watershed are given in Figure 6. Accordingly, the measured SOC values of natural forest (N = 12) and cropland (N= 24) and in some degree also *Eucalyptus* plantation (N=20) showed two peaks. The measured SOC value for bushland (N=22) followed normal distribution. The model estimates showed one peak in all cases. Simulated SOC stocks agreed well with measured values for natural forest and *Eucalyptus* plantation land uses. However, the model somewhat underestimated the SOC value of bushland land use. Although the modelled value for cropland was not appear fitted well with the measured SOC values, the means were not statistically different (Figure 6 & 7).

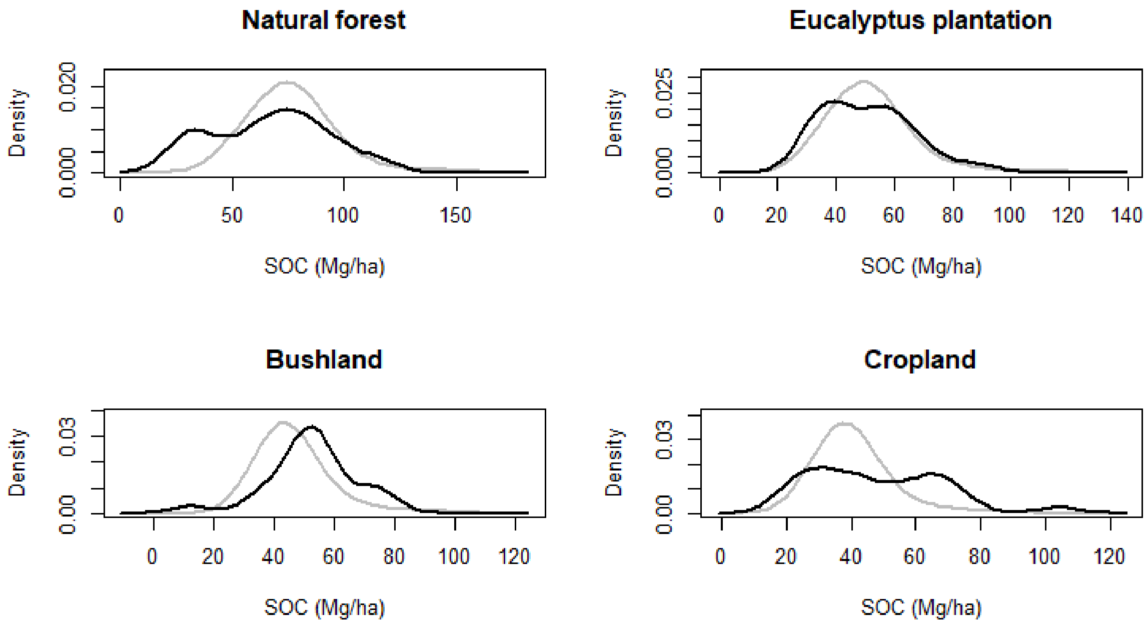


Figure 6 Density plots of soil C modelled with Q model (grey line) and from measured soil carbon stock (black line) of the Birr watershed, Ethiopia. N = 231 for Q-model simulations and 12, 22, 24 and 20 for measured soil C of natural forest, bushland, cropland and *Eucalyptus* plantation, respectively.

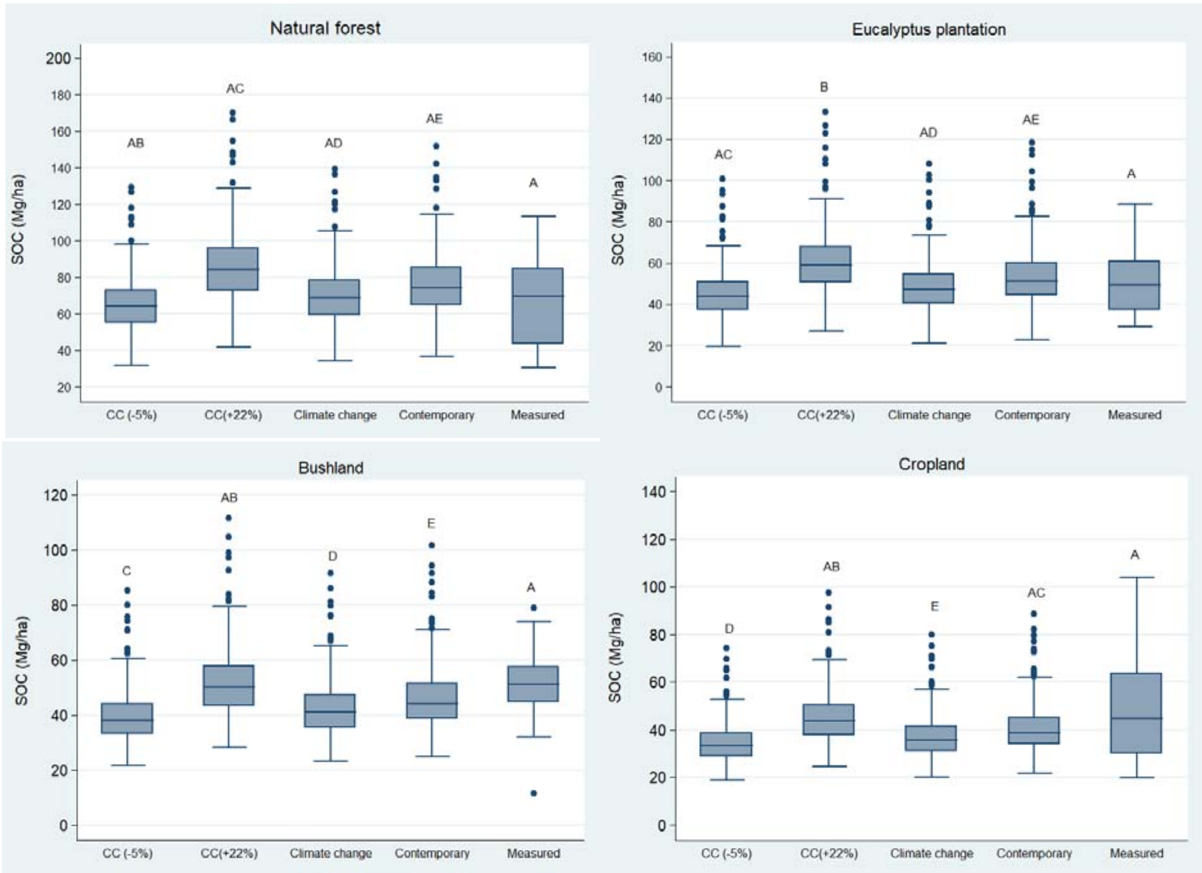
3.2 Soil organic carbon stocks of different land uses

The average measured SOC stock of different land use was ranged from 48.1 Mg ha^{-1} in croplands to 66.9 Mg ha^{-1} in natural forest soils. Comparing of the mean measured SOC stock values using one way ANOVA indicated that SOC level of natural forest land use was significantly higher than SOC stock measured in *Eucalyptus*, cropland and bushland land uses ($p<0.05$). The corresponding Q model simulations of the SOC content of the different land uses was ranged from 48.1 Mg ha^{-1} estimated for croplands to 66.9 Mg ha^{-1} estimated for natural forests. Comparing the mean SOC stock values of different land uses using ANOVA showed that the mean modelled SOC values were significantly different ($p<0.05$).

Table 3 Mean (range) SOC stock (Mg ha^{-1}) values measured (reported by Wondimagegn, 2015) and simulated with the Q model under contemporary climate. N = 231 for Q-model simulations and 12, 22, 24 and 20 for natural forest, bushland, cropland and *Eucalyptus* plantation, respectively.

Land use	Modelled	Measured
Natural forest	76.4[a] (36.8 - 151.9)	66.9[a] (30.4 - 113.6)
Eucalyptus plantation	53.6[b] (23.0 - 118.4)	50.8[b] (29.3 - 88.6)
Bushland	46.2[c] (24.8 - 101.6)	52.0[b] (11.3 - 78.8)
Cropland	40.4[d] (21.7 - 88.7)	48.1[b] (19.9 - 104.0)

[a, b, c, d.] *Post Hoc tests and land use types which share the same letters do not differ significantly at 0.05 significance level*



[A, B, C, D, E] *Post Hoc tests and groups which share the same letters do not differ significantly at 0.05 significance level*

Figure 7 boxplots showing measured and modelled (different scenarios) median values of SOC stocks of different land uses in Birr watershed. N = 231 for Q-model simulations and 12, 22, 24 and 20 for measured soil C of Natural forest, Bushland, cropland and *Eucalyptus* plantation, respectively. CC (-5%) stands for litterfall decrease by 5% and CC (22%) stands for litterfall increase by 22% under climate change. The median, the 25th and 75th percentile values of predicted and observed SOC are shown in the figure. Dot values are outliers.

Another way of comparing the measured and modelled estimates (at different scenarios) is by boxplots as indicated in Figure 7. Based on this, the mean modelled values of SOC under contemporary climate were within the range of the measured values in all land uses. Kruskal wallis test indicated that the mean measured and modelled SOC values under contemporary climate were not significantly different for all land uses ($p>0.05$) except bushland in which the mean measured value was significantly higher than the modelled value ($p<0.05$).

3.3 Impact of climate change on SOC

Simulations for the different land use classes under climate change scenario revealed that future climate would have a negative consequence on SOC stocks if not litterfall increased (Figure 8). After 100 simulation years, under no change in litterfall production scenario, climate change would deplete SOC by 6.2, 4.6, 3.7, and 3.2 Mg ha^{-1} in natural forest, *Eucalyptus* plantation, bushland, and cropland land uses, respectively. The loss would be more (between 5.8-11.1 Mg ha^{-1}) if the litterfall production drops by 5%. The losses in SOC stocks under climate change and with 5% decrease in litterfall scenarios were significant for bushland and cropland ($p<0.05$) but not for natural forest and *Eucalyptus* plantation. Although climate change will have a negative impact on SOC, the overall impact on SOC stock would be positive if the litter production would increase by 22% due to increase in temperature and carbon dioxide concentration in the atmosphere. Under this scenario, a net accumulation of 9.4, 7.6, 5.7, and 4.9 Mg ha^{-1} of SOC in natural forest, *Eucalyptus* planation, bushland, and cropland land uses, respectively, was predicted (Figure 8). This increase was significant only for *Eucalyptus* plantation ($p<0.05$) as shown in Figure 7.

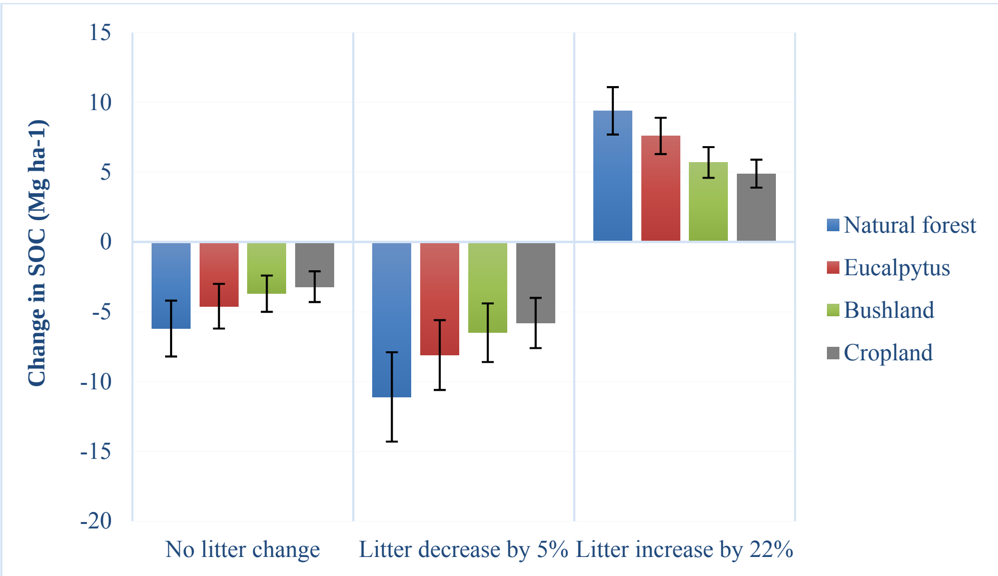


Figure 8 SOC changes (Mg ha-1) due to climate change at different litter production scenarios at the end of 100 simulations years. The bars indicate average values and error bars are standard deviations (N=231).

In terms of relative loss, SOC stock would decrease by around 8% in all land uses due to climate change if litterfall production remains the same (Table 4). The soil carbon loss would worsen if the litterfall production would decrease due to climate change. On average, SOC would decrease by 14 to 15.1% under litterfall decrease scenario in all land uses over 100 years. However, under increase in litterfall scenario, the impact of increased decomposition rate was compensated by litter increase and lead to a net accumulation of SOC. It would result 12.1-14.2% increase in SOC in all land uses as shown in Table 4.

Table 4 Mean (range) values of simulated SOC stocks and relative change (%) of different land uses under future climate with different litter production scenario (N=231).

	Contemporary	Climate change					
		No litterfall change		Litterfall (-5%)		Litterfall (+22%)	
	Mean (range)	Mean (range)	Change (%)	Mean (range)	Change (%)	Mean (range)	Change (%)
Natural forest	76.4 (36.8-151.9)	70.2 (34.3-139.2)	-8.1	65.3 (32.0-129.5)	-14.5	85.8 (42.0-170.0)	12.3
Eucalyptus	53.6 (23.0-118.4)	49.0 (21.2-108.4)	-8.6	45.5 (19.7-100.7)	-15.1	61.2 (27.2-133.1)	14.2
Bushland	46.2 (24.8-101.6)	42.5 (23.1-91.5)	-8	39.7 (21.6-85.2)	-14.1	51.9 (28.3-111.7	12.3
Cropland	40. (21.7-88.7)	37.2 (20.2-79.8)	-7.9	34.6 (18.8-74.3)	-14.4	45.3 (24.6-97.4)	12.1

3.4 Impact of land use change on SOC stock

Based on the simulations, this study indicated that LUC would result in both accumulations and losses of soil carbon over 100 years depending the type of scenario. Loss of SOC was predicted when natural forests were converted into other land uses under all climate scenarios. In contrast, a conversion of cropland to *Eucalyptus* led to increase of SOC stocks under all climate scenarios (see Figure 10 & Table 5).

Under the contemporary climate, LUC from natural forest to cropland resulted a net loss of 20.7 Mg ha^{-1} SOC within 100 years, which is the highest among the LUC scenarios. In addition, land use conversions from natural forest to bushland, natural forest to *Eucalyptus,* and bushland to cropland could result 17.3, 15.6, and 3.4 Mg ha^{-1} of soil carbon loss, respectively. In the contrary, conversion scenarios from cropland to *Eucalyptus* and bushland to *Eucalyptus* led a net accumulation of 5 Mg ha^{-1} and 1.7 Mg ha^{-1} soil carbon in 100 years, respectively, as indicated in Figure 10.

Under contemporary climate, the highest relative loss (27.1%) was observed under natural forest to cropland conversion scenario followed by natural forest to bushland change (22.7%). In addition, land use conversion from natural forest to *Eucalyptus* (20.4%) and from bushland to cropland (7.4%) were the other scenarios that led to a net loss of SOC. Conversely, conversion of cropland to *Eucalyptus* planation resulted the highest SOC accumulation (12.5%). Land use change from bushland to *Eucalyptus* plantation was also the other scenario that resulted positive change in SOC (3.6%) under the current climate as indicated in Table 5.

Temporal development of SOC changes due to LUC with time over 100 simulation years for different climate scenarios are given in Figure 9. In most scenarios, the major accumulation or loss of soil carbon due to land use conversion occurred in the first 10 to 20 years. After that the change is little and/or almost stabilized after 50 years for bushland to cropland, natural forest to cropland and bushland to cropland conversions. However, land use conversions to *Eucalyptus* plantation did not follow similar trend like other land use changes as the values oscillate up and down every 7 years, which is the rotation period.

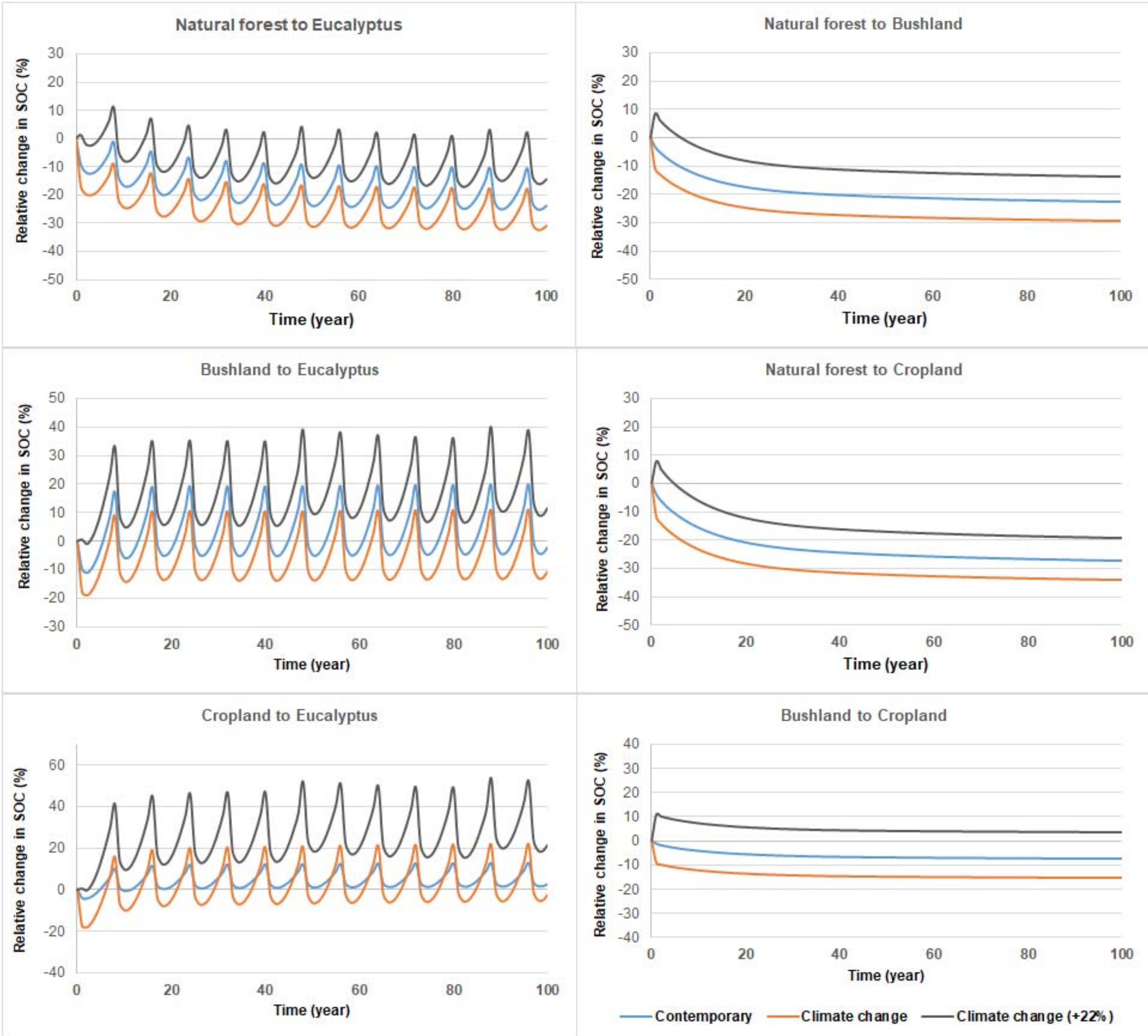


Figure 9 Changes in SOC (%) for mean modelled values due to LUC under contemporary and future climate scenarios simulated for 100 years (n = 231). For climate change scenario, no change in litter production and 22% increase in litterfall were included.

3.5 Combined impact of land use change and future climate on SOC

The combined impact of land use conversions and climate change on SOC exhibited additive interaction (Table 5). Under no change in litterfall scenario, there would be 21.1, 22.6, 25.9, 2.3 and 7 Mg ha^{-1} C loss in the soil stock due to increased decomposition from natural forest to *Eucalyptus* , natural forest to bushland, natural forest to cropland, bushland to *Eucalyptus* , and bushland to cropland LUC scenarios in 100 years, respectively. Under litterfall increase scenario, 7.5, 10.7, and 14.7 Mg ha^{-1} of SOC would be deducted from the stock for the LUC scenarios from natural forest to *Eucalyptus,* natural forest to bushland, and natural forest to cropland, respectively. In the contrary, SOC would accumulate under the LUC scenarios from bushland to *Eucalyptus* (8.8 Mg ha^{-1}), bushland to cropland (1.7 Mg ha^{-1}), and cropland to *Eucalyptus* (12 Mg ha^{-1}) which indicate the climate change effect is cancelled out by increase in litter production (Figure 10).

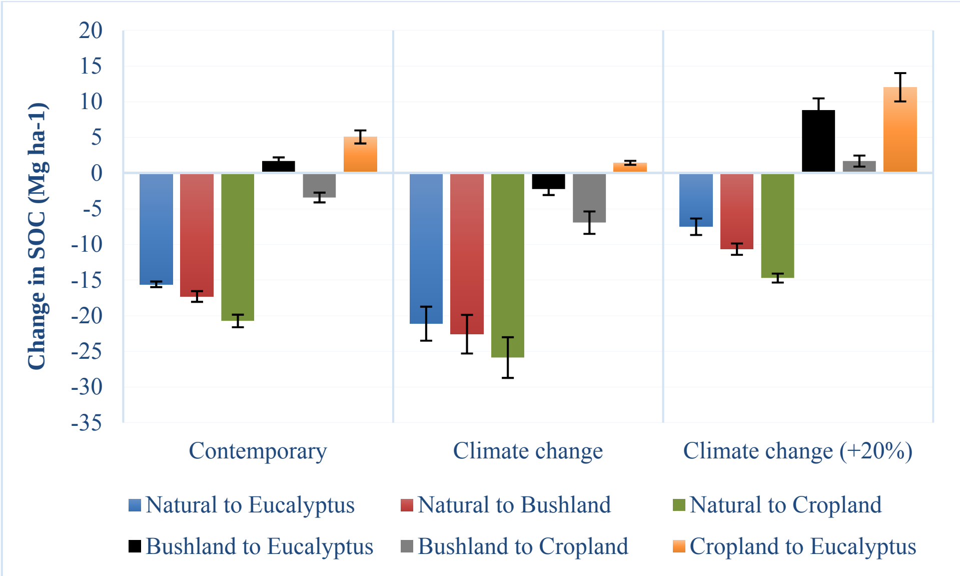


Figure 10 Changes in SOC (Mg ha-1) due to land use change under different climate scenarios at the end of 100 simulations years. The bars indicate average values and error bars are standard deviations (N=231).

Table 5 Mean (range) estimates (N=231) of LUC impacts on SOC stock at different climate scenarios after 100 simulation years in Birr watershed, Ethiopia.

From	To	Scenario					
		Contemporary		**Climate change**		**Climate change (+22%)**	
		Mean(range)	Change (%)	Mean(range)	Change (%)	Mean(range)	Change (%)
Natural forest	*Eucalyptus*	60.8 (26.5 - 137.1)	-20.4	55.3 (24.3 - 124.6)	-27.6	68.9 (31.0 - 152.9)	-9.8
	Bushland	59.1 (27.9 - 140.1)	-22.7	53.8 (25.8 - 125.4)	-29.6	65.7 (31.5 - 153.1)	-14.0
	Cropland	55.7 (25.4 - 136.4)	-27.1	50.5 (23.4 - 121.8)	-33.9	61.7 (28.5 - 148.7)	-19.3
Bushland	*Eucalyptus*	47.9 (20.2 - 104.5)	3.6	43.0 (18.7 - 95.9)	-4.9	55.0 (24.2 - 117.8)	19.1
	Cropland	42.8 (22.2 - 97.8)	-7.4	39.3 (20.7 - 87.9)	-15.0	47.9 (25.2 - 107.1)	3.6
Cropland	*Eucalyptus*	45.5 (19.0 - 96.9)	12.5	41.8 (17.7 - 89.1)	3.6	52.4 (23.0 -109.5)	29.8

Under no change in litterfall scenario, future climate and LUC resulted an overall decrease in SOC from the minimum 4.9% observed for bushland to *Eucalyptus* to the maximum 33.9% observed for natural forest to cropland land use conversions. However, conversions from cropland to *Eucalyptus* plantation would still increase SOC by 3.6% even with no change in litterfall scenario. The impact of LUC would not be completely counteracted by increase in litterfall for natural forest to *Eucalyptus,* natural forest to bushland, and natural forest to cropland land use change scenarios, which contributed 9.8%. 14% and 19.3% decrease in SOC, respectively. However, LUC from bushland to *Eucalyptus* and bushland to cropland would lead to a relative increase in SOC by 19.1% and 3.6%, respectively even under climate change as it would be compensated by litterfall increase (Table 5).

4. DISCUSSION

4.1 Soil organic carbon stocks

The simulated mean and range of SOC stocks of the natural forest agreed well with the measured ones (Wondimagegn, 2015). A similar range was reported by Assefa *et al*. (2017) in the highlands of Northwest part of Ethiopia. In contrary, Kassa *et al*. (2017) measured higher SOC stock (320 - 417 Mg ha^{-1}) in natural forest soils in the White Nile catchment in Southwest Ethiopia. The higher SOC level in Kassa *et al.* (2017) could be explained by differences in forest species, climate, and soil characteristics, which may have a significant effect on the soil organic matter pool (Batjes, 2014) by influencing litterfall production and soil-forming factors. A review study by Gebeyehu *et al*. (2017) indicated soil type is one of the factors resulting SOC spatial variability in agroecosystems in Ethiopia.

The mean simulated SOC stock for the *Eucalyptus* plantation (50.8 Mg ha^{-1}) was in agreement with a study done in Mozambique by Guedes (2017) predicted ~50 Mg C ha^{-1} stock for *Eucalyptus* forest using Q model. However, Guedes (2017) found higher mean measured SOC stock (138.8 Mg ha^{-1}). A higher mean SOC stock (185.8 Mg ha^{-1}) was measured in *Eucaliptus saligna* planted soils in the central highland of Ethiopia (Tesfaye *et al.,* 2016). The reason for the lower estimated SOC value in this study may be lower plant C inputs, which in turn could be depended on climatic factors, and soil characteristics. Historic land use could also be another factor that created SOC level variations. These simulations were done by assuming no historical land use change.

The SOC stock level estimated for bushland were ranging from 24.8 to 101.6 Mg ha^{-1} and was inconsistent with previous findings by Tesfaye *et al.* (2016) and Gebeyehu *et al.* (2017) who measured *ca.* 35 Mg ha^{-1} of SOC under degraded land covered with shrubs and under grazing lands, respectively, in Ethiopia.

Soil C under cultivated land was 40.4 Mg ha^{-1} on average. This value was lower than SOC stock of other land uses, which is mainly due to lower litter inputs. Gebeyehu *et al*. (2017) found closely similar SOC stock in soils cultivated with cereals in Ethiopia ranging from 36.6 to 102 Mg ha^{-1}. The result also agreed with the finding by Assefa *et al*. (2017) who found from 31 Mg ha^{-1} in Kattasi site to 116 Mg ha^{-1} in Gelawdios site in arable soils in the highlands of Northwest Ethiopia. Another study conducted by Tesfaye *et al.* (2016) in the central highland of Ethiopia found 98.1 Mg ha^{-1} SOC under croplands, which is more than double to the present finding. The variation might come from differences in crop types that determine litter input amount as well as soil type and local climate which govern decomposition rate.

4.2 Impact of climate change on SOC

Predictions using RothC and HadCM3LC soil carbon models revealed that climate change would lead to a net loss of organic carbon in global soils including the tropics (Jones *et al*., 2005).

In this study, climate change contributed to around 8% loss of SOC in all land use scenarios assuming litter input would stay as the current. Moreover, this loss would increase to 14-15% if litterfall production falls by 5% from the current amount in all land uses. However, the impact of climate change on decomposition rate would be counteracted by the increase in plant carbon input by 22% that could lead to accumulation of SOC ranging from 12.1% in the croplands to 14.2% in soils planted with *Eucalyptus*. A simulation study conducted to predict the effects of climate change on SOC dynamics in the Mediterranean region employing CarboSOIL model showed an overall trend towards decreasing of SOC stocks in the upper soil parts (0–50 cm) but overall increase in SOC in the deeper sections of the soil in different land uses (Munoz-Rojas *et al*., 2013). In most cases, climate change mainly temperature increase decreases SOC stock by facilitating soil organic matter decomposition. This is because SOM decomposition is more sensitive than net primary production, which ultimately result a net loss of SOC (Lal *et al.,* 2015).

4.3 Impact of land use change on SOC dynamics

Land use conversion is the direct cause for human induced soil organic carbon loss (Smith, 2008a) and the problem is worse in tropical and subtropical regions (Don *et al*., 2011). Because of this land use change is the second most source of anthropogenic GHG emission by affecting carbon stocks of terrestrial ecosystems significantly.

In general, the simulations indicated that LUC scenarios from natural forest to other land use resulted net loss of SOC, whereas, afforestation with *Eucalyptus* scenarios resulted a net gain of SOC in Birr watershed.

All changes in land use from natural forest resulted in SOC stock losses within a few decades, which is in consistent with Deng *et al*. (2016) review study. The reduced inputs of litter are suggested to be the main reason for high losses of soil C when converting forests into other land uses (Post & Kwon, 2000; Smith, 2008b; Assefa *et al*., 2017). Different studies have reported similar losses of soil C stocks due to deforestation in Ethiopia in the range from 2.3 Mg ha^{-1} to 8.0 Mg ha^{-1} per year (Assefa *et al*., 2017, Kassa *et al*., 2017). Another study conducted by Kassa *et al.* (2017) at different sites of Southwest Ethiopia indicated LU conversions of natural forest to cropland led to annual loss of SOC within the range of 3.3 to 8.0 Mg ha^{-1}. Belay *et al.* (2018) predicted 40% loss of soil carbon mainly organic after 40 to 50 years of converting forests into agricultural land using ecosystem model Biome-BGC in the Amhara region of Ethiopia. This indicates the net annual SOC loss due to deforestation in this study seemed low compared to previous findings. This could be because of the fact that the Q model does not incorporate soil C losses due to erosion, fire and ploughing factors in the process descriptions. Hence, it ignores other causes of soil carbon loss other than decomposition.

In the contrary, conversion scenarios from cropland to *Eucalyptus* and bushland to *Eucalyptus* led a net accumulation of 12.5% (5 Mg ha^{-1}) and 3.6% (1.7 Mg ha^{-1}) soil carbon after 100 years, respectively. This is mainly due to more plant C input was added into the soil than decomposition rate that led to accumulation of SOC. Tesfaye *et al*. (2016) found an annual SOC accumulation of 1.8 Mg ha^{-1} after 28 years of *Eucalyptus saligna* planation on a degraded land in southern Ethiopia. The study also indicted that planting of different tree species on croplands resulted 56.4% more SOC storage. The more SOC gain in Tesfaye *et al*. (2016) finding could be explained by many factors. Firstly, since it is based on field measurements, it might include all factors that govern SOC development, whereas, the Q model does not consider all factors that exist in the real environment and their interaction. Secondly, the amount of litter input may be higher as it depends on the tree species and climate. SOC stock also depends on the soil type. Generally, planting of cropland or degraded land with *Eucalyptus* is the better option to restore the SOC lost due to many factors. However, considering *Eucalyptus*'s negative ecological consequences on soil organisms, other soil properties, and hydrology at the same time is important (Zewdie, 2008; Martins *et al.*, 2013).

4.4 Combined impact of climate change and LUC

Climate change and land use conversion showed additive effect in this study. Under no litter change scenario, except conversion of cropland to *Eucalyptus* all other LUC scenarios resulted in an overall decrease in SOC with varying amounts (2.3 to 21.1 Mg C ha^{-1}) after 100 years in which bushland to *Eucalyptus* and natural forest to cropland scenarios were responsible for the least and the most loss of SOC, respectively. In addition, the loss of SOC due to LUC would not be compensated by increase in litter input for the LUC scenarios that involve deforestation of natural forest under litter input increase by 22% scenario. However, a net accumulation of SOC for the other LUC scenarios was predicted.

4.5 Model uncertainty

Factors such as high cost and extensive effort requirement make soil inventories unrealistic though they are more accurate to estimate soil carbon changes. For this reason, the use of soil carbon models is preferable. However, in modelling many factors contribute for the existence of uncertainties in soil carbon simulation (Peltoniemi *et al*., 2007). Model context, driving variables, parameters, and model structure are the main sources of uncertainties in soil carbon models. For this reason, maximum efforts should be put in during the whole process of modelling in order to reduce uncertainties as low as possible. In the use of models as a decision support tool, it is very important to communicate uncertainties in the science-policy-management interference (Walker et *al*., 2003).

In this study, different sources of uncertainties that may affect the results were anticipated and proper precaution was taken in order to reduce them to the least possible level. These uncertainties were related to driving variables, historic land use, model parameter values, model assumptions related erosion, fire, and ploughing factors. These factors, for example, may either underestimate the impacts of deforestation or overestimate the impact of afforestation with *Eucalyptus*. There are different possibilities to reduce uncertainties in model estimates of soil Q stocks. For instance, collecting litterfall data for each land use for the specific site can reduce the uncertainty related to litterfall production amount. Conducting litter decomposition study and identifying the soil type, nitrogen & clay content of the soil are also important to get specific values for model parameters, which depend on such factors, *e.g.* initial litter quality (q_o), decomposer growth efficiency (e_o) and decomposer growth rate changes with quality (β).

4.6 Implications of the study

Soil organic matter, which governs nutrient availability, soil stability, flux of trace GHGs between land and atmosphere interface, is impacted by change in land use and climate (Smith *et al*., 1999). Particularly, influencing the flux of GHGs by these factors needs to get more attention from climate change point of view. Therefore, estimating the impacts of environmental changes particularly land use conversion and changing climate on SOC pools is crucial for identifying the scenarios that have significant impacts on the balance of GHGs. This is essential in formulating climate related policies in order to reduce the release of these notorious gases.

The government of Ethiopia has shown ambitions towards reducing anthropogenic GHGs emission with the aim to reduce the 'business as usual' level by 64% by the year 2030 (MEFCC, 2018). Therefore, estimating the contributions of land use and climate change factors is important to meet the objective of intended nationally determined contribution.

5. CONCLUSION

The present study revealed that the model was able to reflect the measured soil C stocks in all land uses except bushland, which was slightly underestimated. The estimated mean total SOC stock under current climate was found to be higher in natural forests (76.4 Mg ha^{-1}) and lower in croplands (40.2 Mg ha^{-1}). Climate change would negatively affect SOC unless the litterfall production increase by 22% scenario would happen. Under contemporary climate, all land use change scenarios led to a net loss of SOC except land use conversions to *Eucalyptus*. The combined effect of land use change and future climate was additive. If litterfall production remains unchanged, SOC loss due to climate change would occur in all LUC scenarios apart from cropland to *Eucalyptus* conversion. Litterfall production increase by 22% would not compensate decomposition caused SOC depletion under climate change for the LUC scenarios from natural forest to other land uses. In general, the study showed the importance of preserving natural forests followed by planting of *Eucalyptus* on croplands and bushlands in order to maintain soil C stocks. These options play a crucial role in mitigating GHGs responsible for climate change. Finally, conducting of further studies on similar topic by collecting litterfall production data for each land uses and by performing litter decomposition study to get specific parameter values is recommended to find more accurate estimates.

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