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The combined impacts of land use change and climate change on soil organic carbon stocks in the Ethiopian highlands

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A B S T R A C T

Land Use Change (LUC), especially deforestation in tropical regions, significantly contributes to global anthropogenic greenhouse gas (GHG) emissions. Here, we address potential combined impacts of LUC and Climate Change (CC) on Soil Organic Carbon (SOC) stocks in the Ethiopian highlands. The soil model Q was employed to predict SOC stocks for various combinations of LUC and CC scenarios until the year 2100. Four reference scenarios (cropland, bushland, natural forest, and *Eucalyptus* plantations under contemporary climatic conditions) were evaluated against reported measurements of SOC stocks. We studied impacts of six common LUC scenarios, including deforestation and planting *Eucalyptus*, on SOC stocks under contemporary and future climates. To assess the impact of CC, effects of elevated temperature (mean annual temperature + 2.6 °C) together with three litterfall scenarios (no change in litterfall, a 5% reduction and 22% increase, designated CC_0, CC_d, and CC_i, respectively) were considered to test potential vegetation responses to increases in temperature and atmospheric CO_2 concentrations. Most of the tested combinations of LUC and CC led to losses of SOC stocks. Losses were most severe, both relatively and absolutely, in the deforestation scenarios: up to 30% was lost if natural forest was converted to cropland and temperature increased (under the CC_0 scenario). Gains in SOC stocks of 4–19% were modelled when sparse vegetation was converted to more dense vegetation like *Eucalyptus* plantation with substantially increased litterfall (the CC_i scenario). Elevated temperature accelerated decomposition rates, leading to circa 8% losses of SOC stocks.

We conclude that effects of LUC and CC on SOC stocks are additive and changes in litterfall caused by LUC determine which has the largest impact. Hence, deforestation is the biggest threat to SOC stocks in the Ethiopian highlands, and stocks in sparse vegetation systems like cropland and bushland are more sensitive to CC_0 than LUC. We recommend conservation of natural forests and longer rotation periods for *Eucalyptus* plantations to preserve SOC stocks.

Finally, we suggest that use of the Q model is a viable option for national reporting changes in SOC stocks at Tier 3 within the LULUCF sector to the United Nations Framework Convention on Climate Change (UNFCCC) as it is widely applicable and robust, although it only requires input data on a few generally available variables.

1. Introduction

Globally, the major anthropogenic threats to soil organic carbon (SOC) stocks are deforestation and subsequent erosion, as well as climate change (CC) (Don et al., 2011; Guo and Gifford, 2002; Jones et al., 2005; Tian et al., 2015). After fossil fuel combustion, Land Use Change (LUC) is the second largest contributor of anthropogenic greenhouse gas (GHG) emissions to the atmosphere (IPCC, 2014). Friedlingstein et al. (2020) estimated that LUC is responsible for emissions of 1.6 ± 0.7 Gt of C-CO_2 equivalents annually to the atmosphere during the last decade (2010–2019), but there are still great uncertainties about emissions due to LUC. In addition, projections using

Abbreviations: CC, Climate change; LUC, Land use change; LULUCF, Land use, Land use change and Forestry; SOC, Soil organic carbon; UNFCCC, the United Nations Framework Convention on Climate Change.

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the RothC SOC model and HadCM3LC climate model have indicated that CC could be responsible for 54–80 Gt of SOC loss by 2100 (Jones et al., 2005). Hence, understanding the concomitant effects of LUC and CC on SOC dynamics is essential for formulating comprehensive mitigating actions and sustainable land use management.

A number of studies have demonstrated the importance of LUC for global SOC stocks, including soil C in tropical ecosystems (Deng et al., 2016; Don et al., 2011; Guo and Gifford, 2002). Driven by rapid population growth and increasing demand for agricultural products, LUC is most prevalent in tropical regions (Betru et al., 2019; Lambin et al., 2001). Consequently, countries in these regions contribute almost 75% of the global annual LUC-induced anthropogenic GHG emissions (Pan et al., 2011). The estimated net effect of LUC on SOC stocks strongly depends on the type of conversion scenario. According to Don et al. (2011), conversion of primary forest to cropland has caused the highest SOC losses (20–32%) and afforestation of grasslands and croplands has provided the highest SOC gains (12–33%).

Climatic factors like temperature, precipitation, and humidity control SOC stocks by influencing plant and litter production, litter decomposition, and soil respiration rates (Taylor et al., 2017; Wu et al., 2011). Net Primary Production (NPP) can be used as a proxy to estimate quantities of litterfall. However, predicting the influence of climate change on NPP, and thus litterfall, is complex due to several feedback mechanisms related to temperature and atmospheric CO_2 concentration as well as water and nutrient availability (Cao et al., 2001; Cao and Woodward, 1998; Gärdenäs et al., 2011; Melillo et al., 1993). For instance, changes in climate (including elevated increases in temperature and reductions in precipitation) are expected to reduce NPP by 5 to 21% in tropical ecosystems (Cao and Woodward, 1998; Melillo et al., 1993). In such cases, CC can be expected to result in lower SOC stocks as litterfall decreases and higher temperatures may enhance decomposition rates. In contrast, if the changes in climatic factors are accompanied by rises in atmospheric CO_2 concentrations, NPP may increase by 22 to 27% in tropical ecosystems (Cao and Woodward, 1998; Melillo et al., 1993). Increases in ambient CO_2 concentrations may result in higher water use efficiency in tropical ecosystems, thereby promoting plant productivity. However, it is essential to note that plants' responses to elevated CO_2 concentration are plant-specific, and depend on the plant's acclimatization capacity and growing conditions, such as water and nutrient availability (Dusenge et al., 2021; Toreti et al., 2020).

Some countries listed as Annexes of the United Nations Framework Convention on Climate Change (UNFCCC), hereafter Annex countries, use inventory systems and/or models for reporting of changes of SOC within the Land Use, Land Use Change and Forest (LULUCF)-sector at Tier 3, the highest level, in their National Greenhouse Gas Inventories (IPCC, 2006). Models can also be used to compare effects of different LUC scenarios and predict potential long-term combined effects of changes in land use and climate on SOC stocks (Nabiollahi et al., 2019; Tian et al., 2015). Peltoniemi et al. (2007) give an overview of models used for national reporting of changes in SOC stocks to the UNFCCC, such as YASSO (Lehtonen et al., 2016), CENTURY (Chiti et al., 2010) and RothC (Farina et al., 2017). The Q model (Ågren and Bosatta, 1998) is a soil C model used for estimating changes in national soil carbon in Swedish forests (Ågren et al., 2007; Ortiz et al., 2011; Ortiz et al., 2013). The model has been evaluated against SOC measurements acquired in the Swedish National Forest Inventory (Ågren et al., 2007, Ortiz et al., 2011; Ortiz et al., 2013), long-term bare ground fallow experiments in Europe (Menichetti et al., 2019), and observations of natural forests and *Eucalyptus* plantations in Mozambique (Olsson et al., 2019). In the study reported here, we explored the possibilities for using the Q model for national reporting of changes in SOC stocks due to LULUCF- activities in a tropical area.

As in other tropical countries, land use conversion is common in Ethiopia (Tilahunet al., 2022; Hailu et al., 2020). In the Ethiopian highlands, croplands and *Eucalyptus* plantation expanded at the expense of natural forest in various parts of the country during the 20th century (Gebrehiwot et al., 2014; Kassa et al., 2017; Tilahun et al., 2022). Several studies have quantified the impact of changes in land use/cover on SOC stock dynamics in the Blue Nile basin of Ethiopia using measurements, statistical modelling or large-scale ecosystem modelling (Abegaz et al., 2016; Assefa et al., 2017; Belay et al., 2018). In this study, we provide an integrated analysis of the potential combined effects of LUC and future climate on SOC stocks in the Blue Nile basin. The aims of this study were to quantify and analyse potential impacts of Climate Change, common Land Use Change scenarios, and their combined effects on the development of SOC stocks up to 2100 in the Birr catchment of the Blue Nile basin in Ethiopia, using the Q model and data from previous field studies in the area.

2. Material and methods

2.1. Site description

The study was conducted in the Birr catchment of the Blue Nile Basin in Ethiopia, which covers an area of 980 km^2 within latitudinal and longitudinal ranges of 10.5–11.250° N and 37.25–37.750° E (Gebrehiwot et al., 2014). The mean annual precipitation and mean daily temperature in the catchment are 1730 mm and 16 °C, respectively (Gebrehiwot et al., 2011; Mellander et al., 2013). The most common soil types are Haplic Luvisols and deep Alisols, while tuff basalt rocks dominate the bedrock (Gebrehiwot et al., 2011; Gebrehiwot et al., 2014). The elevation declines from >3100 m in the northern-eastern part to <1900 m in south-western parts. In 2000, the dominant land uses were cultivated land (44%), open bushland (34%), natural forests (13%) and *Eucalyptus* plantations (9%) (Gebrehiwot et al., 2014).

2.2. The soil C model and its input

The soil model Q (Ågren and Bosatta, 1998; Ortiz et al., 2011) was used to estimate changes in SOC stocks due to changes in land use and climate. The Q model calculates SOC stocks over time based on the theory of continuous litter cohorts, where each cohort is defined by the timing, amounts and initial quality of litterfall (Ågren and Bosatta, 1996; Ågren and Bosatta, 1998; Ortiz et al., 2011). Plant litterfall is the source of new carbon added to the soil, and the decomposition rate of litter fractions varies with the time required for organic material to be colonized entirely by microbes (Hyvönen and Ågren, 2001). In this study, three litterfall groups were distinguished: 1) needles/leaves, 2) branches, and 3) stems and stumps/coarse roots. The parameters used were: initial quality of fine litter (q_{0n}), initial quality of woody fractions (q_0w), microbial decomposer growth efficiency (e_0), rate of decrease in quality (η_{11}), shape of decomposer quality response (β), time to total colonization of branches (max_b), time to total colonization of stems and stumps (max_s), and basic decomposer growth rate (u_0) (Table 2). We used the model version described by Ortiz et al. (2011), which includes a module for calculating initial SOC stocks assuming they are in steady state, i.e., that losses in SOC stocks through decomposition are balanced by gains through litterfall (Ågren et al., 2007).

The model is driven by mean annual air temperature and mean annual quantities of litterfall. For the contemporary climatic conditions, we used the average temperature (16 °C) for the years 1962–2004 recorded by the Ethiopian Meteorology Agency, as compiled by Mellander et al. (2013). For climate change, we used the mean temperature increase (+2.6 °C) predicted for 2050 to 2100 by seven GCMs (General Circulation Models) as locally downscaled by Mellander et al. (2013).

We specified the amount of litterfall under each of the four land uses in the study area: natural forest, *Eucalyptus* plantation, open bushland, and cropland (Table 1). Annual litterfall data were obtained from previous studies conducted in the Birr catchment, and if no reports providing required data were found, data related to the Blue Nile basin and other highland areas of Ethiopia were used (Table 1). The dominant tree species in natural forest were *Croton macrostachyus*, *Cordia africana*,

Table 1
Mean annual litterfall production under indicated land uses in the Q model. The cited studies are: a= Bernhard-Reversat and Loumeto (2002), b= Demessie et al. (2012), c = Lisanework and Michelsen (1994), d= Abegaz et al. (2016). Proportions of different litter fractions were taken from Descheemaeker et al. (2006).

Land use	Mean litterfall ($Mg\ C\ ha^{-1}\ yr^{-1}$)	Litter fraction proportions			References
		Leaf (%)	Branch (%)	Stem & stump (%)	
Natural forest	7.3	75	15	10	a,b,c
Eucalyptus	5.8	75	15	10	b,c
Bushland	5.3	80	10	10	d
Cropland	4.7	80	10	10	d

Acacia abyssinica, *Erythrina abbyssinica*, and *Phoenix reclinate*) (Senamaw et al., 2018; Solomon Gebrehiwot personal communication, 2018). Litterfall data for forested land (natural and *Eucalyptus*) were calculated from average values presented in the literature (Table 1).

Local people commonly collect firewood, circa 3526 kg ha^{-1} yr^{-1} according to Olsson (2004), from forests in the area. Hence, we reduced the estimated annual amounts of litterfall in both forest types by this amount to obtain more accurate estimates of net yearly litter inputs to the soil.

The main crops are maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), teff (*Eragratis teff*), and finger millet (*Eleusine coracana*), in addition to pulses and oil crops (Senamaw et al., 2018). The litterfall data for cropland and bushland were based on amounts recorded by Abegaz et al. (2016) in another catchment of the Blue Nile Basin. Abegaz et al. (2016) corrected litterfall amounts for usages of crop residues such as fodder, grazing or fuel. Proportions of litter fractions (leaves/needles, branches as well as stems and stumps) under considered land uses were taken from Descheemaeker et al. (2006) and the corresponding studies cited in Table 1.

The ranges of values for model parameterization were taken from Ortiz et al. (2011) for southern Swedish pine and spruce forests (Table 2). We adjusted two model parameters: initial quality (q_{0n}) of fine litter and the shape of the decomposer quality response (β), which we assumed to be most sensitive to factors such as litter chemical properties (for example, the litter C:N ratio), and soil properties like clay and moisture content.

Table 2
Q model parameter estimates used in the simulations. Average, minimum, and maximum values of the parameter sets ($n = 231$) are based on data presented by Ortiz et al. (2011) with adjustment of q_{0n} and β.

Parameter	Description	Unit	Values		
			Mean	Minimum	Maximum
q_{0n}	Initial quality of fine litter	–	1.2	0.9	1.4
q_{0w}	Initial quality of coarse litter	–	1.1	0.9	1.3
e_0	Microbial decomposer growth efficiency	–	0.26	0.20	0.30
η_{11}	Rate of decrease in quality	–	0.35	0.30	0.40
β	Shape of decomposer quality response	–	6.9	5.0	9.0
Max_b	Time required for total colonization of branches	Year	20.9	1.0	40.0
Max_s	Time required for total colonization of stems/stumps	Year	36.2	10.4	60.0
u_{00}	Parameter in u_0, the decomposer rate	–	0.07	0.04	0.09
u_{01}	Parameter in u_0, the decomposer rate	–	0.02	0.01	0.02

2.3. Model scenarios

In total, 34 scenarios were defined as combinations of four land use and six LUC scenarios under contemporary climatic and climate change conditions)(Fig. 1).

Simulations for the land use categories natural forest, *Eucalyptus* plantation, open bushland, and cropland under the contemporary climatic conditions with their specific litterfall rates were used as reference scenarios.

Six common LUC scenarios were considered (Gebrehiwot et al., 2014; Senamaw et al., 2018). These were conversions of: natural forest to bushland, natural forest to cropland, bushland to cropland, bushland to *Eucalyptus* plantation, cropland to *Eucalyptus* plantation, and natural forest to *Eucalyptus* plantation. To simulate effects of LUC, we used the parameter values to estimate initial SOC stocks under the reference land use and changed the driving variable litterfall to the litterfall rates of the new, converted land use. For example, the simulations of the conversion of natural forest to bushland had the initial SOC-stock of natural forest and litterfall rate of bushland.

All simulations covered 100 years. The first 99-year period was used as a spin-off period, which was particularly important for allowing enough time to model long-term effects of changes on the SOC stocks in the LUC scenarios. The impact of CC and/or LUC was assessed by comparing the estimated SOC stock at simulation year 100 of a scenario with the SOC stock of its reference land use at simulation year 100. Likewise, in the model evaluation, we estimated SOC stocks at simulation year 100 for reference land uses under contemporary climate and compared them with measured SOC values associated with the respective land uses (further details are provided below and in Appendix A, the supplementary information).

The annual mean temperatures in the contemporary climate and the climate change scenarios were 16 °C and 18.6 °C, respectively (Mellander et al., 2013). The CC scenarios included three alternatives of litterfall rates based on potential plant production responses to increases in temperature and/or atmospheric CO_2 concentrations: CC_0, unchanged litterfall; CC_i, a 22% increase in litterfall; and CC_d, a 5% reduction in litterfall, as predicted by Cao and Woodward (1998). The LUC scenarios were combined with two of the CC scenarios: the one with unchanged litterfall (CC_0) and the one with increased litterfall (CC_i).

2.4. Model evaluation of reference scenarios

Values for SOC stocks under relevant land uses measured by Amanuel et al. (2018) in the Ethiopian highland soils of the Birr catchment were used to evaluate the model and uncertainties of its output. Using 12, 22, 24 and 20 samples, they obtained average values of 29.62, 18.92, 21.22 and 21.44 Mg C ha^{-1} for SOC stocks in the top 20 cm of natural forest, bushland, cropland, and *Eucalyptus* plantation soils, respectively. They sampled soils under the same land use classes in both the highlands and lowlands of the Birr catchment, roughly in proportion to their relative areas. We combined all the data regarding each land use as we were modelling the catchment-scale stocks.

We extrapolated SOC measurements of the top 20 cm presented by Amanuel et al. (2018) to estimate SOC stocks in the top metre of soils using a model by Assefa et al. (2017), which is based on a model describing the vertical distributions of roots by Gale and Grigal (1987) and describes the vertical distribution of SOC (Appendix A, the supplementary information Table S1). We chose the top metre soil as it includes 100% of SOC stocks under all reference land uses, and significant, land-use-specific proportions are present between 20 and 100 cm depth (FAO and ITPS, 2015; Assefa et al., 2017, Appendix A, the supplementary information Table S1. The Kruskal Wallis One-way ANOVA test was applied to determine whether mean values of measured SOC stocks differed under different land uses. *R studio* (Allaire, 2012) was used for this analysis.

The model performance was evaluated by comparing mean values,

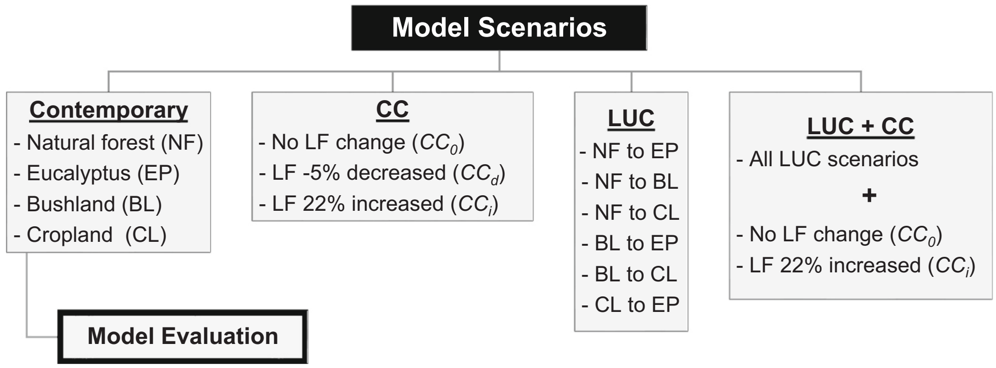

Fig. 1. Schematic diagram of the tested model scenarios and model evaluation. The reference scenarios are a combination of contemporary climate and four Land Use classes (NF = Natural Forest, EP = *Eucalyptus* Plantation, BL = Bushland and CL = Cropland). The Climate Change (CC) scenarios combine assumptions of elevated temperature and altered litterfall (LF) and six common Land Use Change (LUC) scenarios are included. The model predictions were evaluated using data presented by Amanuel et al. (2018).

ranges, and density distributions of measured values with simulated values for stocks under each land use under the contemporary climate at simulation year 100. Values of initial litter quality (q_{0n}) and shape of decomposer (β) parameters were manually adjusted to improve data fits to the reference (contemporary climate) scenarios. Using these performance indicators, we selected the parameter combinations that provided the best fits to the data and applied them for estimating effects of CC and/or LUC on SOC stocks.

The predictive performance of the model was also assessed quantitatively using normalized average error (*NAE*), relative mean bias (*rB*), and variance ratio (*VR*) indices, as recommended by Janssen and Heuberger (1995) (Appendix A, the supplementary information Table S2).

3. Results and discussion

3.1. Reference scenarios and model evaluation

The average measured SOC stocks under the considered land uses, extrapolated to 1 m depth based on data by Amanuel et al. (2018), ranged from 48.1 Mg C ha^{-1} in croplands to 66.9 Mg C ha^{-1} in natural forest soils. The SOC stocks of natural forest land were significantly larger than the measured SOC stocks in *Eucalyptus* plantation, cropland, or bushland ($p < 0.05$, Table 3). The corresponding Q model estimates of the SOC stocks under the land uses ranged from 46.3 Mg C ha^{-1} for croplands to 76.4 Mg C ha^{-1} for natural forests after a simulation period of 100 years. The modelled SOC stocks of natural forest, bushland and cropland were stable during the 100 years, while the stocks in *Eucalyptus* plantation oscillated due to the 8-year rotation period (Fig. 4b).

Our modelled SOC stocks for natural forest, *Eucalyptus* plantation, bushland, and cropland (Table 3, Appendix A, the supplementary information) were consistent with measured stocks in the Birr catchment. Distributions of the measured values and model estimates of SOC stocks under each of these land uses are presented in Fig. S1 (Appendix A, the supplementary information). The modelled estimates had one peak in all cases. The measured SOC values for natural forest ($N = 12$) and cropland ($N = 24$) had two peaks: a relatively low peak associated with samples collected in the highlands and a higher peak associated with samples from the lowlands (Fig. S1). The bimodal nature of observations affects the comparison of observed and simulated values (Tables 3 & S2) as the means and standard deviations of observations are poorer descriptors of the actual distributions than when observations are unimodally distributed.

The measured and simulated mean SOC stocks under the natural forest system, *Eucalyptus* plantation, and cropland in the Birr catchment were towards the lower end of reported ranges of mean values for other highland areas of Ethiopia (Table 3). There is high variability in estimates of SOC in natural forest land, which can be attributed to variations in forest species, climate, altitude and soil characteristics (Batjes, 2014; Delgado-Baquerizo et al., 2018). The simulated SOC stocks for *Eucalyptus* plantation are consistent with modelled stocks in Mozambique (Olsson et al., 2019), but was lower than measured stocks in *Eucalyptus*-planted soils in Ethiopia (Assefa et al., 2017; Tesfaye et al., 2016) and Mozambique (Guedes et al., 2018). The lower estimates of SOC stocks we obtained may be due to variations in historic land use or present management, as a longer *Eucalyptus* rotation period may result in higher SOC stocks. In addition, according to our simulations (Fig. 4b), changes in SOC stocks may vary up to 20% during an 8-year rotation period due to increases in litterfall rates as the trees grow. Hence, measured SOC stocks may depend on when samples are taken in a rotation period. The stocks estimated for bushland agreed well with findings of a study on degraded shrubland in Ethiopia (Tesfaye et al., 2016). For cropland, the estimated SOC stocks fell within the range of measured stocks in arable soils in the highlands of northwest Ethiopia (Assefa et al., 2017). Gebeyehu et al. (2017) found that Ethiopian cropland soil has relatively low SOC stocks compared to other tropical soils, and attributed this to a high prevalence of rain-fed farming systems in Ethiopia.

Table 3
Mean SOC stocks (with ranges in parentheses) down to 1 m depth (Mg C ha^{-1}) in the Birr catchment: extrapolations of values measured by Amanuel et al. (2018) and values obtained with the Q model under the contemporary climate ($N = 231$ for Q model simulations and 12, 22, 24 and 20 measurements of natural forest, bushland, cropland, and *Eucalyptus* plantation soil, respectively). Measured stocks under land use types with different lowercase letters (a or b) significantly differ according to post hoc tests of measured data (ANOVA, $\alpha < 0.05$). For comparison, ranges of mean SOC stocks in Ethiopia and Mozambique reported by previous authors for the reference scenarios are presented: 1= Assefa et al. (2017), 2= Belay et al. (2018), 3= Demessie et al. (2013), 4= Tesfaye et al. (2016), 5= Guedes et al. (2018).

Land use	Measured mean (range) (Mg C ha^{-1})	Simulated mean (range) (Mg C ha^{-1})	Range of mean SOC stocks in other studies (Mg C ha^{-1})
Natural forest	66.9[a] (30.4–113.6)	76.4 (36.8–151.9)	60–240[1,2,3,4]
Eucalyptus plantation	50.8[b] (29.3–88.6)	53.6 (23.0–118.4)	50–186[1,4,5]
Bushland	52.0[b] (11.3–78.8)	52.2 (28.0–114.2)	35–93[1,4]
Cropland	48.1[b] (19.9–75.0)	46.3 (24.8–101.6)	31–165[1,2,3,4]

3.2. Impact of climate change on SOC

Simulations of stocks under the considered land use classes under the climate change scenarios indicate that anticipated climate change will lead to a loss of SOC stocks if litterfall does not increase substantially (Fig. 2, Table 4). The mean SOC stocks were depleted by, on average, 6.2, 4.6, 4.2, and 3.7 Mg C ha^{-1} in natural forest, *Eucalyptus* plantation, bushland, and cropland, respectively, after 100 years under the climate change scenario with unchanged litterfall amounts (CC_0 in Fig. 2, left). The mean loss at year 2100 was higher (between 6.7 and 11.1 Mg C ha^{-1}) if litterfall dropped by 5% with climate change (the CC_d scenario). Hereafter, the presented modelled estimates of SOC stocks are for the

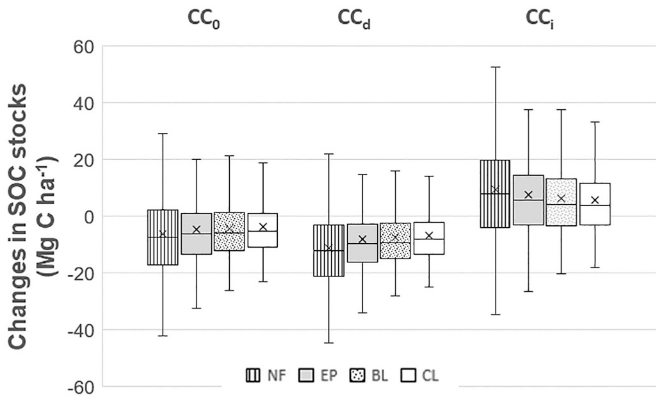

Fig. 2. SOC changes (Mg C ha^{-1}) after 100-year simulation due to climate change, CC_0 = Climate change (elevated temperature with no change in litterfall), CC_d = CC with a 5% reduction in litterfall and CC_i = CC with a 22% increase in litterfall. Mean values of 231 simulations are represented by crosses, while bottom, middle and top lines of boxes represent the 25th, 50th and 75th percentiles, respectively, and whiskers indicate the 95th percentiles (defined as the range without outliers).

end of the 100-year simulation period, unless stated otherwise.

In contrast, a 22% increase in litterfall (CC_i) counteracted the losses due to increased decomposition and led to accumulation of mean SOC under all land uses. Under this scenario, mean net accumulations at the year 2100 were found, ranging from 6 Mg C ha^{-1} in cropland to 9 Mg C ha^{-1} in natural forest, on average (Fig. 2, right).

Results for stocks under the considered land uses were consistent in terms of relative losses and gains. Climate change itself caused 8–9% loss of SOC stocks (Table 4), with deterioration to 14–15% if litterfall dropped, ultimately leading to depletion of SOC stocks under all land uses (Table 4). This follows the Q model assumption that a temperature increase accelerates soil organic matter decomposition and microbial respiration, as reported by Bond-Lamberty and Thomson (2010).

The simulated SOC losses due to climate change were similar to those obtained in modelling of SOC stocks in cropland under various management scenarios in northern Ethiopia (Mesfin et al., 2021). Mesfin et al. (2021) predicted annual losses of 0.008–0.013 Mg C ha^{-1} in unmanaged croplands and 0.015–0.025 Mg C ha^{-1} in managed croplands, while we estimated annual losses of 0.037 Mg C ha^{-1}. The predicted acceleration of the decomposition of soil organic matter by increases in temperature was more than compensated by the predicted 22% increase in NPP in response to increases in atmospheric CO_2 concentration and temperature. This suggests that soils in the Birr catchment will still be able to act as carbon sinks under CC conditions if NPP increases within a credible range, as suggested by Cao and Woodward (1998). However, the potential increase in NPP may be limited by water and/or nutrient availability (Kimball, 2016). Moreover, growth rates of tropical forests may already be close to their thermal optima. For example, in field experiments in Rwanda, Dusenge et al. (2021) found that late-succession tree species, which dominate in natural forest, had no apparent capacity to acclimate to a warmer climate by increasing their net photosynthesis, and hence NPP.

3.3. *Impact of land use change on SOC stocks*

3.3.1. *Contemporary climate*

All but one of the tested LUC scenarios resulted in reductions in mean SOC stocks under contemporary climatic conditions (Fig. 3, Table 5). Losses of SOC stocks were most pronounced when natural forest was converted to other land uses, and highest for conversion from natural forest to cropland, a net loss of 17.2 Mg C ha^{-1} within 100 years, corresponding to nearly a quarter of total SOC stocks of natural forests (Tables 1 and 5). Conversion of natural forest to bushland resulted in the smallest loss of the natural forest conversion scenarios, but still up to 13.7 Mg SOC ha^{-1} or 18% reductions of the total SOC stocks in natural forests (Fig. 3, Table 5). Intermediate relative losses were found for the bushland conversions to *Eucalyptus* plantation (−4%) or cropland (−7%), and for these conversions small gains in SOC stocks were also found within the 25–75% percentiles of the simulated values (Fig. 3). In contrast, the cropland into *Eucalyptus* conversion resulted in an average

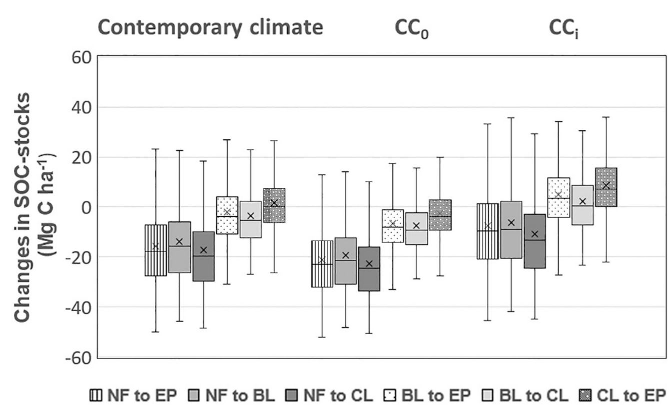

Fig. 3. Changes in SOC (Mg C ha^{-1}) due to Land Use Change (NF – Natural Forest; EP – *Eucalyptus* plantation; BL – Bushland; CL – Cropland) under indicated climate scenarios: Contemporary, CC_0 (climate change with no change in litterfall) and CC_i (climate change with a 22% increase in litterfall) at the end of the 100-year simulations. Mean values of 231 simulations are represented by crosses, while bottom, middle and top lines of boxes represent the 25th, 50th and 75th percentiles, respectively, and whiskers indicate the 95th percentiles (defined as the range without outliers).

Table 4
Mean values (with ranges in parentheses) of simulated SOC stocks and relative changes (%) under the reference land uses, in anticipated future climate and indicated litterfall scenarios: CC_0 (elevated temperature, litterfall unchanged), CC_d (elevated temperature, with a 5% reduction in litterfall) and CC_i (elevated temperature, with a 22% increase in litterfall) (N = 231). For *Eucalyptus* plantation, the mean stocks refer to mean stocks in the last complete rotation period, during the years 2093–2100, as stocks in the plantations vary within rotation periods (see Fig. 4b).

	Contemporary	Climate change					
		CC_0		CC_d		CC_i	
	Mean (range) (Mg C ha^{-1})	Mean (range) (Mg C ha^{-1})	Change (%)	Mean (range) (Mg C ha^{-1})	Change (%)	Mean (range) (Mg C ha^{-1})	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	52.2 (28.0–114.2)	48.0 (26.1–103.2)	−8.1	44.7 (24.3–96.0)	−14.4	58.6 (31.9–126.0)	12.3
Cropland	46.3 (24.8–101.6)	42.6 (23.2–91.5)	−8.0	39.6 (21.5–85.1)	−14.5	51.9 (28.3–111.6)	12.1

Table 5
Mean estimates (N = 231), with ranges in parentheses, of LUC impacts on SOC stocks under the climate scenarios contemporary, CC_0 (elevated temperature with unchanged litterfall), and CC_i (elevated temperature with a 22% increase in litterfall) at the end of the 100-year simulation in the Birr catchment of Ethiopia. For conversion to *Eucalyptus* plantations, the mean stocks refer to mean stocks in the last complete rotation period, during the years 2093–2100, as stocks in the plantations vary within rotation periods (see Fig. 4b).

From	To	LUC scenarios in combination with climate scenarios					
		Contemporary		CC_0		CC_i	
		Mean (range) (Mg C ha^{-1})	Change (%)	Mean (range) (Mg C ha^{-1})	Change (%)	Mean (range) (Mg C ha^{-1})	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	62.7 (30.6–144.1)	−17.9	57.2 (28.4–129.1)	−25.1	70.2 (34.7–158.1)	-8.1
	Cropland	59.2 (28.0–140.2)	−22.5	53.9 (25.9–125.5)	−29.5	65.7 (31.5–153.1)	−14.0
Bushland	*Eucalyptus*	50.3 (21.3–112.1)	-3.6	46.1 (19.7–102.8)	−11.8	57.6 (25.4–126.2)	10.4
	Cropland	48.7 (25.4–110.8)	-6.7	44.7 (23.6–99.5)	−14.4	54.5 (28.8–121.5)	4.4
Cropland	*Eucalyptus*	47.9 (20.2–104.5)	3.5	44.0 (18.7–95.9)	-5.1	55.0 (24.1–117.8)	18.8

SOC gain of about 3% or 1.6 Mg C ha^{-1} during 2093–2100, the last complete simulated rotation period (Figs. 3 and 4b). The major change in SOC stocks due to LUC occurred in the first 30 years and subsequently levelled off (Fig. 4). In conversions to cropland, the primary tillage may accelerate the SOC losses during the first decades. However, the effects of tillage are not considered in the Q model.

LUC scenarios from natural forest to other land uses resulted in substantially larger SOC losses than climate change scenarios CC_0 and CC_d. This reflects the Q model's sensitivity to changes in litterfall and suggests that SOC stocks are strongly influenced by any action that changes rates of litterfall. Reduced amounts of litterfall and more frequent harvesting of *Eucalyptus* are the likely reasons for the relatively high soil C losses associated with deforestation of natural forest (Abegaz et al., 2016; Assefa et al., 2017). Our model estimates for SOC stock losses associated with conversion of natural forest to *Eucalyptus* plantation agree well with losses reported by Assefa et al. (2017) and Tesfaye et al. (2016), coresponding to 17–29% of the original SOC stocks. Assefa et al. (2017) predicted a larger loss for conversion of natural forest to bushland (43%) than our estimate (18%), as shown in Table 5. Studies in the Ethiopian highlands have reported a large range of SOC losses, 12–85%, due to clearance of forests for agricultural purposes (Abegaz et al., 2020; Don et al., 2011; Belay et al., 2018; Kassa et al., 2017). For instance, Belay et al. (2018) predicted 40–80% loss of soil carbon after 40 to 50 years of deforestation based on the Biome-BGC ecosystem model.

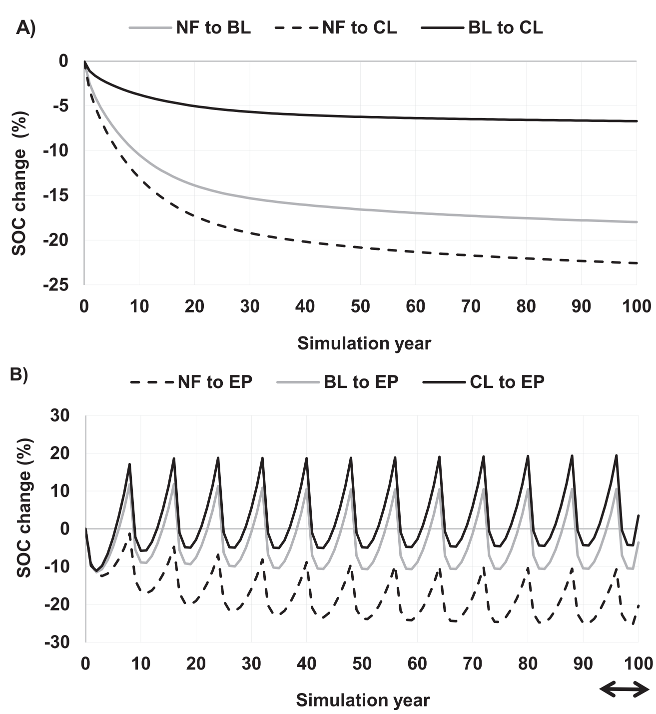

Fig. 4. Temporal development of changes in SOC (%) due to Land Use Change: **(A)** conversions to bush or cropland and **(B)** conversion to *Eucalyptus* plantation. NF – Natural Forest; EP – *Eucalyptus* plantation; BL – Bushland; CL – Cropland under contemporary climate (N = 231). The oscillating pattern in Fig. 4b is due to harvesting of EP every 8 years. Tables 3-5 present average values for the last complete rotation period between years 93–100, marked by a double-headed arrow.

We conclude that conservation of natural forest is a viable strategy for conserving SOC stocks in the Birr catchment. This would also result in the largest accompanying conservation of ecosystem C, as in tropical forest ecosystems about two thirds of the C stocks are stored in biomass and a third in the soil (Pan et al., 2011).

In contrast to the substantial gain in SOC stocks (40–57%) under LUC from bushland to *Eucalyptus* plantation reported by Tesfaye et al. (2016) and Assefa et al. (2017), in our simulation there was a net average loss of SOC after 100 years (Fig. 3). The difference in results could be due to variations in soil type, soil depth and degree of soil degradation of the reference land use before conversion, as the cropland and bushland examined by Assefa et al. (2017) were strongly degraded. Moreover, the measured SOC stocks in Birr catchment were relatively low (Table 3). Additionally, the litter decomposition rates of relatively recalcitrant *Eucalyptus* litter as reported by Olsson et al. (2019) may have been overestimated in this study.

Our results suggest that afforestation of bushland soils with *Eucalyptus* plantations might not be sufficient to preserve SOC stocks in the Birr catchment, unless some measures restricting harvests are also imposed.

3.3.2. Combined effects of land use change and climate change

The land use conversions and climate change had additive effects on simulated SOC stocks (Table 5, Fig. 3). For each of the LUC scenarios, there were 4 to 6 Mg C ha^{-1} higher losses of mean SOC stocks in combination with the CC_0 scenario than in combination with contemporary climatic conditions. Changes (both absolute and relative) in SOC stocks were highest for conversions of natural forests. Hence, we anticipate that the magnitude of SOC stock losses due to deforestation would be aggravated by anticipated CC in the absence of positive plant production responses to increases in temperature and atmospheric CO_2.

With a 22% increase in litterfall (CC_i), our quantified SOC losses due to LUC were alleviated by 8–14% compared to LUC in contemporary climatic conditions (Table 5, Fig. 3). There were even net gains in mean predicted SOC stocks for conversions of sparse vegetation, such as bushland and cropland, to more dense vegetation types such as Eucalyptus plantation with increased litterfall.

Our results clearly indicate that combined effects of future climate and LUC on the SOC stocks in ecosystems of the Birr catchment depend on the type of LUC and vegetation responses to climate change. For ecosystems with low litterfall under current land use, such as croplands that are harvested every year, anticipated increases in temperature (CC_0) will have stronger effects than the considered LUCs on SOC stocks. LUCs and anticipated temperature increases (CC_0) will have effects of similar magnitude on ecosystems with intermediate litterfall under current land use, for example bushland. For ecosystems with high litterfall under current land use, such as natural forests, our results indicate that LUC will have a larger impact than CC_0. Hence, deforestation is a bigger threat than climate change to SOC stocks, in the Birr catchment, and these effects may last at least 100 years.

3.4. Limitations and strengths of model estimates of SOC changes for National Greenhouse Gas Inventories

Accurate modelling of changes in SOC stocks using process-based models depends, among other factors, on the chosen model's capacity to reflect theoretical understanding of processes involved in soil organic matter formation and decomposition (Luo et al., 2017; Wieder et al., 2018). Walker et al. (2003) identified the context and scenarios, model assumptions, driving variables, and model parameters as the main sources of uncertainty in model-based decision support activities. They also stressed the importance of assessing and communicating uncertainties for establishing and meeting credible policy targets and measurements.

The Q model we employed here for predicting effects of LUC and CC has limitations. For example, it does not incorporate external factors responsible for either losses of soil carbon such as erosion, tillage, and wildfire, or gains, such as sedimentation of organic C-rich materials after flooding. This could lead to either underestimation or overestimation of SOC stocks. For example, erosion is often reported after deforestation in Ethiopia and could result in soil losses of up to 500 t ha^{-1} yr^{-1} (Amsalu and Mengaw, 2014).

In addition, the Q model does not explicitly incorporate effects of water and nutrients dynamics on litterfall and decomposition processes, which could be substantial. For instance, frequent use of N fertilizers in cropland could lead to higher N availability and NPP (Agegnehu et al., 2016) and high N availability can enhance SOC accumulation (Tian et al., 2015). On the other hand, land use conversions that increase harvest intensities can lead to depletion of nutrients if no fertilizers are applied. The availability of different N compounds in the soil may also affect the sensitivity of soil organic matter to climate change, by affecting heterotrophic respiration, nutrient cycling and Net Ecosystem Production (Ågren et al., 2013; Gärdenäs et al., 2011). As the Q model does not consider the dynamics of water, heat, carbon and nutrients, we used the model parameter microbial decomposer growth efficiency, $e0$, to reflect the overall conditions for microbes, considering impacts of, among other factors, nutrients, and soil moisture content.

Additional uncertainty might arise from the model parameters. Most used in this study were parametrized for soils of Swedish forests (Ortiz et al., 2011). The exceptions were litter quality (q_o) and shape of decomposer quality response (β) parameters, which we adjusted to resemble those of more easily decomposed litter than litter from coniferous trees in a nutrient-poor environment. Menichetti et al. (2019) found in a model evaluation against field experiments conducted in six European countries that the parameters initial litter quality and microbial efficiency are site-specific. We recommend further evaluation of model parameters against empirical data.

The assumed responses of vegetation to temperature and CO_2 increases also include uncertainties. A meta-analysis of experimental investigations of wheat yield responses to elevated CO_2 found that yield responded positively to increases up to 550 ppm CO_2 and were highest in low-productivity systems (Toreti et al., 2020). It also found that the optimum CO_2 concentrations for NPP is positively related to temperature, but only 1/8 of the vegetation response studies included in the review were conducted in areas with tropical climates, and none in Africa (Toreti et al., 2020). We encourage researchers to examine effects of elevated temperature and CO_2 concentration, in conjunction with other relevant factors, experimentally in tropical regions, especially Africa, to address these knowledge gaps.

Nevertheless, a state-of-the art model like the Q model can be used to make predictions based on the best present knowledge of the possible developments of SOC stocks for likely LULUCF and CC scenarios. This is especially important for the tropical regions as they are responsible for most of the global annual LUC-induced anthropogenic GHG emissions and there is high uncertainty about these emissions (Pan et al., 2011; Friedlingstein et al., 2020), as already mentioned. Thus, elucidating the combined effects of LUC and CC on SOC dynamics is crucial for formulating effective mitigating strategies and sustainable land use management.

The Q model has been used to verify estimated changes in SOC stocks in the extensive soil inventory of the Annex country Sweden (Ortiz et al., 2011, 2013). Our study demonstrates that it can be used by Non-Annex and Annex countries without an extensive soil inventory to report LULUCF-related changes in SOC stocks at Tier 3 to the UNFCCC as the model displays wide applicability and robustness, although it only requires input data on a few generally available variables. This is highly important as several countries, that have limited information about historical land use, soil inventory data and/or resources to estimate SOC changes, currently opt to report at Tier 1, if at all. Hence, it can be used to reduce uncertainties and increase confidence in countries' National Greenhouse Gas Inventory reports.

4. Conclusions

This study contributes to the body of research on SOC stocks generally, and in Ethiopia specifically, by examining combined effects of future climate (2000−2100) and LUC on SOC stocks. These combined effects are important to consider when designing adaptation and mitigation strategies to address climate change and soil degradation due to LUC.

We conclude that effects of LUC and CC on SOC stocks are additive, and their relative importance depends on the magnitude of the change in litterfall caused by the LUC. In accordance with our scenarios assumptions, LUC regulates SOC-stocks by altering litterfall and CC by accelerating decomposition rates and CC may in addition, alter litterfall as well. Hence, deforestation has such a strong impact on SOC stocks. For systems with low litterfall, such as systems with sparse vegetation (e.g., cropland), the increases in temperature associated with anticipated climate change (as in the CC_0 scenario) contribute more strongly to the combined effects of LUC and CC on SOC stocks than LUC. The combined effects of cropland and bushland LUCs and CC can only result in a gain in SOC stocks if climate change causes a substantial continuous increase in NPP, and thereby litterfall (as in the CC_i scenario) that exceeds the impact of accelerated decomposition rates. LUC alone (i.e., under contemporary climatic conditions) resulted in a mean net loss of SOC stocks in all LUC scenarios except the cropland to *Eucalyptus* conversion, which resulted in a small mean SOC gain.

Generally, conservation of natural forests is a viable strategy for preserving SOC stocks. This would also result in the largest accompanying gain in ecosystem C, as in tropical forest ecosystems about two thirds of the C stocks are stored in biomass and a third in the soil.

Finally, we advocate use of a model like the Q model as a viable option for countries with limited information on historical land use or resources, such as non-Annex parties of the UNFCCC, to improve the accuracy of their national reporting of changes in SOC-stocks from Tier 1 to Tier 3 within the LULUCF sector.

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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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2023.e00613.

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