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Modeling Soil Organic Carbon Changes under Alternative Climatic Scenarios and Soil Properties Using DNDC Model at a Semi-Arid Mediterranean Environment

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Abstract: Soil organic carbon (SOC) is one of the central issues in dealing with soil fertility as well as environmental and food safety. Due to the lack of relevant data sources and methodologies, analyzing SOC dynamics has been a challenge in Morocco. During the last two decades, process-based models have been adopted as alternative and powerful tools for modeling SOC dynamics; whereas, information and knowledge on the most sensitive model inputs under different climate, and soil conditions are still very limited. For this purpose, a sensitivity analysis was conducted in the present work, using the DeNitrification-DeComposition (DNDC) model based on the data collected at a semi-arid region (Merchouch station, Morocco). The objective is to identify the most influential factors affecting the DNDC-modeled SOC dynamics in a semi-arid region across different climatic and soil conditions. The results of sensitivity analysis highlighted air temperature as the main determinant of SOC. A decrease in air temperature of 4 °C results in an almost 161 kg C ha^{-1} yr^{-1} increase in C sequestration rate. Initial SOC was also confirmed to be one of the most sensitive parameters for SOC. There was a 96 kg C ha^{-1} yr^{-1} increase in C sequestration rate under low initial SOC (0.005 kg C ha^{-1}). In the DNDC, air temperature in climatic factors and initial SOC in variable soil properties had the largest impacts on SOC accumulation in Merchouch station. We can conclude that the sensitivity analysis conducted in this study within the DNDC can contribute to provide a scientific evidence of uncertainties of the selected inputs variables who can lead to uncertainties on the SOC in the study site. The information in this paper can be helpful for scientists and policy makers, who are dealing with regions of similar environmental conditions as Merchouch Station, by identifying alternative scenarios of soil carbon sequestration.

Keywords: soil organic carbon; DNDC model; climate conditions; soil properties; food safety

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1. Introduction

Soil organic carbon (SOC) plays an important role in determining soil fertility, soil structure, nutrient retention, susceptibility to land degradation, and water holding capacity, and therefore sustains food production [1–5]. The improvement of this major soil component is of high importance, especially for soils with intrinsically low levels of organic matter in their surface layers. Carbon (C) sequestration in agricultural lands is a key approach to reduce industrial CO_2 emissions, attenuate global warming, and improve biological, physical, and chemical soil properties [6–8]. In general, SOC storage is greatly influenced by environmental factors including climate conditions, vegetation, soil properties, farming management practices, relief, and land use [9–12]. The regional temperature (T) and precipitation (P) influence the SOC's role as a source or sink [13,14]. Field et al. [15] pointed out that the average temperature will greatly rise by the end of this century. For this purpose, greater knowledge has recently been perceived about climate change effects on the SOC changes in Morocco. Mediterranean agricultural areas have typically a lower SOC than temperate zones depending on seasonal dryness and particular climate features [16,17].

These areas are often degraded and highly vulnerable to climate change because of water scarcity and high risk of desertification. Therefore, most Mediterranean soils should deal with SOC depletion leading to low soil fertility [18–20]. Unfortunately, these trends might lead to a decrease of crop productivity that threatens food safety. Furthermore, soil C sequestration is a function of both primary production and decomposition of soil organic matter (SOM) in agricultural soils, and thus, climatic fluctuations in T and P have a substantial impact on SOC changes [21–24]. Several scientists worldwide focused on the impacts of changing T or P on SOC stocks in order to understand the role of climatic factors on long-term development of soil C in a given area [25–27]. Increases in air T speeds up the SOC decomposition rates by increasing soil C mineralization and respiration [28–30]. Furthermore, P is regarded as a critical component of the soil organic C sequestration [31]. Water is a major driver of chemical and biological activities at different levels: Plant growth, survival, photosynthesis, soil respiration, and microbial activity. Therefore, P patterns deeply affect the function and structure of terrestrial ecosystems [32]. The function and structure of terrestrial ecosystems will be profoundly affected by P patterns fluctuations. On the other hand, the SOC in agroecosystems is simultaneously influenced by the soil properties (i.e., soil pH, initial SOC and clay content). Texture represents one of the key soil variables considering its tight correlation with root growth, thermic conductivity, gas exchange and aggregates [33]. This soil component has been reported as a crucial factor determining the accumulation of SOM. Furthermore, clay particles stabilize SOM against microbial mineralization, improve soil water retention, and have a high cation exchange capacity [34,35]. Therefore, low clay soils are mostly associated with low availability of nutrients and water for plant growth [36]. Soil pH regulates soil nutrient bioavailability, SOM turnover, and a range of other soil activities, thus influencing SOC levels [37,38]. According to Aciego Pietri and Brookes [39] and Andersson and Nilsson [40], soil pH affects microbial activity, hydrolysis and protonation processes, and therefore impacts the decomposition of SOM. Similarly, Saby et al. [41] stated that the predominant environmental component is the initial SOC, which negatively influences SOC. In fact, higher initial SOC in soils can lead to significant SOC losses at early stages due to the favorable environment for microbial communities, resulting in faster microbial decomposition and a lower SOC sequestration rate [42]. This is especially true under Mediterranean conditions where decreased T stimulates microbial activity. All the above climatic and edaphic parameters influence greatly SOC content.

Over the past two decades, process-based biogeochemical models have been developed and used widely among researchers for assessing the impacts of numerous factors driving C storage in soils and generating scenarios for studying SOC dynamics. However, uncertainty associated with this process-based model is unavoidable, as knowledge of model input parameters derived from sparse data is imperfect. Hence, modeling outputs without representation of uncertainty have very deficient value for decision-making [43]. Towards to minimize the uncertainties of models parameters and thus to enhance the accuracy of the modeled results, sensitivity analysis is usually used to assess the sensitivity of model output parameters to the input parameters [44], and identify the crucial parameters controlling model outputs [45].

In a previous study, we validated the DNDC model in Merchouch station during the period of 2008–2016 using the local climate, soil data and farming management conditions in order to simulate the SOC trends [46]. In this study, we simulated SOC changes under a number of alternative scenarios by varying climatic conditions and soil properties over 9 years based on a validated DNDC model under a no-tillage system in Merchouch station. The major objectives of our study were as follows: (1) evaluate the sensitivity of simulated SOC to several inputs parameters, including temperature, precipitation, clay content, soil pH, and initial SOC in DNDC model, and (2) identify through this sensitivity analysis the main factors that affect SOC during the nine simulated years, thus revealing scenarios for SOC sequestration.

2. Materials and Methods

2.1. Description of Study Site

This research was carried out at the Merchouch plateau in Morocco. A mean annual temperatures and rainfall of 23 °C and 450 mm, respectively, characterize the Mediterranean climate of this region. The experimental site is classified as Vertisol according to the world reference base for soil resources (WRB) [47]. The soil has an initial SOC content below 2%, a basic pH, and more than 0.50% clay content. More detailed information about the study site can be found in a previous publication [46].

2.2. Treatments

In this study site, the trial consists of no-tillage (NT) system since 2004 performed on 2 ha. The NT were ploughed, according to farmers' practice in the region based on wheat-legumes rotation. The NT method consists of a single operation which holds an opening of 2–3 cm from the ground with a special NT drill allowing to put the seeds at 5 cm depth. Winter wheat was sown in mid-November at a 140 kg ha^{-1} seed rate, while lentil was sown at seed rate of 40 kg ha^{-1} in mid-December. Wheat and lentil received a rate of 150 and 100 kg ha^{-1}, respectively, of complex fertilizer (14% N-28% P_2O_5-14% K_2O) before sowing. At the end of February, wheat received 100 kg ha^{-1} of urea. About 30% of the crop residues were maintained at the surface after harvest.

2.3. Description of DNDC Model

The DNDC is a process-based model originally developed to simulate nitrogen and carbon dynamics in agroecosystems in the U.S [48,49]. The DNDC consists of six sub-models as shown in Figure 1. The soil climate sub-model calculates soil temperature and moisture profiles based on soil physical properties, daily weather and plant water use. The plant growth sub-model tracks crop growth and partitioning of the biomass into grain, stalk and roots. The decomposition sub-model simulates the disintegration of SOM driven by the soil microbial respiration. The nitrification sub-model calculates growth of nitrifiers and oxidation of ammonium to nitrate. The denitrification sub-model operates at an hourly time step to simulate denitrification and the production of nitric oxide, nitrous oxide, and dinitrogen. The fermentation sub-model simulates methane production and oxidation under anaerobic condition. The interaction among the six sub-models enables DNDC to simulate a broad range of biochemical and geochemical processes that occur in both aerobic and anaerobic conditions.

2.4. Required Data for DNDC Model Initialization

Collecting suitable input data for running the DNDC model at a research location is a crucial task. The climate data, soil properties and agricultural management practices for the study area were collected.

2.4.1. Climate and Soil Data

The meteorological data from 2008 to 2016 for the study site were obtained from the Moroccan General Direction of Meteorology, including the daily precipitation and the maximum and minimum air temperature. The soil data were collected from the study site.

2.4.2. Farming Management Practices Data

The agricultural management practices dataset including the tillage method, rates of nitrogen fertilizer applied, dates of planting and harvest, and the crop residue rates returned at surfaces after harvest were collected from the farming management database of the National Institute of Agricultural Research. The cropping dataset for Merchouch station for both winter wheat and legumes including the physiological and phenological parameters (e.g., water requirements, biomass partitions, C/N ratio, cumulative thermal degree-days, and maximum yield) is also considered important for running the DNDC.

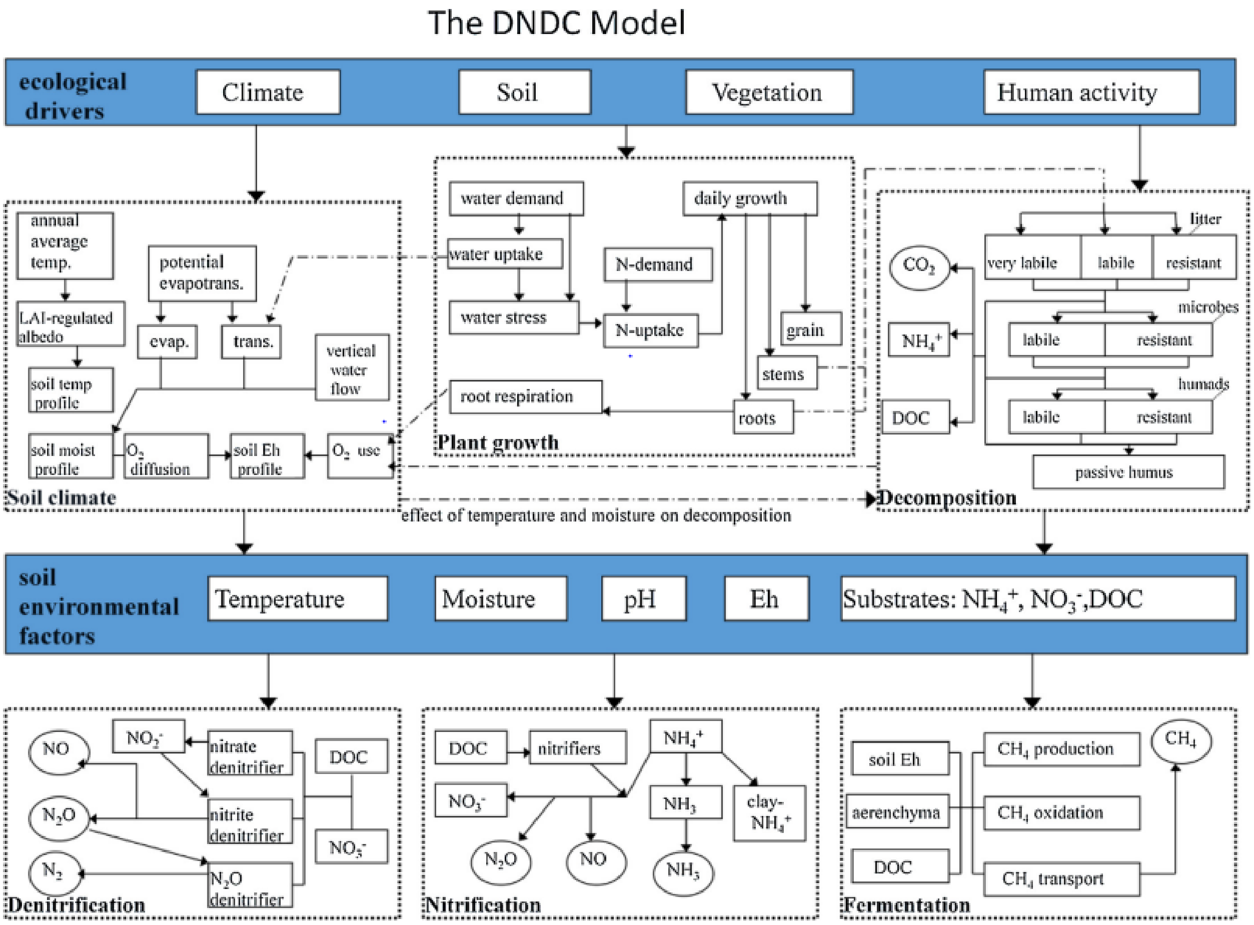

Figure 1. Structure of the DNDC model [50].

2.4.3. DNDC Model Verification at the Study Site

The model performance was assessed for Merchouch station under no-tillage practice in a previous publication [46]. The root mean square error (RMSE) and the Pearson correlation coefficient (r) were calculated to verify the DNDC model performance and the modeled results acceptability. The high r (0.83) and low RMSE (0.33) between measured and simulated values indicate that the DNDC model generally showed a good performance in simulating SOC stocks at the experimental site.

2.5. Baseline and Alternative Scenarios

The model was firstly run with a baseline scenario under no-tillage system as mentioned above with similar climatic and soil conditions of Merchouch station. The weather and management data from 2008 to 2016 were selected to compose the baseline scenario with the annual precipitation of 450 mm, temperature of 23 °C, soil clay fraction of 0.50%, initial SOC content of 1.2%, and soil pH of 7.6 based on the conditions at the experimental site in the 9 simulated years. In order to test the sensitivity of the DNDC (version 9.5) model to the variability of factors influencing SOC such as, precipitation, temperature, initial SOC, clay content, and soil pH, a sensitivity analysis was conducted within the model. Alternative scenarios were compiled for this purpose by changing the five selected factors. The daily maximum and minimum temperature from every day were set to increase or decrease by 2 °C and 4 °C, respectively. The amount of precipitation for every rainfall event was set to increase or decrease by 10% and 20%. The soil properties including initial SOC, clay content, and soil pH were constructed within the ranges of 0.5–3%, 0.19–0.63%, and 5.3–9.6, respectively. The DNDC model was run under each alternative scenario while keeping others constant. The details of the baseline and alternative climatic scenarios are presented in Table 1. Note that the baseline and alternative scenarios used the same farming management practices. The ranges tested for variable environmental factors constituting the alternative scenarios were mostly selected according to [51–53] and are based on a survey carried out by the National Institute of Agricultural Research.

Table 1. Baseline and alternative scenarios data.

Scenario	Conditions or Variations
Baseline	Climate: 2008–2016, daily T and P data with mean annual temperature 23 °C and precipitation 450 mm Clay content: 0.50%, SOC 1.2%, pH 7.6, Crop: winter wheat-legumes, Crop residue: 30% Tillage: No-tillage system
Change in temperature	Decrease and increase by 2 °C and 4 °C
Change in precipitation	Decrease and increase by 10% and 20%
Change in Clay content%	0.19, 0.34, 0.40, 0.63
Change in initial SOC content (kg C kg^{-1})	0.005, 0.02, 0.03
Change in Soil pH	5.3, 6.5, 8.9, 9.6

After the model runs with the scenarios, 9-year average SOC changes were calculated in 0–50 cm soil layer for each alternative scenario to assess their increase or decrease compared to the baseline scenario.

Additionally, C sequestration rate was calculated according to Equation (1) [54] for the baseline and each alternative climatic and soil scenarios.

$$C\ sequestration\ rate = \frac{Ce - Cb}{t} \tag{1}$$

where Ce and Cb are SOC stocks (kg C ha^{-1}) at the end and at the beginning of the experiment, respectively, and t is the duration of the experiment (years).

2.6. Sensitivity INDEX

In this study, the sensitivity of modeled SOC stocks to the variability of the inputs parameters selected with DNDC model was determined by calculating the sensitivity index according to [55–57] (Equation (2)).

$$SI = \frac{\frac{(O_2 - O_1)}{O_{avg}}}{\frac{(I_2 - I_1)}{I_{avg}}} \tag{2}$$

where SI is the relative sensitivity index, I_1, I_2 are the minimum and maximum input values for a specific parameter, I_{avg} is the average of I_1 and I_2, O_1, O_2 are the model output values corresponding to I_1 and O_2, and O_{avg} is the average of O_1 and O_2. A positive SI value refers to a positive correlation between the simulated results and the selected input parameter, whereas a negative value indicated a negative relationship. Higher absolute value of the index corresponds to larger input impact on the output. Moreover, a negative value indicates an inverse association between the input and the output.

3. Results

3.1. SOC Changes under Alternative Soil Properties

Soil properties have a major role in regulating the biogeochemical cycle of C in agroecosystems [58]. By varying initial SOC content, clay content and soil pH. Eleven alternative soil conditions were considered to represent the range of pH, SOC and clay content commonly observed in the study site.

The sensitivity analysis test indicated that the SOC was sensitive to initial SOC and clay content. In fact, a decrease in initial SOC and/or an increase in clay content enhance SOC stocks. The modeled results revealed that over simulated years, the annual mean SOC stock in 0–50 cm soil layer decreased by 3% and 4% when the initial SOC content increased from 0.012 kg C kg^{-1} (Baseline), to 0.02 kg C kg^{-1} and 0.03 kg C kg^{-1}, respectively. However, the SOC stock increased by 2% when the initial SOC content decreased to 0.005 kg C kg^{-1} (Figure 2). These results implied that soils with higher initial SOC content tend to lose more SOC stock, probably due to high decomposition rate and aerobic conditions. Higher initial SOC content condition can provide a favorable environment for microbial community, which negatively influences the C accumulation. Moreover, if the clay content shifted from 0.50% (baseline), to 0.19%, 0.34%, 0.40%, and 0.63%, the SOC stock decreases by 3%, 1%, 0.6%, and increases by 1%, respectively (Figure 3). On the other hand, our simulations demonstrated that SOC stock increases by 0.7%, 0.5%, and 1%, when soil pH shifted from 7.6 (Baseline), to 5.3, 8.9 and 9.6, respectively. However, it decreases by 0.9% when soil pH decreases to 6.5 (Figure 4). This can be explained by the limited microbial activities under alkaline and acidic pH conditions. Figure 5 exhibited the C sequestration rates under alternative soil property scenarios in Merchouch station. There was a 42–112 kg C ha^{-1} yr^{-1} decrease in C sequestration rate when the clay content was reduced by 0.19–0.40% from the baseline. Moreover, this rate increases by 48 kg C ha^{-1} yr^{-1} under 0.63% clay content. On the other hand, increasing SOC content from the baseline to 0.02 kg C ha^{-1} and 0.03 kg C ha^{-1} tends to decreases C sequestration rate by 90 kg C ha^{-1} yr^{-1} and 111 kg C ha^{-1} yr^{-1}, respectively. However, decreasing SOC content to 0.005 kg C ha^{-1} raises this rate by 96 kg C ha^{-1} yr^{-1}. Moreover, increasing soil pH from 7.6 to 9.6 and 8.9 leads to an increased C sequestration rate by 30 kg C ha^{-1} yr^{-1} and 28 kg C ha^{-1} yr^{-1}, respectively. Similarly, by decreasing soil pH by 5.3, C sequestration rate increases by 27 kg C ha^{-1} yr^{-1}. However, a decrease in pH soil from the baseline to 6.5 tends to decrease C sequestration rate by 87 kg C ha^{-1} yr^{-1}. Furthermore, the calculated sensitivity index for the impacts of soil properties listed in Table 2 indicates that the SOC was positively correlated with soil clay content and soil pH, and negatively associated with initial SOC. According to our modeling study, we can conclude that SOC improved under 0.63% of clay content, acidic and alkaline soil pH conditions (5.3, 8.9, and 9.6), with low initial SOC content (0.005 kg C kg^{-1}).

Table 2. Calculated sensitivity indices quantifying the sensitivity of modeled SOC stocks to the variability of the inputs parameters.

Parameter	Baseline	Range Tested	Sensitivity Index (SI) of SOC Stocks
Annual temperature (°C)	23	Decrease by 2 °C and 4 °C and increase by 2 °C and 4 °C	−0.2
Total annual precipitation (mm)	450	Decrease by 10% and 20% and increase by 10% and 20%	0.04
Clay content%	50.5%	0.19, 0.34, 0.4, 0.63	0.03
Initial SOC content (kg C kg $^{-1}$)	0.01	0.005, 0.02, 0.03	−0.03
Soil pH	7.6	5.3, 6.5, 8.9, 9.6	0.003

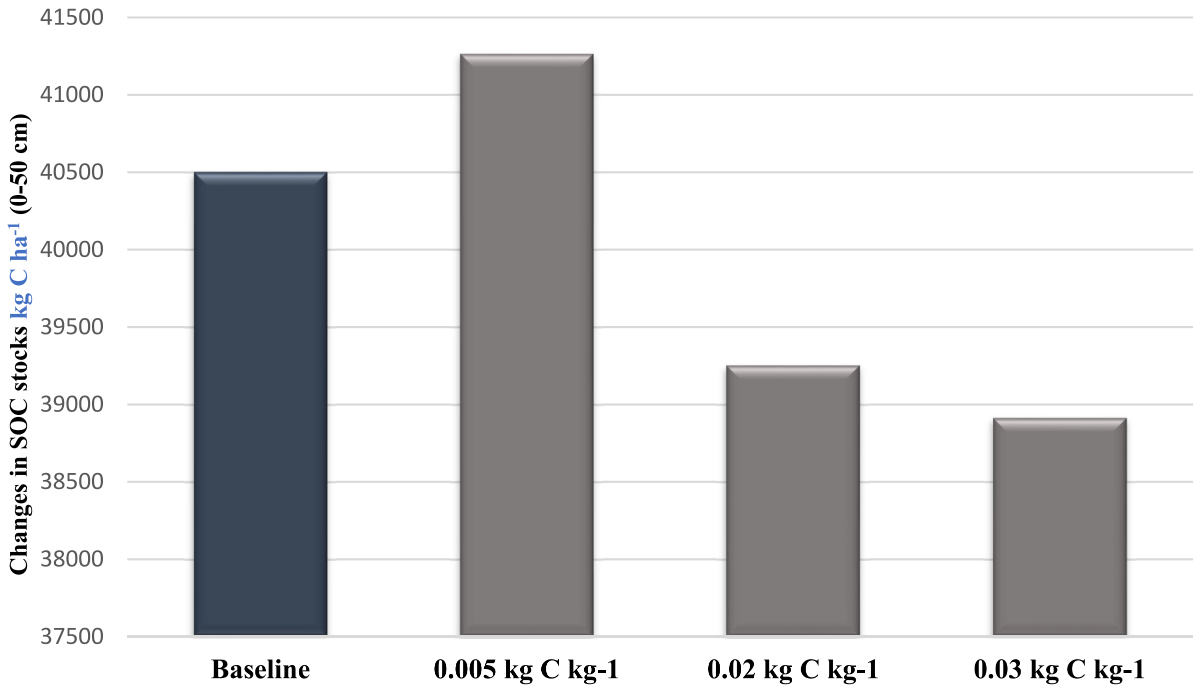

Figure 2. Modeled 9-year average SOC changes with varied initial SOC content in Merchouch station.

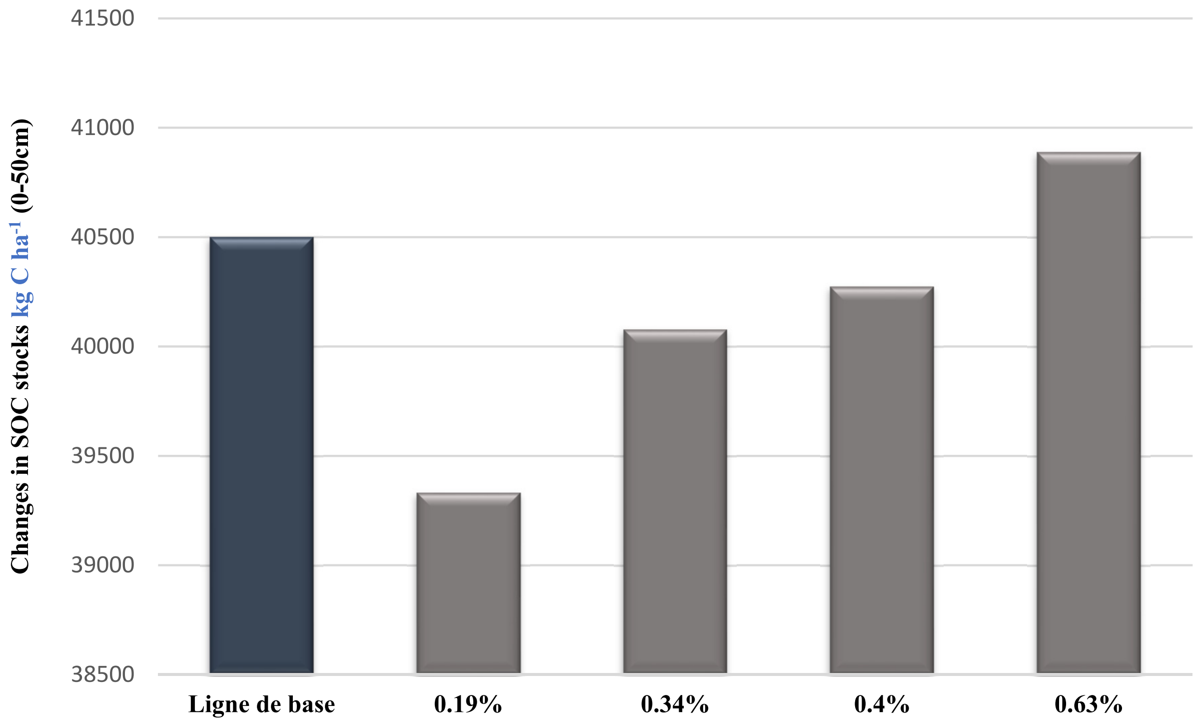

Figure 3. Modeled 9-year average SOC changes with varied clay content in Merchouch station.

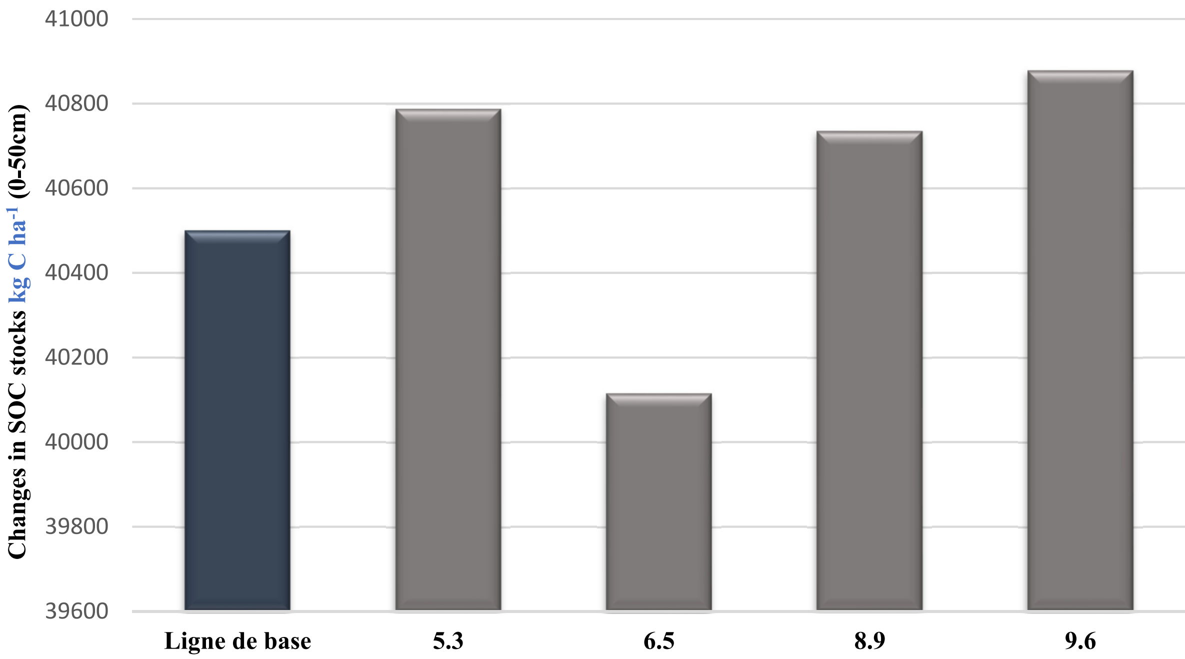

Figure 4. Modeled 9-year average SOC changes with varied pH of soil in Merchouch station.

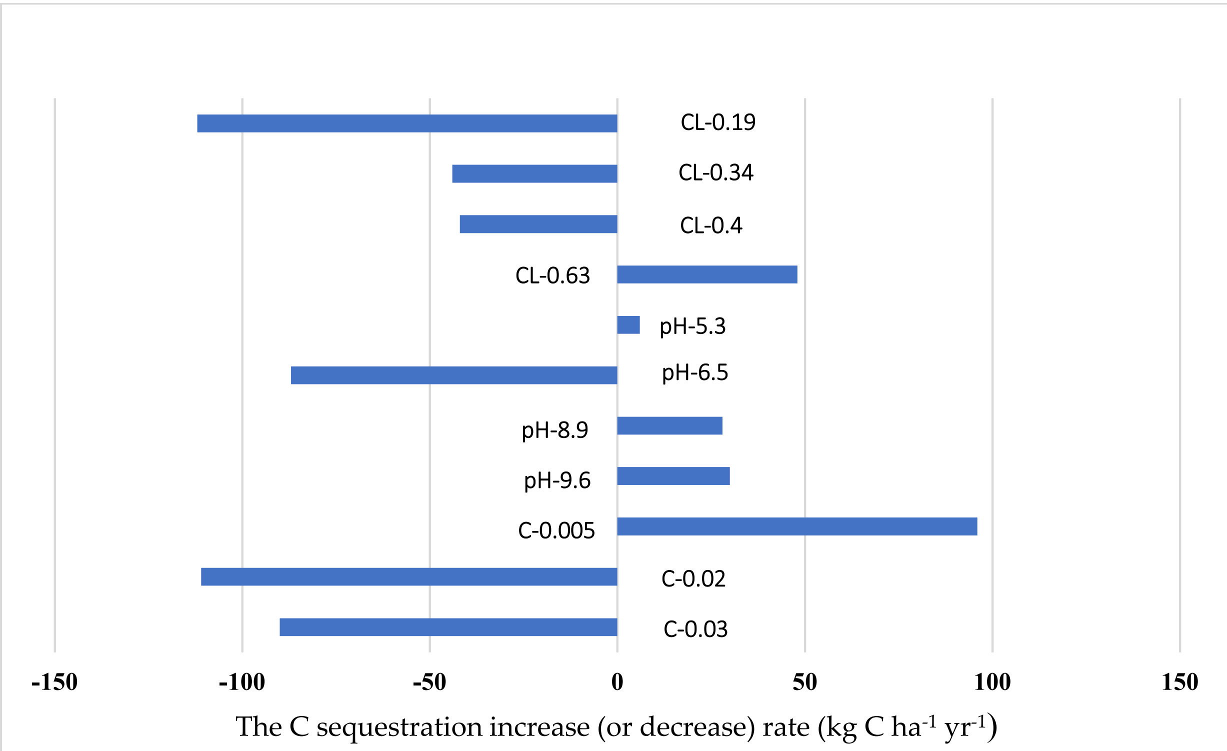

Figure 5. The C sequestration rates increase (or decrease) under alternative soil properties scenarios in Merchouch station: CL-0.19, CL-0.34, CL-0.4 and CL-0.63- decrease in clay from baseline (0.50%) to 0.19%, 0.34%, 0.4% and increase to 0.63%; C-0.005, C-0.02 and C-0.03- decrease in initial SOC content from baseline (0.01 kg C ha^{-1}) to 0.005 kg C ha^{-1}, and increase to 0.02 kg C ha^{-1} and 0.03 kg C ha^{-1}.

3.2. SOC Changes under Alternative Climatic Factors

Precipitation and temperature are key determinants of SOC decomposition [31,59,60]. Four scenarios of alternative T were run for the selected site in Merchouch for nine years. The simulation results showed that the 9-year average SOC changes would increase by 1% and 3.4% and decrease by 1.3% and 4% by decreasing and increasing T by 2 °C and 4 °C, respectively (Figure 6). Similarly, four scenarios were set for P by considering a decrease or increase percentage of 10% and 20% for each rainfall event at daily time step. On one hand, our modeled results indicate that a precipitation increase of 10% and 20% from the baseline would raise the SOC stock by 0.1% and 0.5%, respectively (Figure 7). On the other hand, decreasing P by 10% and 20% decreases the SOC stock by 0.1% and 1.4%, respectively. Our simulations showed that the rate of C sequestration was slower under higher T in this study site. In details, increasing air T by 2 °C and 4 °C from the baseline decreases C sequestration rate by 99 kg C ha^{-1} yr^{-1} and 93 kg C ha^{-1} yr^{-1}, respectively (Figure 8). In contrast, C sequestration rate increased by 39 kg C ha^{-1} yr^{-1} and 161 kg C ha^{-1} yr^{-1} when decreasing T by 2 °C and 4 °C, respectively. Furthermore, the difference in C sequestration rate between the baseline and alternative P scenarios would range from -67 kg C ha^{-1} yr^{-1} to 21 kg C ha^{-1} yr^{-1} (Figure 8). This finding underlined the importance of the climate on SOC accumulation. The sensitivity index presented in Table 2 indicated a negative correlation between SOC and T, and a positive one with P. Our model results revealed that the SOC was more sensitive to T than P in Merchouch station.

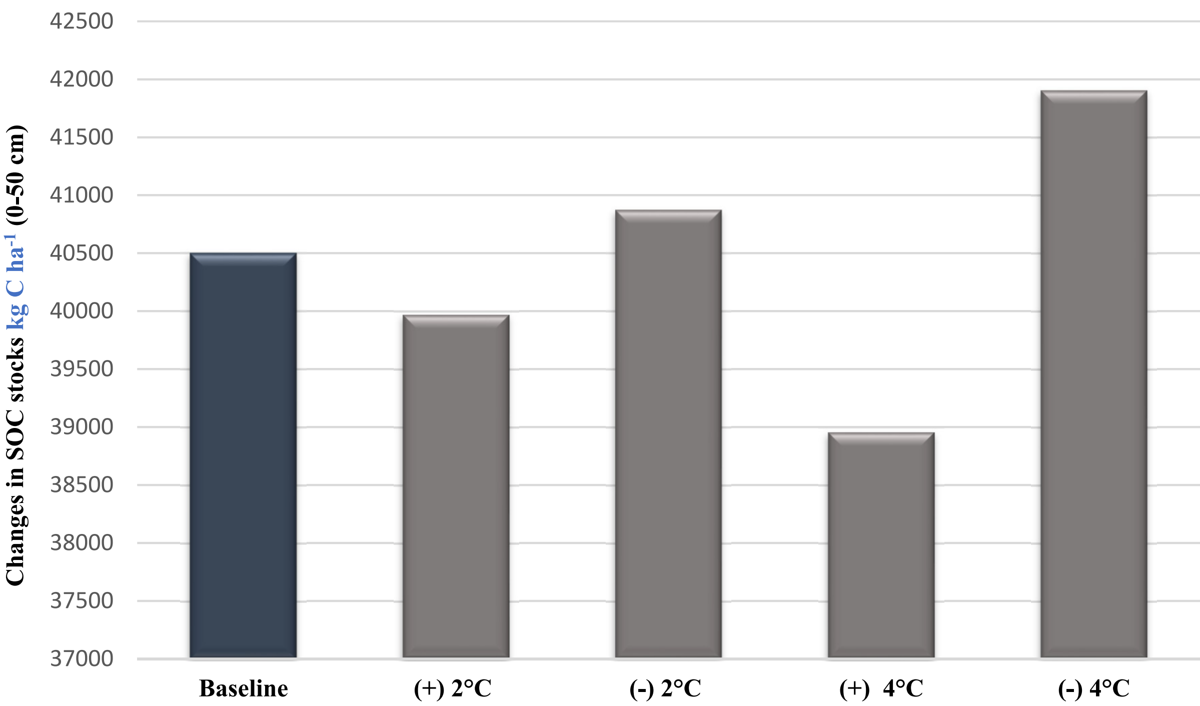

Figure 6. Modeled 9-year average SOC changes by decreasing or increasing temperature by 2 °C and 4 °C, in Merchouch station.

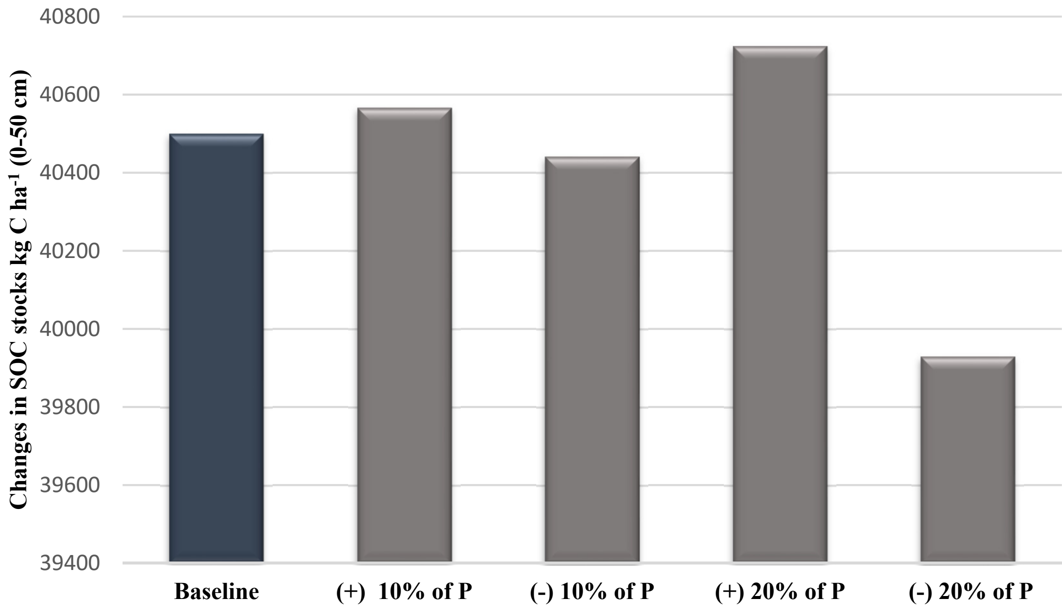

Figure 7. Modeled 9-year average SOC changes by decreasing or increasing precipitation by 10%, and 20% in Merchouch station.

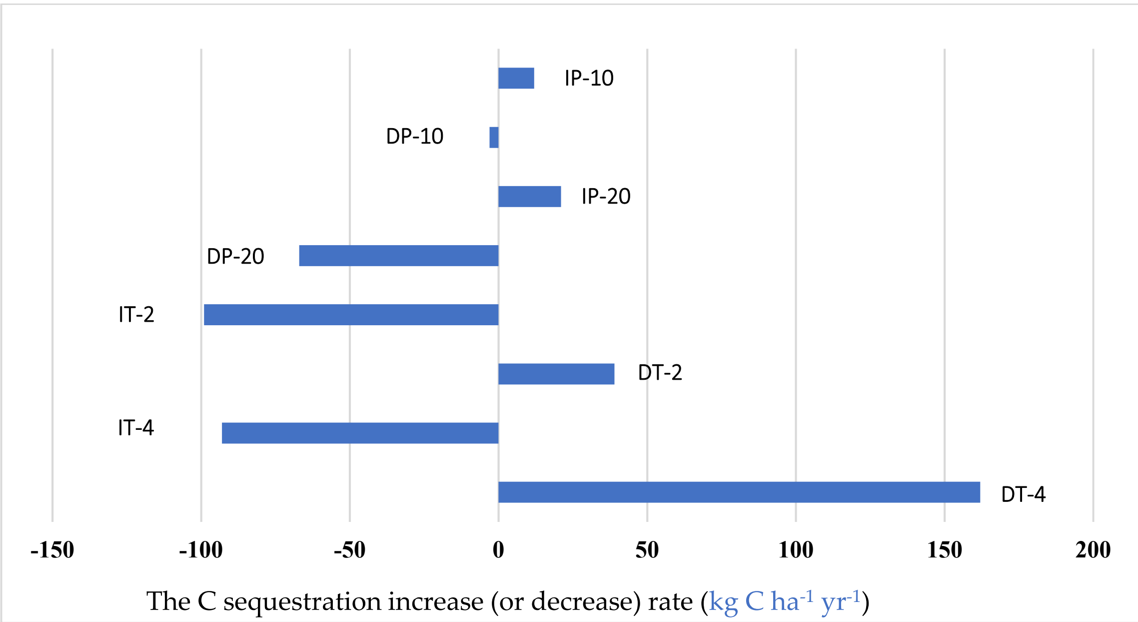

Figure 8. The C sequestration rates increase (or decrease) under alternative climatic change scenarios in Merchouch station: IP-10, IP-20, DP-10 and DP-20—Increasing and decreasing precipitation by 10% and 20%, respectively; IT-2, IT-4, DT-2 and DT-4—Increasing and decreasing air temperature by 2 °C and 4 °C, respectively.

4. Discussion

The sensitivity analysis conducted in the present work assessed separately the impact of five input parameters on simulating SOC changes in DNDC model. The sensitivity index of each input presented in Table 2. ranged from 0.003 to 0.2. The modeled data showed that the DNDC was more sensitive to temperature in climatic factors followed by initial SOC and clay content in soil properties over the nine simulated years. Many researchers support our findings and confirm that DNDC model was more sensitive to temperature, initial SOC, and clay content [60–62].

Our simulations predicted an important SOC depletion under warmer scenarios. This loss of SOC under elevated temperature can be explained by several candidate mechanisms. On one hand, the microbial activities are dense under elevated soil temperature, which leads to accelerated SOC decomposition rate [62–66]. On the other hand, high soil respiration positively correlated with increased temperature, decreases SOC accumulation, especially under semi-arid environments [67]. Global-scale studies had also revealed that the functions and activities of microorganisms including respiration, growth, and the substrate uptake, are dependent greatly to temperature variations [68–70]. Some quantitative studies have also stated that under warming conditions, SOC decomposition is mainly controlled by the structural and functional changes in the microbial community [71]. Another study [63] assessed that an increase in air temperature would effectively cause an SOC loss, which supports our findings.

In semi-arid agricultural regions where rain-fed crops dominate, changes in precipitation patterns have a potential influence on SOC content and its dynamics [67]. Our finding pointed out that temperature was more sensitive than precipitation in the study site; however, the impact of precipitation on SOC cannot be ignored. It is known that precipitation is one of the most important factors controlling SOC cycling [72]. Our model results showed that an increase in precipitation patterns by 10% and 20% could improve C sequestration rates in the soil by 12 and 21 kg C ha^{-1} yr^{-1}, respectively. In contrast, the SOC loss is possible as results of reduction in soil moisture due to less precipitation. This finding is consistent with further studies [73–76], which revealed that C sequestration rate increases as precipitation increases. On one hand, SOC accumulation can be affected by soil moisture by influencing the quantity of plants' C input to soils, as well as the decomposition rate of those C inputs [77]. On the other hand, water availability and its spatial distribution in soil matrix can affect the spatial accessibility and degradability of SOC for decomposers, and then change the SOC decomposition process [78]. Many previous modeling studies have stated a relationship between SOC accumulation and soil moisture, in line with our findings. For example, Post et al. [79] and Tayebi et al. [27] pointed out that soil C density increases due to improved crop production under rainfed farming systems characterized by high soil moisture. Similarly, Zhang et al. [80] indicated that SOC accumulation is expected to be slower under high demand areas for mined groundwater. Similarly, Grogan et al. [81] acquired also the same results using the DNDC model. Antecedent studies conducted in regions, with similar environmental conditions to our study area, has proved that lower water availability due to drought periods in semi-arid regions limits the increase of C inputs, and therefore leads to SOC depletion [67,80,82].

However, the results of the current study do not support some previous research. Peinetti et al. [83] showed that excessive water from heavy rainfall events leads to nitrogen leaching from the upper layer of soil to deeper ones, and thus decreases crop biomass. Consequently, the low returns of the crop residues to the soil decrease SOC stocks. Our outcome is also contrary to that of Meier and Leuschner [84], who found that SOC continuously decreases with high annual precipitation (>900 mm yr^{-1}) compared to low (<600 mm yr^{-1}).

The simulations carried out in the present study revealed that, the variation of soil properties was reflected on the modeled SOC stocks. Within the DNDC, a sensibility test of modeled SOC to clay content, initial SOC, and soil pH was conducted. The results clearly indicate that SOC was primarily sensitive to initial SOC in soil variability. According to the calculated SI, SOC had a negative correlation with initial SOC parameter. Our modeled results found also that soil with greater initial SOC displayed greater SOC loss. This finding are consistent with previous studies [41,85,86]. The labile organic C components are a major energy source for microbes, resulting in a higher soil respiration and thus a reduced amount of C stored in the soil [87–92]. Soils with high initial SOC content provide a good environment for microbe's communities, witch increase microbial activities and growth, and accelerate decomposition rate; leading to decreased C sequestration rate [93]. Another study carried out under similar environmental conditions using the DNDC, emphasized that low initial SOC conditions were apparently favorable for SOC accumulation [80].

Similarly, Matus et al. [94] and Paul [95] emphasized that soils with lower initial SOC content enable larger ability for enhancing C pool accumulation. Higher SOC sequestration rates were observed on sites with low initial SOC content under semi-arid conditions [96].

It can be seen clearly thought our simulations that modeled SOC in DNDC is also sensitive to clay content following initial SOC. A positive correlation have been obtained from calculated SI between clay content and SOC changes (Table 2). Under 0.63% of clay content, the C sequestration rate increases by 48 kg C ha^{-1} yr^{-1} (Figure 5). This clay effect can be explained by the mechanism proposed by Six et al. [35], who explains that the very small spaces between clay particles can trapped soil organic matter inside it, which limits microorganism's accessibility; and thus reduce SOC decomposition. Large area of fine clay fractions favors the generation of organo-mineral complexes that protect C against microbial oxidation [97–99]. Our results are in line with previous works. For example, Chellappa et al. [100], Camaratto et al. [101], and Liu et al. [102], highlighted a great association between SOC accumulation and high clay content soil compared to poor ones under similar environmental conditions. It was concluded that Merchouch station have a higher potential for SOC sequestration under high clay content condition. This result is in line with the results obtained by Moussadek et al. [53].

In this study, soil pH is identified to be the least sensitive parameter among the tested factors. This outcome is in agreement with a previous study using DNDC [73]. However, our modeled results showed that under alkaline condition with soil pH ranging from 8.9 to 9.6, an increase by 30 and 28 kg C ha^{-1} yr^{-1} in C sequestration rate was observed (Figure 5). Similarly, under acidic soil pH condition, the C sequestration would increase by 27 kg C ha^{-1} yr^{-1}. On the other hand, nearly neutral pH value tends to decrease C sequestration rate by 87 kg C ha^{-1} yr^{-1}. These outcomes are in line with other studies [103,104]. Soils with an alkaline soil pH produce an unfavorable environment for microbial growth [87,105], thereby benefiting SOC sequestration. Furthermore, microorganisms have difficulty to survive and growth under acidic soil pH conditions, which represents an antipathetic environment [40]. On the other hand, nearly neutral pH value for soils provide a favorable living environment for microbes communities, which accelerate SOC decomposition, and thus resulting in low C sequestration rate [106].

5. Conclusions

Our study conducted at Merchouch station, a semi-arid region in Morocco with a structured dataset, on midterm based on DNDC model. A sensitivity analysis within the DNDC was carried out, with the priority of each input parameter separately, to identify the more impacting parameters on SOC dynamics. The effective use of this sensitivity analysis can provide an insight into the quality of the model prediction. The simulations highlighted that the temperature is the most influential parameter for simulating SOC changes in DNDC. The C sequestration was large during simulated years when temperatures were small, and vice versa. Moreover, various variable soil properties play a crucial role in the C sequestration as well. The initial SOC and clay content can be considered also as sensitive factors in soil properties parameters following temperature in climatic factors. However, soil pH had less sensitivity to modeled SOC. With the guidance of sensitivity analysis, more scientific policies and reasonable measures could be applied for an efficient carbon sequestration, in order to alleviate the negative effect of several scenarios. The present study represents the modeled SOC changes that are attributable to each single input parameter separately. Further studies will be needed to analyze the combined effects of inputs parameters on SOC, knowing that most of the parameters (e.g., climatic factors) act collectively, and simultaneously rather than separately on SOC dynamics.

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