Pol. J. Environ. Stud. Vol. 32, No. 3 (2023), 2563-2570

DOI: *10.15244/pjoes/158766* ONLINE PUBLICATION DATE: 2023-03-08

Original Research

Variation and Influencing Factors of Soil Organic Carbon Across an Alpine Desert Ecosystem of Tibetan Plateau

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Received: 21 October 2022

Accepted: 28 December 2022

Abstract

Deserts soils acted as important soil carbon pools in arid and semiarid regions. Soil organic carbon (SOC) contents and its driven factors remained unclear in alpine deserts on the Tibetan Plateau. In this study, we sampled 223 soil profiles, and analyzed SOC values under 0-30 cm. It was indicated that average and median of SOC were approximately 4.86 and 3.80 g/kg. SOC contents were divided into four groups. The largest group was approximately 3.32 g/kg (145 profiles, $P<0.05$) when air temperature and altitude were higher than 1.49ºC and 2793 m with lower precipitation of 173.4 mm encircling with Qaidam basin. Future increasing precipitation scenario would be an effective countermeasure to increase SOC in this region. Furthermore, SOC of the smallest group was 13.7 g/kg when precipitation was over 371.5 mm in the south of Qinghai Lake. Alpine desert SOC were mainly controlled by total nitrogen and pH and precipitation with R^2 of 0.87 ($P<0.001$). In addition, increasing nitrogen deposition and mineral decomposition significantly increased desert soils organic carbon storage.

Keywords: alpine deserts, structural equation model, precipitation, SOC

Introduction

Global mean air temperature i was 0.84ºC above the 20th-century, this was the sixth highest among 1880-2021 record [1]. Increasing atmosphere greenhouse gases have been the major driver of global warming due to anthropogenic activities [2-3]. Increasing soil carbon is an appealing way to prevent carbon emissions [2, 4-5].

Soil organic carbon (SOC) may represent 25% of the potential of natural climate solutions [2]. Chinese land biosphere was a robust sink of 0.2-0.25 petagrams (Pg) carbon, and Tibetan Plateau ecosystems covered about 10% [5-6]. Alpine soils are increasingly recognized for carbon sequestration in high-altitude ecosystems [7-9]. Natural desert lands contain some 7.84 Pg of organic carbon in China [10]. Deserts soil organic carbon contents were 4.37, 2.12 and 1.50 g/kg in the northwestern China, Norwest Mexico, and Israel Negev deserts [11-13]. There was a significant difference on SOC contents across global deserts. Qaidam Basin covered an area over 250,000 km^2 [14]. However, SOC

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content characteristic was underlying indistinct because of little data in this region. In this study, we considerably sampled typical desert soils nearly 10 km upper 0-30 cm mixture, including 223 observations with coincident measurement method. This could accurately evaluate desert soil organic carbon contents in Qaidam Basin.

Soil family types and land use were main driving factors on SOC contents and storage [15-16]. Grassland types affected ecosystem carbon densities and contents [7-8]. Root-derived inputs are major contributors to soil carbon in temperate land ecosystems [17]. Increased soil available nutrients had higher positive effects on carbon contents [3,18]. Improving N-use efficiency are important for decreasing soil carbon losses from acidification [19-20]. Soil nitrogen nitrification and denitrification rates increased significantly with pH, this would decrease soil total nitrogen [4, 12]. The addition of minimum temperature led to a significant increase in soil carbon sequestration capacity [9]. Desert grasslands SOC decreased with mean annual temperature, but increased significantly with annual precipitation [10, 12, 21]. Greenhouse gas emissions from peatlands drained for agriculture could be greatly reduced [22-23]. Temperature and precipitation interaction significantly affected SOC density in alpine steppe and cropland [5, 7, 24].

In this study, we hypothesized that there were significant regional variability changes in SOC contents in Qaidam basin. Moreover, soil pH and precipitation and air temperature significantly affected SOC contents in alpine deserts. Future increasing precipitation scenario was intensive countermeasure to enhance SOC contents.

Material and Methods

Study Area and Sites

Main vegetation types were described in Qinghai Plateau including alpine desert, alpine steppe, alpine meadow and without vegetation (Fig. 1). This study was conducted in alpine desert ecosystem with a plateau continental climate in Qaidam Basin. Average air temperature and precipitation were −3.68ºC and 92.94 mm. Altitude ranged from 2600 to 3200 m. Soil types mainly included grey-brown desert soil, aeolian sandy soil, and saline alkali soil.

Alpine deserts were dominated by *Kalidium foliatum, Sympegma regelii, Nitraria tangutorum, Salsolacollina pall, Artemisia sphaerocephala, Tamarix chinensis, Ceratoides latens, Ephedra przewalskii, Haloxylon ammodendron, Reaumuria kaschgarica, Reaumuria songarica, Peganum harmala, Lyciumchinense miller.*

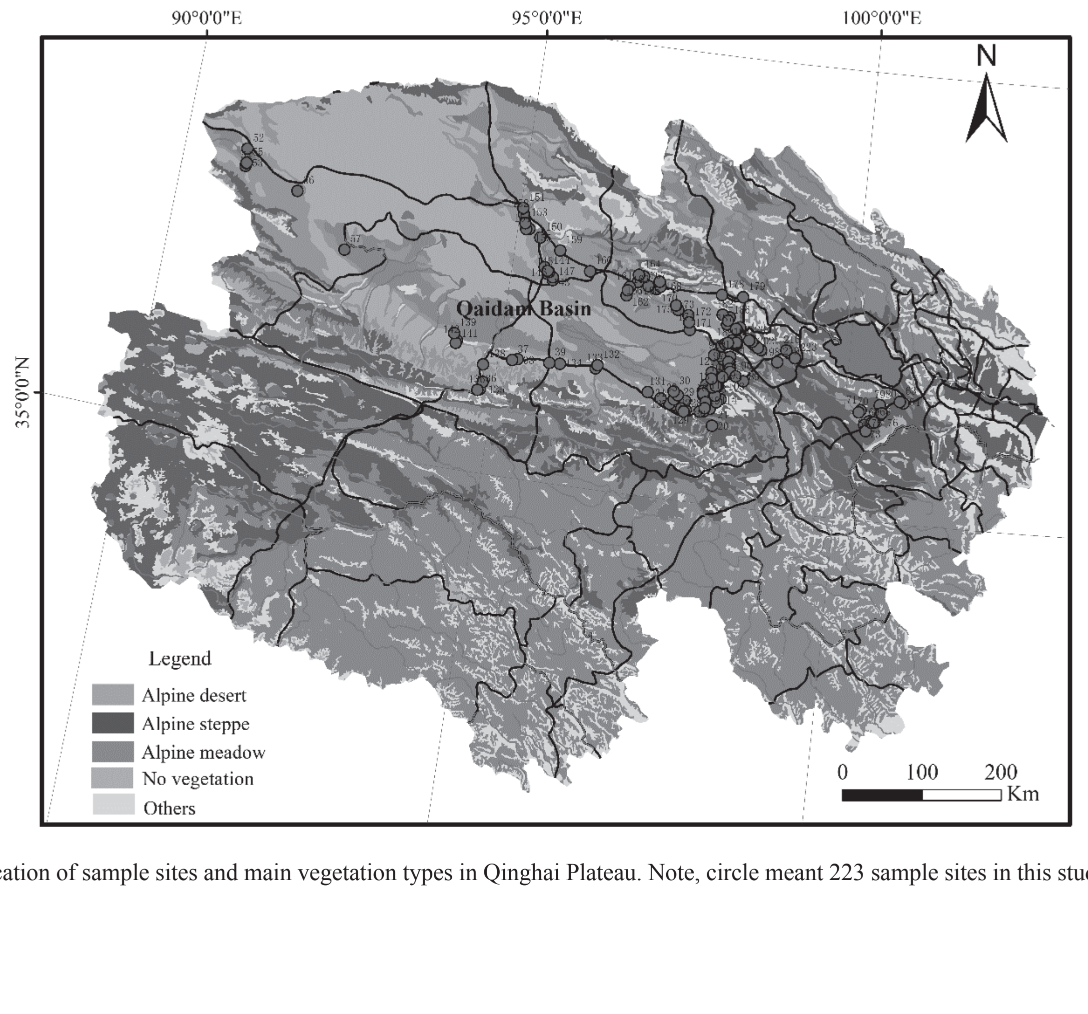

Fig. 1. Location of sample sites and main vegetation types in Qinghai Plateau. Note, circle meant 223 sample sites in this study.

Experimental Design and Analysis Method

Qaidam Basin was dominated by alpine deserts. We selected typical deserts as our research objects every 10 km across main roads reference to 1:1 million Chinese vegetation maps. Thus, total 223 observations were collected in this study (Fig. 1) as far as possible representative for total deserts soil types. In every sample site, we carefully gathered upper 30 cm mixture of soils to accurately evaluate SOC contents. Meanwhile three replicated soils were collected in August 2017 and 2018. Furthermore, altitude and longitude and latitude data were recorded. All soil samples were deposited by air drying, and then passed through a 2 mm soil mesh sieve.

Soil organic carbon contents were analyzed by TOC-5000A analyzer (Shimadzu corporation, Japan) using dry oxidation method. Total nitrogen (TN) and total phosphorus (TP) were analyzed by Elemental Analyzer (PE2400IICHN, German) and perchloric acid sulfuric acid dissolution molybdenum antimony anti colorimetry. Furthermore, pH was measured by automatic titrator with a pH (H_2O) probe (PHS-3C, China). Altitudes were recorded by global positioning system (GPSMAP 66s, China). Average monthly climate data was downloaded from http://worldclim.org for 1970-2020 with 1 km^2 spatial resolutions.

Statistical Methods

Cluster analysis of SOC and TN were conducted by multivariate regression trees through "mvpart" package in R-3.3.4 version. This analysis could distinguish main environment factors range under different SOC and TN distribution pattern. One-way analysis of variance was performed by "aov" package among four groups of SOC and TN contents (P<0.05). Drive factors of climate factors (precipitation, air temperature, and altitude) and soil characteristics (total phosphorus, pH) on SOC and TN were analyzed by structural equation model using "piecewiseSEM" package.

Results

Variation in Alpine Desert SOC and TN and TP in Tibetan Plateau

Averaged SOC was approximately 4.86±0.26 g/kg with high variation coefficient around 81.14% in Qaidam Basin (Table 1). Median value of SOC was 3.80 g/kg and ranged from 0.54 to 24.34 g/kg with 15 outlier values over 11.2 g/kg (Fig. 2).

Mean total nitrogen was around 4.62±0.25 g/kg with much high variation coefficient around 82.95% (Table 1). Median value of total nitrogen was 3.64 g/kg ranging from 0.67 to 27.69 g/kg with 17 extreme outlier values over 10.0 g/kg. Mean and median value of total phosphorus were 5.20±0.09 and 5.45 g/kg with low variation coefficient ranging from 1.81% to 10.67% (Fig. 2). The variation coefficient of total phosphorus was much lower than total nitrogen.

Cluster Analysis of SOC and TN by Multivariate Regression Trees

Both soil organic carbon and total nitrogen contents were divided into four groups. The SOC was approximately 3.32 g/kg (145 sites, P<0.05) and

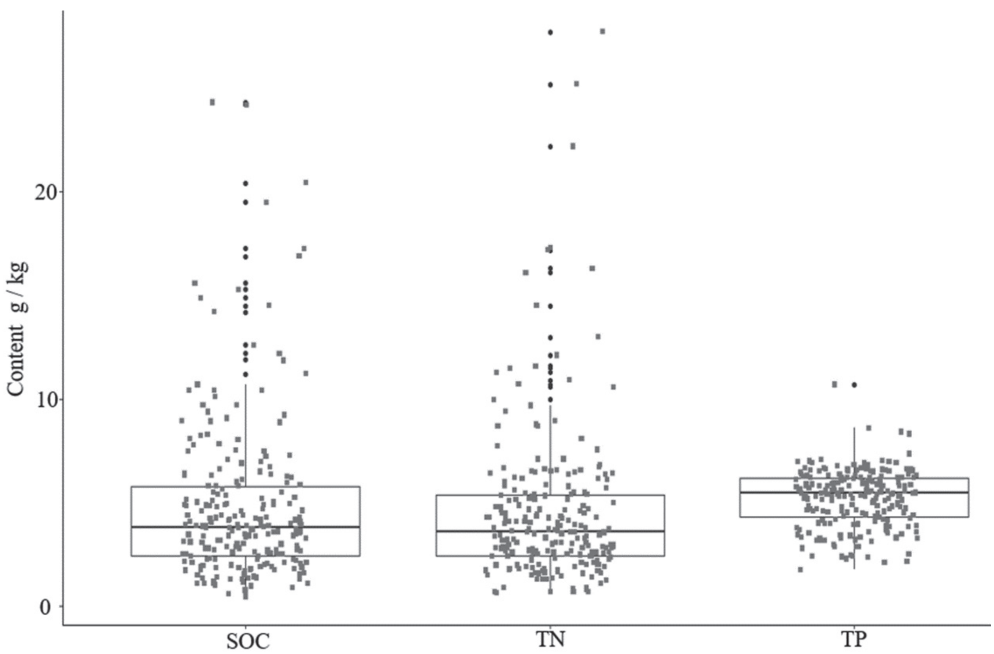

Fig. 2. Soil organic carbon and total nitrogen and phosphorus contents in alpine desert plots.

Table 1. Mean and variation coefficient of soil organic carbon and total nitrogen and phosphorus contents in alpine desert plots.

Item	Mean and stand error g/kg	Variation coefficient %
Soil organic carbon	4.86±0.26	81.14
Total nitrogen	4.62±0.25	82.95
Total phosphorus	5.20±0.09	25.91

significantly lower than others, when precipitation was lower than 371.5 mm in the largest group (Fig. 3). These soil profiles encircled and intensively distributed the east of the Qaidam basin. Meanwhile, air temperature and altitude were higher than 1.49ºC and 2793 m. The second group was approximate 6.48 g/kg including 52 sample sites when air temperature was lower than 1.49ºC (Fig. 4). It was located intensively at the east of the basin. The third group of SOC contents was averaged 7.88 g/kg including 16 sample sites, and distributed intensively at the south of basin with lower altitude under 2793 m. The smallest group of SOC contents were relative higher approximately 13.7 g/kg when precipitation was above 371.5 mm at the south of Qinghai Lake (Fig. 4).

The largest group included 161 sample sites approximately 3.48 g/kg of total nitrogen when precipitation was under 371.5 mm, and air temperature was higher than 1.49ºC (Fig. 3). Meanwhile, altitude threshold was 3655 m. Total nitrogen was nearly 12.8 g/kg at higher altitude. Furthermore, soil total

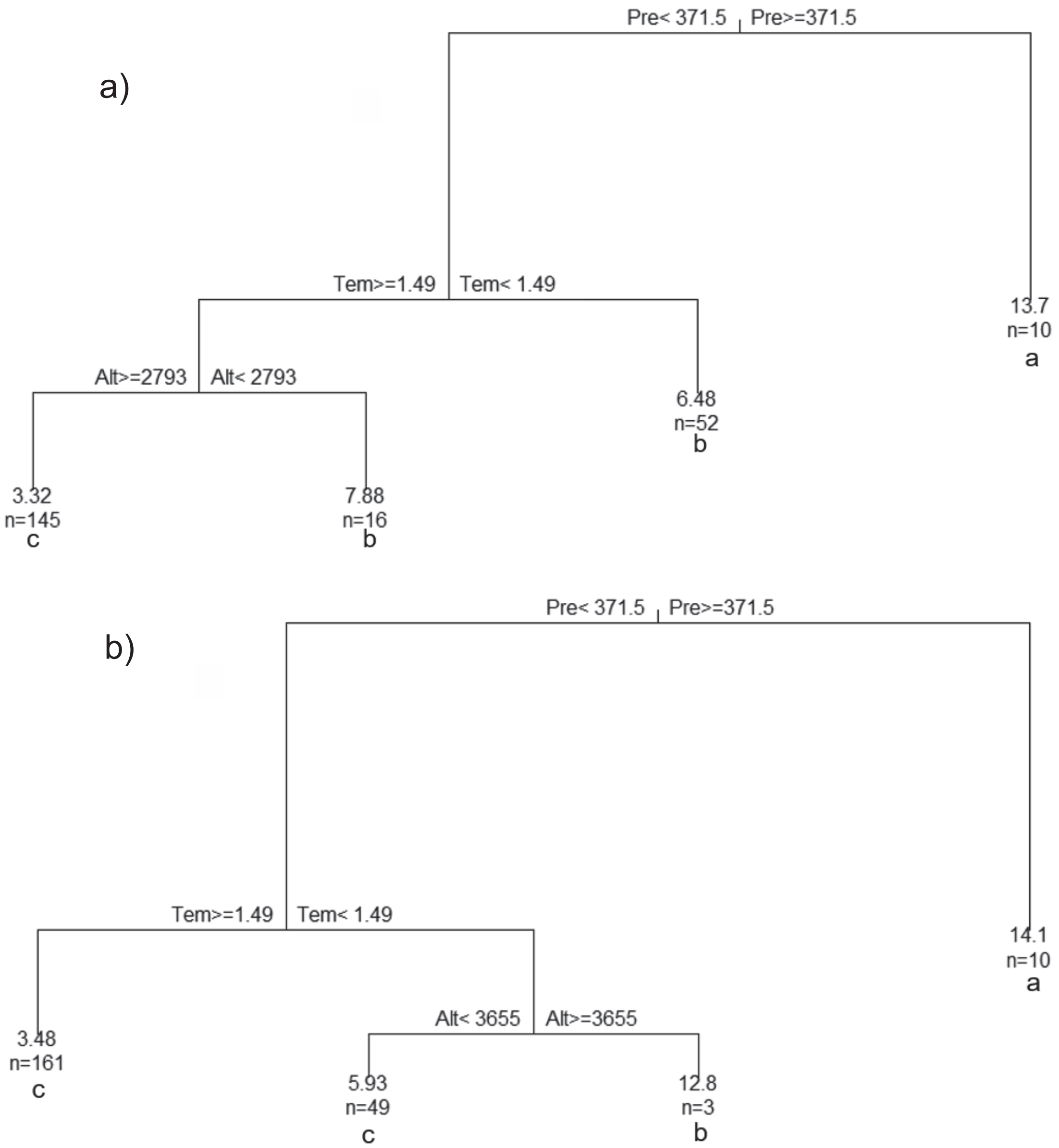

Fig. 3. Cluster analysis of SOC (A) and TN (B) contents under different precipitation and air temperature and altitude by multivariate regression trees. Note: different letters meant there was significant difference on SOC and TN (P<0.05).

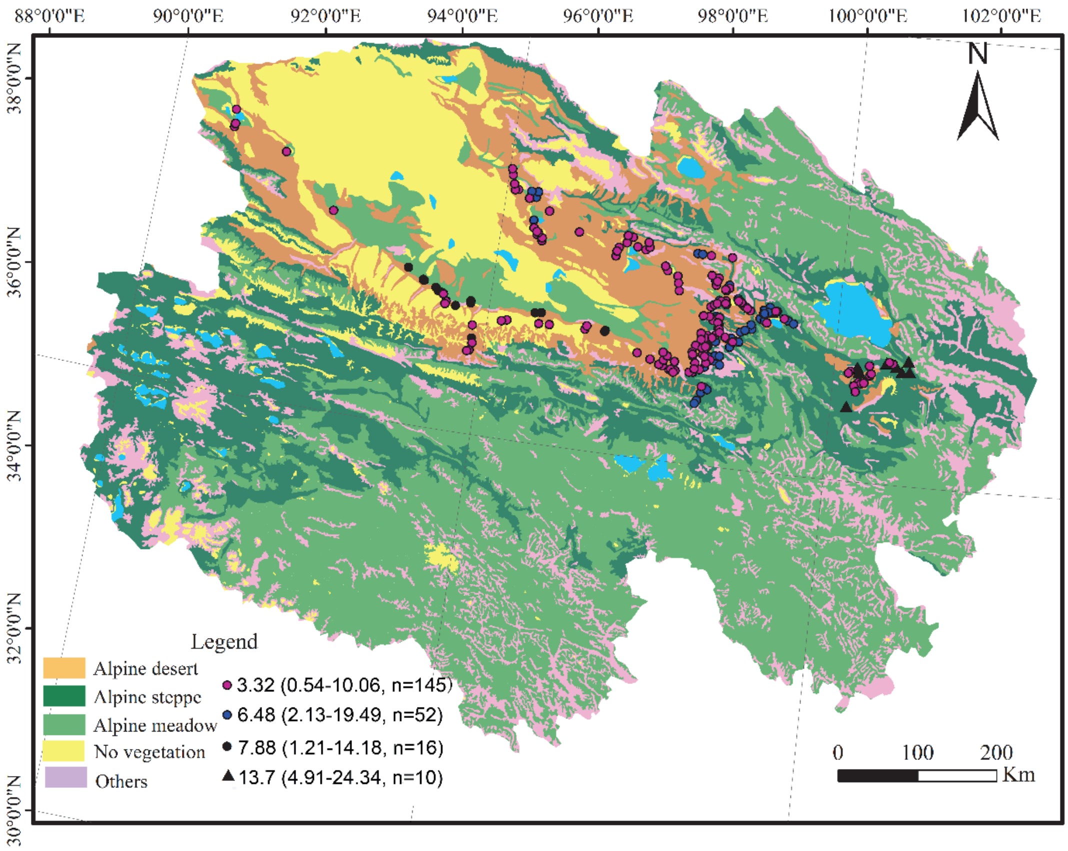

Fig. 4 Distribution pattern of four groups of SOC contents under different precipitation and air temperature and altitude across Qaidam Basin. Note: different colors meant the main location of the four groups of SOC contents.

nitrogen seemed higher under higher altitude and lower temperature conditions.

Structural Equation Model Revealed Main Affected Factors on Desert SOC and TN and pH

Desert SOCs were mainly affected by TN, pH and precipitation using structural equation model with R^2 of 0.87 among six factors (Fig. 5). Affected coefficients of TN and pH and precipitation were 0.99 and −0.21 and −0.16, separately (P<0.001). However, total phosphorus and altitude and air temperature took weak roles in affecting SOC contents. Soil total nitrogen contents were positively driven by precipitation with effect coefficient of 0.37 (P<0.001). Both temperature and altitude took weakly negative role in soil nitrogen. Furthermore, air temperature affected positively soil pH (P<0.05).

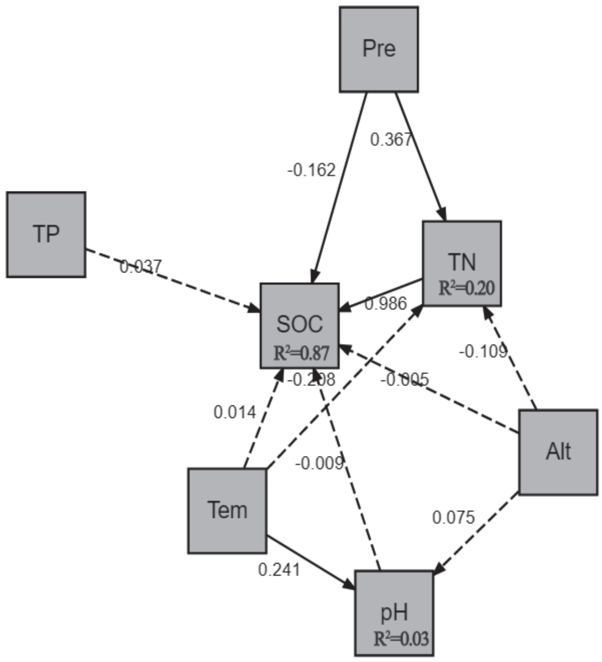

Fig. 5. Effects of soil chemical characteristic and climate factors on SOC (R^2 = 0.87) and TN (R^2 = 0.20) by structural equation model. Note: Pre, TP, TN, SOC, Alt, and Tem were precipitation, total phosphorus, total nitrogen, soil organic carbon, altitude, and air temperature. Solid and dotted lines indicated significant and insignificant effect, separately. ($\chi 2$ = 0.294, P = 0.864, d_f = 2).

Discussion

Paris Agreement aimed to hold air temperature below 2ºC above pre-industrial levels [1]. Protecting SOC pools could deliver many benefits to nature ecosystems and people [2, 16]. Land biosphere absorbed approximately 45% of annual anthropogenic carbon emissions in China [6]. Over 6% of the world's land is affected by the salinity across 100 countries mostly in arid and semiarid regions [25-26]. Deserts soils play a vital role in regulating greenhouse gases concentrations in the atmosphere [3, 12]. Desert grasslands use may improve the status of soil organic carbon and nitrogen dynamics [19].

Soil organic carbon and microbial biomass carbon contents varied remarkably among the different species communities in desert grasslands and shrubs [11, 27]. Average SOC contents of nondegraded and degraded grasslands were 34 and 24 g/kg on Tibetan Plateau [8]. SOC was 25.01 g/kg with 55.26% variation coefficient in karst mountainous area indicating moderate variation [15]. Deserts soil organic carbon contents were 7.05, 3.94 and 1.56 g/kg in West Jilin Province and Inner Mongolia and Tarim Basin in China [10]. Furthermore, desert soil organic carbon was 5.47 and 5.30 g/kg across Central Iran and India salt deserts, separately [25, 28]. It was indicated that deserts SOC presented spatial heterogeneity.

In this study, desert soil organic carbon contents in Qaidam basin were higher than both Inner Mongolia and Xinjiang Tarim Basin. Furthermore, it was similar with Iran and India deserts. However, it was much lower than desert grasslands in Jilin Province. Meanwhile, we also revealed that much spatial heterogeneity has existed in Qaidam basin. SOC contents ranged from 0.54 to 24.34 g/kg with variation coefficient of 81.14%. This result validated our hypothesis that there were significant regional variability changes in SOC contents in Qaidam basin. Furthermore, the SOC contents were divided into four groups. The precipitation ranged from 37 to 369 mm (173.4±6.7 mm) in the largest groups. Air temperature and altitude varied from 1.50 to 5.28ºC (2.93±0.08ºC), and from 2796 to 3530 m (3091±13 m). The SOC was lowest in the largest groups ($p<0.05$) because both high altitude and lower precipitation limited plants biomass inputs, but higher air temperature increased organic carbon mineral decomposition. Future increasing precipitation would be effective countermeasure to increase SOC in this region. Meanwhile, the SOC was highest approximately 13.7 g/kg with 10 soil profile. Its precipitation and air temperature ranged from 371 to 514 mm (410.5±15.40 mm), and from 0.94 to 3.34ºC (2.01±0.28ºC) with average altitude of 3134 m. The precipitation and air temperature were much rich, and lower than the lowest group, respectively. This could increase deserts SOC in the south of Qinghai Lake. In addition, SOC contents were affected by precipitation, air temperature and altitude in this region.

Soil pH can affect the content of soil organic carbon by changing plant growth and soil respiration [29-30]. The spatial distribution of SOC is related to pH and annual precipitation in Israel deserts [12]. Desert SOC contents were negatively correlated with soil pH [29]. In addition, we also discovered that soil pH was negatively affected SOC contents in Qaidam basin. It was because there are different degrees of salinization in desert ecosystems. Furthermore, growth of vegetation was seriously restricted by high saline alkali soil, and it greatly reduced the input of soil organic carbon.

Precipitation was driven factor on SOC contents across the desert ecosystem of Hexi Corridor [31]. The SOC concentrations were significantly positively correlated with annual precipitation in northern China [29]. Microbial activity decreased strongly in saline soils by decreasing osmotic potential at lower water content [25]. Mean annual temperature was more important to determine SOC than other abiotic factors in arid desert grasslands [21]. In this study, it was indicated that deserts SOC was significantly driven by precipitation in Qaidam basin. Over the past several decades, Tibetan Plateau showed an increase in precipitation [32-33]. Then, increasing regional precipitation perhaps decreased desert soils organic carbon storage in future climate scenarios.

Nitrogen is essential to regulate the ecosystem functions and services [30]. A close spatial similarity was observed between SOC contents and total nitrogen [28]. SOC was significantly correlate with total nitrogen ($r = 0.997$, $P<0.01$) in the desert of Minqin [34]. In the present study, deserts soil organic carbon contents were also positively driven by total nitrogen. Nowadays, average annual nitrogen deposition increased by approximately 8 kilograms per hectare between the 1980s and the 2000s [35]. Deserts soil organic carbon contents would increase significantly with adding nitrogen deposition and mineral decomposition.

Conclusion

Desert soil organic carbon contents ranged with high variation coefficient in Qaidam Basin. Cluster analysis revealed that soils organic carbon contents were divided into four groups by multivariate regression trees. Future climate scenario of increasing precipitation would be intensive countermeasure to increase SOC in this region. All TN and pH and precipitation were main driven factors on SOC by structural equation model. With nitrogen deposition and mineral decomposition increasing, deserts soil organic carbon contents would increase significantly in Qaidam basin.

Acknowledgments

This work is supported by The National Natural Science Foundation of China (U21A20186), and transformation projects in Qinghai Province (2022-NK-135), leading talents of the Kunlun talents in Qinghai Province, CAS "Light of West China" for interdisciplinary innovation team and forest monitoring sample plot of Qilian Mountains (QHTX2021010).

Conflicts of interest

All authors declare no conflict of interest.

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