Pol. J. Environ. Stud. Vol. 31, No. 3 (2022), 2881-2893
DOI: 10.15244/pjoes/144190 ONLINE PUBLICATION DATE: 2022-02-28

Original Research

Soil Organic Carbon, Total Nitrogen and Their Densities of *Nitraria Tangutorum* Nebkhas at Different Succession Stages on the Edge of Ulan Buh Desert

Yajuan Wei[1], Xiaohong Dang[1,2]*, Ji Wang[1,2], Yan Gao[1]

[1]College of Desert Control Science and Engineering, Inner Mongolia Agricultural University, Hohhot 010018, PR China
[2]Inner Mongolia Hangjin Desert Ecological Position Research Station, Erdos, Inner Mongolia 017400, PR China

Received: 8 July 2021
Accepted: 23 November 2021

Abstract

This study aimed to determine if the succession of *Nitraria Tangutorum* nebkhas could change soil nutrients in the Jilantai desert, Inner Mongolia. Four succession stages including rudimental stage (RUD), developing stage (DEV), stabilizing stage (STA) and degrading stage (DEG) were regarded as succession patterns. We collected 588 soil profile samples within a 0-100 cm depth from different succession stages of *N. tangutorum* nebkhas. We determined the vertical distributions of soil organic carbon (SOC), total nitrogen (TN) and their densities to 1 m depth. The results indicated that soil depths and successional stages had significantly impact on SOC and soil organic carbon density (SOCD), and soil depths had significant impact on TN and soil nitrogen density (SND). SOCD showed firstly increased and then decreased, and SND showed an increasing trend with the succession of *N. tangutorum* nebkhas. SOCD and SND showed as the following order: STA (860.60 g/m^2) >DEG (753.00 g/m^2)>DEV (737.60 g/m^2)>RUG (678.18 g/m^2) and DEG (83.75 g/m^2)>STA (83.68 g/m^2)>DEV (83.06 g/m^2)>RUG (73.42 g/m^2), respectively. The stratification ratios (*SR*) of SOC and TN gradually decreased with soil depth in different succession stages, and there was no significant difference in *SR*s of SOC and TN for each succession stage. Redundancy analysis (*RDA*) revealed that soil depth, silt content, soil water content (SWC) and successional stage directly drove SOCD and SND of *N. tangutorum* nebkhas. Therefore, understanding the vertical distribution of the SOC and TN at different succession stages has great significance for accurately estimating the SOCD and SND storage in the desert areas.

Keywords: *Nitraria tangutorum*, nebkhas; succession stage, soil organic carbon, total nitrogen, Jilantai desert

*e-mail: dangxiaohong1986@126.com

Introduction

Soil organic carbon (SOC) and total nitrogen (TN) formed a main terrestrial carbon and nitrogen pool [1]. SOC is not only an important indicator of soil quality but also closely related to atmospheric CO_2 concentration [2-3]. Around the world, about 1300-1500 Pg C is stored in the form of organic matters in the 0-100 cm soil layer [4], and its carbon storage is 2-3 times that of vegetation and atmosphere, respectively [5]. Since soil has a great SOC storage capacity, and even its slight changes could have important implications for atmospheric CO_2 concentration [6-8]. Soil nitrogen, as one of the massive elements essential for plant growth and development, has an important regulatory role in the nutrient cycling of ecosystems, in which storing and cycling of soil carbon and nitrogen is a mutually coupled process [9]. SOC and TN contents are mutually coupled, and SOC fixation has long been limited by soil TN [10-11]. Therefore, we can not study individual cycles of SOC and soil TN in isolation. For instance, Soil C/N ratio is important to evaluate the use efficiency of soil TN by vegetation and soil microorganisms [12]. Soil organic carbon density (SOCD) and total nitrogen density (SND) are driven by several factors, such as vegetation types, soil characteristics (eg. SOC, TN and pH), climate, ecosystem types and vegetation succession stages. Changes in SOC and TN affect various biochemical reactions and microbial activities in soil, thus further affect soil fertility [13]. Therefore, research on SOC and soil TN levels is of great significance to accurately estimate ecosystem carbon storage.

The desert ecosystems play an important role in the terrestrial ecosystem due to its unique structure and function [14]. The area of the desert ecosystem accounts for about 30% of the terrestrial system, and its carbon storage accounts for about 8% carbon pool of the terrestrial ecosystems. Desert ecosystem has a high carbon sequestration potential (mainly absorbing large amounts of CO_2 from the air), its carbon cycle process is a vital part of carbon cycle in terrestrial ecosystems [15]. Soil carbon sequestration, closely related to vegetation types, soil types and ecological environment, can increase soil carbon storage in desert ecosystems [16]. Therefore, to accurately estimate soil carbon and nitrogen storage in the desert ecosystem, it is of great significance to study the cycle and sink management of carbon and nitrogen in global terrestrial ecosystems.

Nebkhas of different sizes are commonly observed in arid, semi-arid and semi-humid desert areas. As a momentous part of the desert ecosystem, nebkha is a kind of wind-driven sedimentary landform developed under the influence of vegetation [10], nebkha, as the linkage between local climate and environment, has the function of soil and water conservation, wind prevention and sand fixation [15]. Previous studies have focused on the distribution of nebkhas [10], its morphological characteristics [17], vegetation diversity and productivity [18], sediment characteristics and supply, and its influencing factors [19-20]. These studies have reported that the formation of nebkhas is mainly controlled by wind intensity, sand sources and vegetation coverage. Plants that can form nebkhas are triangular-shaped or cylindrical-shaped, and the reverse occurred in the case of rhombus-shaped [21]. The presence of nebkhas strongly influences abiotic factors, biotic factors and gradually forms a highly heterogeneous fertile island effect [22]. The process of fertile island effect is complex mutual interactions between vegetation and nebkhas in the desert area [23-24]. Generally, studies show that nebkhas were mainly composed of very fine, fine and medium sand and the proportion of fine sand increased with vegetation coverage [25]. Changes in SOC and TN of nebkhas were intimately related to the coverage degree, soil particles and soil moisture [26]. The degree of fertility effect varied among nebkhas types, and the better soil nutrients of dense shrubs in nebkhas formation [27]. Furthermore, soil organic matter, total phosphorus and soil moisture at the later growth stage were higher than those at the early growth stage [28]. Although some scholars have carried out extensive efforts to study the protection benefits of *N. tangutorum* nebkhas. However, the effect of vegetation growth on soil nutrient status of nebkhas is still poorly understood. Since the evolution process of nebkhas is a complex process of interaction between vegetation and soil [29]. However, it is still unknown if soil nutrients of nebkhas are related to its successional stages, especially the characteristics of SOC and TN vary according to soil depth inside nebkhas.

The Ulan Buh Desert is located in the ecotone with a very fragile vegetation ecosystem from semi-arid area to arid area of northern China. Plant communities consist of shrubs and semi-shrubs with many annual herbaceous species, *N. tangutorum* is a typical xerophytes shrub with wide adaptability and strong resistance to arid environment. As an important plant component of the Ulan Buh Desert, *N. tangutorum* also serves as the pioneer species for fixing extensive shifting sand and stabilizing the desert environment [30]. Researches on *N. tangutorum* nebhas is important to provide a theoretical basis for a reasonable assessment of the status of carbon and nitrogen storage in the Jilantai desert ecosystem. However, the effects of *N. tangutorum* nebhas on its abiotic and biotic environment are not fully understood. Therefore, *N. tangutorum* nebkhas in the Jilantai desert area was taken as the research object. The following specific questions were addressed: (1) to test whether soil nutrients differ with the development and soil depth of *N. Tangutorum* nebkhas; (2) to analyze whether SOCD and SND are driven by selected biotic and abiotic factors; and (3) to test whether SOC and TN differ with the development and soil depth of *N. Tangutorum* nebkhas.

Materials and Methods

Study Sites

The study area is located on the southwest edge of Ulan Buh Desert (105º47′08“-105º47′38“E, 39º46′58“-39º47′40“N, 960-979 m.a.s.l.). The area has a typical temperate continental monsoon climate. Mean annual precipitation here is 100-140 mm (1986-2019), 83% of which is mainly concentrated in July to September with large interannual variations. The annual mean temperature is 8.6ºC, with an extreme maximum value of 40.4ºC and the extreme minimum value of -31.2ºC. The prevailing wind direction is west-northwest throughout the year of winds >3.5 m/s. Mean annual potential evaporation, sunshine duration and the frost-free period are 3006 mm, 3316 h and 160 d, respectively. The study area is mainly located in fixed sandy land, where the terrain gently undulating characterizes the local landscape without human activities. The predominant soil is aeolian sandy soil mainly consists of coarse sand and silt. Aeolian sandy soil is characterized by weak development and impoverished nutrients. The groundwater level has fallen from 1-5 m in 1958 to 10-15 m in 2012 [31]. Mean soil moisture content at depth of 0-100 cm is 0.48%-0.86%, the soil density is 1.58-1.63 g/cm^3 and soil pH is 8.90-9.22 in all cases, suggesting that the soils in our study area are strongly alkaline. The natural vegetation is mainly composed of *N. tangutorum* with a density of 48 nebhas/hm^2. The common herbaceous species are *Artemisia desertorum*, *Agriophyllum squarrosum,* and *Elymus dahuricus* (Fig. 1).

Experimental Design and Soil Sampling

Fieldwork was performed in mid-August 2019 at Jilantai Desert located on the southwest edge of Ulan Buh Desert. Seven experimental plots of 100 m×100 m were randomly selected with the distance among them less than 1 km. The sampling plots are arranged far away from the highway to prevent the interference of human activities. The classification of *N. tangutorun* nebkhas referred to the method of Tengberg and Chen [10] and the actual situation of the sample plots were selected. The succession of *N. tangutorun* nebkhas was divided into four stages:(1) rudimental stage (RUD), (2) developing stage (DEV), (3) stabilizing stage (STA), and (4) degrading stage (DEG). These classifications are based on the factors of nabkhas morphological characteristics (including long axis, short axis, height, and form), vegetation coverage, plant species and crust condition. The thresholds of each stage are listed in Table 1. During the field investigation, 3 *N. tangutorun* nebkhas with the same size, height and developmental stage were selected in each plot. The long axis, short axis and height of each *N. tangutorun* nebkhas were measured. Three 1 m × 1 m herb quadrats were set up on the windward slope and leeward slope, and the species, plant numbers and heights of herbs in the quadrats were recorded.

In each sample plot, the soil samples were collected from 0-5, 5-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm depths on the top of each successional *N. tangutorun* nebkhas using a steel sampler (100 cm^3). In total, soil samples (four successional stages at seven depth levels) were collected to represent each sampling plot. 3 soil samples at the same sampling depths were mixed as the composite soil sample, a total of 588 soil samples (7 sample plots×4 successional stages×7 soil depths×3 replicates). Soil samples were transported to the laboratory in sealed plastic bags, air-dried and then passed through a 2 mm sieve to discard roots and other debris.

The Malvern 3000 laser diffractometer was used to analyze the soil particle size classification of each composite soil sample, the ring knife method was used to determine the soil bulk density and the drying method was adopted to identify soil moisture. Soil pH was measured in a soil-water ratio of 1:2.5 (weigh/weight) with a pH meter (STARTER3100, USA). SOC

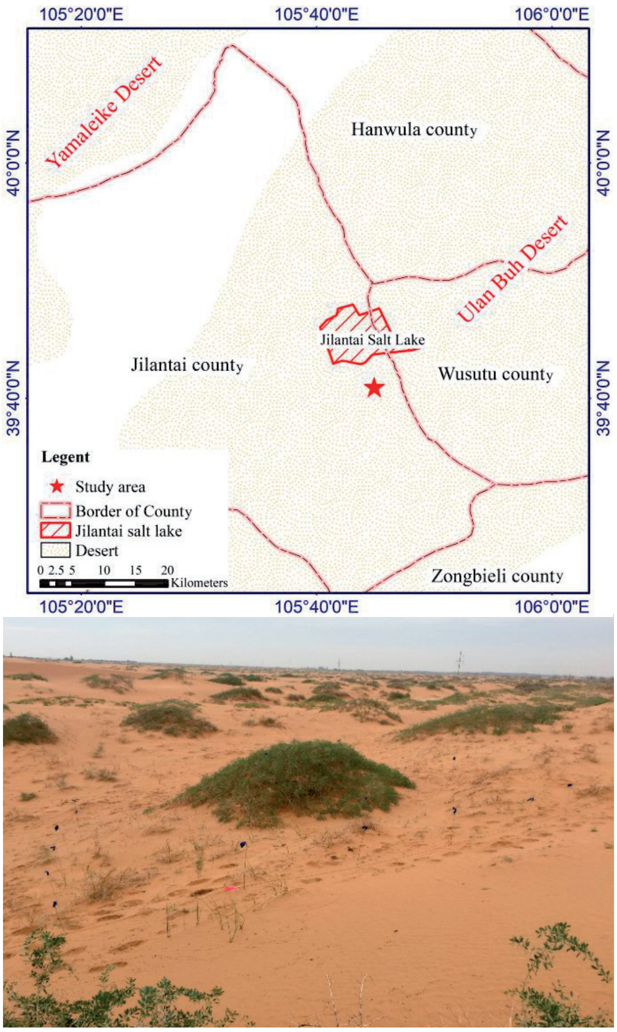

Fig. 1. Location of the study area in Inner Mongolia, northern China.

Table 1. Classification standard of *N. tangutorun* nebkhas successions [10].

Stages of succession	Long axis/m	Short axis/m	Height/m	Plant height/cm	Vegetation coverage/%	Species number	Species	Form	Vegetation status	Crusts condition
RUD	3.95±0.47	3.22±0.37	0.59±0.22	33.33±8.25	34.00±14.32	2	*N. Tangutorum, A. squarrosum*	Irregular shape	the plant grows well without the death rate	no crust on the windward slope and sporadic crust on the leeward slope
DEV	5.03±0.32	4.02±0.55	0.81±0.18	72.00±12.30	42.67±8.11	3	*N. Tangutorum, A. arenaria, A. squarrosum*	Semi-ellipse	The plants grow as multiple plants and grow well without a death rate	The windward slope and leeward slope have a large area of physical crust
STA	5.08±0.89	4.51±0.64	0.92±0.12	61.33±11.45	60.33±10.29	4	*N. Tangutorum, A.arenaria, E.dahuricus, A. squarrosum*	Semi-ellipse	The plant grows well and the death rate was low	The windward slope is dominated by quicksand, while the leeward slope has most crusts
DEG	6.17±1.21	4.48±0.52	1.32±0.33	43.00±5.42	45.67±5.58	3	*N. Tangutorum, A.arenaria, A. squarrosum*	Semi-oval	The plant grows as a single plant, the growth condition was not good, and the death rate accounted for more than half.	The windward slope, leeward slope, and their two sides are mainly quicksand, and the slope surface is uneven.

was measured by the potassium dichromate external heating method, TN was measured by the Kjeldahl method [32].

Statistical Analyses

SOCD was calculated as follows:

$$SOCD_i = C_i \times D_i \times H_i \times (1 - 0.01G_i) \times 10 \quad (1)$$

Where $SOCD_i$ is the SOC density of soil layer i (g/m^2), C_i, D_i, H_i, and G_i represent the SOC content (g/kg), soil bulk density (g/cm^3), thickness (cm), and the content of gravels (%) larger than 2 mm in soil layer i, respectively. The *SND* (g/m^2) was also computed similarly.

For 0-100 cm soil depth, total *SOCD* (T-SOCD) (g/m^2) was calculated for a certain soil depth as follows [33]:

$$T - SOCD_j = \sum_{i=1}^{n} SOCD_i \quad (2)$$

The total *SND* (T-SND) (g/m^2) was also calculated similarly.

To understand the effect of *N. tangutorum* nebkhas succession on soil quality, the concept of *SR* was introduced to overcome the inherent differences in soil types and climates, which is defined as the ratio of nutrient content in the surface layer to that in the deep layer [34]. Soil stratification ratio (*SR*) was proposed by Franzluebbers [35], which was defined that the ratio of the soil surface to that of a lower depth.

$$SR_{i-1} = \frac{SOC_1}{SOC_i} \quad (3)$$

Where SOC_1 (g/kg) is the SOC of 0-5 cm soil layer; SOC_i is SOC of certain soil depth. In this study, six *SR*s (SR_1, SR_2, SR_3, SR_4, SR_5 and SR_6) for SOC at seven different depths were calculated.

The *SR*s of soil TN was also calculated similarly.

Kolmogorov Smirnov test (*K-S* test) was conducted on soil variables by SPSS 22.0. The results showed that soil data of *N. tangutorum* nebkhas in different successional stages were consistent with a normal distribution ($P>0.05$). Significant differences of soil variables among different successional stages were analyzed using an ANOVA analysis. Redundancy Analysis (*RDA*) was conducted using Canoco 5.0 (Biometry, Wageningen, Netherlands). Figures were drawn with Origin 2018. We expressed the data based on mean±standard deviation (*SD*).

Table 2. Two-way ANOVAs of the effects of successional stage, soil depths and their interactions on physicochemical properties.

Factor	*F* (*P*) value	SOC	TN	C/N	SOCD	SND	Soil water content	Bulk density	pH	Clay	Silt	Sand
Successional stage	*F*	10.309	4.007	1.191	2.955	1.37	1.586	6.038	13.368	1.358	0.698	1.063
	P	<0.001	<0.05	0.321	<0.05	0.261	0.203	<0.001	<0.001	0.265	0.557	0.372
Soil depth	*F*	3.956	2.068	0.937	66.092	69.974	8.786	1.593	8.627	20.709	9.078	14.518
	P	<0.001	0.072	0.476	<0.001	<0.001	<0.001	0.166	<0.001	<0.001	<0.001	<0.001
Successional stage*Soil depth	*F*	1.763	2.152	1.267	1.324	0.952	1.948	2.003	4.222	0.883	0.997	1.336
	P	0.055	<0.05	0.245	0.209	0.524	<0.05	<0.05	<0.001	0.600	0.477	0.202

*Indicates significant difference at 0.05 level ; * * indicates significant difference at 0.05 level.

Results

Changes of Soil SOC, TN, and C/N of *N. tangutorun* Nebkhas at Different Successional Stages

Two-way ANOVA analysis revealed that successional stage and soil depth were significantly different in SOC, and successional stage had a significant difference in TN. The interactive effect of successional stage and soil depth was significant effect on TN. However, there was no significant difference in C/N between successional stage and soil depth (Table 2). These findings suggested that successional stage and soil depth induced spatial variability of SOC, the succession of nebkhas induced spatial variability of TN.

Soils of *N. tangutorun* nebkhas had low contents of SOC and TN and firstly increased and then decreased with succession stages. SOC and TN did not show any increasing pattern with depth (Fig. 2a, b). The mean SOC contents were 0.42-0.58 g/kg in 0-100 cm depth across the entire succession stages. At 0-50 cm, SOC firstly increased and then decreased with succession, and increased by 20.97%-96.37% from the RUD to the STA, and reduced by 6.91%-86.03% compared with STA. There was no significant difference in SOC among four succession stages at 5-10 cm and 50-100 cm (Fig. 2a). Overall, the SOC firstly increased and then decreased with soil depth and decreased to the lowest level at 10-20 and 20-30 cm during the RUD and DEG, respectively. SOC showed a gradually decreasing trend with soil depth and decreased to the lowest level at 50-70 and 70-100 cm during the DEV and STA, respectively. The mean TN content ranged from 0.05 to 0.06 g/kg across the entire 0-100 cm soil profiles. There was no significant difference in TN content throughout succession processes (except 20-30 cm and 50-70 cm) (P>0.05). Compared with RUD, TN content

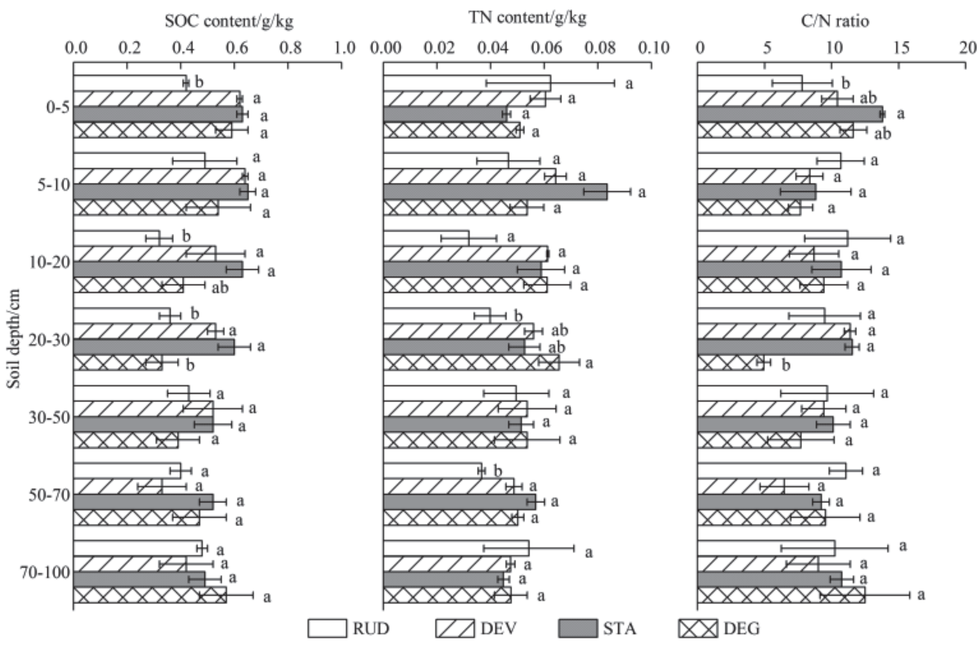

Fig. 2. Changes in SOC, TN and C/N in the soil of *N. tangutorun* nebkhas at 0-100 cm at different successional stages. Values are meas±SD (n = 21). Different lowercase represents a significant difference between different development stages of the same soil layer (P<0.05).

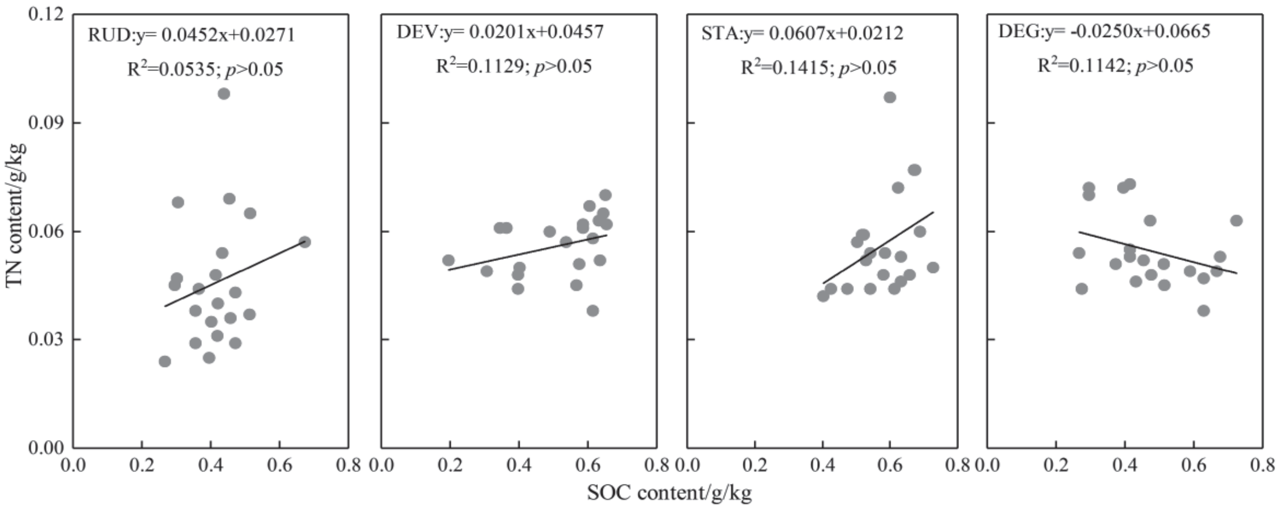

Fig. 3. Correlation between SOC and TN contents of *N. tangutorun* nebkhas at different successional stages.

of DEV, STA and DGE at 20-30 cm increased by 41.01%, 32.29%, 64.74%. At 50-70 cm, the TN content of DEV, STA and DGE increased by 32.93%, 55.25% and 36.85% compared with RUD, respectively ($P<0.05$). The changes in TN showed a wave pattern with soil depth in each succession stage (Fig. 2b). The mean C/N ratio was 9.07-10.63 within 0-100 cm soil layers throughout all succession processes. There was no significant difference (except 0-5 cm and 20-30 cm) in each succession stage ($P>0.05$). Compared with RUD, the C/N ratio of DEV, STA and DGE at 0-5 cm increased by 33.54%, 76.37% and 48.72%, respectively. The C/N ratio of DEV and STA at 20-30 cm increased by 19.90% and 21.60%, respectively ($P<0.05$), and decreased by 47.87% ($P<0.05$). The change in C/N showed a wave pattern with soil depth in each succession stage (Fig. 2c).

The regression analysis was conducted between mean values of SOC and TN content at the depths of 0-100 cm in different succession stages. The results showed that R^2 increased firstly and then decreased with the succession stages. However, there was a positive correlation between SOC content and TN content in RUD, DEV, and STA, and a negative correlation in DEG (Fig. 3). Regression analysis indicated that as the succession of *N. tangutorun* nebkhas, and there was no synchronization between SOC content and TN content.

Vertical Distribution Characteristics of Soil SOCD and TND at Different Successional Stages

Two-way ANOVA revealed that successional stage and soil depth had significant differences in SOCD, and soil depth had a significantly different in SND, and successional stage had no significantly different in SND (Table 2). There were significant differences in SOCD among four succession stages ($P<0.05$), SOCD of each soil depth (except 70-100 cm) increased firstly and then decreased with succession stages. Compared with RUD, SOCD of DEV, STA and DEG at 0-5 cm increased by 42.34%, 42.72% and 38.01%, respectively. SOCD of DEV, STA and DEG at 10-20 cm increased by 58.34%, 86.22% and 23.23% respectively. SOCD of DEV and STA at 20-30 cm increased by 46.36% and 59.76% respectively, and DEG decreased by 12.81% (Table 3). SOCD showed a gradually increasing trend from the surface layer to the deep layers.

SND fluctuated enormously throughout successional process, differing among depths of 5-10, 10-20, 20-30 and 50-70 cm. Compared with RUD, SND of DEV, STA and DEG at 5-10 cm increased by 29.60%, 65.66% and 9.67%, respectively. At 10-20 cm, SND of DEV, STA and DEG increased by 85.15%, 76.56% and 85.88% compared with RUD, respectively($P<0.05$). SND of DEV, STA and DEG at 20-30 cm increased by 38.77%, 25.28% and 58.45% compared with RUD, respectively; At 50-70 cm, SND of DEV, STA and DEG increased by 26.79%, 53.90% and 32.17% compared with RUD ($P<0.05$), respectively. However, compared with RUD, SND of DEV, STA and DEG at 70-100 cm decreased by 11.78%, 13.60% and 9.70%, respectively. SND increased from surface to deep layers among four successional stages (Table 3).

As shown in Table 4, variation in SOCD and SND at different depths among four successional stages showed that SOCD and SND of DEV, STA and DEG were higher than RUD. SOCD at different depths among four successional stages showed that STA>DEV>DEG>RUD. In addition, for 0-20 cm, there was no significant difference in SOCD at other soil depths. Compared with RUD, SOCD of DEV, STA and DEG at 0-20 cm increased by 43.95%, 56.09% and 10.76%, respectively ($P<0.05$) (Table 4). SND of 0-100 cm soil among four succession stages were shown as DEG>STA>DEV>RUD, and there was an obvious difference between 0-20 cm and 0-30 cm. Compared with RUD, SND of DEV, STA and DEG at 0-20 and 0-30 cm increased by 36.88%, 35.20%, 26.87%

Table 3. SOCD and SND of *N. tangutorun* nebkhas at different successional stages.

Soil depth/cm	SOCD/g/m^2				SND/g/m^2			
	RUD	DEV	STA	DEG	RUD	DEV	STA	DEG
0-5	34.96±1.58b	49.76±13.14a	49.89±1.14a	48.25±7.21a	5.16±2.67a	4.83±0.61a	3.62±0.12a	4.14±0.25a
5-10	41.01±12.94a	50.51±8.62a	50.47±3.23a	43.21±13.68a	3.93±1.23b	5.09±0.38ab	6.51±0.92a	4.31±076ab
10-20	53.24±11.44b	84.29±242.74ab	99.14±15.41a	65.61±15.94ab	5.22±1.90b	9.66±0.11a	9.21±1.53ab	9.70±2.07a
20-30	59.19±9.48bc	86.63±7.45ab	94.56±12.47a	51.61±12.47c	6.57±1.35b	9.11±0.70ab	8.23±1.30ab	10.40±1.61a
30-50	136.21±39.11a	166.39±51.69a	163.50±32.95a	124.97±43.63a	15.57±4.79a	17.16±4.13a	16.14±2.00a	16.83±5.07a
50-70	130.64±11.82a	102.45±36.44a	168.01±5.84a	148.17±44.93a	11.88±0.90c	15.06±1.28b	18.28±1.24a	15.70±0.82ab
70-100	222.93±16.65a	197.56±61.26a	235.04±46.69a	271.19±66.78a	25.11±9.87a	22.15±1.07a	21.69±1.68a	22.67±4.47a

Values are means±SD (n = 21). Different lowercase represents a significant difference between different development stages of the same soil layer (P<0.05).

Table 4. SOCD and SND in 0-100 cm of *N. tangutorun* nebkhas at different successional stages.

Soil depth/cm	SOCD (g m^2)				STN (g m^2)			
	RUD	DEV	STA	DEG	RUD	DEV	STA	DEG
0-10	75.97±9.70a	100.28±0.66a	100.37±1.90a	91.45±16.65a	9.09±2.65a	9.92±0.76a	10.13±0.85a	8.45±0.82a
0-20	129.20±7.24b	184.57±19.38ab	199.50±14.45a	157.06±25.07ab	14.31±2.57b	19.58±0.67a	19.34±1.21a	18.15±0.87ab
0-30	324.61±31.00a	437.59±63.09a	457.56±51.45a	333.64±59.02a	20.87±1.96b	28.69±1.22a	27.57±0.83a	28.55±0.21a
0-50	324.61±31.00a	437.59±63.09a	457.56±51.45a	333.64±59.02a	36.44±5.02a	45.85±4.58a	43.71±2.36a	45.38±5.11a
0-70	455.25±22.01a	540.04±62.08a	625.56±47.29a	481.80±93.20a	48.31±4.37a	60.91±5.62a	61.98±1.36a	61.08±5.74a

Values are means±SD (n=21). Different lowercase represents a significant difference between different development stages of the same soil layer (P<0.05).

Table 5. Percent of the SOCD and SND in every depth related to the whole profile.

Soil depth/cm	SOCD (g/m^2)				STN (g/m^2)			
	RUD	DEV	STA	DEG	RUD	DEV	STA	DEG
0-10	11.19±1.30a	13.79±1.76a	11.66±0.18a	12.11±0.31a	12.30±2.62a	11.93±0.14a	12.11±1.02a	10.18±1.37a
0-20	19.04±0.76c	25.05±0.44a	23.17±1.38ab	20.91±1.46bc	19.82±4.39a	23.62±0.80a	23.1±1.19a	21.87±2.35a
0-30	27.78±0.79a	36.95±1.96a	34.14±2.41a	34.12±6.93a	29.08±5.75a	34.60±0.94a	32.94±0.73a	34.33±3.60a
0-50	47.82±4.02ab	59.11±2.26a	53.11±5.28ab	44.42±5.11b	50.13±7.20a	55.08±2.05a	52.23±2.59a	54.15±2.30a
0-70	67.10±2.38a	73.42±5.07a	72.64±4.65a	63.86±5.88a	66.6±8.06a	73.2±2.19a	74.08±1.55a	73.01±2.98a

Values are means±SD (n = 21). Different lowercase represents a significant difference between different development stages of the same soil layer (*P*<0.05).

and 37.47%, 32.08%, 36.81%, respectively (*P*<0.05) (Table 4).

Except for 0-10 cm, the percentage of SOCD and SND firstly increased and then decreased, and showed a wave pattern among different soil depths at each successional stage. At 0-20 cm, the percentage of SOCD in RUD was significantly lower than that of DEV, STA and DEG (*P*<0.05). At 0-50 cm, the percentage of SOCD in DEV was significantly higher than that of DEG (*P*<0.05). This means the successional stage did not affect the SND (Table 5).

The SR of SOC and TN Content at Different Successional Stages

SR of SOC and TN tended to decrease with soil depth at different successional stages. Under the same soil layer, there was no significant difference in *SR* of SOC and TN in each successional stage. *SR* of SOC and TN during RUD, DEV, STA, DEG were 0.16-0.91, 0.27-0.99, 0.22-0.99, 0.18-1.19 and 0.21-1.37, 0.22-0.95, 0.17-0.56, 0.19-0.97 at the depths of 0-5, 5-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm, respectively. These findings showed that lower SOC and TN stability in different soil depths of *N. tangutorun* nebkhas (Fig. 4).

Changes in SOCD and SND in Soil Properties

It was found that there were negative significant correlations among SWC, pH, soil depth and sand content with SOCD, STD, SOC and TN. SOC, TN, SOCD and SND were significantly positively correlated with silt and clay contents. The successional stage was positively correlated with SOC, TN, SOCD and SND (Fig. 5).

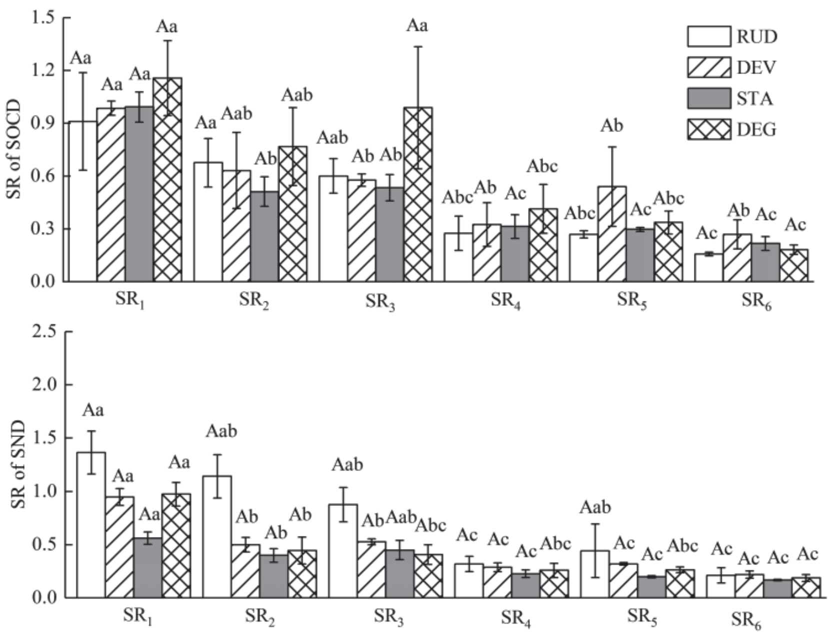

Fig. 4. *SR* of SOC and TN of *N. tangutorum* at different succession stages. Different capital letters represent a significant difference between different development stages of the same soil layer (*P*<0.05); different lowercase represent a significant difference between different soil layers in the same development stage (*P*<0.05).

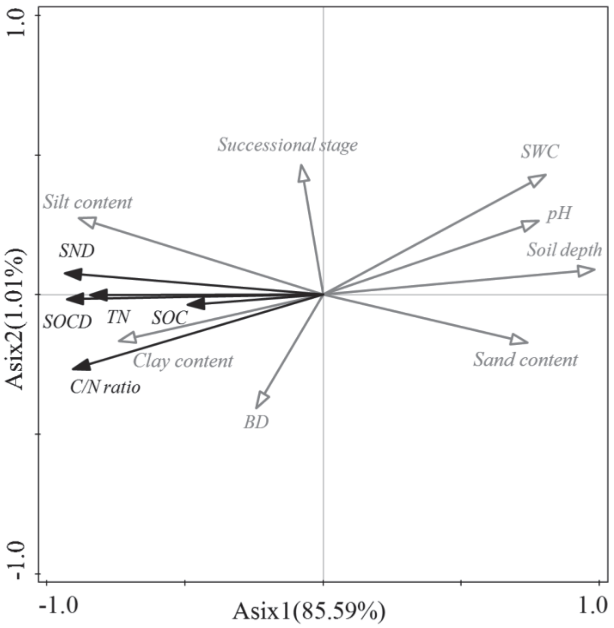

Fig. 5. PCA of SOCD, SND and soil properties at different successional stages. PCA axes 1 and 2 explained 85.59% and 1.01% of the variation, respectively. SOC: soil organic carbon content; TN: total nitrogen content; BD: bulk density; SOCD: soil organic carbon content density; SND: total nitrogen density; SWC: soil water content.

The order of importance of soil physicochemical factors to SOCD and SND was as follows: soil depth>silt content>SWC>successional stage>clay content>sand content>pH>SD. Among these indicators, soil depth, silt content, SWC and successional stage were the main factors affecting SOCD and SND, which account for 73.7%, 14.1%, 10.4% and 1.0% of the interpretation of all soil physicochemical factors. Other soil physicochemical factors had no significant influence (Table 6).

Discussion

Variation Characteristics of Soil SOC, TN Content and C/N during the Succession of *N. tangutorum* Nebkhas

SOC and TN contents are important indexes to evaluate soil nutrients [36]. Our results indicated that mean SOC and TN contents firstly increased in RUD and then decreased in STA. This agrees with Wang et al. [27] regarding soil nutrients increased gradually with the development of nebkhas. The reason for this pattern is mainly related to vegetation coverage (Table 1) and silt and clay contents, especially in the 0-30 cm soil depths [27, 29]. On the one hand, as vegetation coverage of *N. tangutorum* nebkhas continues to increase and its surface accumulates a considerable amount of litters, and are decomposed and stored in the soil [37-38]. When the vegetation coverage of *N. tangutorum* nebkhas increased, and the wind-break and sand-fixation ability increased, which increased the proportion of silt and clay particles in the surface soil [39]. It was conducive to soil nutrient accumulation and improvement of SOC and TN sequestration capacity [40-41]. The SOC of *N. tangutorum* nebkhas in our study had high heterogeneity in the vertical direction. Rather, the change in soil TN was non-heterogeneity. This result is not in accordance with previous findings that succession stages and soil depths were important factors affecting the SOC of *N. tangutorum* nebkhas [27, 42-43]. This consequently indicates that accumulations of soil C and N were not well coupled. It is well known that 95% of soil N is derived from soil organic matter [36], and soil nutrient redistribution is strongly influenced by precipitation, stem flow and infiltration [44]. Clearly, soil SOC and TN found in *N. tangutorum* nebkhas entered the system as a result of these important processes, thus forming fertile islands. Yet, dry climatic conditions with limited rain and strong evaporation result in low soil moisture and input of organic carbon to the soil. Even worse, soil organic matter was difficult

Table 6. Importance sequencing and Duncan test of physicochemical factors.

Soil physicochemical factors	Explains /%	Contribution/ %	*F*	*P*	Importance sequencing
Soil depth	60.6	73.7	390	0.002	1
Silt content	9.3	14.1	10.7	0.006	2
SWC	3.0	10.4	5.3	0.022	3
Successional stage	0.9	1.0	5.3	0.010	4
Clay content	0.2	0.3	1.4	0.202	5
Sand content	<0.1	<0.1	0.4	0.652	6
pH	<0.1	<0.1	0.3	0.736	7
SD	<0.1	<0.1	0.4	0.68	8

SOC: soil organic carbon content; TN: total nitrogen content; BD: bulk density; SOCD: soil organic carbon content density; SND: total nitrogen density; SWC: soil water content.

to maintain at a high level due to the poor structure of aeolian sandy soil [39, 45-46].

Soil C/N is an index to measure the nutrient balance of soil C and N and soil quality evaluation [47-48]. Our study indicated that the C/N ratio is between 9.07 and 10.63, indicating that the decomposition rate of soil organic matter is greater than the accumulation rate [49]. This result was in accordance with Xu et al. [50] who showed that mean C/N ratio is 9.00 in the global desert. One reason for this might be the drought climate and soil environment in the Jilantai Desert, which is the main factors hindering nutrient accumulation of *N. tangutorum* nebkhas, when SOC level was seriously insufficient, the accumulation of SOC and TN was not synchronous, which verified the previous observations [51]. Through regression analysis of SOC and TN, it is found that there is a positive correlation between SOC and TN in RUE, DEV and STA, and a negative correlation in DEG. This indicates that the priming effect of SOC may occur in the DEG. That is, the results showed that SOC tend to decrease following soil N input under certain conditions [52-53].

Variation Characteristics of SOCD and SND during the Succession of *N. tangutorum* Nebkhas

Previous studies showed that the desert ecosystem had a strong carbon sequestration potential and was an important area for CO_2 fixation [42]. It is generally accepted that SOCD and SND are the result of the natural environment and human activities [54]. Our results indicated that SOCD at a depth of 0-100 cm in *N. tangutorum* nebkhas was significantly lower than the mean SOCD of 0-100 cm in Tengger Desert (1.936 g/m^2) [55], indicating that soil nutrient content was low in Jilantai desert. Moreover, SOCD firstly increased then decreased with the succession of *N. tangutorum* nebkhas and was at STA. Compared with that of RUG, which increased by 8.76%, 26.90% and 11.03% in DEV, STA and DGE, respectively (P<0.01). The reason for this phenomenon is mainly related to the difference in aboveground biomass of *N. tangutorum* nebkhas. As vegetative succession progressed, aboveground biomass firstly increased in RUD and then decreased in STA and reached a peak in STA throughout the succession. Simultaneously, aboveground biomass of *N. tangutorum* nebkhas directly influences soil carbon and nitrogen inputs, and is a key factor affecting plant carbon and nitrogen storage. In addition, SND was significantly lower than the Chinese national averages (2.3 kg/m^2) [56], Qinghai Tibet plateau (2.01 kg/m^2) [57] and deserts in northwest China (447.5 g/m^2) [58]. SND increased with the succession of *N. tangutorum* nebkhas, which was 13.13%, 13.97%, and 14.07% in DEV, STA and DGE higher than that of RUG (P>0.01), illustrating that soil nitrogen fixation capacity increased gradually with the growth of *N. tangutorum* [44]. Due to the rapid growth and strong deep roots system of *N. tangutorum* shrubs, more SOC and TN were sequestered in the soil, which resulted in the intensification of SOCD and SND [59]. In this study, the RDA analysis showed that SOCD and SND are closely related to soil depth, silt content, soil moisture and successional stage. The effect of soil depth on SOCD and SND strongly depends on differences in soil water content, root distribution and microbial activity [55]. Soil moisture has key implications for the water uptake of plant root systems, soil animals and microorganisms secrete hydrophobic organic matter. Which in turn, affects redistribution of soil nutrients, and soil water scarcity limits soil carbon and nitrogen accumulation [60]. The silt content affects the stability and decomposition rate of organic matter via nutrient cycling and microbial activity [61]. The successional stage could facilitate the accumulation of SOCD and SND via carbon and nitrogen sequestration capacity of the desert ecosystem. In RUD of nebkhas succession, litters and soil nutrients can not be efficiently accumulated, and soil crusts can not be formed under small canopies of young *N. tangutorum* shrubs (Table 1). As *N. tangutorum* nebkhas develops, soil crust formation is facilitated by increased soil nutrient input. The formation of soil crusts can enhance soil stability and fertility, and reduce soil wind erosion [62-63]. Together with the interactions among soil microbial processes, soil microorganisms, soil water, litter and nutrients, thereby increased the nutrient input to the *N. tangutorum* nebkhas [64].

Variation Characteristics of the SR during the Succession of *N. tangutorum* Nebkhas

The successional stage in this study had no significant effects on *SR* of SOC and TN within the same soil depth, indicating that changes in *SR* triggered by *N. tangutorum* nebkhas succession were not significant to SOC and TN accumulation. In this study, the *SR* of SOC and TN decreased significantly with soil depth, which was not consistent with Fernandez-Romero et al. [33]. Soil carbon and nitrogen sequestration may predominately occur in the topsoil due to the effects of *N. tangutorum* nebkhas succession processes. Factors including litters, root biomass, vegetation coverage, moisture and particle sizes can contribute to surface soil quality across successions [65-66]. In our study, the *SR*s of soil SOC at DEG was greater than RUG for *N. tangutorum* nebkhas at different successional stages, while the reverse was found for soil TN. This may result from the possibility that priming effect of SOC may occur at DEG [52]. This is also evidenced by negative correlation between SOC and TN at DEG. Recent research has suggested that soil quality of farmland could be improved when *SR*>2 [35, 67]. However, in our study, it is not appropriate to use 2 as an indicator to assess the quality of *N. tangutorum* nebkhas. If *SR*s of SOC and TN in RUG were used as a reference, the succession of *N. tangutorum* nebkhas was not significant for SOC and TN pools. It may be the result of the combined effect of nutrient supplementation and nutrient expenditure from below. Together with soil water-thermal conditions in the soil that restricts timely supplementation of nutrients from upper soil to the lower layers. Accordingly, the *SR*s of SOC and TN were not significant at different successional stages.

Despite this, our results highlighted the importance of overall understanding towards soil nutrient cycling, and SOC, TN and their densities of *N. tangutorum* nebkhas with the development of the nebkhas. Carbon and nitrogen sequestration was affected by the succession of *N. tangutorum* nebkhas in the shrub-dominated desert ecosystems. Human intervention of *N. tangutorum* nebkhas in stabilizing stage is needed to prevent soil nutrient loss. If not, arid desert ecosystems can easily become emitters. This information may improve our understanding of the nutrient cycling process of *N. tangutorum* in different successional stages in the oasis-desert ecotone. To provide information for accurate estimation of C change in arid desert areas and global climate change, our study on the mechanism of soil *N. tangutorum* carbon and nitrogen storage change is not in-depth enough. Changes in soil carbon and nitrogen stocks in *N. tangutorum* nebkhas are related to climate change, anthropogenic impacts, geological and hydrogeological conditions, wind strength and sand sources. In the following research, we should focus on the impact of the environment for in-depth discussion and research. Some differences in carbon and nitrogen stocks in the *N. tangutorum* nebkhas in different regions were also caused by these factors. Therefore, future work on the carbon and nitrogen stocks of *N. tangutorum* nebkhas in different regions and their influence mechanisms needs to be strengthened.

Conclusions

Our results suggested that succession stages of *N. tangutorum* nebkhas and soil depth had significant effects on the degree of SOC content and SOCD, and soil depth had a significant difference in TN content and SND in the Jilantai desert area. SOC and TN profiles in the Jilantai desert were characterized by low density at a depth of 0-100 cm, with a low level of 678.18-860.60 g/m^2 and 73.42-83.75 g/m^2, respectively. Soil depth, silt content, SWC and successional stage promote the SOCD and SND. *SR* change resulting from *N. tangutorum* nebkhas succession change had no remarkable effects on SOC and TN accumulation. Based on the results of our study, it is clear that the ongoing success of *N. tangutorum* nebkhas will not significantly change soil carbon and nitrogen sequestration. The results are helpful to the accurate estimation of soil carbon and nitrogen storage in desert ecosystems.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (41967009).

Conflict of Interest

The authors declare no conflict of interest.

References

1. WINOWIECKI L., VAGEN T.G., MASSAWE B., JELINSKI N.A., LYAMCHAI C., SAYULA G., MSOKA E. Landscape-scale variability of soil health indicators: effects of cultivation on soil organic carbon in the Usambara Mountains of Tanzania. Nutrient Cycling in Agroecosystems. **105**, 263, **2016**.
2. ZHENG H.B., LIU, W.R., ZHENG J.Y., LUO Y., LI R.P., WANG H., QI H. Effect of long-term tillage on soil aggregates and aggregate-associated carbon in black soil of Northeast China. PLOS ONE. **13**, 1, **2018**.
3. KIRSCHBAUM M.U.F. Will changes in soil organic carbon act as a positive or negative feedback on global warming? Biogeochemistry. **48**, 21, **2000**.
4. POST W.M., EMANUEL W.R., ZINKE P.J., STANGENBERGER A.G. Soil carbon pools and world life zones. Nature. **298**, 156, **1982**.
5. BATJES N.H. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science. **47**, 151, **1996**.
6. VAUGHAN E., MATOS M., RIOS S., SANTIAGO C., MARIN-SPIOTTA E. Clay and climate are poor predictors of regional-scale soil carbon storage in the US Caribbean. Geoderma. **354**, 1, **2019**.
7. DAI E.F., ZHAI R.X., GE Q.S., WU X.Q. Detecting the storage and change on topsoil organic carbon in grasslands of Inner Mongolia from 1980s to 2010s. J. Geographical Sciences. **24**, 1035, **2014**.
8. LAL R. Soil carbon sequestration to mitigate climate change. Geoderma. **123**, 1, **2004**.
9. SUN X.C., CHEN F.J., YUAN L.X., MI G.H. The physiological mechanism underlying root elongation in response to nitrogen deficiency in crop plants. Planta. **251**, 1, **2020**.
10. TENGBERG A., CHEN D.L. A comparative analysis of nebkhas in central Tunisia and northern Burkina Faso. Geomorphology. **22** (2), 181, 1998.
11. GARDENAS A.I., ÅGREN G.I., BIRD J.A., CLARHOLM M., HALLIN S., INESON P., KATTERER T., KNICKER H., NILSSON S.I., NASHOLM T., OGLE S., PAUSTIAN K., PERSSON T., STENDAHL J. Knowledge gaps in soil carbon and nitrogen interactions-From molecular to global scale. Soil Biology and Biochemistry. **43**, 702, **2010**.
12. ZHANG Z.C., HOU G., LIU M., WEI T.X., SUN J. Degradation induces changes in the soil C:N:P stoichiometry of alpine steppe on the Tibetan Plateau. J. Mountain Science. **16**, 2348, **2019**.
13. MAIA S.M.F., OGLE S.M., CERRI C.C., CERRI C.E.P. Changes in soil organic carbon storage under different agricultural management systems in the Southwest Amazon Region of Brazil. Soil & Tillage Research. **106**, 177, **2010**.

14. LI C.F., ZHANG C., LUO G.P., CHEN X., MAISUPOVA B., MADAMINOV A.A., HAN Q.F., DJENBAEV B.M. Carbon stock and its responses to climate change in Central Asia. Global change biology. **21**, 1951, **2015**.
15. LI Y., WANG Y.G., HOUGHTON R.A., TANG L.S.Hidden carbon sink beneath desert. Geophysical Research Letters. **42**, 5880, **2015**.
16. HU X.Q., LI W.Z., CHEN J., NIE X.D., LIU J.Y., WANG L.X., NING K. Carbon sequestration benefits of the grain for Green Program in the hilly red soil region of southern China. International Soil and Water Conservation Research. **9** (2), 271, **2021**.
17. LANG L.L., WANG X.M., HASI E., HUA T. Nebkha (coppice dune) formation and significance to environmental change reconstructions in arid and semiarid areas. J. Geographical Sciences. **23**, 344, **2013**.
18. ZHAO Y.C., GAO X., LEI J.Q., LI S.Y., CAI D.X., SONG Q. Effects of wind velocity and nebkha geometry on shadow dune formation. J. Geophysical Research-earth Surface. **124**, 2579, **2019**.
19. ZHOU H., ZHAO W.Z., LUO W.C., LIU B. Species diversity and vegetation distribution in nebkhas of *Nitraria tangutorum* in the Desert Steppes of China. Ecological Research. **30**, 735, **2015**.
20. ZHAO Y.C., GAO X., LEI J.Q., LI S.Y Nebkha alignments and their implications for shadow dune elongation under unimodal wind regime. Geomorphology. **365**, 1, **2020**.
21. LI J.C., YAO Q., WANG Y., LIU R.T., ZHANG H. Grain-size characteristics of surface sediments of nebkhas at the southern margin of the Mu Us dune field, China. Catena. **183**, 1, **2019**.
22. CHANG Z.F., ZHANG J.H., SHI X.G.,WANG Q., ZHANG D.K., DUAN X.F Correlation between nebkhas formation ability and silhouette layer parameters of desert plants.IOP Conference Series: Earth and Environmental Science. **191** (1), 1, **2018**.
23. DONG X.W., ZHANG X.K., BAO X. L., WANG J.K. Spatial distribution of soil nutrients after the establishment of sand-fixing shrubs on sand dune. Plant Soil & Environment. **55** (7), 288, **2009**.
24. DONG M., TAKAMURA H., HUDABERDI M. Formation and internal structure of *Tamarix* cones in the Taklimakan Desert. J. Arid Environments, **50**, 81, **2002**.
25. YANG Y.Y., LIU L.Y., SHI P.J., ZHANG G.M., QU Z.Q., TANG Y., WEN H.M., XIONG Y.Y., WANG J.P., SHEN L.L. Morphology, spatial pattern and sediment of *Nitraria tangutorum* nebkhas in barchans interdune areas at the southeast margin of the Badain Jaran Desert, China. Geomorphology. **232**, 182, **2015**.
26. 2LIU X.X., XIE Y.H., ZHOU D.D., LI X.J., DING J., WU X.Q., WANG J., HAI C.X. Soil grain-size characteristics of *Nitraria tangutorum* nebkhas with different degrees of vegetation coverage in a desert-oasis ecotone. Polish Journal of Environmental Studies. **29**, 3703, **2020**.
27. WANG X., MA Q., JIN H., FAN B.L., WANG D.B., LIN H.L. Change in characteristics of soil carbon and nitrogen during the succession of *Nitraria Tangutorum* in an arid desert area. Sustainability. **11**, 2, **2019**.
28. CAO C.Y., ABULAJIANG Y., ZHANG Y., FENG S.W., WANG T.T., REN Q., LI H.L. Assessment of the effects of phytogenic nebkhas on soil nutrient accumulation and soil microbiological property improvement in semi-arid sandy land. Ecological Engineering. **91**, 582, **2016**.
29. ZHANG P.J., YANG J., ZHAO L.Q., BAO S. SONG B.Y. Effect of *Caragana tibetica* nebkhas on sand entrapment and fertile islands in steppe-desert ecotones on the Inner Mongolia Plateau, China. Plant & Soil, **347** (1-2), 79, **2011**.
30. DANG X.H., PAN X, GAO Y, LIU Y., WANG Z.Y., MENG Z.J. Spatial heterogeneity of wind-eroded soil particles around *Nitraria tangutorum* nebkhas in the Ulan Buh Desert. Écoscience. **26**, 347, **2019**.
31. SONG G.H. Study on groundwater dependent ecosystem and ecological mechanisms of vegetation succession in desert lake-basin Region. Chang′an University, **2012** [In Chinese].
32. BAO S.D. Agricultural Chemistry Analysis of Soil. China Agriculture Press, **2000**.
33. FERNANDEZ-ROMERO M.L., LOZANO-GARCIA B., PARRAS-ALCANTARA L.Topography and land use change effects on the soil organic carbon stock of forest soils in Mediterranean natural areas. Agriculture, Ecosystems & Environment. **195**, 1-9, **2014**.
34. WANG Y.F., FU B.J., LV Y.H., SONG C.J., LUAN Y. Local-scale spatial variability of soil organic carbon and its stock in the hilly area of the Loess Plateau, China. Quaternary Research. **73**, 70, **2008**.
35. FRANZLUEBBERS A.J. Soil organic matter stratification ratio as an indicator of soil quality. Soil & Tillage Research. **66**, 95, **2002**.
36. CLEMMENSEN K.E., BAHR A., OVASKAINEN O., DAHLBERG A., EKBLAD A., WALLANDER H., STENLID J., FINLAY R.D., WARDLE D.A., LINDAHL B.D. Roots and associated fungi drive long-term carbon sequestration in boreal forest. Science. **33**, 1615, **2013**.
37. ZUO X.A., ZHAO X.Y., ZHAO H.L., GUO Y.R., ZHANG T.H., CUI J.Y. Spatial pattern and heterogeneity of soil organic carbon and nitrogen in sand dunes related to vegetation change and geomorphic position in Horqin Sandy Land, Northern China. Environmental Monitoring and Assessment. **164**, 29, **2010**.
38. YANG H.T., LI X.R., LIU L.C., GAO Y.H., LI G., JIA R.L. Soil water repellency and influencing factors of *Nitraria tangutorun* nebkhas at different succession stages. J. Arid Land, **6** (3), 300, **2014**.
39. DONG X.W., ZHANG X. K., BAO X.L., WANG J.K. Spatial distribution of soil nutrients after the establishment of sand-fixing shrubs on sand dune. Plant Soil & Environment. **55**, 288, **2009**.
40. ZHOU X.J., AN X.L., DE PHILIPPIS, R., YE C.R., KE T. ZHANG Y.R., CHEN L.Z. The facilitative effects of shrub on induced biological soil crust development and soil properties. Applied Soil Ecology. **137**, 129, **2019**.
41. BIMULLER C., MUELLER C.W., VON LUTZOW M., KREYLING O., KOLBL A., HAUG S., SCHLOTER M., KOGEL-KNABNER I. Decoupled carbon and nitrogen mineralization in soil particle size fractions of a forest topsoil. Soil Biology & Biochemistry. **78**, 263, **2014**.
42. EVANS R.D., KOYAMA A., SONDEREGGER CHARLET T.N., NEWINGHAM B.A., FENSTERMAKER L.F., HARLOW B. JIN V.L., OGLE K., SMITH S.D., NOWAK R.S. Greater ecosystem carbon in the Mojave Desert after ten years exposure to elevated CO_2. Nature Climate Change. **4**, 394, **2014**.
43. JIA X.H., LI X.R., ZHOU Y.Y., LI Y.S. Storages and distributed patterns of soil organic carbon and total nitrogen during the succession of artificial sand-binding vegetation in arid desert ecosystem. Environmental Science. **33**, 938, **2012** [In Chinese].
44. ZHANG P.J., YANG J., ZHAO L.Q., BAO S., SONG B.Y. Effect of *Caragana tibetica* nebkhas on sand entrapment

and fertile islands in steppe-desert ecotones on the Inner Mongolia Plateau, China. Plant and Soil. **347**, 79, **2011**.

45. YEMADJE P.L., CHEVALLIER T., GUIBERT H., BERTRAND I., BERNOUX M. Wetting-drying cycles do not increase organic carbon and nitrogen mineralization in soils with straw amendment. Geoderma. **304**, 68, **2017**.
46. WANG Z.F., ZHENG F. Impact of vegetation succession on leaf-litter-soil C:N:P stoichiometry and their intrinsic relationship in the Ziwuling Area of China's Loess Plateau. J. Forestry Research. **5**, 1, **2020**.
47. LIU Y.Q., MA W.H., KOU D., NIU X.X., WANG T., CHEN 532 Y.L., CHEN D.M., ZHU X.Q., ZHAO M.Y., HAO B.H., ZHANG J.B., YANG Y.H., HU H.F. A comparison of patterns of microbial C:N:P stoichiometry between topsoil and subsoil along an aridity gradient. Biogeosciences. **17**, 2009, **2020**.
48. PUISSANT J., JONES B., GOODALL T., MANG D.N., BLAUD A. GWEON H.S., MALIK A., JONES D.L., CLARK I.M., HIRSCH P.R., GRIFFITHS R. The pH optimum of soil exoenzymes adapt to long term changes in soil pH. Soil Biology & Biochemistry. **138**, 1, **2019**.
49. BENGTSSON G., BENGTSON P., MANSSON K. F. Gross nitrogen mineralization, immobilization, and nitrification rates as a function of soil C/N ratio and microbial activity. Soil Biology & Biochemistry. **35**, 143, **2003**.
50. XU X. F., THORNTON P. E., POST W. M. A global analysis of soil microbial biomass carbon, nitrogen and phosphorus in terrestrial ecosystems. Global Ecology and Biogeography. **22** (6), 737, **2013**.
51. FU X.L., SHAO M.A., WEI X.R., HORTON R. Soil organic carbon and total nitrogen as affected by vegetation types in northern Loess Plateau of China. Geoderma. **155**, 31, **2010**.
52. YEMADJE P.L., CHEVALLIER T., GUIBERT H., BERTRAND I., BERNOUX M. Wetting-drying cycles do not increase organic carbon and nitrogen mineralization in soils with straw amendment. Geoderma. **304**, 68, **2017**.
53. USSIRI D.A.N., LAL R. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. Soil&Tillage Research. **104**, 39, **2009**.
54. LEI D., SWEENEY S., SHANGGUAN Z. Long-term effects of natural enclosure: carbon stocks, sequestration rates and potential for grassland ecosystems in the Loess Plateau. Clean-Soil, Air, Water. **42** (5), 617, **2014**.
55. MORA J L., GUERRA J.A., ARMAS-HERRERA C.M., ARBELO C.D., RODRIGUEZ-RODRIGUEZ A. Storage and depth distribution of organic carbon in volcanic soils as affected by environmental and pedological factors. Catena. **123**,163, **2014**.
56. TIAN H.Q., CHEN G.S., ZHANG C., MELILLO J.M., HALL C.A.S. Pattern and variation of C:N:P ratios in China's soils: a synthesis of observational data, Biogeochemistry. **98**, 139, **2010**.
57. WANG Y.F., FU B.J., LV Y.H., SONG C.J., LUAN Y. Local-scale spatial variability of soil organic carbon and its stock in the hilly area of the Loess Plateau, China. Quaternary Research. **73**, 70, **2008**.
58. TIAN H.Q., WANG S.Q., LIU J.Y., PAN S.F., CHEN H. ZHANG C. SHI X.Z Patterns of soil nitrogen storage in China. Global Biogeochemical Cycles. **20**, 1, **2006**.
59. YANG H.T., LI X.R., WANG Z.R., JIA R.L., LIU L.C., CHEN Y.L., WEI Y.P., GAO Y.H., LI G. Carbon sequestration capacity of shifting sand dune after establishing new vegetation in the Tengger Desert, northern China. Science of The Total Environment. **478**,1, **2014**.
60. YANG H.T., LI X.R., LIU L.C., GAO Y.H., LI G., JIA R.L. Soil water repellency and influencing factors of *Nitraria tangutorun* nebkhas at different succession stages. J. Arid Land. **3**, 300, **2014**.
61. SONG B.L., YAN M.J., HOU H., GUAN J.H., SHI W.Y., LI G.Q., DU S. Distribution of soil carbon and nitrogen in two typical forests in the semiarid region of the Loess Plateau, China. Catena. **143**, 159, **2016**.
62. LIU Y.M., YANG H.Y., LI X.R., XING Z.S. Effects of biological soil crusts on soil enzyme activities in revegetated areas of the Tengger Desert, China. Applied Soil Ecology. **80**, 6, **2014**.
63. BELNAP J., GILLETTE D.A. Vulnerability of desert biological crusts to wind erosion: The influences of crust development, soil texture, and disturbance. J. Arid Environments. **39**, 133, **1998**.
64. AGUIAR M.R., SALA O.E. Patch structure, dynamics and implications for the functioning of arid ecosystems. Trends in Ecology & Evolution. **14**, 273, **1999**.
65. IMADA S., TANIGUCHI T., ACHARYA K., YAMANAKA N. Vertical distribution of fine roots of *Tamarix ramosissima* in an arid region of southern Nevada. J. Arid Environments. **92**, 46, **2013**.
66. HAO F., ZHAO W.W., DARYANTO S., FU B.J., WANG S., WANG Y.P. Vertical distributions of soil organic carbon and its Influencing factors under different land use types in the desert riparian zone of downstream Heihe River Basin, China. J. Geophysical Research: Atmospheres. **123**, 7741, **2018**.
67. WANG Y.F., FU B.J., LU Y.H., SONG C.J., LUAN Y. Local-scale spatial variability of soil organic carbon and its stock in the hilly area of the Loess Plateau, China. Quaternary Research. **73**, 70, **2010**.