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Change in Characteristics of Soil Carbon and Nitrogen during the Succession of *Nitraria Tangutorum* in an Arid Desert Area

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Abstract: The shrub *Nitraria tangutorum* is distributed widely in arid desert areas, and plays a critical role in the desert–oasis ecosystem. This study quantified varying characteristics of carbon (C) and nitrogen (N) in the soil at four stages—the initial stage (IS), stable stage (SS), degradation stage (DS), and severe degradation stage (SDS)—in a steppe ecosystem in the desert of northwestern China. The results indicated that *N. tangutorum* experienced both expansion and deterioration as a decline of 50.7% occurred in the available soil water due to agricultural utilization, and the plant community transformed from being shrub-dominated to annual herb-dominated. At soil layer depths between 0–100 cm in the *N. tangutorum* nebkha dune ecosystem, organic C and total N storage was 1195.84 g/m^2 and 115.01 g/m^2 during the SDS, respectively, with an increase of 11.13% and 12.59% from the IS. In addition, the storage of C and N in the soil increased during the IS as well as the SS, when most of the C and N were accumulated, and the storage decreased during the DS and SDS, as the *N. tangutorum* communities declined. At soil layer depths between 0–100 cm in the desert steppe ecosystem, the highest storage levels of C and N were 8465.97 g/m^2 and 749.29 g/m^2 during the SS, and the lowest were 1076.12 g/m^2 and 102.15 g/m^2 during the IS, respectively. The changes and accumulation of C and N were greater in the deeper (40–100 cm) layer than in the surface layer of soil (0–40 cm). Lastly, changes in soil organic carbon (SOC) as well as in the total nitrogen (TN) were strongly related to the coverage degree, water content in soil, and the ratio of fine soil particles (silt and clay). To sum up, the intensive development of water resources has vastly reduced the ability of *N. tangutorum* vegetation to sequester C and N in the desert of Minqin. Efforts to perform ecological restoration and reverse desertification in the Minqin Desert should focus on preventing the unreasonable exploitation of water resources in order to maintain stable *N. tangutorum* communities.

Keywords: carbon sequestration; nebkhas; soil organic carbon; total nitrogen; vegetation succession; arid desert area; restoration

1. Introduction

Understanding the cycles of carbon (C) and nitrogen (N) in soil in ecosystems is essential for estimating their influence on global climate change [1] and determining the ecological strategy (i.e., conservation) of particular land ecosystems [2]. Deserts and dry shrub lands have great potential to sequester C because of their large extents, and because soil organic carbon (SOC) contents are relatively low as a result of extensive and prolonged land degradation [3,4]. In addition, accurate estimates of C change in arid desert areas can inform climate change mitigation efforts on global scales. Nebkhas are the most common landforms in arid desert areas, and their origination and development are considered the indicators for the change in the local climate and environment [5]. Consequently, research related to nebkhas has increased in recent years.

The presence of nebkhas has been considered a distinctive indicator of land degradation and the intensification of wind erosion [6], of a significant decrease in land production, and also of the degradation of an ecological environment [7]. Thus, most studies focusing on the formation and development of nebkhas are related to vegetation [8,9], climate change [10], anthropogenic influence [6], geological and hydrogeological conditions [11–13], wind strength [14], and sand source [15]. However, nutrient cycling in nebkhas, which determines changes in C and N in arid systems through vegetation–soil feedback [16], has not been sufficiently studied. The literature review shows that the research focusing on the ecological function of nebkhas has been limited [17]. Only a few papers have considered sand fixation and the reduction of wind erosion [18], the protection of biodiversity [11], or the enrichment of soil water and nutrient content in nebkhas [19,20].

Shrub-dominated vegetation is the major vegetation type in arid and semi-arid areas, and plays a crucial role in deserts [5]. Shrubs and nebkha dunes are known to develop interdependently [21]. In areas that are arid and semi-arid, the character of shrubs does determine the size of nebkha dunes [16]. Nevertheless, the succession of vegetation in desert ecosystems is mainly influenced by rainfall, groundwater, and soil nutrients. Variation in groundwater depth will directly impact vegetation in the areas under study. Previous studies have revealed that vegetation dies when the level of groundwater drops to a certain degree [22]. Moreover, the growth of vegetation is also determined by nutrients, especially soil oil matter (SOM) and total nitrogen (TN). In arid and semi-arid regions, "fertile islands" (where organic carbon (OC) and N can be kept) were often formed beneath nebkhas [23]. Therefore, changes in the storage of C and N are responses to variations in the ecosystem. In addition, the SOC and TN content in the nebkhas can be used to reveal the development of regional vegetation [24]. However, little is known about how C and N vary at different successional stages of shrub vegetation.

Xerophyte *N. tangutorum* is a dominant shrub in the deserts in China, and is best known for its great tolerance to salt and drought, as well as its highly opportunistic water-use strategy [12]. It is reported that there are about 152,000 hm^2 of *N. tangutorum* shrub forest in the Minqin Desert, which accounts for 31.6% of the natural shrub forest in that area [25]. The shrub forms the primary ecological barrier for the Minqin Oasis [25]. However, the ecological function depends on the succession of *N. tangutorum* vegetation on the nebkhas [26]. Thus, studying the succession of *N. tangutorum* vegetation is vital for evaluating the damage of this ecosystem and developing a strategy for its restoration [26]. Interest in *N. tangutorum* nebkhas is increasing, and numerous studies have described the characteristics of its vegetation and soil nutrient contents [27,28], the structure and quantitative characteristics of its communities [29], its seed germination effects on water and salinity stresses [30], the changing characteristics of its soil seed banks [25], the impact of clonal reproduction as well as the allocation of biomass of layering modules [31], its diversity in species and the distribution of vegetation [32], the relationships of its vegetation and precipitation to soil respiration [33] and its root distribution and water uptake dynamics [13]. However, knowledge on the characteristics of C and N in soil during the succession of *N. tangutorum* communities is still limited, especially in the arid desert regions of northwest China.

In the current study, a space-for-time method was used, and the hypothesis was that the different stages of succession would impact C and N content and the storage of nutrients differently, and that the relationship between C, N, and succession develops in a linear manner in the steppe ecosystem of the desert. The objectives of the study are as follows: (1) to determine the variations in the content of SOC and TN between 0–100 cm depth in soil during the four successional stages of *N. tangutorum* vegetation in an arid desert area; (2) to examine the total as well as average increases of C and N storage during the four successional stages of *N. tangutorum* nebkhas; and (3) to look into the interrelationship between the storage of C and N and plant diversity in the *N. tangutorum* ecosystem.

2. Materials and Methods

2.1. Study Area

The current study is located in Minqin County (38°05′–39°06′ N, 103°02′–104°02′ E, 180–650 m.a.s.l.) in the northeast of the Hexi Corridor (Gansu province) [17]. The region is a typical oasis, with the Badain Jaran Desert in the northwest and the Tengger Desert in the east. This area has a temperate desert climate with a mean annual precipitation of 113.2 mm and a mean annual potential evaporation of 2604.3 mm. Its mean annual temperature is 7.6 °C. The prevailing winds are northwest and west–northwest throughout the year, with an average annual speed of 2.5 $m \cdot s^{-1}$. The total mean annual typical days with sandstorms, strong winds, rising sand, and airborne dirt is 25.0, 26.3, 37.5, and 29.7, respectively (meteorological data calculated from observations at Minqin Desert Control Experiment Station from 1961–2010). Alternating nebkhas, moving dunes, and lowland areas undulating gently characterize the local landscape. The predominant soil is aeolian sandy soil characterized by nutrient depletion and severe wind erosion. The sandy soil is comprised primarily of coarse sand and silt. The surface water resources of Minqin Country have decreased from 573,100,000 m^3 in the 1950s to around 100,000,000 m^3 at the beginning of this century [34]. The distance from the surface to the groundwater table has shown an increase from 2.2 m in 1961 to 19.2 m in 2006. The annual increase is 0.50–0.71 m [34]. The local sand-stabilizing vegetation is comprised of deciduous trees and shrubs. Deciduous trees are mainly *Populus euphratica* and *Elaeagnus angustifolia*, which die from drought. The sand-stabilizing shrubs, including *Nitraria* spp., *Haloxylon ammodendron*, *Caragana korshinskii*, and *Tamarix* spp., tend to deteriorate due to extensive anthropogenic activities, such as the building of the Hongyashan Reservior in the upstream of Shiyang River and the extensive groundwater exploration for human beings [6,35]. The dominant species on *N. tangutorum* nebkhas at the different successional stages are listed in Table 1 (after Jin et al. 2013) [29]. *N. tangutorum* accounts for about 31.2% of all shrubs in Gansu Liangucheng National Nature Reserve, where the total area of shrubs is 23.41×10^4 hm^2. This area is considered to be one of the major sources of sandstorms in China and has severe sandstorms, rising sand, and airborne dirt [36].

2.2. Experimental Design and Soil Sampling

The present study was carried out in an enclosed area to prevent grazing in Liangucheng National Nature Reserve from May to October 2010. Based on the morphology, vegetation growth status, and soil condition of the nebkhas, four different areas with obvious gradients of vegetative succession were selected as experimental sites. According to the successional stage classification standards, which mainly comprised the extent of shrub vegetation, the morphological characteristics of the nebkhas, and the status of soil crust of *N. tangutorum* nebkhas in this region [25], the selected experimental nebkhas at Hongtujing, Qingtuhu, Sanjiaocheng, and Shajingzi villages were divided into four successional stages: an initial stage (IS), stable stage (SS), degraded stage (DS), and severely degraded stage (SDS). Six 30 m × 30 m plots were chosen in each successional stage at each experimental nebkha, for a total of 24 shrub plots for shrub vegetation surveys. Within each of these plots, five small quadrats (1 m × 1 m) were chosen, one in the center and four at the corners of the plots, demarcating a total of 120 shrub quadrats for herbaceous plant surveys.

At each shrub plot, the long axis, short axis, height, coverage, and crust status of the nebkha was determined, and the biomass, length of branch, height, shrub vegetation composition, and numerical characteristics of the subsequent *N. tangutorum* community was measured as well (Table 1). In each small quadrat for herbaceous plant surveys, the species composition, coverage, density, and frequency of the herbaceous plants were recorded (Table 1).

In each plot of shrub *N. tangutorum*, three sampling ditches were dug for soil samples collected at six depths (0–5 cm, 5–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm), with three replicates. Soil samples were put in sealed plastic bags for transfer to the laboratory. Simultaneously, the bulk density of soil at the six layers in all of the quadrats was measured using a soil corer, a steel cylinder with a volume of 100 cm^3, with three replicates. On an oven-dry mass basis, after drying samples at 105 °C for 24 h, the soil water was determined gravimetrically. Each sample was thoroughly sieved in the laboratory at two mm to get rid of roots and debris. According to McClaran et al. (2008), the changes in the soil characteristics of nebkha are most obvious at five cm [37]. Part of each sieved sample from the topsoil was air-dried. It was stored at room temperature until the investigation of its particle size distribution as well as chemical attributes could be performed.

2.3. Data Collection and Analysis

Jia et al. (2002) estimated the biomass of the *N. tangutorum* shrub in this study area with biomass allometric functions using data obtained in 2002 [35]. We used the same biomass allometric functions to estimate the shrub biomass aboveground, belowground, in clay, and inside the dunes in the present study. The four models are as follows [35]:

$$Y_{aboveground} = -0.278 + 0.32X_1 - 1.094X_2 + 8.951X_3;$$

$$Y_{belowground} = -0.672 + 1.034X_1 - 4.029X_2 + 28.574X_3;$$

$$Y_{internal\ dune} = -0.432 + 0.863X_1 - 4.02X_2 + 28.204X_3;$$

$$Y_{clay} = -0.24 + 0.171X_1 - 0.01X_2 + 0.369X_3.$$

where $Y_{aboveground}$ stands for aboveground biomass, $Y_{belowground}$ stands for belowground biomass, $Y_{internal\ dune}$ stands for the biomass inside the dunes, Y_{clay} stands for the biomass in the clay; and X_1, X_2, and X_3 stand for the length, width, and height of the *N. tangutorum*-dominated nebkhas, respectively.

The distribution of soil particle size was determined by the pipette in a cylinder of sedimentation, with Na-hexametha phosphate as the agent for dispersing [38]. Walkley and Black's $K_2Cr_2O_7$–H_2SO_4 oxidation method was adopted to measure SOC and active organic carbon (AOC) (Nelson and Sommers, 1982) [39]. TN was measured using the Kjeldahl procedure (UDK 140 Automatic Steam Distilling Unit, Automatic Titroline96, Italy) (ISSCAS, 1978). The equation showing the amount of OC and TN in each soil layer is summarized below [40]:

The storage of soil OC or TN = (soil area) × (soil depth) × (soil bulk density) × (average content of OC or TN).

To get the total storages of SOC and TN at 0–100 cm, their storage in each sampling soil layer was summed.

SPSS was used to analyze all the data. One-way ANOVA was adopted for determining the differences among the successional stages. To ensure the assumptions of ANOVA for homogeneity and normality of variance, we applied the log transformation method to transform the data when needed, and followed by multiple comparisons test (Tukey's honestly significant difference test). Significant differences between successional stages were identified by taking $\alpha \leq 0.05$ as significant. The relationship between the corresponding variables was evaluated by using Pearson's correlation coefficients [20]. Figures were drawn with Origin 9.0 (Origin Lab, Northampton, MA, USA).

Table 1. Main characteristics of *N. tangutorum* nebkhas at different successional stages. IS: initial stage, SS: stable stage, DS: degradation stage, SDS: severe degradation stage.

Stages of Succession	Sites and Geographical Coordinates	Species	Population Coverage of *N. tangutorum* (%)	Vegetation Coverage (%)	Aboveground Biomass (kg·m^{-2})	Community Coverage (%)	Long Axis (m)	Short Axis (m)	Height (m)	Species Number	Annual Herb	Crust Status
IS	Hongtujing 39°8′ N, 103°11′ E	*Nitraria tangutorum, Nitraria sphaerocarpa, Peganum harmala, Asparagus gobicu, Allium mongolicum, Stipa capillata, Phragmites australis, C1eistogenes songorica, Eragrostis poaeoides, Oxytropis aciphylla, Astragalus galactites, Olgaea leucophylla, Artemisia ordosica, Echinops gmelini, Convolvulus gortschakovii, Reaumuria songarica, Suaeda glauca, Salsola ruthenica, Corispermum hyssopifolium*	31.83 ± 6.19 ^{b}	57.86 ± 6.53 ^{a}	0.71 ± 0.12 ^{ab}	37.6 ± 14.8 ^{b}	2.27 ± 0.27 ^{c}	2.01 ± 0.33 ^{b}	0.49 ± 0.07 ^{b}	19	5	Sand surface is shifting, small area of physical crust forming
SS	Qingtuhu 39°29′ N, 103°22′ E	*Nitraria tangutorum, Artemisia sphaerocephala, Suaeda glauca, Kalidium foliatum, Salsola ruthenica, Eragrostis poaeoides, Phragmites australis*	57.14 ± 3.45 ^{a}	65.80 ± 5.89 ^{a}	1.83 ± 0.98 ^{a}	64.7 ± 3.7 ^{a}	5.59 ± 0.41 ^{bc}	3.33 ± 0.28 ^{b}	0.85 ± 0.08 ^{ab}	7	3	Sand surface is shifting, small area of physical crust forming
DS	Sanjiaocheng 38°35′ N, 103°12′ E	*Nitraria tangutorum, Nitraria sphaerocarpa, Tribulus terrestris, Reaumuria songarica, Echinops gmelini, Suaeda glauca, Agriophyllum squarrosum, Lyciumru thenicum*	28.77 ± 4.97 ^{c}	32.89 ± 5.68 ^{b}	0.62 ± 0.11 ^{ab}	32.4 ± 3.5 ^{bc}	9.65 ± 1.98 ^{a}	6.18 ± 1.37 ^{a}	0.96 ± 0.12 ^{ab}	8	4	Mainly biological crust with fracture appearance
SDS	Shajingzi 38°21′ N, 102°35′ E	*Nitraria tangutorum, Tribulus terrestris, Bassia dasyphylla, Salsola ruthenica, Agriophyllum squarrosum, Suaeda glauca, Limonium aureum, Pugionium cornutum, Eragrostis pilosa, Eragrostis poaeoides*	18.93 ± 3.53 ^{d}	20.50 ± 3.33 ^{b}	0.20 ± 0.03 ^{b}	23.5 ± 6.5 ^{c}	6.42 ± 0.59 ^{b}	4.50 ± 0.45 ^{ab}	1.25 ± 0.28 ^{a}	10	8	Sand surface is shifting, small area of biological crust left

Values represent means ± SD (n = 3). Values with the same letters within a row do not show significant difference at $P < 0.05$.

3. Results

3.1. Changes in Topsoil Texture During Succession

The succession of *N. tangutorum* vegetation had a significant effect on the distribution of particle size and soil water content in nebkha topsoil (0–5 cm) ($P < 0.05$) (Table 2). As *N. tangutorum* vegetative succession progressed, the clay and silt content increased sharply between the IS and the DS, but surprisingly decreased in the SDS. The clay and silt contents were 4.5 and 3.8 times greater during DS than IS, while they were reduced by 35% and 60% during the SDS stage, respectively (Table 2). In general, the contents of clay and silt increased by 259.5% and 94.5% throughout the entire succession process, respectively (Table 2). Compared with IS, the soil water content increased by 2.7% during SS, and was reduced by 17.3% from SS to DS, and by 41.9% from DS to SDS (Table 2). The differences of sand content, bulk density, and soil water content among different successional stages were not significant. The changes in bulk density were not noticeable.

Table 2. Changes in topsoil texture of *N. tangutorum* nebkhas at the different successional stages.

Items	Stages of Succession			
	IS	SS	DS	SDS
Clay content (%)	0.79 ± 0.10 ^{c}	2.91 ± 0.67 ^{b}	4.37 ± 0.82 ^{a}	2.84 ± 0.13 ^{b}
Silt content (%)	3.67 ± 0.32 ^{c}	8.31 ± 1.82 ^{b}	17.81 ± 4.45 ^{a}	7.14 ± 0.37 ^{b}
Sand content (%)	95.54 ± 0.41 ^{a}	88.78 ± 2.49 ^{a}	77.81 ± 5.22 ^{b}	90.02 ± 0.48 ^{a}
Bulk density (g/cm^3)	1.47 ± 0.06 ^{a}	1.42 ± 0.05 ^{a}	1.35 ± 0.06 ^{a}	1.41 ± 0.07 ^{a}
Soil water content (%)	0.73 ± 0.29 ^{a}	0.70 ± 0.09 ^{a}	0.62 ± 0.09 ^{a}	0.36 ± 0.03 ^{a}

Values represent means ± SD (n = 3). Values with the same letters within a row do not show significant difference at $P < 0.05$.

3.2. Variations in Aboveground and Belowground Biomass during Succession

All the measures of biomass, except for clay biomass, showed similar patterns of fluctuation during *N. tangutorum* succession (Figure 1). Although a sharp decline in biomass was observed during the DS stage, the biomass aboveground and belowground, the biomass inside the dunes, clay biomass, and total biomass increased by 151%, 152%, 146%, 290%, and 127% from the IS to the SDS, respectively (Figure 1). The highest values of the biomass aboveground and belowground, biomass inside the dune, clay biomass, and total biomass were 3.38, 2.86, 2.88, 13.03, and 2.24 times as large as the lowest value during the IS, respectively (Figure 1). The degree of fluctuation was much greater in clay biomass than in the biomass aboveground, belowground, inside the dunes, and the total biomass in both the expanding and receding stages.

3.3. Changes in Soil SOC and TN Content

The OC content at the different layers of soil fluctuated markedly along the gradient of vegetative succession. SOC content at the depths of 0–5 cm, 40–60 cm, 60–80 cm, and 80–100 cm increased sharply from the lowest level in the IS to the peak in the SS, and then decreased gradually during the DS and SDS (Table 3). SOC content in the soil layers from 5–20 cm increased drastically from the IS to SS, and increased continuously to the peak in the DS, and then strikingly decreased to the lowest level in the SDS (Table 3). SOC content in the soil layers from 20–40 cm rapidly reached the peak prior to the SS, and then dropped off steeply to the lowest level during the SDS (Table 3). In general, SOC contents at 0–5 cm, 40–60 cm, 60–80 cm, and 80–100 cm increased by 75%, 6.3%, 39.6%, and 183% throughout succession, respectively. SOC decreased by 27.5% and 10.3% at the 5–20 and 20–40 cm depths, respectively, from the IS to the SDS (Table 3).

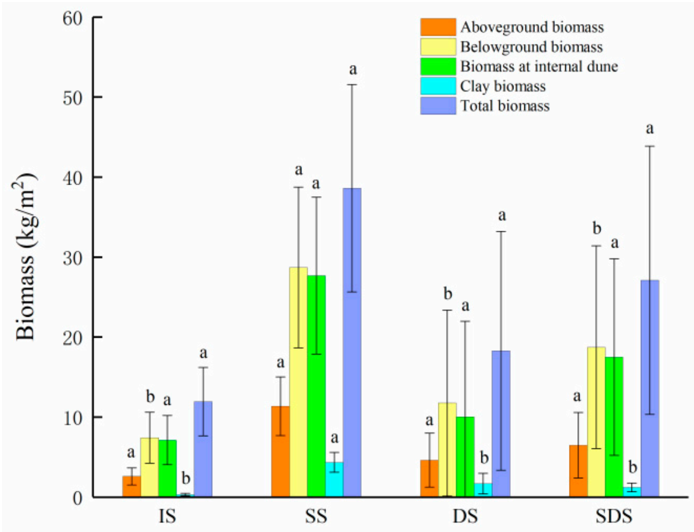

Figure 1. Changes in the biomass aboveground and belowground throughout *N. tangutorum* nebkha succession. IS: initial stage; SS: stable stage; DS: degraded stage; SDS: severely degraded stage. Different lowercase letters indicate a significant variation of biomass difference among different successional stages at the 0.05 level ($P < 0.05$). The SD is indicated with error bars.

Table 3. Changes in SOC and TN content (g/kg) at different soil depths during the different successional stages.

Depth (cm)	Stage of Succession			
	IS	**SS**	**DS**	**SDS**
SOC (g/kg)				
0–5	0.76 ± 0.38 ^{b}	5.00 ± 2.75 ^{a}	3.96 ± 2.18 ^{a}	1.33 ± 0.59 ^{b}
5–20	1.09 ± 0.05 ^{ab}	6.45 ± 4.03 ^{a}	6.57 ± 0.04 ^{a}	0.79 ± 0.10 ^{b}
20–40	0.87 ± 0.04 ^{b}	5.99 ± 3.71 ^{a}	3.81 ± 0.45 ^{a}	0.78 ± 0.00 ^{b}
40–60	0.64 ± 0.21 ^{b}	12.08 ± 4.74 ^{a}	3.92 ± 2.31 ^{ab}	0.68 ± 0.25 ^{b}
60–80	0.53 ± 0.11 ^{b}	6.29 ± 4.04 ^{a}	4.07 ± 0.76 ^{ab}	0.74 ± 0.25 ^{b}
80–100	0.29 ± 0.12 ^{b}	5.98 ± 2.13 ^{a}	3.17 ± 0.11 ^{b}	0.82 ± 0.12 ^{b}
Average	0.70 ± 0.29 ^{b}	5.90 ± 3.68 ^{a}	4.25 ± 1.44 ^{a}	0.86 ± 0.28 ^{b}
TN (g/kg)				
0–5	0.07 ± 0.03 ^{b}	0.28 ± 0.23 ^{a}	0.38 ± 0.24 ^{a}	0.12 ± 0.06 ^{b}
5–20	0.11 ± 0.01 ^{ab}	0.33 ± 0.35 ^{ab}	0.62 ± 0.10 ^{a}	0.07 ± 0.01 ^{b}
20–40	0.08 ± 0.00 ^{b}	0.30 ± 0.32 ^{a}	0.34 ± 0.02 ^{a}	0.08 ± 0.01 ^{b}
40–60	0.07 ± 0.03 ^{b}	0.76 ± 0.27 ^{a}	0.32 ± 0.15 ^{b}	0.07 ± 0.03 ^{b}
60–80	0.04 ± 0.01 ^{b}	0.79 ± 0.25 ^{a}	0.38 ± 0.05 ^{b}	0.07 ± 0.03 ^{b}
80–100	0.03 ± 0.01 ^{b}	0.69 ± 0.22 ^{a}	0.30 ± 0.02 ^{b}	0.07 ± 0.01 ^{b}
Average	0.07 ± 0.03 ^{b}	0.52 ± 0.30 ^{a}	0.39 ± 0.14 ^{a}	0.08 ± 0.03 ^{b}
C/N				
0–5	11.20 ± 0.13 ^{a}	17.97 ± 0.12 ^{a}	10.39 ± 0.09 ^{a}	10.94 ± 0.10 ^{a}
5–20	10.32 ± 0.05 ^{a}	19.48 ± 0.11 ^{a}	10.64 ± 0.44 ^{a}	10.72 ± 0.20 ^{a}
20–40	10.31 ± 0.38 ^{a}	20.10 ± 0.12 ^{a}	11.17 ± 0.22 ^{a}	9.77 ± 0.00 ^{a}
40–60	9.77 ± 0.07 ^{a}	15.86 ± 0.18 ^{a}	12.21 ± 0.15 ^{a}	10.20 ± 0.09 ^{a}
60–80	11.72 ± 0.12 ^{a}	7.93 ± 0.16 ^{a}	10.66 ± 0.17 ^{a}	10.26 ± 0.09 ^{a}
80–100	11.24 ± 0.11 ^{a}	8.73 ± 0.10 ^{a}	10.72 ± 0.06 ^{a}	10.98 ± 0.15 ^{a}
Average	10.79 ± 0.78 ^{a}	10.81 ± 1.07 ^{a}	10.97 ± 0.88 ^{a}	10.49 ± 0.66 ^{a}

Table 3. *Cont.*

Depth (cm)	Stage of Succession			
	IS	SS	DS	SDS
AOC (g/kg)				
0−5	0.53 ± 0.26 [a]	2.19 ± 1.96 [a]	2.69 ± 1.57 [a]	0.87 ± 0.37 [a]
5−20	0.73 ± 0.07 [a]	2.51 ± 2.83 [a]	4.44 ± 0.10 [a]	0.55 ± 0.12 [a]
20−40	0.58 ± 0.08 [a]	2.35 ± 2.58 [a]	2.73 ± 0.44 [a]	0.54 ± 0.10 [a]
40−60	0.43 ± 0.16 [b]	5.90 ± 2.95 [a]	2.82 ± 1.76 [ab]	0.48 ± 0.19 [b]
60−80	0.38 ± 0.05 [b]	6.54 ± 3.20 [a]	2.93 ± 0.41 [ab]	0.44 ± 0.12 [b]
80−100	0.21 ± 0.10 [c]	5.23 ± 1.39 [a]	2.26 ± 0.04 [b]	0.51 ± 0.04 [bc]
Average	0.48 ± 0.19 [b]	4.12 ± 2.56 [a]	2.98 ± 0.98 [a]	0.56 ± 0.18 [b]

SOC: soil organic carbon; TN: total nitrogen; C/N: carbon/nitrogen ratio; AOC: active organic carbon. Values are means ± SD (n = 3). Values with the same letters within a row do not show significant difference at $P < 0.05$.

The TN content fluctuated enormously throughout vegetative succession, differing between depths of 0–5 cm, 5–40 cm, and 40–100 cm. TN content increased sharply at 0–5 cm from its lowest level during the IS to its peak during the DS, and then it decreased gradually during the SDS (Table 3). Before the DS stage, the soil TN content increased obviously at both 5–20 and 20–40 cm, and reached its peak during the DS. Then, TN declined sharply to its lowest level during the SDS. TN content at 40–60 cm, 60–80 cm, and 80–100 cm increased sharply from the lowest levels during the IS to the peak in the SS, and then decreased gradually during the DS and SDS (Table 3). Overall, the TN content increased by 71.4%, 75.0%, and 133.3% at depths of 0–5 cm, 60–80 cm, and 80–100 cm, respectively; meanwhile, it decreased by 36.4% at 5–20 cm, and was maintained at 20–40 cm and 40–60 cm, from the IS to the SDS (Table 3).

The average C/N values increased slightly in both SS and DS, and slightly declined in the SDS, with only a slight drop (−2.8%) throughout succession (Table 3). The changes in C/N differed greatly among the different soil depths in each successional stage. The C/N values at 0–60 cm were much greater than those at 60–100 cm during the SS.

The AOC in soil increased sharply during the SS, but started to decrease precipitously in both the DS and SDS, resulting in only a slight increase (16.7%) throughout all of succession (Table 3). The changes in AOC also differed greatly among different soil depths at each successional stage. The AOC content at 40–100 cm was much higher than at 0–40 cm during the SS. During the DS, the AOC content at 40–100 cm started to drop, while the content at 0–40 cm was still increasing. The differences of soil AOC content at 0–40 cm were not significant among the different successional stages, while those in 60–100 cm layers and their average in 0–100 cm were significant.

Changes in the content of SOC and TN from the IS to SS were greater than those between the DS and SDS, which were in turn greater than changes between the SS and DS. The average content of SOC and TN at 0–100 cm increased by 22.9% and 14.2%, respectively, from the IS to the SDS.

3.4. Changes in the Storage of C and N in the Soil

The storage of SOC and TN at 0–100 cm in depth fluctuated considerably throughout succession, but overall, there was a slight increase. SOC and TN storage increased by 11.13% and 12.59% from IS to SDS ($P < 0.05$) (Table 4). The storages of SOC and TN were the highest during the SS, with values of 8465.97 gm^{-2} and 749.29 gm^{-2}, respectively. The amounts of C and N were the lowest during the SDS, with values of 1076.12 gm^{-2} and 102.15 gm^{-2}, respectively (Table 4). Compared with the degree of change and the rate of SOC and TN storage in the surface soil layer (0–40 cm), those in the middle soil layer (40–100 cm) were much higher. The total values of SOC and TN storage were 6.87 and 6.33 times greater during the SS than the IS.

Table 4. Changes in the storage of SOC and TN in the soil at 0–100 cm during the different successional stages.

Depths	Stages of Succession			
	IS	SS	DS	SDS
SOC storage (g/m^2)				
0−5	60.08 ± 17.31 [b]	224.07 ± 144.01 [a]	255.28 ± 91.63 [a]	102.00 ± 31.84 [b]
5−20	254.99 ± 14.31 [b]	793.20 ± 629.22 [a]	1280.67 ± 8.84 [a]	182.24 ± 9.56 [b]
20−40	294.89 ± 18.41 [b]	967.84 ± 750.25 [a]	1142.70 ± 47.97 [a]	242.37 ± 19.39 [b]
40−60	195.66 ± 48.81 [b]	2309.50 ± 948.00 [a]	1207.55 ± 523.14 [a]	196.81 ± 1.32 [b]
60−80	173.69 ± 37.82 [b]	2237.37 ± 859.42 [a]	1235.00 ± 78.95 [ab]	226.97 ± 19.54 [b]
80−100	96.81 ± 31.80 [c]	1933.99 ± 392.43 [a]	972.60 ± 80.89 [b]	245.44 ± 23.73 [bc]
Total	1076.12 ± 168.46 [b]	8465.97 ± 3723.34 [a]	6093.81 ± 831.42 [a]	1195.84 ± 105.38 [b]
TN storage (g/m^2)				
0−5	5.38 ± 1.31 [b]	20.41 ± 11.95 [a]	24.52 ± 10.28 [a]	9.32 ± 3.19 [b]
5−20	24.72 ± 2.26 [b]	72.86 ± 55.33 [a]	120.36 ± 13.56 [a]	17.03 ± 0.19 [b]
20−40	28.57 ± 0.52 [b]	85.73 ± 64.80 [a]	102.51 ± 0.14 [a]	24.82 ± 1.03 [b]
40−60	20.06 ± 6.74 [b]	200.67 ± 55.83 [a]	98.78 ± 35.01 [a]	19.30 ± 1.02 [b]
60−80	14.81 ± 3.20 [b]	192.60 ± 56.83 [a]	116.27 ± 1.75 [ab]	22.19 ± 0.24 [b]
80−100	8.61 ± 2.87 [b]	177.01 ± 40.30 [a]	90.82 ± 9.04 [b]	22.36 ± 1.60 [b]
Total	102.15 ± 16.91 [b]	749.29 ± 285.03 [a]	553.25 ± 69.78 [a]	115.01 ± 7.28 [b]

Values are means ± SD (n = 3). Values with the same letters within a row do not differ significantly at $P < 0.05$.

3.5. Changes in the Storage of Soil C and N in Relation to Vegetative Succession

To confirm how vegetative succession affects the storage of soil C and N, the distribution of soil particle size, soil texture, and all of the biomass were correlated with the storage of C and N of *N. tangutorum* nebkhas. Through the correlation analysis, it was found that the storage of soil SOC and TN correlated positively significantly ($P < 0.01$), for which the correlation coefficient was 0.997 (Table 5). The results showed that bulk density and SOC and TN storage correlated negatively and significantly ($P < 0.01$), for which correlation coefficients were −0.695 and −0.688, respectively (Table 5). The correlation analysis also showed there were no significant correlations among the storage of soil SOC and TN with vegetation coverage, aboveground biomass, belowground biomass, clay biomass, total biomass, soil water content, clay content, and silt content ($P > 0.05$) (Table 5). There were significant negative correlations among soil water content, sand content, and slit content ($P < 0.05$), with correlation coefficients of −0.879 and −0.718, respectively, while no correlations were found with other soil properties and vegetative characteristics (Table 5). Moreover, a correlation analysis showed that there was a significant negative correlation between sand content and TN storage, with a correlation coefficient of −0.997 ($P < 0.01$) (Table 5); while the correlation between the sand content and SOC was not significant ($P > 0.05$), with a correlation coefficient of −0.444 (Table 5).

Table 5. Relationship between the SOC and TN storage, soil properties, and vegetative characteristics during the different successional stages.

Correlation	SSOC	STN	BD	VC	AB	BB	CB	TB	SWC	CC	SC
STN	0.997 **										
BD	−0.695 **	−0.688 **									
VC	0.753	0.744	−0.635								
AB	0.708	0.701	−0.860	0.719							
BB	0.628	0.621	−0.816	0.654	0.994 **						
CB	0.891	0.890	−0.938	0.836	0.946	0.904					
TB	0.623	0.620	−0.822	0.622	0.990 **	0.999 **	0.896				
SWC	0.501	0.496	0.300	0.756	0.098	0.003	0.346	−0.038			
CC	0.594	0.604	−0.697	−0.067	0.325	0.299	0.407	0.333	−0.276		
SC	0.543	0.555	0.692 *	0.668 *	0.626	0.647 *	0.442	0.687 *	−0.718 *	0.959 **	
SAC	−0.444	−0.997 **	0.979 **	0.890 **	0.774 **	0.828 **	0.395	0.865 **	−0.879 **	0.659 *	0.710 *

* $P < 0.05$, ** $P < 0.01$. SSOC: storage of soil organic carbon; STN: storage of total nitrogen; BD: bulk density; VC: vegetation coverage; AB: aboveground biomass; BB: belowground biomass; CB: clay biomass; TB: total biomass; SWC: soil water content; CC: clay content; SC: silt content; SAC: sand content.

4. Discussion

In arid desert ecosystems, vegetation restoration results in C and N sequestration [19], while vegetation decline or desertification results in C emissions [41]. The two opposing processes each appeared throughout the successional gradient of vegetation in the present study, and greatly impacted the SOC and TN content and storage in desert regions. Although the C and N pools are comprised of both plants and soil, the soil C pool is considered the main pool, occupying more than 90% of the C in arid and cold ecosystems [28]. Hence, only C and N in soil were investigated in this study.

4.1. Effects of N. Tangutorum Succession on Soil C and N Content

Variation in vegetation affects the C and N sequestration capacity of the soil where it lives [42], and these influences differ among soil depths [43]. In this study, the ratio (population coverage of *N. tangutorum*/vegetation coverage) increased from 55% (IS) to 92% (SDS) (Table 1), indicating that *N. tangutorum* tended to be more dominant in vegetation community along the successional stages. Hence, more C and TN were sequestered in the soil during SS stages, due to the fast-growing characteristic and strong deep roots system of *N. tangutorum* [13]. In addition, vegetative succession affects changes in the storage of soil C and N via soil properties and soil biological potential, and biomass related to shrub nebkhas. The variation trends in the average content and storage of the SOC and TN at depths from 0–100 cm were the same as the dynamic changes of the vegetation at each successional stage. This strongly supports related studies where SOC changed with the variety of sand-binding vegetation in desert ecosystems [33,44,45]. However, different soil depths affect the C and N sequestration at significantly different degrees with the expansion of vegetation. During the IS, the shallow layer had much higher contents of SOC and TN than the deeper layer. In fact, the nutrient contents of the deeper layer (40–100 cm) were quite low, and decreased with the layer gradient, which agrees with other studies [44]. This can be explained by the higher inputs of organic materials in the shallow soil. Throughout succession, the greatest number of species appeared in this stage. Most of the species were herbaceous (Table 1), with roots distributed at depths between 0–40 cm, which were mostly in the soil layer between 5–20 cm. In addition, the shrub communities were primarily composed of seedlings, with the roots distributed between 0–40 cm [46].

Compared with the changes in the SOC, TN content, and AOC content, as well as the storage of SOC and TN in the shallow layer (0–40 cm), those in the middle layer (40–100 cm) were much greater, with the C and N contents sharply increasing in the SS. This mechanism may occur in response to three factors. First, the *N. tangutorum* became the dominant species when most of the annual herbs species vanished due to interspecific competition [47], with the more efficient water use by the shrub with its dimorphic rooting habit [13]. As the shrubs grew, their roots extended to the middle layer (40–100 cm), absorbed more water, and input more C and N into the soil [13]. Second, the majority of the roots of the *N. tangutorum* community were found at 40–100 cm after the shrubs matured [12]. Third, the decomposition of herbaceous plant litter occurred more rapidly at the surface than the shrub decomposition of shrub withered root detritus in the middle soil [48]. Therefore, more C and N were emitted through soil respiration in the surface layer.

The steep drop in the soil C and N contents were mainly attributed to the same rapid decline in the biomass and coverage of the nebkhas vegetation. The recession of *N. tangutorum* nebkhas has greater influence in the middle soil layer than at the surface. This can be explained by the decay of *N. tangutorum* nebkhas, which results in a decreased nutrient input in the soil at the surface and middle layers. Furthermore, the appearance of shallow-rooted annual forbs and grasses compensate for some of the nutrient loss at the surface. The loss of SOC and TN storage began in the DS, mainly because the storage of the total C and N dropped sharply in the middle soil layer (40–100 cm), although that in the surface soil layer (0–40 cm simultaneously) increased significantly. This further demonstrates that soil degradation started earlier in the middle layer than in the surface layer. This can be mainly attributed to the input of C and N from vegetation stopping due to the death of *N. tangutorum* vegetation, which itself was a consequence of the shortage of soil water. That may partially be explained by the smaller

C/N value in the middle layer (40–100 cm) (Table 3), which can accelerate microbiological degradation and the mineralization of N.

Due to the excessive irrational allocation of surface water and agricultural development, the groundwater level has fallen sharply in this study area [31]. In the initial stages of successional *N. tangutorum* communities, the vegetation developed, and hence the soil water was augmented slightly. However, the vegetation deteriorated during the DS, and continued into the SDS due to the significant decrease in available soil water: an overall decline of 50.7% from IS to SDS (Table 2). Water deficits can cause feeder roots to deteriorate at shallow depths [49]. In this study, the average SOC and TN content began to drop during the DS, and the degree of decline increased further during the SDS, which is concordant with the change in the content of soil water. This affirmed the results of previous studies that attributed the degradation of *N. tangutorum* nebkhas to the soil moisture being lower than the wilting point of plants (0.73% in Minqin-moving dunes) [50]. Soil moisture is considered to be the most significant abiotic factor affecting the growth and composition of plant communities in arid ecosystems [51]. This disagrees with Yang and Gao (2000), who reported that the drop in the underground water table does not restrict the growth of *N. tangutorum* in the short term [52].

Desert soil in an arid environment typically has a low content of silt and clay [53], both of which are rich in OC and N [54]. The re-vegetation of local shrubs can build a natural system for sand-binding stabilizing mobile dunes, reducing wind erosion and catching fine particles from the atmosphere, which subsequently increases the proportion of fine silt and clay in nebkha topsoils [55]. In the current study, the contents of SOC and TN sharply increased in the SS with the augments in all the biomass of the *N. tangutorum* shrub nebkhas, while the clay and silt content increased significantly togehter with greater the clay and silt biomass. This also confirmed previous studies where the expansion of vegetation improved C and N sequestration capacity and the physical and microbiological attributes of soil [55]. Moreover, the establishment of vegetation paves the way for the development of soil crusts in desert ecosystems [56], including physical crusts, algal crusts, and moss crusts, which are rich in nutrients [57]. It has been proved that developing biological soil crusts is effective at enhancing aggregate stability [57], enriching the content of organic matter [56], improving the physical as well as chemical properties of soil [56,57], and also improving soil fertility [20]. Thus, vegetation and soil crusts play a vital role in restoring desertified land [58]. In the present study, biological soil crust was found to develop with vegetative community expansion during the IS and SS, with a synchronous increase observed in the soil C and N content. On the contrary, vegetative deterioration accompanied the decrease of soil water content and exacerbated desertification, which accelerated the loss of soil crusts [59]. With the vegetative recession, the clay and silt contents decreased by 35% and 60% in the SDS, while the sand content increased significantly, and the bulk density increased by 4.4%. Together, these indicated an obvious trend in desertification. The average SOC and TN contents decreased by 85.4% and 84.6% from the SS to the SDS. The destruction of biotic crust can explain the sharp loss of SOC and TN content during the SDS after vegetative degradation. Additionally, vegetation succession impacted the clay biomass more greatly than the biomass inside dunes, the aboveground biomass, and the belowground biomass, which may be another cause. Here, wind erosion aggravated the desertification process [59]. This is a further verification that the development of biological soil crusts, the succession of vegetation, and the SOC and TN contents are closely related to each other.

4.2. Effects of Annual Herbs on the Content of Soil C and N

It has been reported that China is the major contributor of CO_2 to the global temperate and frigid zones; thus, China has great potential to sequester C by reversing desertification processes [40]. Recent studies have shown that a trend of sandy desertification persists in the desert area near our research sites due to local climate fluctuation and human activities [15], posing a great threat to the Minqin Oasis [26].

In arid desert steppe ecosystems, the development of shrub nebkhas can enhance the microclimate to support annual herbs [60] through positive mutual feedback loops between vegetation and soil, which makes the vegetations for sand-binding more stable and diverse over time [50,60]. Thus, annual plants functioned importantly in enriching the nutrient in soil in arid ecosystems [61]. However, opposite patterns were observed in the species and annual herbs of this vegetative community (Table 1). The *N. tangutorum* nebkhas changed from shrub-dominated to majority annual herbs, and tended to unstability in the long run. This agrees with the former study by Chen et al. in the desert–oasis ecosystem near this study area [61]. However, the C and N storage showed a significant decrease with the encroachment of annual herbs during shrub deterioration (Table 1) after the DS. These results show that the *N. tangutorum* shrub can sequester more C and N than annual herbs, so the community transformation from shrubs to annual herbs leads to major losses of C and N.

4.3. Changes in the Storage of Soil C and N and Implications for Restoration

The C storage at 0–100 cm depth in this study area is 84.66 ± 3.72 Mg/hm^2 in the SS when the population coverage of *N. tangutorum* reached its top at 57.14 ± 3.45% (Table 3). This value is much higher than the C storage of the 55-year-old restored system of xeric shrubs plantation (10.2+ Mg/hm^2), which is considered a cost-effective method for sequestering CO_2 around the Tengger Desert [42]. This strongly supported the great C sequestration ability of shrub *N. tangutorum*. Moreover, the C storage value in the SS is also significantly higher than the average C storage of major shrublands in China (10.88 ± 0.77 Mg/hm^2) [62], as well as the C storage of *Hedysarum scoparium* nebkhas in the middle reaches of the Shiyang River (18.78 Mg/hm^2) [63]. In addition, C storage in the topsoil and sub-topsoil (5.75 g/kg during the SS) was also markedly higher than in the *Haloxylon ammodendron* plantation (1.5 g/kg) and mobile sand dunes (<0.1 g/kg) in the same study area [19]. This is mainly attributed to the differing carbon sequestration capacities among the different species in the desert ecosystem [64]. The well-developed deep roots of *N. tangutorum* and that most of the C in the desert ecosystem is sequestrated in soil can explain the greater C storage in the present study [42,46].

The results show that the succession of *N. tangutorum* nekbhas in the shrub-dominated desert ecosystems was effective at C and N sequestering in this study. However, the C and N sequestration effect is limited, because there was a huge C and N loss at the end of succession due to desertification. The C and N offset during the succession of *N. tangutorum* nekbhas indicates that the arid desert ecosystem can easily become an emitter if no action is taken to restrain the deterioration of nekbha vegetation.

5. Conclusions

N. tangutorum is the most common desert vegetation in the arid parts of China. Thus, it is an important player in the storage of C and N and the stability of the desert ecosystem. In the Minqin Desert in northwest China, *N. tangutorum* vegetation has experienced both expansion and deterioration, transforming the nekbha vegetation from stable and shrub-dominated to severely degraded and annual herb-dominated, with a slight enrichment of SOC and TN. Therefore, in order to continue to sequester C and N in arid deserts, ecological restoration efforts to reverse desertification should be given priority, including reducing human activities that unreasonably exploit and excessively utilize water resources. Restoration should focus on maintaining the stable stage of vegetative succession, as defined here.

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