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Response of soil inorganic nitrogen dynamics to planting age and vegetation type in artificial sand-fixing land

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Abstract

Vegetation restoration in dryland regions may be a powerful way to control desertification and promote local habitat recovery. In these artificial revegetation systems, ecosystem processes and functioning are strongly determined by nitrogen (N) availability, while soil inorganic N (SIN) is the major available N form and is absorbed as a main N source for plants. However, SIN dynamics, their influencing factors, and their relative importance to the ecosystem of these N-limited systems are not well understood. A field investigation was conducted to examine the monthly variations in SIN and its response to planting age and vegetation type in a typical artificial sand-fixing system in northwestern China. The SIN content in topsoil (0–20 cm) during the growing season ranged from 7.10 to 95.65 mg kg^{-1}, with a mean value of 27.14 mg kg^{-1}. Soil nitrate N had a dominant role in determining SIN monthly dynamics, which showed a fluctuating trend with two peak values in early July and late August. SIN showed a significant increasing trend with the planting age of sand-fixing vegetation, and it was highest for *Nitraria sphaerocarpa* (55.66 ± 5.76 mg kg^{-1}), followed by *Haloxylon ammodendron* (29.81 ± 3.47 mg kg^{-1}) and interspace (11.39 ± 1.13 mg kg^{-1}). SIN displayed a hump-shaped relationship with air temperature ($R^2 = 0.96$, $p < 0.01$) and had a maximum at 19.88°C. The change rate of SIN was positively correlated with accumulated precipitation ($R^2 = 0.99$, $p < 0.05$). SIN was correlated significantly with soil organic carbon (SOC), total nitrogen (TN), and soil clay content. Our results revealed that climatic (air temperature and precipitation), abiotic (soil texture), plant (planting age and vegetation type), and nutrient-related (SOC and TN) factors regulate SIN dynamics in artificial sand-fixing vegetation systems. Climate was the predominant factor affecting soil ammonium N, and soil nutrients (SOC and TN) were the predominant factor affecting soil nitrate N. Therefore, these factors should be integrated into optimizing regional vegetation establishment and improving ecosystem management practices in sand-fixing lands.

Rong Yang and Shiyang Chen contributed equally to the work reported here.

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KEYWORDS
desertification, *Haloxylon ammodendron*, precipitation, sand-fixing vegetation, soil inorganic nitrogen, vegetation restoration

INTRODUCTION

Desertification is the most serious form of land degradation in global drylands, reducing the diversity and stability of ecosystems and altering their structure and function (Reynolds et al., 2007). Vegetation restoration is a practical approach for controlling desertification. Increasing evidence from long-term observations (Li, Li, et al., 2022), manipulative experiments (Li, Xie, et al., 2022), and remote sensing monitoring (Chen et al., 2021) has demonstrated that vegetation restoration in desertified land has a positive effect on constraining wind-blown sand hazards and promoting local habitat recovery. Generally, vegetation recovery and restoration practices in dryland ecosystems have been found to reduce soil erosion (Reynolds et al., 2007), improve vegetation conditions, increase plant primary productivity, and modify soil biochemical cycles (Li, Li, et al., 2022). Recently, a number of studies have shown that vegetation recovery and restoration can increase carbon (C) and nitrogen (N) sequestration by modifying their inputs and outputs in soil (Zhou et al., 2020). A significant enhancement in soil C and N with vegetation rebuilt in desertified land has been widely observed in the Tibetan Plateau (Gou et al., 2019), desert steppe (Du et al., 2021), and the Tengger Desert (Li, Li, et al., 2022). The effects of soil C and N dynamics on biogeochemical cycles and vegetation development are essential in these revegetated ecosystems since the biogeochemical activity of C and N is primarily driven by their availability in soil. However, despite its potential importance, N availability, as well as its response to the planting age and vegetation types after vegetation recovery and restoration in desertified land, has received limited attention.

N is often an imperative nutrient for plant growth, and N availability in soil determines primary productivity as well as many ecosystem processes, such as the nutrient cycle, plant photosynthesis, and C sequestration in terrestrial ecosystems (Liu et al., 2018). Dryland ecosystems demonstrate firm N limits and are conventionally characterized by low N availability, mainly because of low input and relatively high loss rates (Schaeffer & Evans, 2005). In dryland ecosystems, N, after water, is a vital factor that limits plant growth, determines net primary production, affects microbial decomposition (Delgado-Baquerizo et al., 2013), and further influences vegetation community composition, species diversity, and ecosystem function (Wang et al., 2014). As vegetation growth and development are strongly determined by soil N availability, it is crucial to learn more about soil N availability and its influencing factors to better predict ecosystem processes and evaluate its response to environmental changes in dryland ecosystems. However, soil N availability to vegetation is difficult to assess through measurement because of the rapid turnover of soil N pools and intense competition for N between plants and microbes (Liu et al., 2018).

Haloxylon ammodendron, a sizeable xerophytic shrub in Chenopodiaceae with a C4 pathway (Su et al., 2007), is an important species for ecological restoration and recovery in northwestern China, primarily because of its strong tolerance to environmental stresses (eolian sand, salinity, and drought), high seedling and planting survival rates, and rapid-growth properties. Particularly in the desertified land of northwestern China, it is used as the main windbreak and sand-fixing vegetation (Liu et al., 2011). Many studies have been conducted to reveal the physiological and photosynthetic characteristics (Su et al., 2007), water use strategies (Dai et al., 2015), and drought tolerance mechanisms of this species (Lü et al., 2019). In recent years, more attention has been paid to how the planting of *H. ammodendron* regulates soil evolution in sandy desert ecosystems. For instance, Su and Liu (2020) reported that soil organic C (SOC) increased by 5.7 times and the soil salt increased by 6.5 times after planting *H. ammodendron* for more than 40 years in a native desert soil. However, the potential role of *H. ammodendron* in regulating soil N availability and its feedback to ecosystems in these artificial vegetation restoration regions remains poorly understood. Although many studies have revealed that plants used for revegetation might impact N availability, the direction and magnitude of the impact vary greatly with different planted vegetation, climate, and age.

We conducted a field investigation with a planting age gradient of *H. ammodendron* and also considered the different vegetation types in a typical desertified land in the Hexi corridor region of northwestern China. The objectives were to (1) clarify the monthly dynamics of soil N availability (denoted by soil inorganic N, SIN) during the growth period in a typical artificial revegetation system; (2) reveal the effects of planting age and vegetation type on soil N availability; and (3) assess the relative importance of climate, abiotic, vegetation, and soil factors on modulating soil N availability.

MATERIALS AND METHODS

Site and experiment description

The study area is located in the middle region of the Hexi corridor, Northwest China, near the Linze Inland River Basin Research Station (latitude 39°21′ N, longitude 100°11′ E, elevation 1367 m; Figure 1). It has a hyper-arid desert climate. The daily air temperature throughout the year generally shows a single-peak trend, gradually increasing from January to August and then decreasing from August to December (Figure 2).

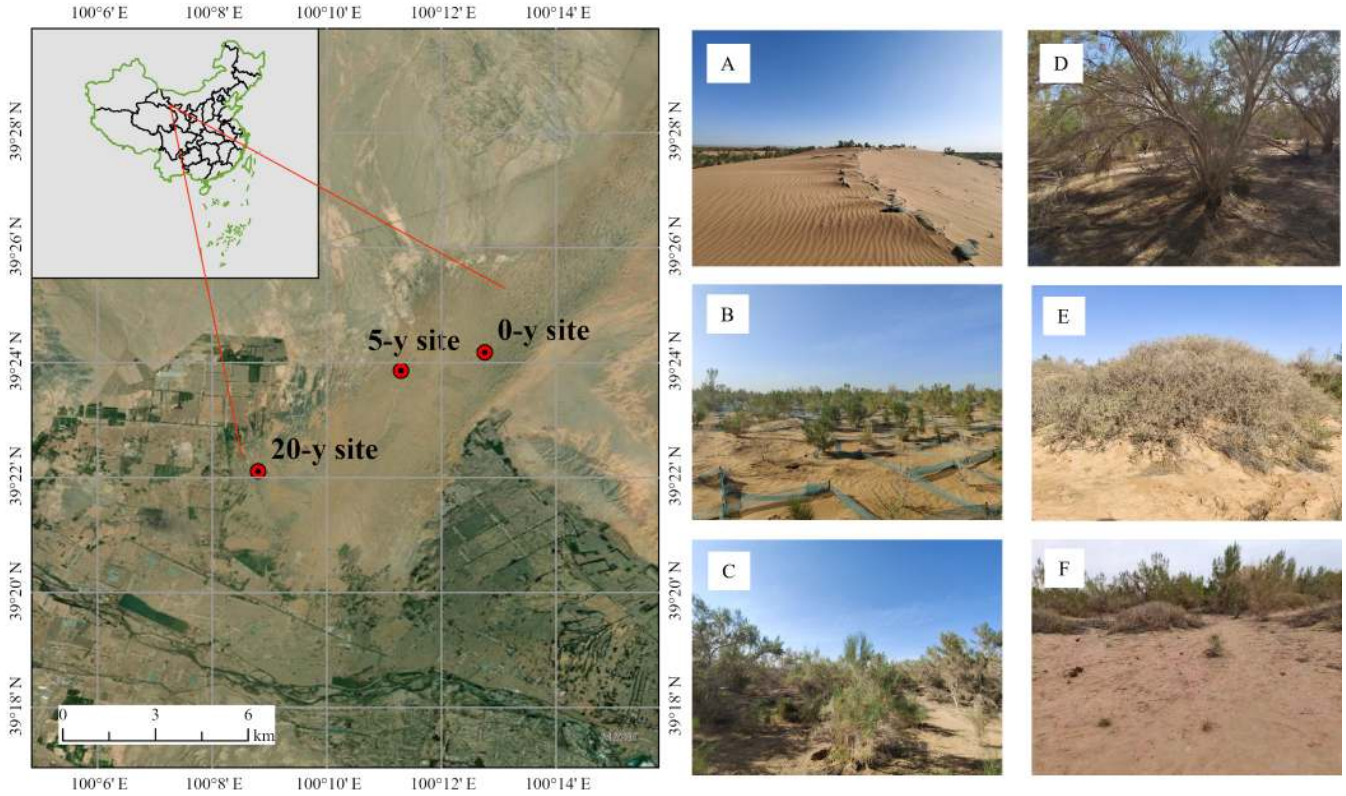


FIGURE 1 Location of the study sites and landscape pictures of different sampling sites: (A) non-vegetated shifting sandy dune (0-year, control); (B) 5-year *Haloxylon ammodendron* forest site (5-year); (C) 20-year *H. ammodendron* forest site (20-year); (D) non-vegetated interspace in 20-year site (NVI, control); (E) *H. ammodendron* in 20-year site (HAS); (F) natural *Nitraria sphaerocarpa* in 20-year site (NSS). Photo credit: Shiyang Chen.

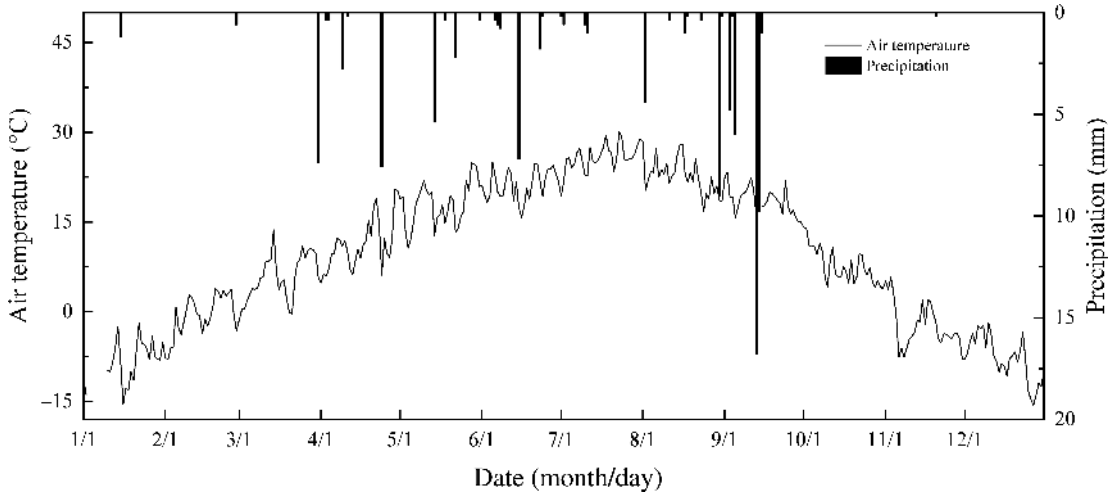


FIGURE 2 Daily air temperature and precipitation in 2021.

The average air temperature in 2021 was 9.6°C, above the long-term (1965–2010) average value of 7.6°C, with a minimum of −17.35°C (January) and a maximum of 30.1°C (July). The total precipitation in 2021 was 96.8 mm, below the long-term average value (1965–2010) of 117 mm. The seasonal variation in precipitation in 2021 closely mirrored the long-term trends, and 90.3% fell between May and September; the maximum value of 38.6 mm occurred in September. The soil is generally sandy textured and classified as eolian sandy soil.

A field investigation was conducted in an artificial vegetation restoration area outside the Linze oasis and at the edge of the northern Badain Jaran Desert. A series of ecological restoration and desertification control projects have been implemented there since 2000 to protect oasis security and avoid wind and sand erosion from the Badain Jaran Desert. *H. ammodendron* was selected as the predominant restoration vegetation for windbreak and sand fixation and planted in the sand dunes after straw checkerboard barriers were installed. Due to continuous planting in every year, *H. ammodendron* forest gradually expanded from the oasis's fringe to the desert's interior, forming a planting age gradient. Hence, the non-vegetated shifting sandy dune (control), 5-year *H. ammodendron* forest, and 20-year *H. ammodendron* forest sites were selected to represent different vegetation planting ages (0, 5, and 20 years, respectively). The non-vegetated shifting sandy dune was selected as 0-year sites, and there was no artificial or natural vegetation (Figure 1A). In the 5-year sites, *H. ammodendron* were planted in the shifting sandy dune after the nylon mesh sand barriers were built in 2016, and the vegetation coverage now reaches 30% (Figure 1B). In the 20-year sites, *H. ammodendron* were planted in 2001, and the vegetation coverage now reaches 70% (Figure 1C). After a long period of vegetation succession and degradation, native natural *Nitraria sphaerocarpa* (which may have grown before *H. ammodendron* planting) and bare interspace (formed due in part to artificial vegetation death and degradation) embedded in the 20-year *H. ammodendron* forests. Thus, in the 20-year sites, the *H. ammodendron* shrubs (Figure 1D), *N. sphaerocarpa* shrubs (Figure 1E), and non-vegetated bare interspace (Figure 1F) (control) were selected to represent different vegetation types and were coded as HAS, NSS, and NVI, respectively. At each site, 10×10 m replicate plots were set up for soil sampling. Fifteen sampling plots in total with three replicates in three sites were set up. In each vegetated plot, the soil samples were taken under the vegetation canopy; non-vegetated plot soil samples were taken at random sampling points.

Field sampling and environmental measurements

To determine the SIN content, including nitrate N and ammonium N, fresh soil samples were collected at intervals of ~15–20 days during the vegetation growth season in 2021. The sampling dates were June 17, July 3, July 19, August 5, August 20, and September 12. At each sampling plot, six samples were taken from the top 0–20-cm soil layer with an "S"-shaped sampling method using a drill (diameter: 5 cm) to make one mixed soil sample. The nitrate N and ammonium N contents in all fresh soil samples were determined immediately in the laboratory in most cases. If they could not be measured instantly, the fresh soil samples were stored at 4°C, and the analysis was completed within a week.

In September 2021, additional samples from the 0–20-cm soil layer were collected from each plot using the same method mentioned above to measure soil physical and chemical properties, including SOC, total C (TC), total N (TN), pH, and particle composition. After air-drying at room temperature, each of the soil samples was divided into two subsamples. One subsample was sieved using a 2-mm sieve for particle size and pH analysis. The other subsample was sieved using a 0.25-mm sieve for chemical property analysis. The bulk density (BD) in the 0–20-cm soil layer was synchronously measured using undisturbed soil cores collected with a 100-cm^3 steel cylinder.

Meteorological data were collected using the ENVIS environmental monitoring system (IMKO, Ettlingen, Germany). The air temperature was monitored using the HMP45D temperature probe (Vaisala, Vantaa, Finland), and precipitation was monitored using the RG50 rain gauge (SEBA, Gewerbestr, Germany).

Laboratory measurements

Approximately 10 g of fresh soil was extracted using 50 mL of 2 M KCl. After 1 h of shaking and 20 min of standing, the solution was filtered through filter paper. The nitrate and ammonium N concentrations (in milligrams per liter) in the extracts were then measured using an automatic discontinuous chemical analyzer (Smartchem140, Alliance Instruments, France), and the reference samples with specific values of nitrate or ammonium N contents were used for quality control in each measurement. Another soil sample was dried and weighted, and the moisture content was calculated using the ratio of dry to wet mass of the soil, which allowed the accurate dry mass of previously analyzed soil samples to be calculated.

The nitrate N and ammonium N contents (in milligrams per kilogram) of the soil were then calculated

according to nitrate and ammonium N concentrations in the extracts (in milligrams per liter), the extract volume (50 mL), and the mass of the dry soil. SIN content is the sum of the nitrate and ammonium N contents.

The SOC was measured using the Walkley–Black method (dichromate oxidation). TC and TN were measured using a dry combustion method with an elemental analyzer (Elementar, Frankfurt, Germany). The pH was measured using a glass electrode in a 1:2.5 ratio of soil and water. Soil particle size distribution was measured using the pipette method after removing organic matter and calcium effect by adding hydrogen peroxide and hydrochloric acid. The methods for determining the physicochemical properties of the soil were used as previously described by Bao (2010).

Statistical analysis

One-way ANOVA was used to analyze the planting age and vegetation type effects on soil nitrate N, ammonium N, and SIN, and a least significant difference (LSD) test was used to determine the significant difference at an $\alpha = 0.05$ level between different planting ages and vegetation types. The regression analysis was used to evaluate the change trend of soil nitrate N, ammonium N, and SIN along with average daily air temperature. The accumulated precipitation ($\sum P$) and the SIN change rate (ΔSIN) between consecutive samples were calculated, and the relationship between them was also evaluated using the regression analysis. Pearson's correlation analysis was used to assess the relationships between the soil properties and SIN, and p values <0.05 were considered significant. Structural equation modeling (SEM) was generated to assess the relative importance of climate, abiotic, vegetation, and soil factors in modulating soil N availability.

Statistical analyses, including one-way ANOVA, the LSD test, and Pearson's correlation, were performed using the statistical software SPSS (version 21, Chicago, USA). The regression analysis was performed using the curve-fitting function in the Origin software (OriginLab 2023; Northampton, USA), and the graphics functions in the OriginLab 2023 software were used to prepare all the figures. SEM was performed using Lavaan package in R soft (version 4.3.2).

RESULTS

Change in soil properties with vegetation type and planting age

The vegetation type significantly affected the soil properties in the surface soil layer (0–20 cm; Table 1). On average, SOC ($F = 17.9$, df = 2, $p < 0.01$) increased sharply from 0.87 ± 0.08 g kg^{-1} in the NVI site to 1.15 ± 0.02 g kg^{-1} in the HAS site and 1.33 ± 0.04 g kg^{-1} in the NSS site. TN ($F = 6.7$, df = 2, $p < 0.05$) in the HAS and NSS sites was 27% and 42% higher than that in the NVI site, respectively. TC ($F = 17.4$, df = 2, $p < 0.01$) was significantly higher in the NVI site compared with the other sites, followed by the NSS and then the HAS site. The pH ($F = 25.9$, df = 2, $p < 0.01$) decreased

TABLE 1 Changes in soil physicochemical properties in topsoil (0–20 cm) associated with vegetation planting age and type.

	Vegetation planting age				Vegetative type			
Variable	**0 year**	**5 year**	**20 year**	***F***	**NVI**	**HAS**	**NSS**	***F***
SOC (g kg^{-1})	0.48 ± 0.03c	0.78 ± 0.06b	1.15 ± 0.02a	68.5***	0.87 ± 0.08b	1.15 ± 0.02a	1.33 ± 0.04a	17.9**
TC (g kg^{-1})	4.20 ± 0.03c	5.06 ± 0.05b	6.74 ± 0.14a	231.6***	7.83 ± 0.11a	6.74 ± 0.14c	7.30 ± 0.14b	17.4**
TN (g kg^{-1})	0.16 ± 0.02c	0.23 ± 0.01b	0.33 ± 0.00a	6.7*	0.26 ± 0.01b	0.33 ± 0.00ab	0.37 ± 0.04a	6.7*
pH	9.32 ± 0.04a	9.77 ± 0.02b	8.80 ± 0.15c	27.5*	8.02 ± 0.06b	8.80 ± 0.15a	8.92 ± 0.03a	25.9**
BD (g kg^{-1})	1.64 ± 0.02a	1.63 ± 0.01a	1.56 ± 0.04a	2.2	1.51 ± 0.01b	1.56 ± 0.04a	1.43 ± 0.02b	7.0*
Sand content (%)	95.65 ± 0.77a	94.89 ± 0.09a	88.36 ± 0.11b	78.8**	82.23 ± 0.40c	88.36 ± 0.11a	85.50 ± 0.48b	69.6**
Clay content (%)	3.65 ± 0.74c	3.77 ± 0.03b	8.44 ± 0.07a	343.2***	11.25 ± 0.19a	8.44 ± 0.07c	10.37 ± 0.37b	34.5**
Silt content (%)	0.70 ± 0.09b	1.34 ± 0.07a	3.19 ± 0.03a	40.5**	6.52 ± 0.29a	3.19 ± 0.03c	4.13 ± 0.13b	86.3**

Note: Treatment codes: 0, 5, and 20 year denote planting age of *H. ammodendron* at 0, 5, and 20 years, respectively; NVI, non-vegetated interspace; HAS, *Haloxylon ammodendron* shrubs; NSS, *Nitraria sphaerocarpa* shrubs. Data are given as mean ± SE; means with different lowercase letters in the same row are significantly different, as determined using one-way ANOVA analysis followed by the least significant difference test. Asterisks following the *F* value (df = 2) indicate significant differences: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Abbreviations: BD, bulk density; SOC, soil organic carbon; TC, total carbon; TN, total nitrogen.

significantly with the sequence HAS > NSS > NVI, and the BD ($F = 7.0$, df = 2, $p < 0.05$) decreased significantly with the sequence HAS > NVI > NSS. For soil texture, soil sandy content ($F = 69.6$, df = 2, $p < 0.01$) was highest in the HAS site, followed by the NSS and NVI sites, whereas clay ($F = 34.5$, df = 2, $p < 0.01$) and silt ($F = 86.3$, df = 2, $p < 0.01$) content were the highest in the NVI site, followed by the NSS and HAS sites.

Vegetation planting age significantly affected soil properties in the surface soil layer (0–20 cm; Table 1). On average, SOC ($F = 68.5$, df = 2, $p < 0.001$) increased sharply from 0.48 ± 0.03 g kg^{-1} in the shifting sandy dune to 0.78 ± 0.06 g kg^{-1} and 1.15 ± 0.02 g kg^{-1}in the 5- and 20-year sites, respectively. TN ($F = 6.7$, df = 2, $p < 0.05$) in the 5- and 20-year sites was 44% and 106%, respectively, higher than that in the shifting sandy dune. Similarly, TC ($F = 231.6$, df = 2, $p < 0.001$) was significantly higher in the 5- and 20-year sites than in the shifting sandy dune, and all increased with increasing vegetation planting age. The pH ($F = 27.5$, df = 2, $p < 0.05$) showed a significant decreasing trend with vegetation plating age, but BD ($F = 2.2$, df = 2, $p > 0.05$) showed no statistical differences among the different vegetation planting ages. For soil texture, soil sandy content ($F = 78.75$, df = 2, $p < 0.01$) decreased significantly, whereas clay ($F = 343.2$, df = 2, $p < 0.001$) and silt content ($F = 40.5$, df = 2, $p < 0.01$) increased significantly with increasing vegetation planting age.

SIN dynamic, vegetation type and planting age effect

Across all sites and the entire study period, nitrate N content in the surface soil layer ranged from 5.35 to 93.03 mg kg^{-1}, with a mean of 25.66 mg kg^{-1}, and ammonium N content ranged from 0.084 to 3.07 mg kg^{-1} with a mean of 1.48 mg kg^{-1}. The SIN content in the topsoil ranged from 7.10 to 95.65 mg kg^{-1}, with a mean of 27.14 mg kg^{-1}, and nitrate N accounted for 71%–98% of the SIN (Figure 3).

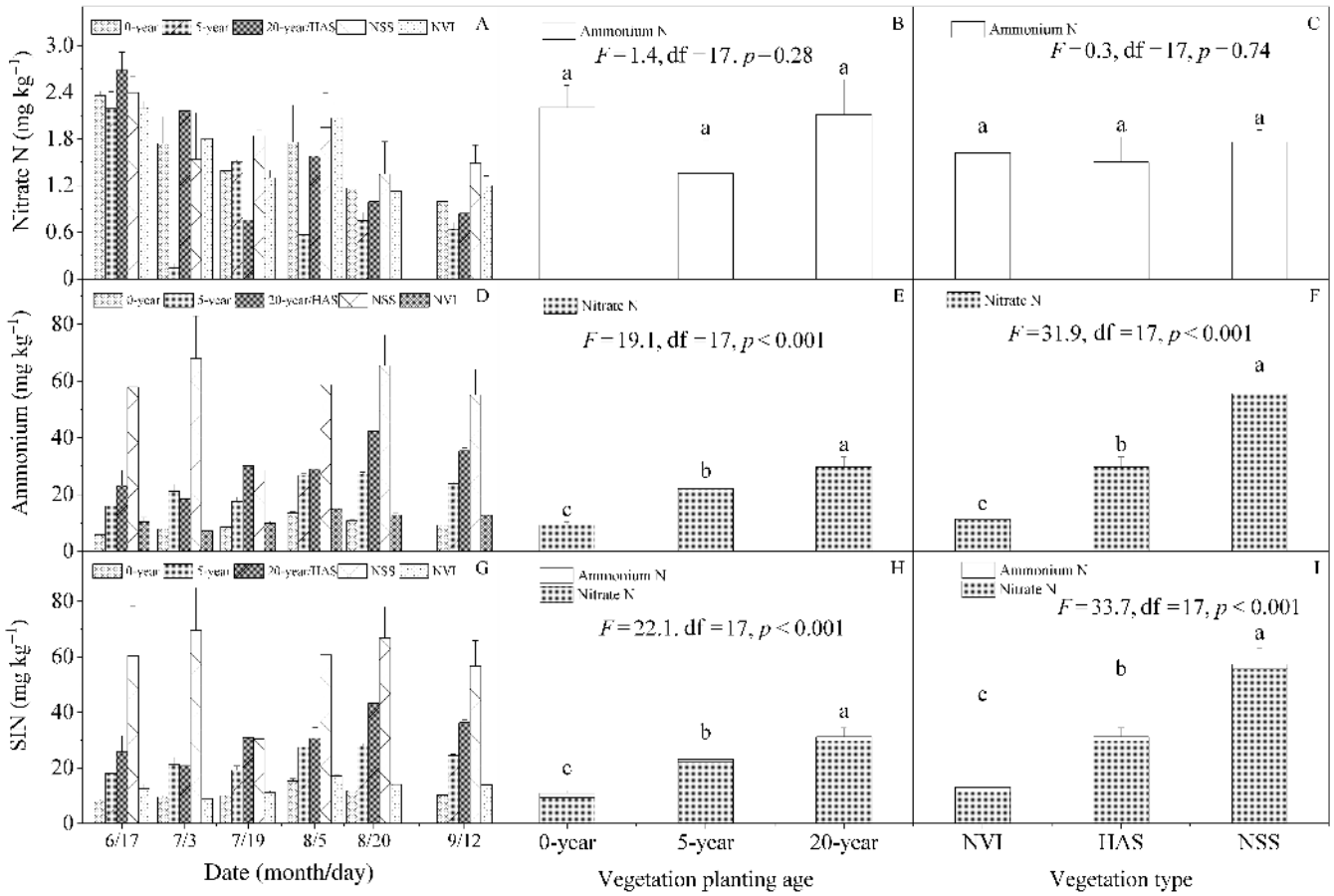


FIGURE 3 Temporal trends and treatment average of soil (A–C) ammonium N, (D–F) nitrate N, and (G–I) inorganic N (SIN) content across all sites during the growth period in 2021. (A, D, and G) the temporal trends of the variables in all sites; (B, E, and H) the average values of the variables in different vegetation planting ages; (C, F, and I) the average values of the variables in different vegetation types. Lowercase letters over the bars denote statistical significance at $p < 0.05$ between treatments. See Table 1 for an explanation of abbreviations.

The nitrate N content in the topsoil exhibited a significant monthly trend for all sites, showing a double peak change trend throughout the observation period from June to September 2021. It increased from June to July, sharply dropped on July 19, increased continuously throughout August, and finally dropped again in September. Ammonium N content in the topsoil generally showed a downward trend during the observation period, and a particular drop appeared on July 19. Since it was mainly composed of nitrate N, the total SIN in the topsoil showed a similar monthly trend with nitrate N over the observation period.

The vegetation type significantly affected the SIN in the surface soil layer. Average nitrate N in the topsoil was the highest in the NSS site (55.66 ± 5.76 mg kg^{-1}), followed by the HAS (29.81 ± 3.47 mg kg^{-1}) and NVI sites (11.39 ± 1.13 mg kg^{-1}) ($F = 31.9$, df = 17, $p < 0.001$). However, the ammonium N content in the topsoil did not exhibit an increasing trend with the vegetation type ($F = 0.3$, df = 17, $p = 0.74$). Similar to nitrate N, vegetation type also significantly affected the SIN in the topsoil ($F = 33.7$, df = 17, $p < 0.001$).

Vegetation planting age significantly affected nitrate N, ammonium N, and SIN content in the surface soil layer. Average nitrate N content in the topsoil sharply increased from 9.31 ± 1.09 mg kg^{-1} in the shifting sandy dune to 22.11 ± 1.91 and 29.81 ± 3.47 mg kg^{-1} in the 5- and 20-year sites ($F = 19.1$, df = 17, $p < 0.001$), respectively. In addition, the vegetation planting improved nitrate N content in the topsoil by 2.4 (5-year) to 3.2 times (20-year) compared with that in the shifting sandy dune. However, the ammonium N content in the topsoil did not exhibit an increasing trend with vegetation planting age ($F = 1.4$, df = 17, $p = 0.28$). Similar to nitrate N, SIN in the topsoil throughout the observation period showed a significant increasing trend with the vegetation planting age ($F = 22.1$, df = 17, $p < 0.001$).

Air temperatures and rainfall affecting SIN

Soil nitrate N showed a hump-shaped trend with air temperature ($R^2 = 0.97$, $p < 0.01$) with a maximum at 22.05°C (Figure 4A). But soil ammonium N did not change significantly with increasing air temperature ($R^2 = 0.59$, $p = 0.12$, Figure 4B). SIN, the total inorganic N, also showed a hump-shaped trend with air temperature ($R^2 = 0.96$, $p < 0.01$) with a maximum at 19.88°C (Figure 4C).

The change rate of SIN (ΔSIN) between two adjacent observation times was calculated to evaluate the effect of precipitation. Considering the lower amount of N loss via leaching in arid regions, the ΔSIN value was roughly equivalent to the N mineralization rate, which is the sum of the SIN change rate and N leaching rate. The results show that precipitation promoted an increase in ΔSIN. ΔSIN was positive when there were rainfall events in the 3 days before sampling, but negative when there were no rainfall events in that period (Figure 5A). Furthermore, our results show that ΔSIN was highly correlated with the accumulated precipitation ($\sum P$) ($R^2 = 0.99$, $p < 0.01$; Figure 5B).

Soil properties affecting SIN

Soil nitrate N was positively correlated with SOC and TN ($r = 0.66$ and 0.64, respectively; all $p < 0.05$), but negatively correlated with BD ($r = -0.69$, $p < 0.05$) (Figure 6). Soil ammonium N was positively correlated with SOC, TN, TC, silt content, and clay content ($r = 0.70$, 0.62, 0.67, 0.65, 0.64, and 0.77, respectively; all $p < 0.05$), but negatively related to pH, BD, and sandy content ($r = -0.65$, −0.74, and −0.73, respectively; all $p < 0.05$). Similar to soil nitrate N, SIN was positively correlated with SOC, TN, and clay content ($r = 0.67$, 0.65, 0.52, and 0.44, respectively; all $p < 0.05$), but negatively correlated with BD ($r = -0.70$, $p < 0.05$; Figure 6). Nitrate N, ammonium N, and SIN were all strongly correlated with SOC, TN, and BD.

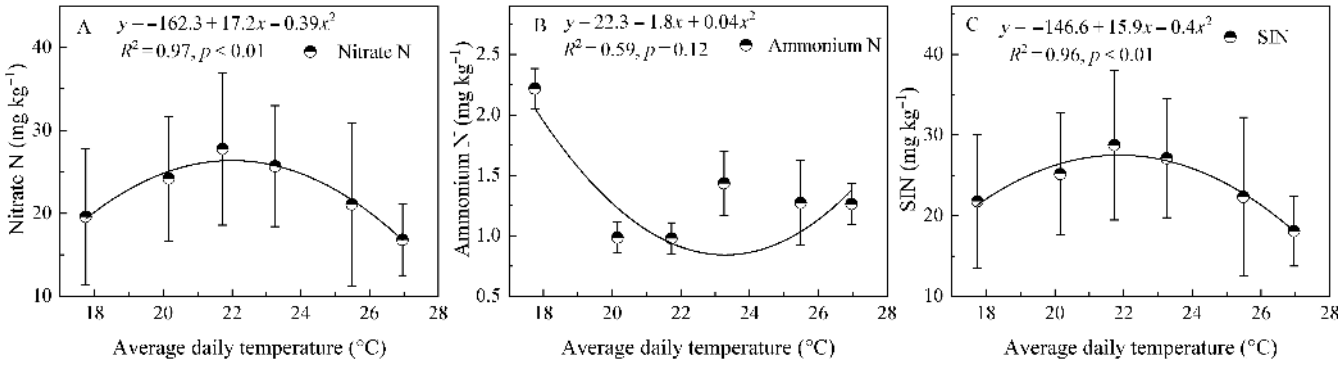


FIGURE 4 Relationships between soil (A) ammonium, (B) nitrate N, and (C) inorganic N (SIN) content and average daily temperature (site means ± SEs).

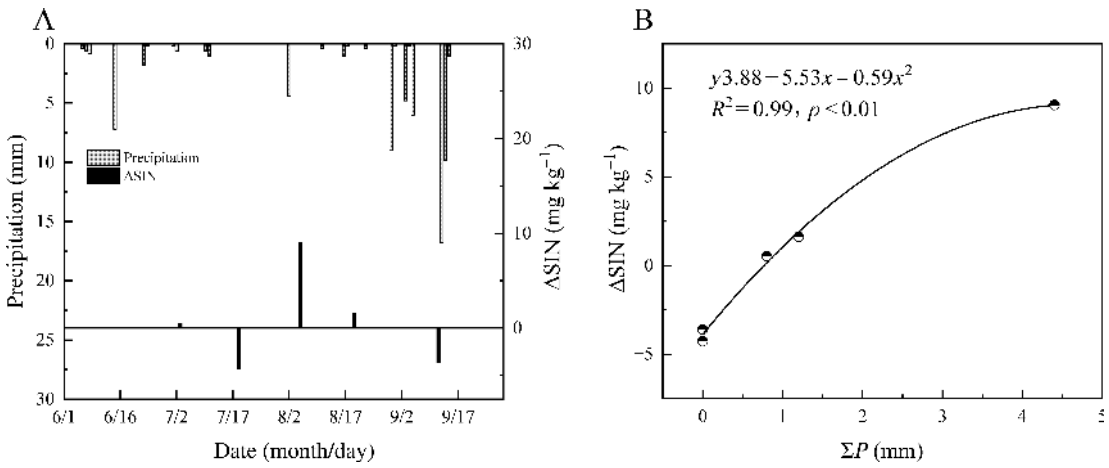


FIGURE 5 (A) Precipitation and ΔSIN trend during the growth period in 2021, and (B) the relationship between ΔSIN and $\sum P$. ΔSIN, the change rate of soil inorganic N between consecutive samples; $\sum P$, accumulated precipitation.

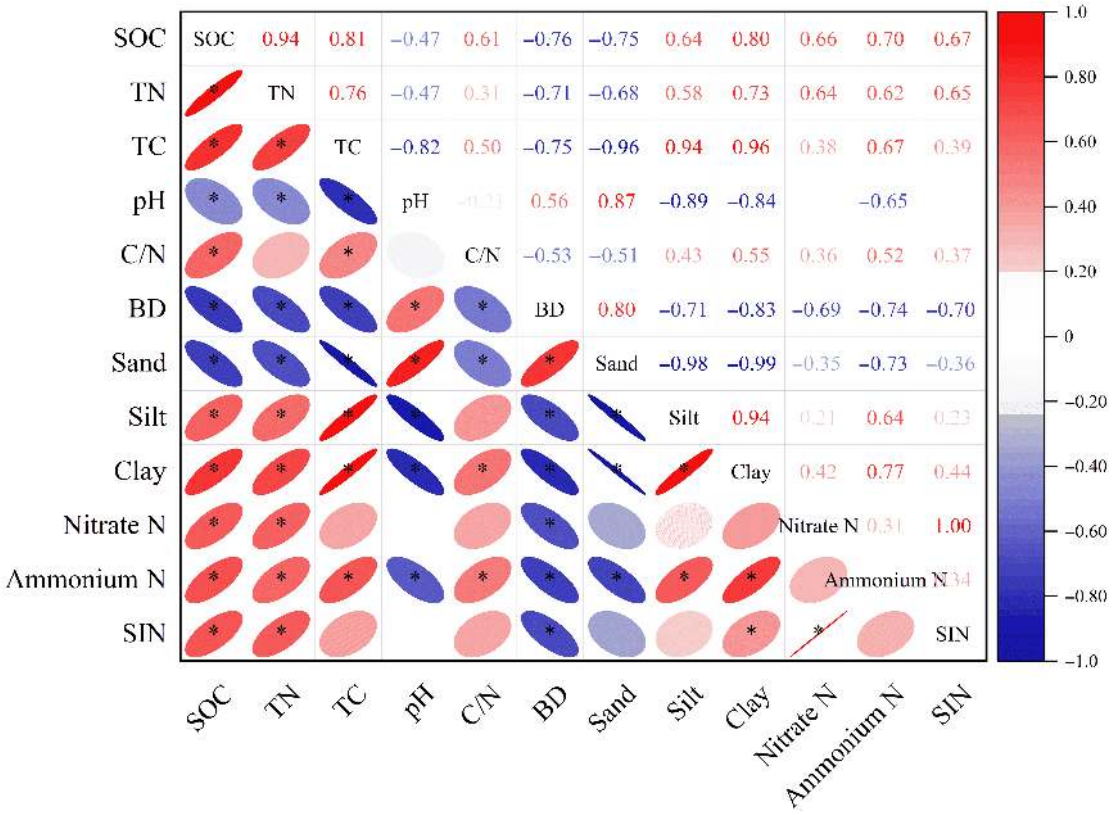


FIGURE 6 Correlation heatmap between soil physicochemical properties (SOC, TC, TN, pH, sandy content, clay content, and silt content) and soil inorganic N (ammonium N, nitrate N, and SIN). See Table 1 for an explanation of variable abbreviations. *$p \leq 0.05$.

DISCUSSION

Monthly dynamics of SIN

Nitrate and ammonium N are the primary available N sources to plants in the soil, and their amounts are determined by soil mineralization and immobilization processes (Peng et al., 2016). In our study, nitrate N content was 2.5–48.5 times higher than the ammonium N content in all treatments over the entire experimental period, indicating that SIN was mainly in the nitrate form in this desertified land. The dominant nitrate N form of SIN in dryland systems has been revealed in many previous studies. Bronson (2008) revealed that ammonium

levels are generally less than nitrate levels in dryland soils, which could be related to rapid nitrification or biological oxidation of ammonium to nitrate. Further, Zhang et al. (2016) confirmed that the N nitrification rate and the ratio of nitrification to mineralization demonstrate significantly higher values in arid soil than in humid soil. Mukherjee (2022) demonstrated that a rapid transformation of ammonium N to nitrate N occurs in aerobic soil and predominantly yields nitrate N and a small amount of ammonium N.

Ammonium N in the topsoil generally showed a downward trend, but nitrate N showed a fluctuating tendency. Because nitrate N also plays a predominant role in determining the monthly dynamics of SIN, SIN showed a fluctuating trend; it increased from June to July, sharply dropped in July, increased continuously throughout August, and dropped again in September. Temperature is an essential factor in regulating soil N availability (Wang et al., 2006), and elevated temperatures stimulate net N mineralization and nitrification rates in various biomes worldwide (Bai et al., 2013). Hence, the monthly dynamics of the SIN could be largely ascribed to fluctuating temperature. Our results indicate that the SIN response to temperature was in agreement with this expectation. For example, air temperature significantly correlated with soil nitrate N and SIN, which can explain 96% and 97% of the variation in nitrate N and SIN. In addition, our study also reveals a temperature threshold of 22.1°C for nitrate N and 19.9°C for SIN (Figure 4). We concluded that it is the optimal temperature for the formation of soil nitrate N and SIN in this sand-fixing vegetation area. We also found that the precipitation positively affected the SIN, and the change rate of SIN significantly increased with the accumulating precipitation. This result is consistent with other studies, which indicate that the drying-wetting cycles caused by precipitation are strongly linked to N cycles in arid and semiarid systems (Austin et al., 2004) and that the processes of plant uptake and microbial assimilation for soil N are temporally synchronous with rainfall events in dryland systems, which is more effective in N transformations (Dijkstra et al., 2012).

Response of SIN to vegetation planting age

Ecological and environmental effects of vegetation restoration on degraded ecosystems have been reported in various terrestrial ecosystems (Ji et al., 2008; Peng et al., 2003). In arid desert ecosystems, vegetation restoration plays a predominant role in influencing ecosystem hydrological and edaphic processes, thus mediating water and nutrient availability, which limits plant growth and ecosystem productivity (Lindh et al., 2022). For example, vegetation restoration changes the temporal–spatial distribution of soil water and its utilization in the dune systems (Li et al., 2014). Our finding that vegetation restoration in sand deserts can significantly improve soil N availability (SIN) agrees with that for the Tengger Desert (Li et al., 2018). We also observed that SIN increased with vegetation planting age, and SIN content was 2.12 and 2.88 times higher at the 5- and 20-year sites, respectively, than in the shifting sandy dune. The trend of SIN increasing with vegetation planting age is in line with the trend of soil N pools. For example, soil TN content was 1.44 and 2.06 times higher at 5- and 20-year sites, respectively, than in the shifting sandy dune. Therefore, soil nutrients increased with planting age, which led to the improvement in SIN; this result is supported by the Pearson correlation between SIN (including ammonium N and nitrate N) and SOC, and TN (Figure 6).

Substrate quantity influences soil N transformations, such as N mineralization and nitrification, thus determining SIN levels. Hu et al. (2021) reported that the amount and quality of soil substrates predominantly drive the enhancement of N transformations in a temperate meadow steppe. Bengtson et al. (2005) reported that N transformation rates in the soil depend on the capacity of C and N pools. In a sandy desert area, the fine particle material combined with various organic C and N components is the key factor defining soil C and N pools (Matus, 2021). Frequent wind erosion, which generally causes the loss of this fine particle material, has negative effect, while the establishment of sand-fixing vegetation, which alleviated soil wind erosion and prevented loss of the fine particle material, thus has positive effect on soil C and N pools in sandy desert areas (Matus, 2021). Our finding that soil clay and silt contents were 2.3 and 4.6 times higher, respectively, at the 20-year sites than in the shifting sandy dune confirmed the positive effect of sand-fixing vegetation in soil fine particles, which agree with the findings of Su and Liu (2020) in the same study area. Furthermore, the establishment of sand-fixing vegetation positively affected SOC and N input. Root and litter residues from sand-fixing vegetation supply the principal organic C and N sources to the soil, and the quantity of C and N input from sandy-fixing vegetation increases with vegetation growth. Furthermore, the increased SOC and N improved the soil structure, accelerated nutrient turnover, and weakened the soil nutrient limit on plant productivity, thus providing positive feedback to the aboveground and underground biomass in the sandy desert ecosystem (Jia et al., 2012). Thus, vegetation establishment in sandy deserts can positively influence the amount and quality of C and N substrate in soil by alleviating the loss of fine particle material and

increasing soil C and N input, thereby accelerating N turnover and generating more inorganic N.

Response of SIN to vegetation type

Significant changes in the N cycle owing to changes in vegetation types have been detected in the subtropics (Zhang et al., 2021) and mountainous ecosystems (Zhu et al., 2023). The vegetation type in a specific climatic area determines the amount and quality of litter and root residue returned to the soil and the active mechanism of humus formation and decomposition (Jia et al., 2012), thus regulating soil N accumulation, transformation, and stabilization (Ning et al., 2023). Our results showed significant SIN differences between *N. sphaerocarpa* and *H. ammodendron*, and the SIN under *N. sphaerocarpa* was 1.8 times higher than that under *H. ammodendron*. Three factors may have contributed to these differences. Firstly, natural *N. sphaerocarpa* survived longer than artificial *H. ammodendron* in the 20-year site, and more litter, and root residue including organic C and N, provide plentiful C and N input. Secondly, *N. sphaerocarpa* has more shallow roots because of clonal reproduction and continuous sand burial (Zhang et al., 2015). Zhang et al. (2015) reported that most *N. sphaerocarpa* roots are distributed in the topsoil and decrease with increasing soil depth. Thus, the dense root systems in *N. sphaerocarpa* provided more N input in the surface soil than that in *H. ammodendron* site. Thirdly, *N. sphaerocarpa* can capture airborne particles, such as litter and dust, more effectively than other species (Zhang et al., 2015); this not only increases the C and N content combined with it but can also improve its ability to protect C and N. Additionally, the inconsistency of environmental conditions, such as soil temperature and humidity, caused by the different vegetation types, also has an impact on soil N transformations and formation of SIN.

Importance of various factors in modulating soil N availability

The SEM results show that climate, vegetation, and abiotic factors have significant effects on soil ammonium N, but vegetation, abiotic factors, and soil nutrients have a significant effects on soil nitrate N (Figure 7). The relative importance of each factor on affecting soil ammonium and nitrate N can also been seen in Figure 7. The climate was the dominate factor affecting soil ammonium N with the highest path coefficient followed by an abiotic factor (pH), and then vegetation, while soil nutrients have no significant effect on soil ammonium N. Soil nutrients were the dominate factor to affect soil nitrate N with highest path coefficient, and followed by abiotic factor (pH), and then vegetation, while climate had no significant effect on soil nitrate N. In Figure 7, it can also be seen that there were strong relationships between vegetation and soil nutrients, and abiotic factors.

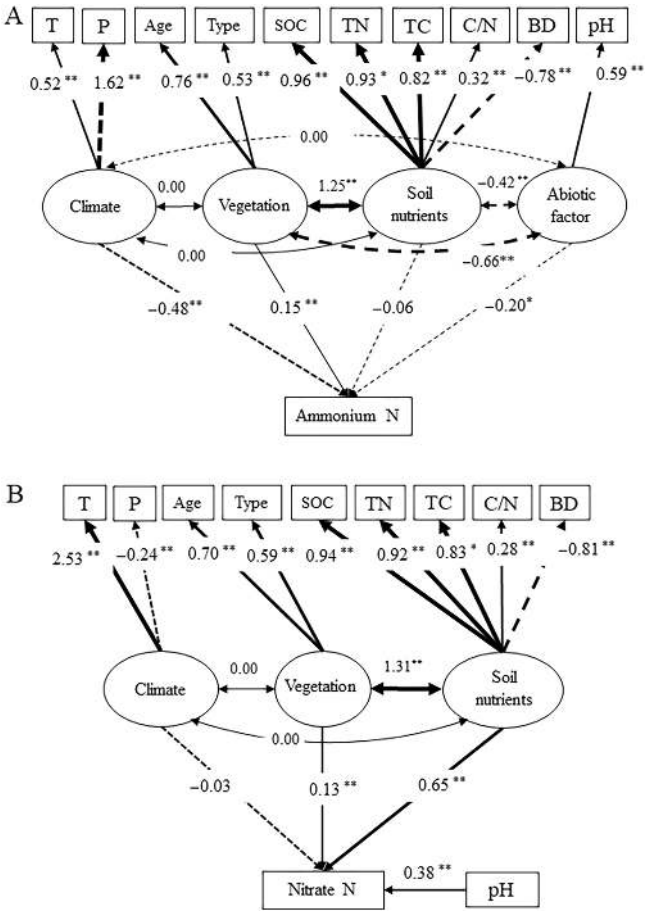


FIGURE 7 Structural equation model with variables and potential causal relationships depicting the effects of climate, vegetation, nutrient-related, and abiotic factors on soil ammonium and nitrate N. The rectangles represent the measured variables, and the ellipses represent the latent variables. Single-headed arrows represent causal relationships, and double-headed arrows represent covarying variables. Solid and dashed arrows indicate positive and negative relationships, respectively. Numbers adjacent to arrows are path coefficients. The path widths are scaled proportionally to the path coefficients. *$p < 0.05$; **$p < 0.01$. The model for ammonium N (A, $p < 0.001$, comparative fit index [CFI] = 0.485, root mean square error of approximation [RMSEA] = 0.485) and nitrate N (B, $p < 0.001$, CFI = 0.484, RMSEA = 0.493) were suggested by the results of model tests. *T*, temperature; *P*, precipitation; Age, planting age; Type, vegetation type. See Table 1 for an explanation of other variable abbreviations.

CONCLUSIONS

A field investigation was conducted in a revegetation system in the dryland region of Northwest China. In this study, the major inorganic N form in the soil was nitrate N, which accounted for 71%–98% of SIN. Accordingly, nitrate N had a predominant role in determining the monthly dynamics of SIN, which showed a fluctuating trend with two peak values in early July and late August. Temperature and precipitation play crucial roles in regulating the monthly variation in soil N availability. Air temperature can explain 97% of the monthly variation in inorganic N, and the accumulated precipitation also has a significant relationship with ΔSIN. Vegetation establishment in sandy deserts can positively influence the quantity and quality of soil C and N substrates, thus significantly improving soil N availability. SIN increased with vegetation planting age and was 1.8 times higher under *N. sphaerocarpa* than under *H. ammodendron*. Our results revealed that climatic (air temperature and precipitation), plant (planting age and vegetation type), abiotic (pH and sand content), and nutrient-related (SOC, TN, and BD) factors play essential roles in regulating SIN dynamics in artificial sand-fixing vegetation systems. Climate was the predominant factor affecting soil ammonium N, and soil nutrients were the predominant factor affecting soil nitrate N. Therefore, these factors should be integrated into optimizing regional vegetation establishment and improving ecosystem management practices in desertified lands.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data (Yang, 2023) are available from Figshare: https://doi.org/10.6084/m9.figshare.22329724.

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