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Modeling of soil organic carbon in the north and north-east of Iran under climate change scenarios

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Abstract. The changes of soil organic carbon and soil carbon decomposition are influenced by temperature and precipitation changes. In the present study, the changes of soil organic carbon under climate change scenarios were estimated by the Rothamsted Carbon model in different land-use areas in the north and north-east of Iran. The total soil organic carbon was observed 106.2 tC/ha in the study area. RothC model was used to simulate the change of SOC at 980 original 50 km × 50 km grids under A2 and B2 climate scenarios during the upcoming decades the study area. Future temperature and precipitation data under both scenarios were predicted by LARS-WG weather generator model based on the IPCC AR4. The simulated results of soil organic carbon illustrated that over the period 2010-2065, SOC will decrease in the study area. The simulation of soil organic carbon strongly suggests that SOC levels will decline due to temperature increase and decline in precipitation, particularly in cultivated lands. SOC is expected to decrease under A2 climate scenario by 8.3 tC/ha and 13.36 tC/ha by the years 2030 and 2065, respectively. Likewise, under the B2 scenario, SOC will have decreased by 8.58 tC/ha and 13.81 tC/ha by the years 2030 and 2065, respectively.

1. Introduction

Soil Organic Carbon (SOC) is an important source of carbon in biosphere. The The amount of SOC as a total measure over soil depth is estimated from approximately 10 tC/ha to around 160 tC/ha in the top 30 cm of soil and at times up to 250 tC/ha in the case of rich soil in undisturbed locations [1]. There is globally an estimated 1400 gigatonnes of SOC, about double the quantity of carbon dioxide in the atmosphere, such that changes in SOC may have a great impact on CO_2 concentrations in the atmosphere [2,3]. There is a direct relationship between the functions of SOC and changes in temperature, precipitation, and CO_2 concentration in the atmosphere [4]. Temperature and precipitation are acknowledged as being two of the most crucial climatic factors and their ability to change the rate of SOC decomposition, plant growth, and microbiological activity has been noted [5,6]. Results from previous studies have shown that with higher temperatures and precipitation, organic material decomposition and CO_2 losses from soil increase and there is a low amount of SOC in warm climatic conditions when compared to cold climates [3].

There are a number of models, as proposed by Falloon et al. [2], Guo et al. [7], and Zimmermann et al. [8], which can study carbon levels in soil over

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a timescale of years to centuries, including Century, DeNitrification-DeComposition (DNDC), Daisy, and RothC models. As a simulation model, the RothC has become popular and been used in many parts of the world to calculate predicted SOC changes [9,10]. RothC is a well-established model for simulating long-term trends in SOC and has been very useful in the analysis of different types of land use, soil, and climatic regions. In China, the RothC model was used to evaluate the increase and decrease of soil organic carbon based on climate change in upland and cropland soils [10]. Also, this model was used in Zambia and Nigeria to estimate soil organic carbon turnover based on temperature function [11,12]. In Norway, Switzerland, and Ireland, RothC model has enabled changes in SOC in grassland and forest soils [13,14]. Their results showed a positive correlation of measured data and modelled results for humified organic matter (HUM), microbial biomass (BIO), and decreases in SOC. This model also considered soil carbon sequestration in agricultural lands at large scale and regional scale [15,16]. A Study done by Yagaski and Shirato [17] demonstrated that increase in CO_2 emission could result in reduction of organic carbon input to agricultural soils in Japan.

In the present study, the evaluation of SOC under climate change was undertaken using the climate change scenarios organized by IPCC. Climate scenarios shown as Al, A2, B1, and B2 indicate varying demographic, social, economic, technological, and environmental evolutions [18]. The A2 scenario explains a very heterogeneous world and the B2 scenario imagines a world that highlights the local solutions to social, economic, and environmental sustainability.

The aim of this study is to simulate the soil organic carbon changes in different geographical regions in the north and north-east of Iran by using RothC model to determine how and to what extent climate change would influence soil organic carbon under scenarios of A2 and B2. The Long Ashton Research Station-Weather Generator (LARS-WG) model simulated temperature and precipitation data for future based on A2 and B2 scenarios.

2. Material and methods

2.1. Research sites

The study area encompasses a range of climates. In the north-east it is dry whereas in the northern region of Iran, it is very humid with heavier rains and dense tree and vegetation cover that extends between latitudes (defined as 38°N to 30°N and 48°E to 59°E) (Figure 1). The study area comprises 19 climate stations across Iran and these stations were classified

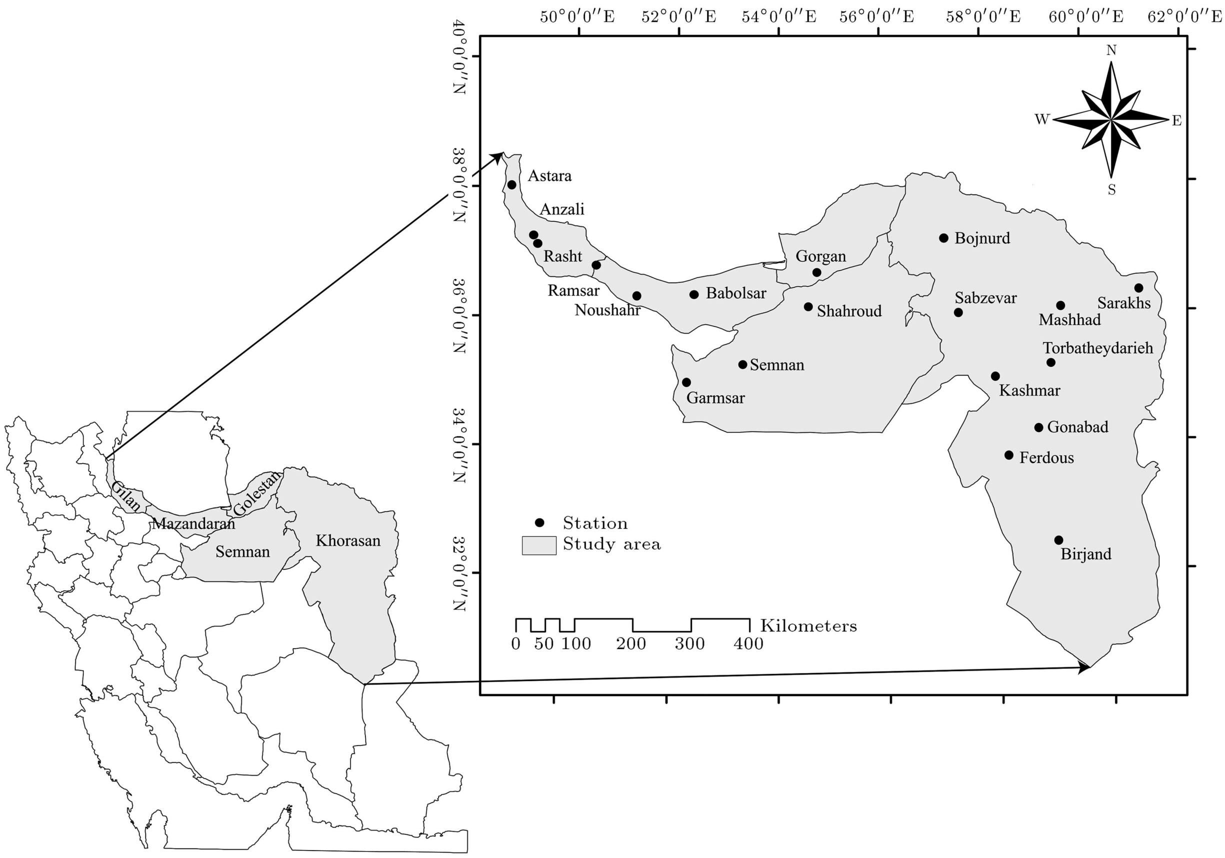

Figure 1. Study area and meteorological stations.

Table 1. Climate classification according to the De Martonne method.

Climate	I
Arid	< 10
Semi-arid	10 - 19.9
Mediterranean	20 - 23.9
Semi-humid	24 - 27.9
Humid	28 - 34.9
Very humid	> 35

using De Martonne's method $I = \frac{P}{(T+10)}$ (Table 1) [19], where T is mean annual temperature (°C) and P is mean annual precipitation (mm). Seven stations (out of nineteen stations) are located in very humid and humid areas, three stations are in a semi-arid region, and nine stations are in an arid region across the study area (Table 2).

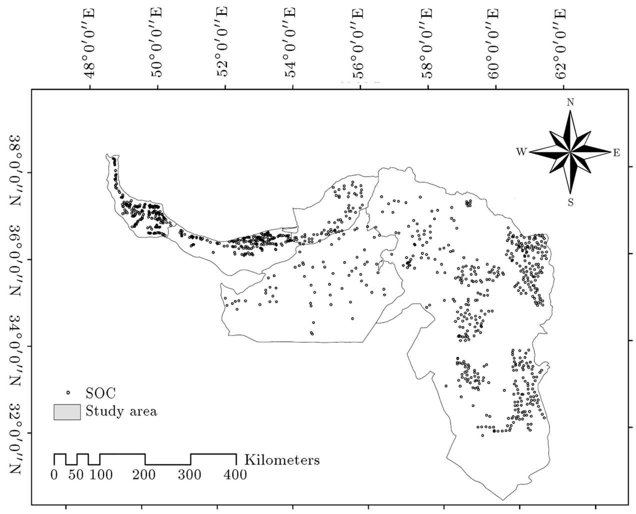

Figure 2. Soil sample distribution in the study area in different geographical zones.

2.2. Soil and land-use data

RothC model needs soil organic carbon, clay content, and soil bulk density. Soil samples were collected from Soil and Water Research Institute of Iran for different sites (forest, agriculture, grassland, and desert). Soil samples were randomly taken from the 0-30 cm soil depth at each field site. The basic soil unit in the 1:250,000 soil map was subgrouped. The distribution of 980 soil samples is shown in Figure 2. The measured carbon fractions (%) were converted to tC ha^{-1} with known soil bulk densities, which had the same units as the output from RothC model. Due to the various climate conditions in the study area, it was divided into five different geographical zones: warm desert, warm temperate forest, cool temperate forest, temperate thorn steppe, and cultivated lands (Figure 3). In this study, land-use data was derived from the world vegetation dataset [20] and Holdridge's life zone classification. Monthly precipitation and temperature data for the five climatic zones of the study area were

Table 2. Location and stations utilized in the study area.

Stations	Latitude (°N)	Longitude (°E)	Elevation (M)	Climate
Anzali	37.28	49.28	-26.2	Very humid
Astara	38.25	48.52	-18.0	Very humid
Babolsar	36.43	52.39	-21	Humid
Birjand	32.52	59.12	1491	Arid
Bojnurd	37.46	57.31	1091	Semi-arid
Garmsar	35.12	52.16	825.2	Arid
Gonabad	34.21	58.41	1056.0	Arid
Gorgan	36.51	54.16	13.3	Humid
Ferdous	34.1	58.10	1293	Arid
Kashmar	35.12	58.28	1109.7	Arid
Mashhad	36.28	59.6	999.2	Semi-arid
Noushahr	36.39	51.3	-20.9	Very humid
Ramsar	36.54	50.4	-20	Very humid
Rasht	37.15	49.36	36.7	Very humid
Sabzevar	36.12	57.43	977.6	Arid
Sarakhs	36.32	61.10	235.0	Arid
Semnan	35.35	53.33	1130.8	Arid
Shahroud	36.25	54.57	1345.3	Arid
Torbat Heydarieh	35.27	59.22	1450.8	Semi-arid

Table 3. Precipitation and temperature changes under A2 and B2 scenarios, compared with the observed data.

Stations	Baseline			A2			B2		
	P (mm)	T_{max} (°C)	T_{min} (°C)	P (rise mm)	T_{max} (rise°C)	T_{min} (rise°C)	P (rise mm)	T_{max} (rise°C)	T_{min} (rise°C)
Anzali	1773	18.9	13.7	13	1.5	0.5	4	1.3	0.2
Astara	1380.9	18.7	11.7	14.6	0.7	0.3	12	0.8	0.4
Babolsar	951.5	21.1	13.8	3.5	1.4	0.6	4.6	1.2	0.3
Birjand	169.8	24.3	8.2	-17.3	1.8	0.5	-16.2	1.5	0.8
Bojnurd	271.0	19.7	6.8	-15.2	1.3	0.7	-13.6	1.01	0.5
Garmsar	128.0	25.8	11.2	-20	0.9	0.1	-19.2	1.1	0.3
Gonabad	144.4	23.8	10.7	-9.6	0.6	0.1	-10.1	0.7	0.3
Gorgan	546.1	18.5	11.2	-5	1.2	0.7	-3.8	1.3	0.6
Ferdous	150.0	24.4	10.02	-17.4	0.8	0.3	-6.3	0.9	0.3
Kashmar	203.2	23.6	11.9	-11.5	1.2	0.5	-12.4	1.4	0.7
Mashhad	254.7	21.6	8.6	-18.3	1.6	0.5	-6.9	1.8	0.9
Noushahr	1318.7	19.6	12.8	-6.3	1.2	0.3	17	1.4	0.6
Ramsar	1216.9	19.4	13.5	17	1.1	0.6	15	0.9	0.4
Rasht	1363.8	20.6	12.1	10.4	1.3	0.4	9.5	1.5	0.8
Sabzevar	200.2	24.7	11.9	-9.6	1.8	0.9	-10.9	1.5	0.6
Sarakhs	193.0	17.9	11.13	-15.3	1.1	0.4	-14.2	1.4	0.5
Semnan	142.8	23.5	13.11	-16.3	1.4	0.3	-17	1.5	0.6
Shahroud	162.5	20.7	9.7	-18.2	1.3	0.9	-17.8	1.6	0.8
Torbat Heydarieh	278.3	21	6.9	-14	1.6	0.7	-13	1.5	0.3

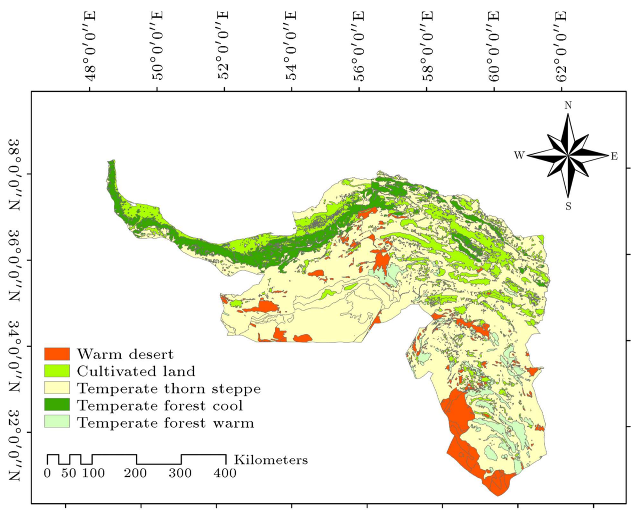

Figure 3. Land-use classification in the study area.

derived using the method proposed by Jenkinson and Rayner [21].

2.3. Climate data

The daily observed precipitation and temperature data from meteorological stations that span a period of 1986 -2010 were obtained from Iran Meteorological Department. The observed climate data were simulated using the LARS-WG model, a stochastic weather generator, based on A2 and B2 emission scenarios [22]. The output results of LARS-WG on 50 km × 50 km grid resolution were used as the input climate data for the RothC model [23]. A2 and B2 emission scenarios were used to estimate the change of soil organic carbon by the years 2030 and 2065. The relative precipitation and temperature data for A2 and B2 scenarios are listed in Table 3.

2.4. Rothamsted carbon model

RothC is a model for the turnover of organic carbon in non-waterlogged topsoil. This model determines the soil carbon turnover process based on soil type, plant cover, moisture content, and temperature. This model uses a monthly data to estimate total organic carbon and microbial biomass carbon in timescales from years to centuries [9]. Based on the RothC assumptions, there are five main compartments. Carbon is transferred by a first-order process from one compartment to the other via decomposition processes. The fractions comprise Resistant Plant Material (RPM), Decomposable Plant Material (DPM), humified organic matter (HUM), microbial biomass (BIO), and Inert Organic Matter (IOM). The IOM is calculated from total soil organic carbon based on Falloon et al. [24] equation IOM= $0{:}049.\text{SOC}^{1:139}$. The concept of IOM, introduced as a mathematical construct, is necessary for calculating soil organic carbon content and $\Delta^{14}C$ of bulk soil data [2]. The quantity of inert organic matter is a major factor in the RothC model results. Inputs to the model are meteorological data (temperature [°C], rainfall [mm], and potential evapotranspiration [mm]), soil clay [%], plant residue inputs, and a soil cover factor. In this model, open-pan evaporation is calculated based on potential evapotranspiration according to Jenkinson and Coleman method (open-pan evaporation = potential evaporation/0.75) [25]. In this study, the model assumes that all the soil contains 20% clay. The ratio of DPM/RPM is set as 0.25 for forest regions, 0.5 for warm deserts and temperate steppes, and 0.67 for cultivated lands and temperate thorn steppes.

3. Results and discussion

3.1. Climate change in different land-use areas

Figures 4 and 5 represent the results of the comparison between monthly temperature and precipitation as observed data with A2 and B2 scenarios in different land uses. The warm desert area shows a slight increase in temperature in future. The maximum predicted temperatures reach 0.5°C and 0.9°C in scenarios A2 and B2, respectively. The results also showed that in the future, precipitation will decrease. The possible explanation for this could be the deserts' typical characteristics of low rainfall, dry air, and incoming solar and outgoing terrestrial radiation, as well as high potential evapotranspiration. Therefore, desert areas generally experience less variability in precipitation and temperature. These findings are all in good agreement with the results of Modarres and Silva [26] and Sadeghi et al. [27]. In the cool temperate forest, the temperature will increase by 0.5°C and 0.4°C under A2 and B2 scenarios in comparison with basic data, respectively. The maximum predicted temperature reaches 1°C in December under A2 scenario. Changes in the predicted temperatures are noticeably smaller in the warmer months. Additionally, the results show that precipitation will increase in this area in the future.

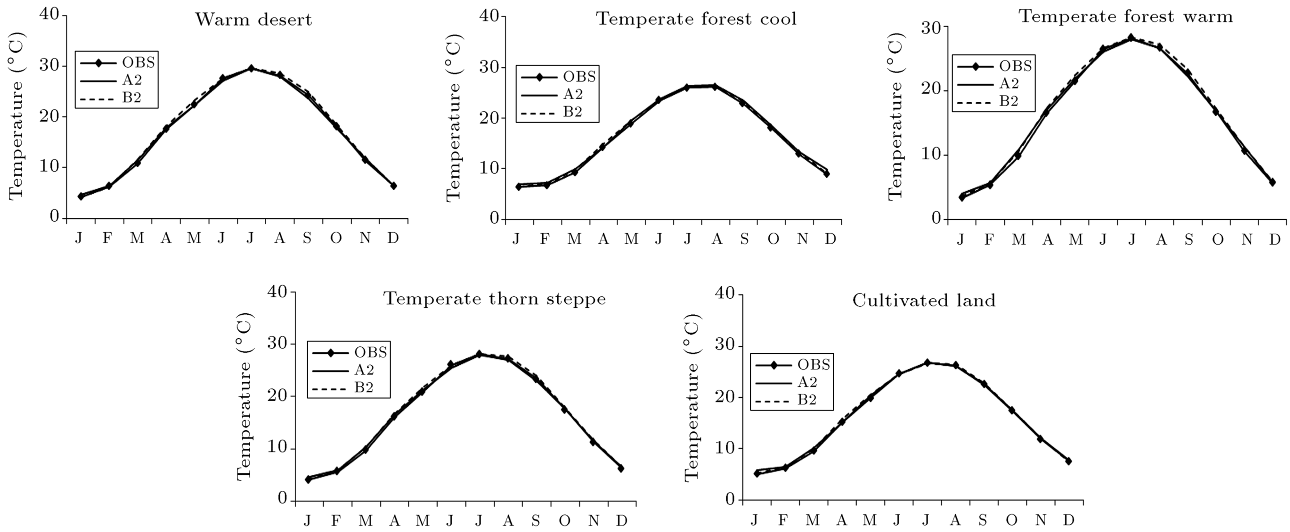

Figure 4. Comparison between observed data and A2 and B2 scenarios for monthly temperature in different land uses.

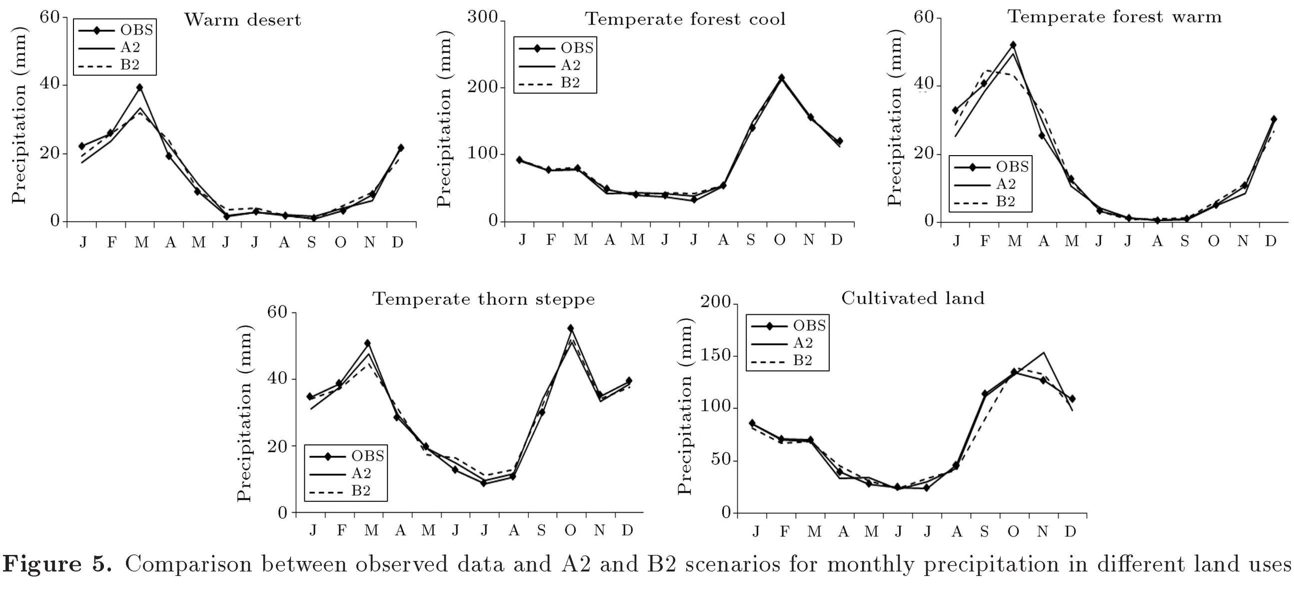

Figure 5. Comparison between observed data and A2 and B2 scenarios for monthly precipitation in different land uses.

The predicted precipitation will rise by about 11.2 mm and 10.8 mm in July and September, respectively. Regarding the predictions for the area of warm temperate forest, temperature is likely to increase in both scenarios with maximum rises of 0.9°C and 0.7°C in November and January, respectively. As for precipitation in this area, predictions suggest that in the future it will decrease during the cold seasons. Analysis of temperature trends showed that the maximum rise of precipitation occurs in the temperate thorn steppe region under A2 and B2 scenarios. Cool temperate forest and cultivated lands are regions most sensitive to increases or decreases in predicted temperature and precipitation in both scenarios. Under the monthly variation, the greatest increase in temperature occurred during the colder months.

Temperatures are expected to increase in the future because in recent years big cities have undergone very rapid urbanization. Population growth, local industries, transportation, and construction increase the temperature and create urban heat islands [28,29,30]. Undoubtedly, these changes can have serious consequences like affecting water resources as well as agriculture and causing prolonged drought. The limitation in using the current climate models is that they do not make estimations of wind and humidity, two particularly important factors in hydrological, ecological, geomorphologic, and agricultural models [31].

3.2. Soil organic carbon under climate change scenarios

The total soil carbon and annual input of soil carbon under different IOMs are shown in Table 4. The model illustrated that the total carbon and carbon input are 106.2 tC/ha^{-1} and 6.58 tC ha^{-1} for all zones, respectively. The results illustrated that more than half (over 60%) of the total soil carbon is distributed between two zones, namely, cool temperate forest and cultivated lands. All the other zones collectively share less than 40% of the soil carbon. From the percentage of annual carbon input to soil, it can be noted that when the decay process is enhanced by temperature and precipitation, a higher amount of annual soil carbon is required to stabilize the carbon content in that area. For example, over 70% of the total annual carbon input to the soil is found in cultivated as well as cool temperate forest zones, while the remaining 30% is located in the other zones. These findings also illustrate that in the warm study areas (like deserts), the lowest amount of annual carbon input could maintain the total soil organic carbon content.

Table 4. Total soil carbon variation under A2 scenario.

Zone	Total C (tC/ha^{-1})	Carbon input (tC/ha^{-1})
Warm desert	3.9	0.26
Temperate thorn steppe	10.5	0.48
Temperate forest cool	41.7	1.02
Temperate forest warm	7.8	2.55
Cultivated lands	42.3	2.27
Total	106.2	6.58

The findings also revealed that the total amount of soil carbon could be expected to be lost from the soil under scenario A2, in comparison to the observed soil organic carbon. The soil organic carbon might decrease approximately 8.3tC/ha^{-1} and 13.36 tC/ha^{-1} by 2030 and 2065, respectively (Table 5). Predictions strongly suggest that the total amount of soil organic carbon will drop to 97.9 tC/ha^{-1} by 2030 and to 92.84 tC/ha^{-1} by 2065. The results show that SOC declines mainly in cultivated lands. The specific decreases of SOC will be 2.5 tC/ha^{-1} and 4 tC/ha^{-1} by the years 2030 and 2065, respectively. Under the A2 scenario, SOC would decrease in warm temperate forests (1.26 tC/ha^{-1}) and cool temperate forests (2.2 tC/ha^{-1}) during 2030 compared to its basic level, while SOC showed predicted decreases of 2.06 tC/ha^{-1} and 3.6 tC/ha^{-1} in these areas during 2030 and 2065, respectively. Figure 6 shows the simulated future changes of SOC compared with its values during 2009-2010 under A2 and B2 scenarios.

The trends of SOC change predicted under the B2 scenario were the same as those predicted under the A2 scenario; however, the rate of SOC change was more under B2 scenario. The changes of soil organic carbon under B2 scenario for 2030 and 2065 are shown in Table 6. The findings illustrated that the amount of SOC

Table 5. Total soil carbon variation under A2 scenario.

Zone	Original SOC (tC/ha^{-1})	C 2030 (tC/ha^{-1})	C 2065 (tC/ha^{-1})	Original SOC -2030 (tC/ha^{-1})	Original SOC -2065 (tC/ha^{-1})
Warm desert	3.9	2.92	2.6	0.98	1.3
Temperate thorn steppe	10.5	9.14	8.1	1.36	2.4
Temperate forest cool	41.7	39.5	38.1	2.2	3.6
Temperate forest warm	7.8	6.54	5.74	1.26	2.06
Cultivated lands	42.3	39.8	38.3	2.5	4
Total	106.2	97.9	92.84	8.3	13.36

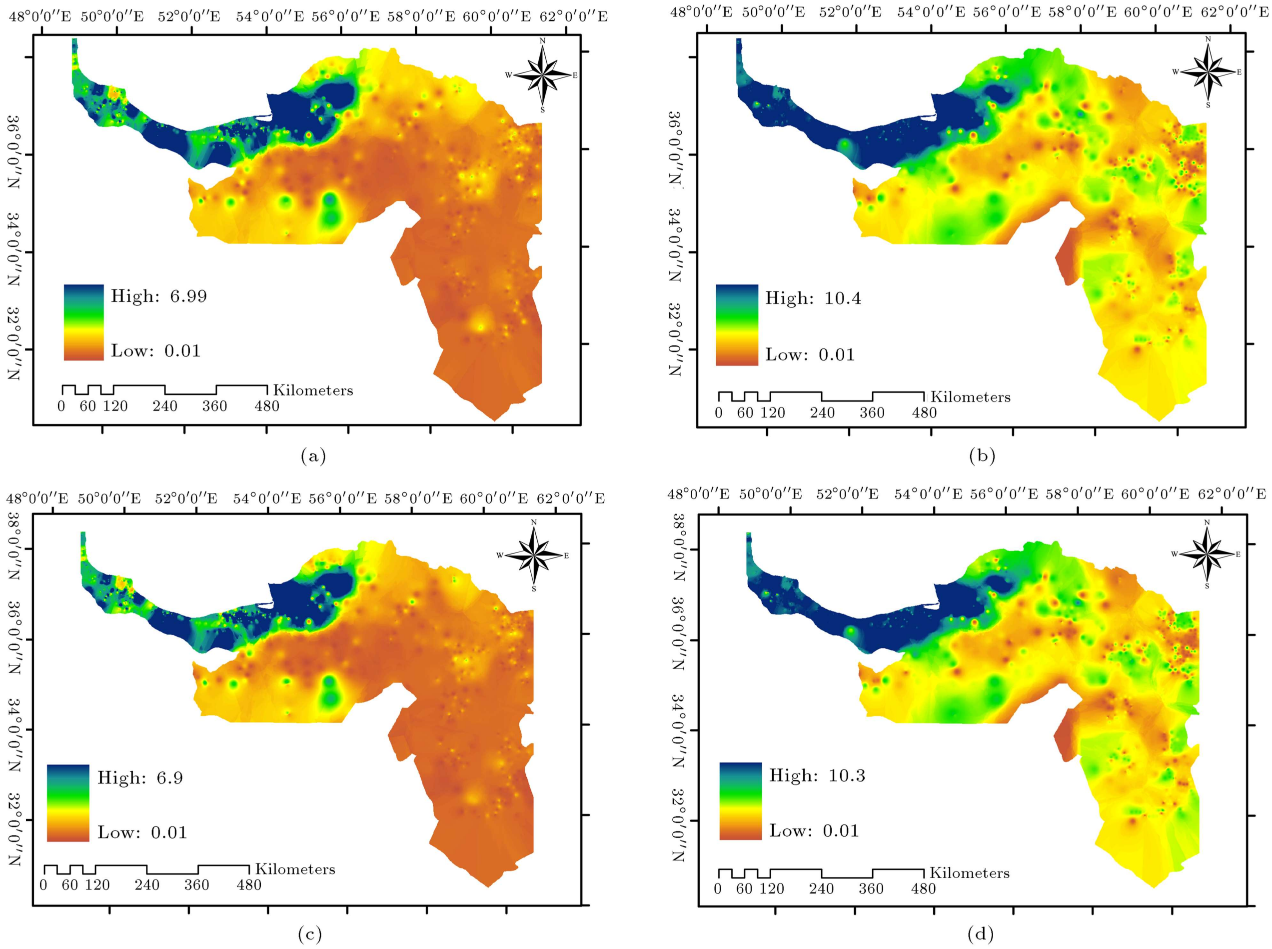

Figure 6. The change of soil organic carbon compared with observed data under A2 and B2 climate scenarios in the north and north-east of Iran: (a) A2 2030; (b) A2 2065; (c) B2 2030; and (d) B2 2065.

Table 6. Total soil carbon variation under B2 scenario.

Zone	Original SOC (tC/ha^{-1})	C 2030 (tC/ha^{-1})	C 2065 (tC/ha^{-1})	Original SOC -2030 (tC/ha^{-1})	Original SOC -2065 (tC/ha^{-1})
Warm desert	3.9	2.98	2.5	0.92	1.4
Temperate thorn steppe	10.5	8.7	7.79	1.8	2.71
Temperate forest cool	41.7	39.5	38.3	2.2	3.4
Temperate forest warm	7.8	6.44	5.1	1.36	2.7
Cultivated lands	42.3	40	38.7	2.3	3.6
Total	106.2	97.62	92.39	8.58	13.81

would decrease in comparison with the original data under changing of temperature and precipitation. The total soil organic carbon showed predicted decreases of 8.58 tC/ha^{-1} and 13.81 tC/ha^{-1} during 2030 and 2065, respectively. The overall amount of reduction in SOC was also notable in cultivated lands in 2030 (2.3 tC/ha^{-1}) and 2065 (3.6 tC/ha^{-1}) compared to the basic data. The SOC was obtained 0.92 tC/ha^{-1} and 1.4 tC/ha^{-1} with a slight decrease for the warm desert area during 2030 and 2065, respectively, compared with the basic data. Under the B2 scenario, the trends in SOC change in 2065 are similar to those predicted for 2030, but the range of change is greater.

In general, modelling results showed that SOC decreased under A2 and B2 climate scenarios in the study area. The pattern of decrease of SOC was greater under B2 scenario than under A2 scenario. Our findings are partially in agreement with the previous studies in different parts of the world [32,33]. Changes in precipitation and temperature can, over time, lead to a reduction in the quantity of soil organic carbon in the soil. A rise in precipitation and temperature can speed up SOC decomposition whilst fluctuations in precipitation and temperature may influence the storage of SOC in any physiographic unit [34,32]. The study by Wan et al. [10] found that SOC decreases at a high rate in northern China compared with southern China. Usually, the higher decrease of SOC happened under B2 scenario. Smith et al. [32] reported that climate impacts would reduce the mean grassland soil carbon stock by 6-10% of the 1990 level by 2080. Friedlingstein et al. [35] found that precipitation could offset the effect of temperature on SOC. Regarding the agricultural regions, apart from the effect of climatic factors, the loss of soil organic carbon was found to accelerate as a result of land misuse through, for example, biological activity and soil mismanagement, commonly caused by humans. As a result, the soil organic carbon contents were reportedly lower than their potential levels in most agricultural soils. In these regions, respiration and decomposition processes take the lead in the process of productivity, causing negative feedback [36,37].

4. Summary and conclusions

This study demonstrated that RothC model is one of the most useful models for soil organic carbon simulation and prediction, because it requires a limited amount of input data such as climate (temperature, rainfall, and evaporation), soil texture (clay content), and land management files. RothC is, therefore, a suitable tool for estimating soil organic carbon changes under different climate change conditions. The results indicated that increasing temperature and decreasing precipitation lead to a change of SOC in different land uses. Based on the modelling results, it can be said that soil organic carbon changes would decrease in the study area under A2 and B2 climate scenarios compared to the basic data at the 0-30 cm depth by the years 2030 and 2065. The total soil organic carbon was 106.2 tC/ha^{-1} during basic year, while it was obtained 97.9 tC/ha^{-1} during 2030 and 92.84 tC/ha^{-1} during 2065 under A2 scenario. The total soil organic carbon was estimated 97.62 tC/ha^{-1} and 92.39 tC/ha^{-1} during 2030 and 2065 under B2 scenario, respectively. The decrease rate of SOC was higher in cultivated lands under both scenarios. The minimal decrease of SOC occurred in warm desert area under A2 and B2 scenarios.

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