Response of Soil Carbon and Nitrogen Fractions to Macropores after the Introduction of *Caragana korshinskii* into Desert Grassland

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Abstract

This study used non-planted plots in the desert steppe area of Yanchi County, Ningxia, as the control (CK) and Caragana korshinskii plots with different planting ages as the study objects to comparatively analyze the effects of Caragana korshinskii introduction on soil carbon and nitrogen fractions and macropores. The results showed that in the 0~10 cm soil layer, compared with CK, soil particulate organic carbon (POC) decreased in the 11 a plot, while the contents of soil organic carbon (SOC), mineral-associated organic carbon (MAOC), easily oxidizable organic carbon (EOC), and dissolved organic carbon (DOC) all increased with planting age, with their peak values occurring in the 26 a, 16 a, 26 a, and 37 a plots, respectively. The contents of total nitrogen (TN) and nitrate nitrogen (NO-3 - N) increased by 74.5% and 868.07% in the 26 a and 37 a plots, respectively. In the 10~20 cm soil layer, TN in the 26 a plot increased by 196.4%, and ammonium nitrogen (NH+4 - N) in the 37 a plot increased by as much as 22.8%. CT scanning showed that the soil macropore network evolved with planting age, with pore number density increasing by 131% in the 37 a plot and connectivity being optimal (177.95) in the 16 a plot. Soil macropore development had significant stage-specific correlations with carbon and nitrogen fraction contents, and pore formation could promote the accumulation of active organic carbon; the high pore connectivity in the 16 a and 26 a plots promoted soil nitrogen transformation; whereas the pore structure in the 37 a plot tended to become more complex, leading to differentiation in soil carbon and nitrogen storage efficiency.

Full Text

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Response of Soil Carbon and Nitrogen Fractions to Macropores after the Introduction of *Caragana korshinskii* into Desert Grassland

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Abstract: In this study, plots without *Caragana korshinskii* in the desert grassland area of Yanchi County, Ningxia, were used as the control (CK), and plots with different planting ages of *C. korshinskii* were selected as the research objects to comparatively analyze the effects of *C. korshinskii* introduction on soil carbon and nitrogen fractions and macropores. The results showed that, in the 0–10 cm soil layer, compared with CK, soil particulate organic carbon (POC) decreased in the 11-year-old plot, whereas the contents of soil organic carbon (SOC), mineral-associated organic carbon (MAOC), easily oxidizable organic carbon (EOC), and dissolved organic carbon (DOC) all showed an increasing trend with planting age; their peak values occurred successively in the 26-year-old, 16-year-old, 26-year-old, and 37-year-old plots. The contents of total nitrogen (TN) and nitrate nitrogen (NO_3^-–N) increased by 74.5% and 868.07% in the 26-year-old and 37-year-old plots, respectively. In the 10–20 cm soil layer, TN in the 26-year-old plot increased by 196.4%, and ammonium nitrogen (NH_4^+-N) in the 37-year-old plot increased by as much as 22.8%. CT scanning showed that the soil macropore network evolved with age: pore number density increased by 131% in the 37-year-old plot, and connectivity was optimal in the 16-year-old plot (177.95). Soil macropore development and the contents of carbon and nitrogen fractions exhibited significant stage-dependent correlations. Pore formation promoted the accumulation of labile organic carbon; the high pore connectivity in the 16-year-old and 26-year-old plots promoted soil nitrogen transformation; whereas the pore structure in the 37-year-old plot tended to become complex, causing differentiation in soil carbon and nitrogen storage efficiency.

Keywords: artificial *Caragana korshinskii* planting; evolution of carbon and nitrogen fractions; grey relational degree; macropores

Soil organic carbon can enhance soil water-retention capacity, improve soil structure, and promote nutrient cycling. As a limiting nutrient for most plants, soil nitrogen affects plant development by regulating plant morphology and root growth[1]. Carbon and nitrogen are closely linked, and both play significant roles in regulating the structure and function of terrestrial ecosystems[2–3]. Their contents not only markedly affect plant growth but are also key factors in maintaining and improving soil fertility[4]. The dynamic balance of soil carbon and nitrogen pools directly affects the sustainability of ecosystem-service functions and serves as a major carrier for many ecological processes, including ecosystem nutrient cycling, soil water balance, and litter decomposition[5]. In recent years, increasing attention has been paid to the regulatory role of soil structure in carbon and nitrogen cycling. By regulating water transport, gas exchange, and microbial habitats, macropores drive the physical protection and biochemical transformation of organic matter, thereby affecting the occurrence forms and stability of carbon and nitrogen fractions[6]. However, previous studies have paid little attention to the influence of soil macropores on carbon and nitrogen fractions, which has constrained quantitative analysis of the relationship between carbon and nitrogen sequestration mechanisms and pore-space heterogeneity, and has further hindered the formulation of strategies for the coordinated optimization of soil structure and function in ecological restoration[7].

Desert grassland is a transition zone in which typical grassland transforms into desert[8]. It is a frontline area of China' s ecological barrier and has extremely important value in the national ecological-security pattern[9]. Aridity and water shortage, wind erosion, and desertification in desert grasslands lead to low soil carbon and nitrogen reserves and poor component stability, while irrational human activities further intensify nutrient loss and ecological degradation[10–12]. Vegetation restoration, as a core measure for improving soil quality in desert grasslands, influences the vertical distribution and long-term accumulation of carbon and nitrogen through litter input, root expansion, and rhizosphere processes[13]. As a typical sand-fixing shrub in desert grassland, *C. korshinskii* combines drought tolerance, nitrogen fixation, and soil-structure improvement functions[14]. Studies have found that during the long-term process of artificially planting *C. korshinskii* in desert grassland, soil structure undergoes re-degradation as planting age increases, affecting soil carbon and nitrogen sequestration[15]. During long-term vegetation restoration with *C. korshinskii*, will soil carbon and nitrogen fractions and macropore structure also show similar evolutionary patterns? Therefore, this study took *C. korshinskii* plantations of different planting ages in the desert grassland area of Yanchi County, Ningxia, as the objects, and used carbon and nitrogen fraction determination, grey relational analysis, and CT scanning technology to comparatively analyze soil carbon and nitrogen fractions and macropore structural characteristics, with the aim

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In revealing the coupling patterns between the carbon–nitrogen cycle and soil structure during the restoration of desert-steppe vegetation, this study provides guidance for optimizing the planting age of *Caragana korshinskii* plantations on the basis of "structure–function" synergy.

1 Materials and Methods

1.1 Overview of the Study Area

The study area is located in Yanchi County, Wuzhong City, eastern Ningxia (37°57′23″–37°83′47″N, 106°77′99″–107°50′70″E). It lies at the junction of Shaanxi, Gansu, Ningxia, and Inner Mongolia, bordering the Mu Us Sandy

Land to the north and belonging to the Ordos Plateau; to the south it adjoins the Loess Plateau. It is a typical transition zone from grassland to desert, with terrain higher in the south and lower in the north. The study area has a typical continental monsoon climate, with an annual mean temperature of 7.8 °C, annual precipitation of 313.2 mm, and an annual mean number of sand-driving wind events of 19. The main soil types are sierozem and aeolian sandy soil. The vegetation is diverse, and artificially planted *Caragana korshinskii* is an important ecological constructive species in the study area, providing strong support for ecosystem stability and biodiversity conservation[16].

1.2 Sample-Plot Selection and Sampling Methods

1.2.1 Sample-Plot Selection The experiment began in May 2021. The study area is located in degraded desert steppe. To investigate the distribution patterns of artificially planted *Caragana korshinskii* stands of different planting years, four *C. korshinskii* plantations with aeolian sandy soil and similar terrain, elevation, and other environmental factors were selected: 11 a old (planted in 2011), 16 a old (planted in 2006), 26 a old (planted in 1996), and 37 a old (planted in 1985). On gentle terrain, a 200 m × 200 m plot was established (Fig. 1) and divided into 20 m × 20 m grids. Within the plot, *C. korshinskii* stands were distributed at 20–40 clumps per 100 m^2, with a spacing of 6–8 m between planting strips. The *C. korshinskii* shrub patches in each grid were investigated and delineated; in addition, herbaceous plots without planted *C. korshinskii* (dominated mainly by *Artemisia scoparia* and foxtail grass) were selected as the control (CK).

1.2.2 Soil Sample Collection and Determination For the collection of soil carbon and nitrogen fraction samples, 8 sampling points were selected within each *C. korshinskii* plot of a given planting age, and 4 points were selected in CK. Soil samples from 0–10 cm and 10–20 cm were collected in equal amounts using a soil auger. After thorough mixing, 1 kg of soil was retained by the quartering method, placed in a self-sealing bag, labeled, and taken back to the laboratory. Small stones, plant roots, animal remains, and other materials were removed from the soil samples. After natural air-drying and sieving, soil organic carbon (SOC) content was determined using a total organic carbon analyzer (Shimadzu TOC-LCPH)[17]. The sodium hexametaphosphate dispersion method was used to determine the contents of soil particulate organic carbon (POC) and mineral-associated organic carbon (MAOC)[18]. Specifically, 6.0 g of air-dried soil was weighed into a 50 mL plastic bottle, and 30 mL of 5.0 $g \cdot L^{-1}$ sodium hexametaphosphate solution was added. The mixture was shaken at 90 $r \cdot min^{-1}$ for 18 h. After shaking, it was passed through a 53 μm sieve and rinsed with water. The residue on the sieve was POC, and the fraction passing through the sieve was MAOC. The samples were dried at 60 °C, weighed, ground finely, and an appropriate amount was taken to determine organic carbon content; the results were then separately multiplied by the proportion of each fraction in the total soil sample.

Fig. 1 Map showing the distribution of sample plots

mass percentages, thereby obtaining the POC and MAOC contents. The $KMnO_4$ oxidation method was used to determine the content of easily oxidizable organic carbon (EOC); the water-extraction–potassium dichromate oxidation method was used to determine dissolved organic carbon (DOC); a fully automatic Kjeldahl nitrogen analyzer was used to determine total nitrogen (TN)[19]; the alkaline hydrolysis diffusion method was used to determine available nitrogen (AN)[20]; indophenol blue spectrophotometry was used to determine ammonium nitrogen $(NH_4^+ - N)$; ultraviolet spectrophotometry was used to determine nitrate nitrogen $(NO_3^- - N)$; and the subtraction method was used to calculate soluble organic nitrogen (SON)[21]. Soluble organic nitrogen content = soluble total nitrogen content − ammonium nitrogen content − nitrate nitrogen content.

Soil pore samples were collected within the selected plots by choosing relatively flat and open areas and removing surface weeds and litter. The soil profile was then excavated. Using cutting rings 65 mm in height, 50 mm in inner diameter, and less than 0.5 mm thick, undisturbed soil from the 0–10 cm and 10–20 cm layers was collected; four ring samples were collected from each layer for the determination of soil macropores.

1.3 Data analysis

1.3.1 Analysis of soil carbon and nitrogen components

The data were first mean-normalized using the following formulas:

$$X_0 = x_0(k)/av(x_0) \tag{1}$$

$$X_i = x_i(k)/av(x_i) \tag{2}$$

where $av(x_0)$ is the mean value of the reference sequence X_0, and $av(x_i)$ is the mean value of the comparison sequence X_i.

CK was taken as the reference sequence X_0, and the four stand-age sequences were taken as comparison sequences X_i. Grey relational analysis was used to analyze and rank the relational grades of carbon and nitrogen component contents among different stand ages[22]. A larger relational-grade value indicates a higher and closer similarity in the development trends between the two[23]. The relational coefficient was calculated as follows:

$$\xi_i(k) = \frac{\min_i \min_k \Delta_i(k) + \rho \max_i \max_k \Delta_i(k)}{\Delta_i(k) + \rho \max_i \max_k \Delta_i(k)} \tag{3}$$

where ρ is the distinguishing coefficient, generally taking values in the interval $[0, 1]$; here $\rho = 0.5$. $\Delta_i(k)$ is the absolute difference between X_0 and X_i. The relational grade r_i was calculated as follows:

$$r_i = \frac{1}{n}\sum_{k}^{m}\xi_i(k) \tag{4}$$

Finally, in this study, the relational grades were classified according to their values (Table 1).

Table 1 Correspondence between relational level and relational grade

Tab. 1 Correspondence between correlation grade and correlation degree

Relational level	Very weak	Low	Moderate	High
Relational grade	0.3~0.45	0.45~0.6	0.6~0.8	0.8~1

1.3.2 CT scanning and image processing

The nanoVoxel-5000 series dual-source X-ray CT system (manufactured by Sanying Precision Instruments Co. Ltd.; pixel-detail resolution 200 nm, spatial resolution 200 nm, measurable sample size: diameter × height < 600 mm × 1000 mm) was used to scan the undisturbed ring-knife soil samples. After CT scanning, each undisturbed soil column yielded 2,094 transverse slice images. ImageJ software was first used to preprocess all transverse slices, and then Avizo 2019.1 image-processing software was used to perform three-dimensional reconstruction of all transverse images for each soil column, obtaining geometric distribution images of each undisturbed soil sample. In the three-dimensional reconstruction method, binary images were first imported, then integration processing and threshold segmentation were performed in sequence, and the cropping function was used to modify the unit so that the reconstructed model approached the real specimen. The Volume-edit module was used to intercept the cylinder and generate a mask, ultimately obtaining a three-dimensional stereoscopic image with voxels of 0.137 mm/pixel in the X direction × 0.137 mm/pixel in the Y direction × 0.2 mm/pixel in the Z direction.

1.3.3 Statistical analysis

Microsoft Excel 2016 was used to organize the experimental data. One-way ANOVA in IBM Statistics SPSS 20 was used to analyze the significance of differences in soil carbon and nitrogen component contents among different stand ages and soil depths ($P \leq 0.05$). Origin 2022 was used to plot the relationships between soil macropores and carbon and nitrogen components under Caragana korshinskii strips.

2 Results and Analysis

2.1 Evolutionary characteristics of soil carbon components after the introduction of Caragana korshinskii strips in desert grassland

As shown in Fig. 2, the SOC components in the 0–10 cm and 10–20 cm soil layers differed considerably among Caragana korshinskii strips of different ages. Compared with CK, in the 0–10 cm soil layer, except for the 37 a plots, the contents of the soil organic carbon components overall increased with increasing planting age of the strips. The overall pattern of component contents among stand ages was: 26 a > 16 a > 11 a > 37 a. The increases in POC, SOC, and EOC were greatest in the 26 a plots (by 8.76%, 24.1%, and 100.6%, respectively); the increase in MAOC was greatest in the 16 a plots (14.11%); and the increase in DOC was greatest in the 37 a plots (36.8%). In the 10–20 cm soil layer, SOC, MAOC, and DOC all showed significant increasing trends. Compared with CK, POC changed more markedly, with the greatest increase occurring in the 16 a plots (6.2%); soil SOC increased in all cases, among which the SOC of the 26 a plots increased the most with stand age (37.0%); MAOC also showed a significant increasing trend, with the increase in the 37 a plots being the most pronounced (48.3%); however, EOC generally showed a decreasing trend, with only the 11 a plots showing a slight increase (5.75%); DOC showed an overall increasing trend, and the most obvious increase occurred in the 11 a plots (15.5%).

Ranking the relational grades among different stand ages for the same carbon component (Table 2), the relational coefficients between the carbon component contents of the four stand ages and CK in the 0–10 cm and 10–20 cm soil layers ranged from 0.337 to 1.000 and from 0.338 to 1.000, respectively,

Note: POC denotes particulate organic carbon; SOC denotes organic carbon; MAOC denotes mineral-associated organic carbon; EOC denotes easily oxidizable organic carbon; DOC denotes soluble organic carbon. Different lowercase letters indicate significant differences among treatments ($P < 0.05$). The same applies below.

Fig. 2. Carbon component contents in different soil depths of *Caragana korshinskii* forests with different forest ages

Figure 2. Carbon component content in different soil depths of *Caragana korshinskii* forest with different forest ages

Table 2. Correlation degree and ranking of soil carbon components in *Caragana korshinskii* forests of different ages

Tab. 2. Correlation degree and ordination of carbon components of *Caragana korshinskii* in different forest ages

Soil depth/cm	Carbon component	11 a: Correlation degree	11 a: Rank	16 a: Correlation degree	16 a: Rank	26 a: Correlation degree	26 a: Rank	37 a: Correlation degree	37 a: Rank
0–10	POC/(g·kg^{-1})	0.565	5	0.867	1	0.910	2	0.741	2
0–10	SOC/(g·kg^{-1})	0.780	2	0.744	3	0.657	3	0.548	4
0–10	MAOC/(g·kg^{-1})	0.901	1	0.767	2	0.921	1	0.567	3
0–10	EOC/(g·kg^{-1})	0.600	4	0.685	5	0.536	4	1.000	1
0–10	DOC/(mg·kg^{-1})	0.769	3	0.741	4	0.384	5	0.337	5
10–20	POC/(g·kg^{-1})	0.523	5	1.000	1	0.991	1	0.648	2
10–20	SOC/(g·kg^{-1})	0.839	2	0.510	5	0.451	5	0.438	3
10–20	MAOC/(g·kg^{-1})	0.702	3	0.584	3	0.570	2	0.389	4
10–20	EOC/(g·kg^{-1})	0.847	1	0.589	2	0.551	3	0.745	1
10–20	DOC/(mg·kg^{-1})	0.686	4	0.511	4	0.468	4	0.338	5

The average values were 0.701 and 0.619, indicating a relatively close association between forest age and carbon component contents. Analysis showed that the correlation degree between each soil carbon component in *Caragana korshinskii* forests of different ages and the control (CK) differed. In the 0-10 cm soil layer, MAOC and POC had the highest correlation degrees in the 26 a plots (0.921 and 0.910), while EOC had the highest correlation degree in the 37 a plots (1.000). The correlation degree of DOC was relatively low (0.337-0.769), indicating that it was comparatively less affected by forest age. In the 10-20 cm soil layer, POC had the highest correlation degree in the 16 a plots (1.000), SOC and EOC had the highest correlation degrees in the 11 a plots (0.839 and 0.847), the correlation degree of MAOC showed a decreasing trend with increasing forest age, EOC was also relatively high in the 37 a plots (0.745), and DOC had the lowest correlation degree (0.338-0.686).

2.2 Evolutionary characteristics of soil nitrogen components after the introduction of *Caragana korshinskii* into the desert steppe

As shown in Figure 3, under *Caragana korshinskii* stands of different ages, the accumulation of available nitrogen in the 0–10 cm and 10–20 cm soil layers gradually increased, with relatively large differences. In the 0–10 cm soil layer, compared with CK, TN content increased with stand age, with the greatest increase occurring in the 16 a plot (74.5%); AN content increased significantly in the 11 a and 26 a plots, reaching the highest value in the 26 a plot (35.0%, P<0.05); the increases in NH_4^+-N and NO_3^--N were most pronounced in the 37 a plot, reaching 131.8% and 868.1%, respectively; SON content showed an overall increasing trend, with the greatest increase in the 37 a plot (127.7%). In the 10–20 cm soil layer, compared with CK, the contents of TN, AN, NH_4^+-N, NO_3^--N, and SON all changed; TN, AN, and NO_3^--N gradually accumulated with increasing stand age, and the accumulation was greatest in the 26 a plot, at 196.4%, 78.8% (P<0.05), and 948.6% (P<0.05), respectively; NH_4^+-N accumulated most in the 37 a plot, at 22.8%; and SON accumulated most in the 26 a plot, at 246.8%.

Based on the results of grey relational analysis (Table 3), the degrees of association between the contents of each nitrogen component in *Caragana korshinskii* forest soil and CK differed among soil depths. The correlation coefficients of nitrogen components in the 0–10 cm and 10–20 cm soil layers ranged from 0.334 to 1.000 and from 0.335 to 1.00, respectively, indicating overall that stand age was closely associated with soil nitrogen component contents. Specifically, TN in both the 0–10 cm and 10–20 cm soil layers was highly associated with stand age, with correlation coefficients reaching 0.982–1.000 and 0.990–1.000, respectively, and mean values of 0.802 and 0.666. AN showed relatively low association in both soil layers: 0.334–0.814 in the 0–10 cm layer and 0.335–0.817 in the 10–20 cm layer; among them, the 37 a plot had the lowest association, at 0.334 and 0.335, respectively. The association of NH_4^+-N in the 0–10 cm soil layer was 0.913–0.970, with the lowest value in the 37 a plot; in the 10–20 cm soil layer, it decreased to 0.579–0.758, with the highest value in the 11 a plot. The association of NO_3^--N in the 0–10 cm soil layer was 0.380–0.726, with the lowest value in the 37 a plot; in the 10–20 cm soil layer, it further decreased to 0.366–0.649. The association of SON in the 0–10 cm soil layer was 0.684–0.971; in the 10–20 cm soil layer, its correlation coefficients ranged from 0.564 to 0.754 and showed a decreasing trend with increasing stand age.

2.3 Soil macropores after the introduction of *Caragana korshinskii* into the desert steppe

CT scanning and image-processing techniques were used to analyze the three-dimensional structural characteristics of soil macropores in *Caragana korshinskii* stands of different ages. As shown in Figure 4, in the CK plot, soil macropores were relatively dispersed, with smaller pore diameters and lower connectivity. In contrast, in the 37 a plot, the number of macropores increased significantly and connectivity was enhanced, forming a denser network structure.

Note: TN denotes total nitrogen; AN denotes available nitrogen; NH_4^+-N denotes ammonium nitrogen; NO_3^--N denotes nitrate nitrogen; SON denotes soluble organic nitrogen. The same below.

Figure 3. Content of nitrogen components in different soil layers of *Caragana korshinskii* forest at different ages

Fig. 3 Content of nitrogen components in different soil layers of *Caragana korshinskii* forest at different ages

Table 3. Correlation degree and ranking of nitrogen components in soils of *Caragana korshinskii* stands of different ages

Soil layer depth/cm	Nitrogen component	11 a: correlation degree	11 a: rank	16 a: correlation degree	16 a: rank	26 a: correlation degree	26 a: rank	37 a: correlation degree	37 a: rank
0–10	$TN/(g \cdot kg^{-1})$	1.000	1	0.982	1	0.992	1	0.989	1
0–10	$AN/(mg \cdot kg^{-1})$	0.684	5	0.809	4	0.814	3	0.334	5
0–10	$NH_4^+-N/(mg \cdot kg^{-1})$	0.970	3	0.964	2	0.942	2	0.913	2
0–10	$NO_3^--N/(mg \cdot kg^{-1})$	0.718	4	0.726	3	0.572	5	0.380	4
0–10	$SON/(mg \cdot kg^{-1})$	0.971	2	0.834	5	0.684	4	0.786	3
10–20	$TN/(g \cdot kg^{-1})$	0.990	1	0.997	1	1.000	1	0.997	1
10–20	$AN/(mg \cdot kg^{-1})$	0.817	2	0.604	5	0.362	4	0.335	5
10–20	$NH_4^+-N/(mg \cdot kg^{-1})$	0.758	3	0.712	2	0.579	2	0.698	2
10–20	$NO_3^--N/(mg \cdot kg^{-1})$	0.536	5	0.649	4	0.366	4	0.378	4
10–20	$SON/(mg \cdot kg^{-1})$	0.754	4	0.660	3	0.571	3	0.564	3

Fig. 4. Geometric distribution characteristics of soil macropores in 0-20 cm *Caragana korshinskii* forests of different ages

2.4 Interaction between soil carbon-nitrogen components and soil macropores

The structural parameters of soil macropores in *Caragana korshinskii* stands of different ages differed significantly (Table 4). Macropore number density showed a unimodal change with increasing stand age, reaching its peak in the 37 a stand, an increase of 131% compared with CK. This indicates that, with increasing stand age, expansion of *Caragana korshinskii* root systems and soil biological activity significantly increased pore numbers. Macropore length density and volume density exhibited similar trends; in the 37 a stand they were 0.33 $mm \cdot mm^{-3}$ and 0.03 $mm^3 \cdot mm^{-3}$, respectively, significantly higher than those in the other ages. Macropore connectivity reached its maximum in the 16 a stand (177.95), 12% higher than CK, indicating that the connectivity of the pore network was optimal at this stage. The equivalent radius did not differ significantly among forest ages, but that of the 37 a stand was slightly lower than that of the 16 a stand. Macropore surface-area density reached 0.40 $mm^2 \cdot mm^{-3}$ in the 37 a stand, an increase of 100% compared with CK, indicating that the specific surface area of macropores increased significantly with stand age.

Pearson correlation analysis was used to reveal the interaction between soil carbon-nitrogen components and macropore parameters, including number density N_d, length density L_d, volume density ρ_v, surface-area density S_d, equivalent radius r_{eq}, and connectivity C. The results showed (Fig. 5) that the correlations between carbon-nitrogen components and macropore structural parameters differed by developmental stage with stand age. In the 11 a stand, the carbon component POC was significantly positively correlated with volume density ($r = 0.83$, $P < 0.01$) and surface-area density ($r = 0.93$, $P < 0.01$), indicating that new root systems and litter inputs promoted pore development and the accumulation of active carbon. The associations among carbon-nitrogen components were enhanced in the 11 a and 26 a stands. In the 16 a stand, SOC and MAOC showed a strong positive correlation ($r = 0.74$, $P <$

Table 4. Topological structure characteristics of 0-20 cm soil macropores in *Caragana korshinskii* forests of different ages

Sample plot	Number density/(pores $\cdot$ mm^{-3})	Length density/($mm \cdot mm^{-3}$)	Volume density/($mm^3 \cdot mm^{-3}$)	Surface-area density/($mm^2 \cdot mm^{-3}$)	Equivalent radius/mm	Connectivity				
CK	1.03$±0.26$e	0.16±0.05d	0.01±0.05a	0.20±0.51b	0.13±0.01b	158.68±41.75c		11a	1.50±0.48c	0.28±0.0

Note: Different lowercase letters indicate significant differences among forest ages ($P < 0.05$).

(a) All stand ages (b) CK
(c) 11 a (d) 16 a
(e) 26 a (f) 37 a

Color scale: correlation coefficient.

Variables shown: POC, SOC, MAOC, EOC, DOC, TN, AN, NH_4^+-N, NO_3^--N, SON, N_d, L_d, ρ_v, S_d, r_{eq}, and C.

Note: N_d is pore number density; L_d is length density; ρ_v is volume density; S_d is surface area density; r_{eq} is equivalent radius; and C is connectivity.

Figure 5. Correlations between soil carbon and nitrogen components and soil macropore parameters in *Caragana korshinskii* plantations of different ages

Fig. 5 Correlation between carbon and nitrogen components of *Caragana korshinskii* and soil macropore parameters

0.01), the correlation between TN and SON reached 0.67 (P<0.05); in the 26 a stand, the correlation coefficient between DOC and SOC was 0.81 (P<0.01); in the 37 a stand, some carbon and nitrogen components were negatively correlated with macropore parameters: EOC was correlated with surface area density at $r = -0.31$ (P<0.05), and DOC with volume density ⋯

with $r = -0.095$. There were differences in the responses of nitrogen-form transformations to the macropore structure. In the 11 a sample plot, NH_4^+-N was significantly positively correlated with equivalent radius ($r = -0.86, P < 0.01$), and the correlation between NO_3^--N and surface-area density reached 0.67 ($P < 0.01$). In the 16 a sample plot, the correlation coefficients of NO_3^--N with length density and volume density were 0.81 ($P < 0.01$) and 0.71 ($P < 0.01$), respectively, indicating that pore connectivity promoted nitrogen transformation. In the 37 a sample plot, the correlation between NO_3^--N and surface-area density weakened to 0, whereas NH_4^+-N was negatively correlated with equivalent radius ($r = -0.79, P < 0.05$).

The overall data show that the strong positive correlations between SOC and MAOC ($r = 0.67, P < 0.01$), and between TN and SON ($r = 0.66, P < 0.01$), highlight the role of organic carbon in maintaining the macropore structure. Volume density was extremely significantly positively correlated with surface-area density ($r = 0.89, P < 0.01$), while its correlations with POC and DOC were 0.079 and −0.23, respectively, indicating that pore development has differentiated effects on the storage of different forms of organic carbon. Equivalent radius was significantly positively correlated with connectivity ($r = 0.7, P < 0.01$); the influence coefficients of the two on nitrogen-mineralization indices ranged from −0.069 to −0.340, suggesting that the geometric characteristics of macropores exert both positive and negative effects on carbon–nitrogen transformation efficiency by regulating material-transport pathways.

3 Discussion

3.1 Effects of Introducing *Caragana korshinskii* into Desert Grassland on Soil Carbon and Nitrogen Fractions

This study found that the surface soil of *Caragana korshinskii* stands is rich in carbon, and that its carbon and nitrogen contents are the result of biological factors such as plant litter deposition, root exudates, and belowground biomass. In this study, the introduction of *C. korshinskii* significantly changed the contents and distribution patterns of soil carbon and nitrogen fractions in desert grassland. In the 0–10 cm soil layer, SOC, MAOC, EOC, and DOC all accumulated with increasing stand age. Among them, the increase in SOC reached its peak in the 26 a sample plot, MAOC accumulated most significantly in the 16 a sample plot, EOC showed a sharp increase in the 26 a sample plot, and DOC increased most in the 37 a sample plot. This is consistent with the study by Zhang Jin' ai et al.[24] on the Loess Plateau, indicating that the accumulation of active carbon in the surface soil of *C. korshinskii* occurs mainly through litter input. Soil nitrogen content in *C. korshinskii* stands of different ages did not change significantly in the 0–10 cm layer. TN accumulated continuously with stand age; among mineral nitrogen fractions, NH_4^+-N and NO_3^--N increased significantly in the 11 a sample plot, indicating that the soil nitrogen transformation process was significantly enhanced in older stands[25]. In the 10–20 cm soil layer, POC showed the greatest increase in the 16 a sample plot, and both SOC and MAOC accumulated significantly, reflecting that long-term vegetation restoration promoted the binding of organic carbon with mineral particles and enhanced carbon-pool stability[26]. Correlation analysis showed that POC had the highest association with the stand age of the 16 a sample plot, SOC was most closely related to the 11 a sample plot, and DOC accumulated significantly in both soil layers, because the accumulation of plant residues and litter increased continuously with stand age[27]. EOC and POC contents both decreased significantly with increasing soil depth, mainly because surface litter and root inputs were large and microbial activity was relatively high, whereas carbon input decreased in the lower soil layers and decomposition was slower[28]. TN maintained a very high degree of association in all soil layers, indicating the stable contribution of nitrogen fixation by *C. korshinskii* to total nitrogen accumulation[29]. The overall association of AN was relatively low and reached its minimum at the 37 a stand age, implying that the transformation of available nitrogen was strongly regulated by environmental factors. The association of NH_4^+-N decreased significantly with increasing soil depth, indicating that NH_4^+-N dynamics depend on surface biogeochemical processes. The synchronous decrease in the association of NO_3^--N and SON in deeper soil reflects the risk of nitrate-nitrogen leaching and the depth limitation of organic-matter migration[30–31].

3.2 Interactions Between Soil Carbon-Nitrogen Fractions and Macropore Structure After the Introduction of *Caragana korshinskii* into Desert Grassland

CT scanning results showed that the introduction of *C. korshinskii* significantly changed the number, connectivity, and spatial distribution of soil macropores. In the 11 a sample plot, POC and DOC, as well as volume density and surface-area density, were significantly positively correlated; macropore number density increased by 45% compared with the control, forming a dense network-like structure, indicating that the penetration of new roots and the binding effect of exudates promoted pore development[32–33]. Soil-pore connectivity was highest in the 16 a sample plot, indicating that, at this stage, roots and soil biological activity jointly optimized pore connectivity, consistent with the study by Yang Zhiqiang et al.[34] in desert grassland. In the 37 a sample plot, macropore volume density and surface-area density reached peak values, but equivalent radius decreased, possibly related to pore-wall collapse or fine-root infilling caused by root senescence in older stands[35]. The phased evolution of macropore structure was closely related to the developmental cycle of *C. korshinskii* roots. In the 11 a sample plot, rapid fine-root growth formed many new pores. In the 16 a and 26 a sample plots, the interaction between root exudates and soil macropores enhanced pore stability, reflecting that soil aggregates and macropores jointly maintained the storage of stable organic matter[36]. In the 37 a sample plot, coarse-root expansion, reduced fine-root turnover, and accompanying changes in soil structure caused pore morphology to become more complex. This evolutionary pattern provided differentiated microenvironments for soil-water infiltration, aeration, and carbon–nitrogen transport, and is key to understanding changes in ecosystem function in desert grassland.

4 Conclusions

The introduction of *Caragana korshinskii* into degraded desert grassland had profound effects on soil carbon and nitrogen contents and soil structure, and its effects differed significantly among stand ages. These research findings are of great significance for guiding ecological restoration in desertification regions. In practical vegetation-restoration projects, precisely selecting *C. korshinskii* plantings of appropriate ages can effectively optimize

effects on improving soil quality. For areas where it is urgently necessary to improve the content of soil labile carbon and enhance soil aeration, priority may be given to planting young stands of *Caragana korshinskii*, making full use of the capacity of their newly formed root systems to penetrate the soil and create macropores, thereby promoting the accumulation of labile carbon. Under the long-term ecological restoration goal of pursuing stable carbon and nitrogen storage, mature *Caragana korshinskii* stands show clear advantages in stabilizing soil aggregates and enhancing carbon and nitrogen retention. It should be noted that subsequent research should also consider climate-change factors, simulate scenarios of precipitation change and temperature fluctuation, and thereby further reveal the dynamic responses of soil characteristics in *Caragana korshinskii* woodland, enhance the adaptability and disturbance resistance of ecological restoration measures, and ensure the long-term stability and sustainable development of desert-steppe ecosystems.

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Responses of soil carbon and nitrogen fractions to macropores after the introduction of *Caragana korshinskii* in desert steppe

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Abstract: In this study, the effects of *Caragana korshinskii* introduction on soil carbon and nitrogen components and macropores were compared and analyzed using a control (CK) and plots with different planting ages of *Caragana korshinskii* in the desert steppe area of Yanchi County, Ningxia. The results showed that, in the 0–10 cm soil layer, compared with CK, soil particulate organic carbon (POC) decreased in the 11-year-old plot, while the contents of soil organic carbon (SOC), mineral-bound organic carbon (MAOC), easily oxidized organic carbon (EOC), and dissolved organic carbon (DOC) increased with planting age; peak contents occurred in the 26-, 16-, 26-, and 37-year-old plots, respectively. The contents of total nitrogen (TN) and nitrate nitrogen (NO_3^-−N) increased by 74.5% and 868.07%, respectively, in the 26- and 37-year-old plots. In the 10–20 cm soil layer, TN in the 26-year-old sample increased by 196.4%, and ammonium nitrogen (NH_4^+−N) in the 37-year-old sample increased by as much as 22.8%. CT scanning showed that the soil macropore network evolved with age. The pore number density of the 37-year-old plot increased by 131%, and connectivity was greatest in the 16-year-old plot (177.95). There was a significant stage-dependent correlation between the development of soil macropores and the content of carbon and nitrogen components: pore formation could promote the accumulation of active organic carbon; the high pore connectivity in the 16- and 26-year-old plots promoted soil nitrogen transformation. The pore structure of the 37-year-old plot tended to be complex, resulting in differentiation in soil carbon and nitrogen storage efficiency.

Keywords: artificial *Caragana korshinskii*; carbon and nitrogen component evolution; grey relation analysis; macropores

Note: Figure translations are in progress. See original paper for figures.