Catena 206 (2021) 105576

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Soil net nitrogen transformation rates are co-determined by multiple factors during the landscape evolution in Horqin Sandy Land

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ARTICLE INFO

Keywords:
Soil inorganic N
Net N transformation
Landscape type
Sampling time
Annual variation
Landscape evolution

ABSTRACT

Vegetation restoration affects soil N cycling, which in turn strongly affects ecosystem functions, such as plant productivity and N availability. The soil N availability is a major limiting factor for restoring vegetation in semiarid grasslands and affects landscape evolution. However, few studies have focused on how landscape evolution caused by vegetation restoration affects soil N availability and transformation in semiarid sandy grasslands. Here, we conducted a 5-year field experiment from 2015 to 2019 to evaluate the growth season (May–August) changes in soil inorganic N pools and net N transformation rates along a landscape evolution gradient caused by vegetation restoration: mobile dunes, semi-fixed dunes, fixed dunes, and dune grasslands. We examined the relationship between climate factors, vegetation characteristics, soil properties, and soil net N transformation rates in different landscape types through multivariate analyses. The landscape type, sampling time, interannual variation, and their interactive effects significantly affected the soil inorganic N pool and net N transformation rate. Soil nitrate N concentration accounted for 68% of the total inorganic N, and soil nitrification dominated the soil N transformation during landscape evolution. Redundancy analysis revealed that the changes in net N nitrification and mineralization rates during the growing season were closely correlated with climate factors, vegetation characteristics, and soil properties. Variation partitioning analysis showed that the soil net N transformation rate during the growing season was mainly affected by soil properties, whereas soil net N transformation in August for all years was mainly affected by climate factors. These results suggest that soil N availability and transformation during landscape evolution caused by vegetation restoration were co-determined by climatic factors, vegetation characteristics, and soil properties. Therefore, long-term field monitoring should be considered to improve our exploration of soil N transformation changes and their underlying mechanisms in semiarid grassland ecosystems.

1. Introduction

Alterations to soil N cycling as a result of land degradation constitute a strong limiting factor for vegetation re-establishment in semiarid grasslands, and thus N alterations might limit landscape evolution in these areas (Liu et al., 2017; Mueller et al., 2013). Changes in soil nutrients, especially inorganic N concentration, can directly affect plant productivity (Fargione et al., 2007), and thus drive ecosystem changes related to the N cycle. Grazing can alter plant community structure and ecosystem function in arid and semiarid grassland ecosystems (Li et al., 2017). In this way, overgrazing or long-term grazing stress have degraded grasslands, which is reflected in the degradation of vegetation characteristics and soil properties (Zhang and Zhao, 2015). Grazing herbivores can alter soil N availability through two different pathways: (1) directly depositing excreta, such as urine and dung, into the grassland soil, and (2) indirectly regulating plant species composition, such as the grass:forb ratio, and thus modifying the quality of litter supplied to decomposers (Liu et al., 2017; Augustine et al., 2003; Bakker et al.,

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https://doi.org/10.1016/j.catena.2021.105576
Received 25 January 2021; Received in revised form 20 June 2021; Accepted 30 June 2021
Available online 9 July 2021

2009). Thus, excluding grazing disturbance is crucial to restore the degraded vegetation and sustainably manage grasslands. Additionally, exploring the effects of degraded grassland restoration on vegetation characteristics and soil properties is essential to clarify the consequences to soil N availability and N transformation.

Intensified anthropogenic activities and climate change have aggravated desertification and caused landscape evolution, as well as the substantial loss of N from semiarid sandy grasslands (Zhou et al., 2008; Dijkstra et al., 2012). To date, management strategies, such as land enclosure and grazing prohibition policies, have promoted grassland restoration and increased N availability across grassland ecosystems in northern China (Wang et al., 2018). Since sandy grassland restoration can sequester a considerable amount of N element and form mineral N and organic N and subsequently enhance primary productivity (Zuo et al., 2015), it is essential to explore the response of soil N transformation to changes in climate factors, vegetation characteristics, and soil properties that occur during landscape evolution caused by vegetation restoration. Through improving our understanding of the dynamics of soil N availability across landscape evolution gradients, we can predict N sequestration potential and adopt practical management strategies in degraded ecosystems of different landscape types.

Substantial evidence has demonstrated that soil N transformation is spatially heterogenous and modulated by climate, so climate change will have a consequent effect on soil N availability (Carrillo et al., 2012; Liu et al., 2017; Guntinas et al., 2012). Vegetation can also affect soil inorganic N pools and N availability. For instance, higher plant species richness can stimulate soil N transformation processes due to the increased root N concentration and root biomass (Mueller et al., 2013; Wei et al., 2017). Additionally, many studies have shown that soil properties can influence soil N cycling at different time scales, from rapid plant N uptake to the long-term accumulation of organic N during the restoration of degraded vegetation (Jirout et al., 2011; Sun et al., 2020; Aranibar et al., 2004). However, we cannot comprehensively predict the response of vegetation characteristics, soil properties, and N availability to grassland vegetation restoration with climate change mainly owing to the short duration of most studies carried out on the subject (generally $<$ 5 years) (Fornara et al., 2009; Eisenhauer et al., 2011; Reich et al., 2018). Furthermore, to the best of our knowledge, few studies have considered the three factors (climate, vegetation, and soil) together when exploring soil N transformation. Thus, the aim of our study was to explore how changes in climatic conditions, vegetation characteristics, and soil properties affect the soil inorganic N pool and N transformation in a 5-year experiment along a landscape evolution gradient in Horqin Sandy Land, a semiarid sandy grassland.

The Horqin Sandy Land is one of the most severely desertified regions in northern China. With the implementation of protective measures, such as grazing prohibition and returning farmland to forests and grasslands, the degraded vegetation has been restored and formed different landscape types. The restored land contains the following landscape evolution gradient: (1) mobile dunes (MD) with successional pioneer species, gradually recovering to (2) semi-fixed dunes (SFD) colonized mainly by small sand-fixing shrubs, (3) fixed dunes (FD) dominated by annual dominant herbaceous species, and finally (4) dune grasslands (G) where perennial and annual herbs dominate (Zhang et al., 2005; Zuo et al., 2012). We considered each of these successional stages as a landscape type. The successful restoration of Horqin grasslands relied on an annual mean precipitation of 350–500 mm. Such a level of precipitation is key for vegetation to naturally restore a desertified region once overgrazing has been excluded or moderated, which has happened since 2000 (Zuo et al., 2015; Zhao et al., 2005). During the landscape evolution caused by vegetation restoration, N plays an important role in limiting successful restoration of this area (Liu et al., 2017). However, few studies have explored the dynamic changes in the soil inorganic N pool and N transformation rate during the landscape evolution, and the influencing mechanism of soil N transformation in this study area remains unclear.

We aimed to quantify the soil inorganic N pool and net N transformation rate during landscape evolution by testing the following three hypotheses: (1) the soil nitrate and ammonium N concentration (i.e., soil inorganic N pool), as well as the net nitrification and net mineralization rate (i.e., N transformation), increase along the landscape evolution sequence; (2) the soil inorganic N pool decreases over plant growth seasons and years, soil N transformation rates are highest in August with seasonal precipitation and temperature changes and (3) soil N availability decreases with precipitation magnitude, plant height, and vegetation cover, increases with air temperature; soil net N transformation rates increase with plant height and air temperature as the net nitrification rate increasing with precipitation magnitude.

2. Materials and methods

2.1. Site description

The study was conducted in a semiarid sandy grassland in the south-central part of the Horqin Sandy Land (42°55′ N, 120°42′ E; 360 m elevation), Inner Mongolia, northern China. The site falls within a continental semiarid monsoon climate in the moderate temperature zone. The long-term mean annual temperature and mean annual precipitation are 6.4 °C and 360 mm, respectively. Eighty percent of the total precipitation falls from June to August, and monthly mean temperature ranges from −12.9 °C in January to 24.4 °C in July. The annual mean wind velocity is 3.2 to 4.1 $m \cdot s^{-1}$, prevailing in the southwest to south and northwest. The soil is zonal and belongs to the chestnut type according to the Chinese classification and is a Haplic Calcisol according to the FAO (Su et al., 2006). This soil is susceptible to wind erosion, creating denuded soil areas that are then re-colonized by plants (Zuo et al., 2009). This region constitutes a patchwork mosaic characterized by different landscape types (LTs) MD, SFD, FD, and G (Zuo et al., 2012). SFD and FD were naturally restored (i.e., without further intervention) from MD by fencing them with 2-m-high columns and barbed wire since 1995 (SFD) and 1980 (FD) to exclude grazing. MD, SFD, and FD have similar topography and size. G areas have also been fenced to exclude livestock since 1996, and they represent a higher restored stage. The four typical landscape types in sandy grassland restoration included MD with <10% vegetation cover, SFD with 10–60% vegetation cover, FD with more than 60% vegetation cover and G with more than 60% vegetation cover. The sand pioneer plant, an annual forb of *Agriophyllum squarrosum* (Linn.) Moq., is a dominant plant in MD. SFD is dominated by *Artemisia halodendron* Turcz. ex Bess shrub and annual forb of *Corispermum macrocarpum* Bge.. FD is dominated by annual forb of *Artemisia scoparia* Waldst. Et Kit.. G is dominated by annual forb of *A. scoparia* and perennial grass of *Phragmites communis* Trrin. Fund. and *Pennisetum centrasiaticum* Tzvel.. Soil fungal richness in MD and SFD was significantly lower than that in FD and G, soil fungal richness and soil N use efficiency have positively strong correlation with plant growing characteristics such as plant richness, biomass, community-weighted mean plant height, in addition, soil gradient increased fungal richness through indirect effect on vegetation rather than direct effect (Zuo et al., 2008, 2012, 2015).

2.2. Experimental design, soil sampling, and laboratory analysis

Corresponding to the four LTs (MD, SFD, FD, and G), 24 sampling sites were selected with six replicated sites per LT (Fig. A.1). One 20 × 20 m plot was positioned within each sampling site. To examine the inorganic soil N pool and net N transformation rate, we used the *in-situ* closed-top buried-bag incubation method (Raison et al., 1987; Li et al., 2018). We collected soil cores and composite soil samples in May, June, July, and August from 2015 to 2019 during the growing season. At the beginning of each monthly sampling, we randomly drove three PVC tubes (5 cm diameter × 12 cm height) into the soil to collect soil cores, and clipped and removed the plants and litter above the PVC tube brim.

After collecting the PVC tubes, we capped each soil core with gauze on the bottom and with a gas-permeable membrane on the top; then we reburied the tubes in their original site for 4 weeks. Three additional soil cores were collected in every sampling site within a plot. These cores were collected from the surface soil layer (0–10 cm) using a 3-cm-diameter soil auger located near the area where the PVC tubes were placed (~0–5 cm).

Surface cores were hand-sieved through a 2-mm sieve and mixed thoroughly to obtain a composite soil sample (six composite soil samples per LT per monthly sampling). The soil in the PVC tubes was retrieved after 4 weeks, hand-sieved through a 2-mm sieve, and mixed thoroughly to obtain a composite *in-situ* incubated soil sample per plot. Both the composite soil sample and composite *in-situ* incubated soil sample were conserved at 4 °C, and a portion of each composite soil sample or composite *in-situ* incubated soil sample was measured by drying method (oven-dried at 105 °C for 24 h) to determine the soil water content on weight basis (SWC). Additionally, we measured soil temperature (T_s, °C) in the field using a digital soil thermometer by inserting the probe into the surface soil layer for 1 min in each plot. During each monthly sampling, we also investigated the vegetation cover and plant height in each plot. We collected aboveground biomass of each species by the method of mowing and litter mass. Roots in 0–10 cm were also sampled by using a soil auger (10 cm-diameter).

Each fresh composite soil sample and composite *in-situ* incubated soil sample was extracted in 2 M KCl and filtered for colorimetric analysis of nitrate N (NO_3^--N) and ammonium N (NH_4^+-N) concentration. The concentration of NH_4^+-N was analyzed by indophenols blue method. NO_3^--N was calculated by the absorbance value at 220 nm subtracting the two times background absorbance value at 275 nm (He et al., 2017). The aboveground biomass, litter mass and underground biomass were dried at 60 °C for 48 h. The soil total C and N were measured by an elemental analyzer (Costech ECS4010, Italy). After we air dried a portion of the soil sample, the soil suspension pH and suspension EC were also examined with pH (1:2.5, soil: deionized water) and EC meters (1:5, soil: deionized water), respectively (Li et al., 2012). We used a soil auger equipped with a stainless-steel cylinder to collect soil sample then dried the soil sample at 105 °C for 24 h to determine the bulk density. The soil texture was determined by wet sieving, and we used a nest of sieves with openings of 0.25, 0.1, and 0.05 mm to separate the soil sample into four fractions: coarse sand (>0.25 mm), fine sand (0.10–0.25 mm), very fine sand (0.05–0.10 mm), and clay and silt (<0.05 mm) (Li et al., 2012).

2.3. Data calculation and statistical analysis

We calculated the soil net nitrification rate from the difference between NO_3^--N concentration before (composite soil sample) and after (composite *in-situ* incubated soil sample) incubation. The soil net N mineralization rate was calculated from the difference between total inorganic N (NO_3^--N + NH_4^+-N) concentration before and after incubation. Rates were calculated using the following equations:

$$R_n = \frac{NO_3^-\text{-}N_{i+1} - NO_3^-\text{-}N_i}{t_{i+1} - t_i}\# \quad (1)$$

$$R_m = \frac{(NO_3^-\text{-}N_{i+1} + NH_4^+\text{-}N_{i+1}) - (NO_3^-\text{-}N_i + NH_4^+\text{-}N_i)}{t_{i+1} - t_i},\# \quad (2)$$

where R_n is the net nitrification rate, R_m is the net mineralization rate, t_i is the initial date of incubation, t_{i+1} is the final date of incubation, NO_3^--N_i is the nitrate N concentration before incubation, NO_3^--N_{i+1} is the nitrate N concentration after incubation, NH_4^+-N_i is the ammonium N concentration before incubation, and NH_4^+-N_{i+1} is the ammonium N concentration after incubation.

We evaluated the changes in the soil inorganic N pool and soil net N transformation rate for LT, sampling time (ST), interannual variation (IV), as well as their interactive effects using repeated measures analysis of variance (ANOVA). Significant differences were further determined using the least-significant-difference (LSD) test at the level of 0.05. Pearson's correlation and redundancy analysis (RDA) were applied to evaluate the relationship between soil net N transformation rate and climatic factors, vegetation characteristics, and soil properties. The contribution of climatic factors, vegetation characteristics, and soil properties to the soil net N transformation rate was tested by variation partitioning analysis. All statistical analyses were performed in SPSS (version 25.0), and the RDA and variation partitioning analyses were performed in Canoco 5.0.

3. Results

3.1. Dynamic changes in soil inorganic N pool and net N transformation rate during landscape evolution caused by vegetation restoration

Based on the repeated measures ANOVA, the NO_3^--N, NH_4^+-N, and total inorganic N concentration were significantly affected by LT, ST, IV, the interactions between LT and ST, ST and IV, and LT, ST, and IV (Table 1). Additionally, the interaction between LT and IV only affected the NH_4^+-N concentration. The soil NO_3^--N concentration and total inorganic N (NO_3^--N + NH_4^+-N) concentration significantly increased across the landscape evolution gradient, whereas the soil NH_4^+-N concentration showed a decreasing trend from MD to G (Fig. 1). The mean NO_3^--N, NH_4^+-N, and total inorganic N concentration in the four LTs was significantly lower in August compared with that in May, June, and July. The total inorganic N concentration in MD and SFD did not differ among the four months during the growing season, whereas the NO_3^--N and total inorganic N concentration in the other two landscape types did not differ from May to July. The mean NO_3^--N and total inorganic N concentration in the four LTs was the highest in 2015, whereas the NH_4^+-N concentration was the highest in 2017. Additionally, there was a significant interannual fluctuation in mean NO_3^--N, NH_4^+-N, and total inorganic N concentration in the four LTs from 2015 to 2019, and a decreasing trend in the mean NO_3^--N and total inorganic N concentration in the four LTs was observed throughout the duration of our study. The soil nitrate N concentration accounted for ~68% of the soil total inorganic N concentration in the four LTs, suggesting that soil nitrate N dominated the inorganic N pool during the landscape evolution caused by vegetation restoration of sandy grasslands. From MD to SFD, FD, and G, the proportion of soil nitrate N concentration in total inorganic N pools was 54, 62, 75, and 75%, respectively.

The results of repeated measures ANOVA showed that LT, IV, and the interactions between ST and IV, and LT, ST, and IV significantly affected net nitrification and mineralization rates (Table 1, $P < 0.01$). ST and the interaction between LT and IV apparently affected the soil net N mineralization rate, whereas the interaction between LT and ST was found to not affect the soil net N transformation rate. Among the four

Table 1
Effects of landscape type (LT), sampling time (ST), interannual variation (IV), and their interactions on the soil inorganic N pool and net N transformation rate revealed by repeated measures ANOVA.

Variables	NO_3^--N F-values	NH_4^+-N F-values	Total inorganic N F-values	R_n F-values	R_m F-values
LT	21.62***	13.63***	14.17***	4.20**	7.61***
ST	34.70***	52.76***	48.96***	1.83	7.69***
IV	125.19***	253.85***	150.90***	17.08***	24.85***
LT * ST	7.53***	2.95**	6.47***	1.25	0.83
LT * IV	0.49	5.64***	0.71	1.48	1.97*
ST * IV	5.24***	127.08***	19.87***	14.77***	8.29***
LT * ST * IV	2.20***	2.16***	1.74**	2.53***	2.47***

NO_3^--N, nitrate N concentration; NH_4^+-N, ammonium N concentration; R_n, net nitrification rate; R_m, net mineralization rate; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

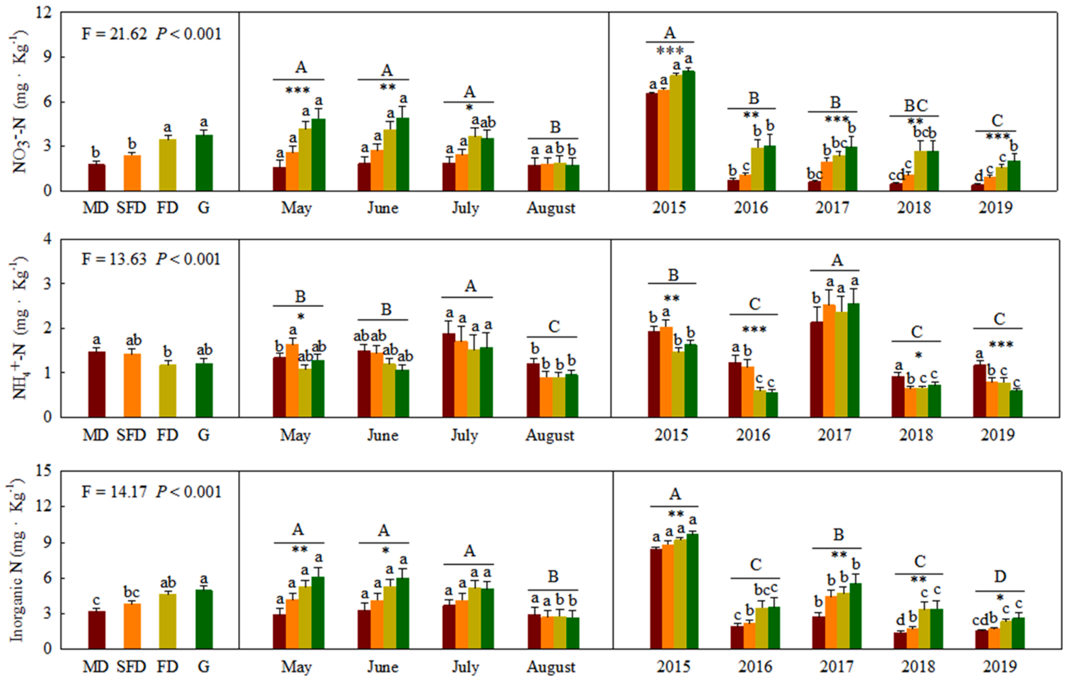

Fig. 1. Dynamic changes in the soil inorganic N pool among the four landscape types during the growth season from 2015 to 2019. Different lowercase letters indicate significant difference among different landscape types, or different months or years in the same landscape type. Different capital letters indicate significant difference among different months or years. The significant differences between different landscape types among the same month or year are indicated by asterisks, *P < 0.05, **P < 0.01, ***P < 0.001. NO_3^--N, nitrate N concentration; NH_4^+-N, ammonium N concentration; MD, mobile dunes; SFD, semi-fixed dunes; FD, fixed dunes; G, dune grasslands.

LTs, the relatively higher net nitrification and net mineralization rates occurred in FD (Fig. 2). The mean net mineralization rate of the four LTs was much lower in July, whereas no significant difference was found among the four months in the mean net nitrification rate of the four LTs. Furthermore, no significant differences were found among the four months during the growing season in the net nitrification rate in SFD, FD, and G. Consistent with the changes in mean NO_3^--N and total inorganic N concentration in the four LTs, the mean net nitrification and mineralization rates of the four LTs were the highest in 2015. As shown in Fig. 2, soil nitrification was the main process dominating soil N mineralization.

3.2. *Correlation of soil inorganic N pool and net N transformation rate with climate factors, vegetation characteristics, and soil properties*

The results of Pearson's correlation analysis showed that soil nitrate N and ammonium N concentration, soil net nitrification, and net mineralization rate were correlated with many factors (Table 2). The NO_3^--N concentration was negatively correlated with precipitation (r = −0.190, P < 0.01) and plant height (r = −0.167, P < 0.01), and it was positively correlated with EC (r = 0.545, P < 0.01) and SWC (r = 0.173, P < 0.01). The NH_4^+-N concentration was negatively correlated with vegetation cover (r = −0.378, P < 0.01), pH (r = −0.235, P < 0.01), and SWC (r = −0.251, P < 0.01) but positively correlated with T_a (r = 0.185,

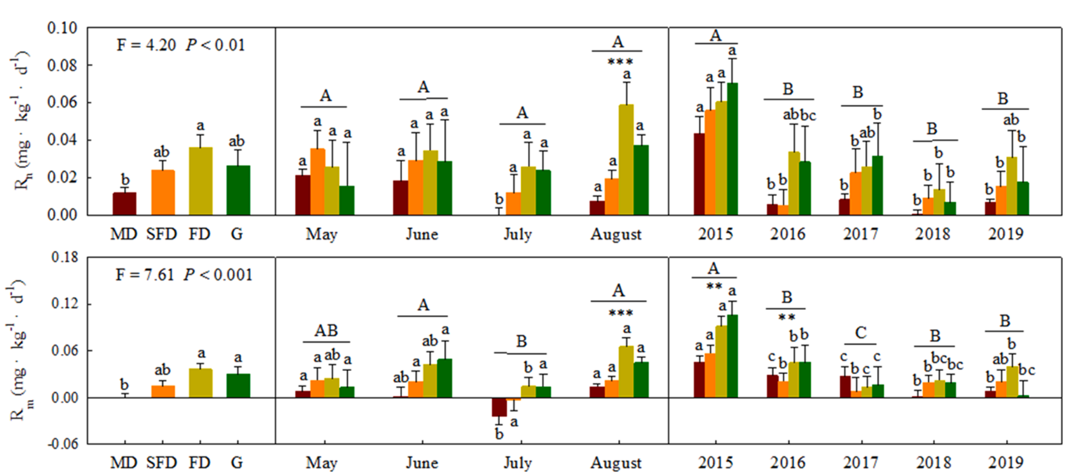

Fig. 2. Dynamic changes in the soil net N transformation rate among the four landscape types during the growth season from 2015 to 2019. Different lowercase letters indicate significant difference among different landscape types, or different months or years in the same landscape type. Different capital letters indicate significant difference among different months or years. The significant differences between different landscape types among the same month or year are indicated by asterisks, **P < 0.01, ***P < 0.001. R_n, net nitrification rate; R_m, net mineralization rate; MD, mobile dunes; SFD, semi-fixed dunes; FD, fixed dunes; G, dune grasslands.

Table 2
Pearson's correlation analysis of the soil inorganic N pool and net N transformation rate with climate factors, vegetation characteristics, and soil properties during landscape evolution.

	NO_3^--N ($mg \cdot kg^{-1}$)	NH_4^+-N ($mg \cdot kg^{-1}$)	Total inorganic N ($mg \cdot kg^{-1}$)	R_n ($mg \cdot kg^{-1} \cdot d^{-1}$)	R_m ($mg \cdot kg^{-1} \cdot d^{-1}$)
T_a (°C)	0.024	0.185**	0.083*	−0.011	−0.033
Precipitation (mm)	−0.190**	0.059	−0.146**	0.120**	0.049
Vegetation cover (%)	0.053	−0.378**	−0.110*	−0.028	0.179**
Plant height (cm)	−0.167**	−0.068	−0.170**	0.199**	0.212**
Suspension pH	−0.024	−0.235**	−0.098*	−0.100*	−0.039
Suspension EC ($\mu s \cdot cm^{-1}$)	0.545**	−0.041	0.415**	−0.021	−0.021
SWC (%)	0.173**	−0.251**	0.067	−0.102*	−0.026
T_s (°C)	−0.051	0.098*	−0.009	0.139**	0.119**

NO_3^--N, nitrate N concentration; NH_4^+-N, ammonium N concentration; R_n, net nitrification rate; R_m, net mineralization rate; T_a, air temperature; EC, electrical conductivity; SWC, soil water content on weight basis; T_s, soil temperature.

$P < 0.01$) and T_s ($r = 0.098$, $P < 0.05$). The total inorganic N concentration was negatively correlated with precipitation ($r = -0.146$, $P < 0.01$), vegetation cover ($r = -0.110$, $P < 0.05$), plant height ($r = -0.170$, $P < 0.01$), and pH ($r = -0.098$, $P < 0.05$) but positively correlated with T_a ($r = 0.083$, $P < 0.05$) and EC ($r = 0.415$, $P < 0.01$). The soil net nitrification rate was negatively correlated with pH ($r =$

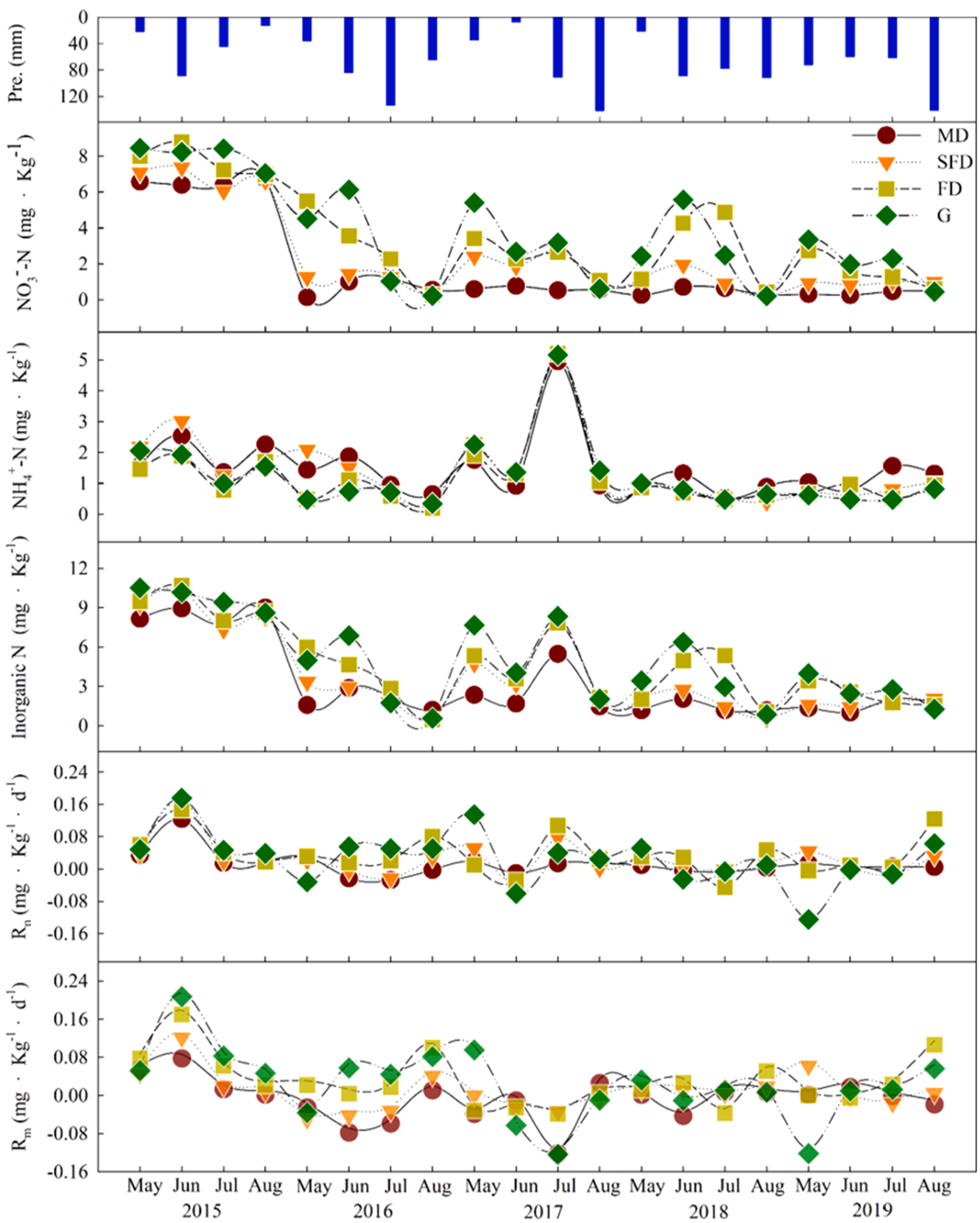

Fig. 3. Changing trends in the soil inorganic N pool and net N transformation rate in four landscape types according to the changes in the magnitude of precipitation events during the growth season from 2015 to 2019. Pre., precipitation; NO_3^--N, nitrate N concentration; NH_4^+-N, ammonium N concentration; R_n, net nitrification rate; R_m, net mineralization rate; MD, mobile dunes; SFD, semi-fixed dunes; FD, fixed dunes; G, dune grasslands. May, June, July, and August were abbreviated to M, JU, JL, and A, respectively. The month is preceded by the year from 2015 (15) to 2019 (19).

−0.100, $P < 0.05$) and SWC (r = −0.102, $P < 0.05$) but positively correlated with precipitation (r = 0.120, $P < 0.01$), plant height (r = 0.199, $P < 0.01$), and T_s (r = 0.139, $P < 0.01$). Additionally, the soil net mineralization rate was positively correlated with vegetation cover (r = 0.179, $P < 0.01$), plant height (r = 0.212, $P < 0.01$), and T_s (r = 0.119, $P < 0.01$). As precipitation negatively affected soil nitrate and inorganic N concentration but positively affected soil net nitrification rate, the soil inorganic N pool and net N transformation rate fluctuated with changing precipitation during the growing season from 2015 to 2019 (Fig. 3)

The RDA analysis demonstrated that the soil net N transformation rate was closely related to climate factors, vegetation characteristics, and soil properties (Fig. 4). According to the RDA analysis run for all data (i.e., from May to August 2015–2019), the first two RDA axes accounted for 27.32% of the total variation in the soil net N transformation rate (Table 3). The ammonium N concentration, nitrate N concentration, plant height, T_a, and vegetation cover could explain 10.1, 8.4, 3.9, 1.7, and 1.4% of the total variation in the soil net N transformation rate, respectively. The RDA analysis of August data for all years, showed that the first two RDA axes accounted for 46.04% of the total variation in the soil net N transformation rate (Table 3). The EC, T_a, and precipitation could explain 14.6, 7.4, and 6.4% of the total variation in the soil net N transformation rate, respectively.

For all data (from May to August 2015–2019), the variation partitioning analysis showed that soil properties (i.e., nitrate N concentration, ammonium N concentration, pH, EC, SWC, and T_s) could explain 11.8% of the total variation in the soil net N transformation rate, whereas vegetation characteristics (i.e., vegetation cover and plant height) only explained 2.9% and climate factors (i.e., T_a and precipitation) only explained 1.3% of the variation (Fig. 5a). Vegetation characteristics and soil properties together explained 4.5%, and soil properties and climate factors together explained 5.0%. Variation partitioning analysis of August data for all years showed that soil properties explained 10.6%, vegetation characteristics explained 5.4%, and climate factors explained 18.7% of the total variation in the soil net N transformation rate (Fig. 5b). Vegetation characteristics and soil properties together explained 2.4% of the variation, and soil properties and climate factors together explained 1.1%. Shared variance for the three factors was 5.5%.

4. Discussion

4.1. Effects of landscape evolution caused by vegetation restoration on soil inorganic N pool and net N transformation rate

Our study indicated that soil nitrate and ammonium N concentration significantly increased with the landscape evolution gradient in our sandy grassland system (Figs. 1 and 2), suggesting that landscape evolution caused by vegetation restoration can promote soil inorganic N accumulation and enhance the soil available N in semiarid sandy grasslands. These results agree with those reported by Chen et al. (2009), Gurlevik and Karatepe (2016), and Li et al. (2018). Furthermore, there was a decreasing trend in NH_4^+-N concentration during the landscape evolution process due to the lower soil organic matter input, which may enhance the microbial autotrophic metabolism that assimilates NH_4^+-N (Tapia-Torres et al., 2015). Sandy grassland restoration will promote biotic and abiotic environmental factors in vegetation and soil, which will have consequences on the soil inorganic N pools (Li et al., 2018). The increased vegetation cover and plant height from MD to G enhanced plant biomass, which directly affected the input of soil organic matter and indirectly altered the soil inorganic N pool (Zhou et al., 2009). The alkaline soil (MD: pH 7.62; G: pH 8.54; Table A.1) promoted soil nitrification, which can satisfy sandy plant growth as they mainly absorb the soil NO_3^--N of inorganic N (Chen et al., 2013; Cheng et al., 2013). The increased SWC (the 64.8% increment from MD to G) and suitable T_s are key factors that affect the soil inorganic N pool in desert regions (Li et al., 2018). Additionally, the loose soil texture and high air permeability in our soils as demonstrated by a previous study (Su et al., 2006) can allow a large proportion of soil NH_4^+-N to convert into NO_3^--N in this semiarid sandy grassland (Keller et al., 2004; Bechtold and Naiman, 2006).

Our findings indicated that the net nitrification rate was higher in FD, and the net N mineralization rate increased from MD to FD or G (Fig. 2). Our previous study has demonstrated that the aboveground biomass and litter mass increased with the restoration of degraded vegetation (Zuo et al., 2015), which may indirectly affect soil N transformation (Rosenzweig et al., 2016). The microbial activity and alkaline soil can significantly stimulate the net nitrification rate (Cheng et al., 2013). Our result is in agreement with a previous study that reported increases in productivity stimulating the soil net N mineralization rate in a grassland ecosystem (Bardgett and Wardle, 2003). As indicated by our study, soil net N transformation rate was closely related to SWC and T_s,

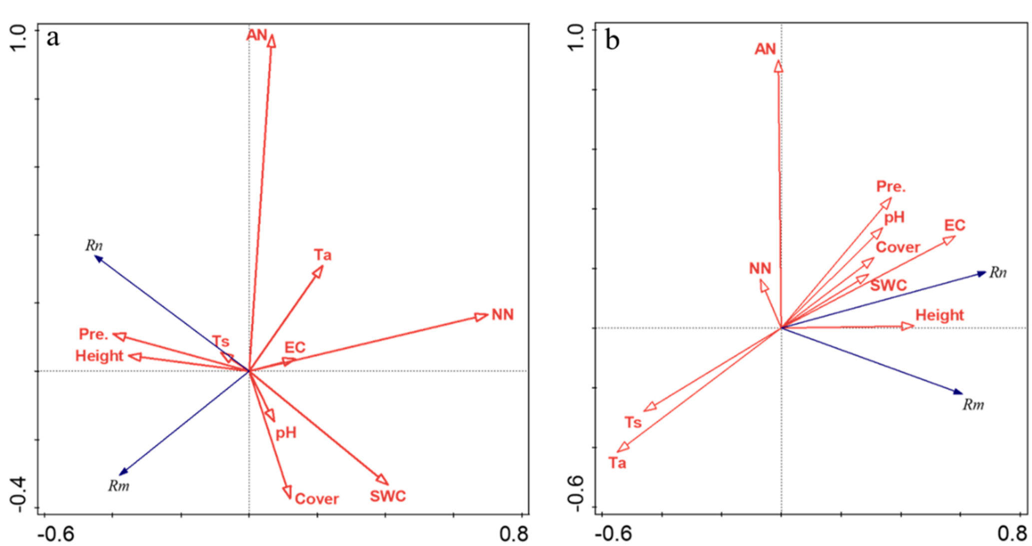

Fig. 4. Relationship of soil net N transformation rate with climate factors, vegetation characteristics, and soil properties revealed by the redundancy analysis. R_n, net nitrification rate; R_m, net mineralization rate; T_a, air temperature; Pre., precipitation; NN, nitrate N concentration; AN, ammonium N concentration; EC, suspension electrical conductivity; SWC, soil water content on weight basis; T_s, soil temperature. a) Analysis of May to August in all years; b) Analysis of August in all years.

Table 3
The proportion of total variation explained by climate factors, vegetation characteristics, and soil properties on soil net N transformation rate revealed by redundancy analysis.

	May to August 2015 to 2019				August 2015 to 2019			
	Explained variation %	*P* values	Axis 1	Axis 2	Explained variation %	*P* values	Axis 1	Axis 2
Explained variation (cumulative)			17.04	27.32			41.86	46.04
T_a	1.7	0.046			7.7	0.02		
Precipitation	0.7	0.16			6.4	0.02		
Vegetation cover	1.4	0.046			2.1	0.138		
Plant height	3.9	0.002			2.7	0.084		
NO_3^--N	8.4	0.002			2.7	0.096		
NH_4^+-N	10.1	0.002			3.5	0.082		
Suspension pH	<0.1	0.928			4.1	0.058		
Suspension EC	0.7	0.16			14.6	0.006		
SWC	<0.1	0.616			0.5	0.526		
T_s	0.4	0.294			1.7	0.174		

T_a, air temperature; NO_3^--N, nitrate N concentration; NH_4^+-N, ammonium N concentration; EC, electrical conductivity; SWC, soil water content on weight basis; T_s, soil temperature.

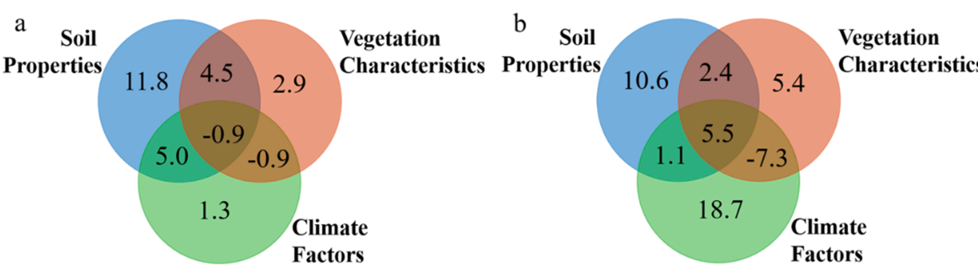

Fig. 5. Variation partitioning analysis of the soil net N transformation rate with climate factors, vegetation characteristics, and soil properties. Soil Properties (i.e., nitrate N concentration, ammonium N concentration, suspension pH, suspension electrical conductivity, soil water content on weight basis and soil temperature); Vegetation Characteristics (i.e., vegetation cover and plant height); Climate Factors (i.e., air temperature and precipitation). a) Variation partitioning analysis of May to August in all years; b) variation partitioning analysis of August in all years.

and the increased SWC and suitable T_s from MD to G can enhance the soil net N transformation rate. A previous study conducted in our study area demonstrated that degraded vegetation restoration increased the proportion of clay content (Guo et al., 2008), leading to a higher proportion in G than FD, thus significantly inhibiting the soil N transformation rate in G (Li et al., 2020).

4.2. Seasonal and interannual patterns of soil inorganic N pool and net transformation rate during landscape evolution caused by vegetation restoration

Soil inorganic N (including NO_3^--N and NH_4^+-N) concentration decreased to its lowest value in August, whereas the net N nitrification and mineralization rate increased over time and peaked in August during the growing season (Figs. 1 and 2). The NO_3^--N and total inorganic N concentration decreased at the same time as the growing vegetation cover and plant height from May to August, suggesting that the soil inorganic N pool decreased as the plants took up N during the growing season (Zhou et al., 2009). The dynamic changes in SWC in each month may also have significantly affected the soil inorganic N pool and N transformation during degraded vegetation restoration (Li et al., 2018). In addition, the soil net N nitrification and mineralization positively correlated with T_s changes during the growing season (Table 2), which could affect the soil microbial activity. The soil net nitrification and mineralization rates in FD and G were significantly higher in August than those in May, June, and July, suggesting that higher T_a may stimulate microbial activity, consequently enhancing soil N transformation (Wen et al., 2016). Additionally, we found that the NO_3^--N concentration was negatively correlated to precipitation. Thus, the highest NO_3^--N concentration and total inorganic N concentration were found in 2015 due to the low precipitation of 168.2 mm during the growing season that year (Fig. 3). We also observed largescale enhancement of the NO_3^--N and inorganic N concentration in August 2015 and June 2017. The lower precipitation of 13.0 mm and 7.4 mm, respectively, may have caused lower aboveground biomass, which consequently decreased the absorption of inorganic N by plants. The drought environment retained abundant inorganic N pool possibly due to the deficient in leaching influences and due to the marginally NO_3^--N absorption as the plant mortality or plant biomass decrease. The leaching possibly decreased soil NO_3^--N content. Precipitation amount increase could have accelerated N leaching by stimulating both soil N availability and water percolation rates at a time when plant uptake was absent (Yahdjian et al., 2006).

The IV of NO_3^--N, total inorganic N concentration, and net N transformation rate was significant during all years from 2015 to 2019 mainly owing to the dynamic changes in growth season precipitation and T_a. The altered precipitation amount in plant growth seasons illustrated that there was a significant increase in the NH_4^+-N concentration at the beginning of the wet period in July 2017 immediately following the dry period in June 2017 (Fig. 3). These results agree with observations from a previous study, which also demonstrated that mineralization flush occurred with low precipitation intensity after soil re-wetting (Hagedorn et al., 1997). In contrast, the net N mineralization rate will significantly decrease at the onset of a heavy precipitation season. SWC, which is strongly affected by precipitation, and the continuous restoration of degraded vegetation can profoundly affect net nitrification and N mineralization rates (Wang et al., 2006). The monthly mean T_a from May to August was 17.2, 20.8, 23.4, and 22.6 °C in 2015; 18.3, 21.8, 24.1, and 22.7 °C in 2016; 18.1, 21.2, 25.4, and 21.7 °C in 2017; 17.7, 22.9, 25.8, and 22.9 °C in 2018; and 18.3, 21.4, 24.5, and 21.2 °C in 2019, respectively. The dynamic changes in T_a from 2015 to 2019 may have also played a considerable role in the changes in the soil inorganic N pool and N transformation by indirectly altering SWC and T_s.

4.3. Climate factors, vegetation characteristics, and soil properties co-affected soil inorganic N pool and net N transformation during landscape evolution

The spatio-temporal heterogeneity of precipitation affects the soil N availability (Liu et al., 2017), influencing soil N mineralization. Precipitation regimes also affect soil organic matter decomposition, and thus influence the soil nutrient cycle (Bai et al., 2012). For instance, the N supply strongly changes with periods of heavy precipitation. There was also a negative correlation between NO_3^--N, total inorganic N concentration, and precipitation too. This result is in agreement with that of a previous study, which demonstrated that the topsoil mineral N concentration significantly declined due to NO_3^--N leaching from a shallow root zone (Hagedorn et al., 1997). Both the precipitation amount and the drought–heavy precipitation frequency definitely affect the N mineralization rate. Precipitation can also indirectly affect the soil inorganic N pool and N transformation by altering the vegetation characteristics (such as vegetation cover, plant height, and plant biomass) and soil properties (such as SWC and T_s). Additionally, T_a strongly affects the microbial activity, thus indirectly affecting soil N transformation (Nguyen et al., 2019).

Vegetation cover and plant height would increase with sandy grassland restoration, concomitantly with increases in the soil fine particle content (Guo et al., 2008), which would consequently reduce the soil evaporation and further improve the soil water holding capacity and thermal conductivity in semiarid sandy grasslands. The soil net N mineralization rate was positively correlated with vegetation characteristics (vegetation cover and plant height), consequently affecting the soil N transformation by altering plant biomass (Zhou et al., 2009). Vegetation cover and plant height determined the plant biomass, which not only determined the inorganic N absorption by plant, but also controlled the organic matter input into the soil after plant death. The different landscape types caused changes in plant community structure and composition, such as litter decomposition, shaded areas, among the MD, SFD, FD, and G.

The soil net N nitrification rate, however, was negatively correlated with the SWC in our study, demonstrating that high SWC would limit soil N nitrification and then cause denitrification (Wen et al., 2016). The result suggested that the SWC is the critical limiting factor in controlling soil N nitrification in semiarid sandy grasslands. The SWC, modulated by precipitation regime, was able to control the denitrification activity and enzyme dynamics, which was concomitantly modulated by soil pH, and both of them consequently affected the NO_3^--N and inorganic N concentration, as well as the net nitrification rate with landscape evolution caused by degraded grassland restoration. Previous study has shown that the SWC and T_s could mostly affect the soil gross mineralization rate (Liu et al., 2017; Keller et al., 2004; Wang et al., 2016). A more active microbial community and more sufficiently mineralizable organic substrate could promote soil N availability. The soil inorganic N pool and N mineralization in the study region were negatively correlated with pH, demonstrating that the higher pH in alkaline environments (pH $>$ 8) of semiarid regions cannot enhance N mineralization (Bai et al., 2005).

5. Conclusion

Our findings indicated that soil inorganic N concentration and net N transformation rate significantly increased with landscape evolution caused by vegetation restoration, suggesting that degraded vegetation restoration can improve soil N availability and transformation in semiarid sandy grasslands. Soil nitrate N was the main form in the inorganic N pool, revealing that the plants in our study area prefer to absorb NO_3^--N. Soil nitrification also dominated the soil N transformation to satisfy the high nutrient demand for plant growing. Climate factors, vegetation characteristics, and soil properties co-determined the dynamic changes in the soil N transformation rate, but the contribution of each factor was not the same. The growth season variation in soil N transformation was mainly affected by soil properties, whereas climate factors played a dominant role in the interannual variation. The precipitation and drought–rewetting period also significantly modulated the inorganic N concentration and N transformation rate during degraded vegetation restoration. These results implied that climate factors interacted with vegetation characteristics and soil properties, which further mediated the soil N availability and N transformation. To the best of our knowledge, the present study is one of the first to consider climate, vegetation, and soil properties together when exploring soil N transformation and estimate the contribution of each factor. These findings enhance our understanding of soil N transformation during landscape evolution caused by vegetation restoration and also indicate that the restoration of degraded vegetation is a long-term process that requires more rapid and effective management practices.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Authors thank all the members of Naiman Desertification Research Station and Urat Desert-grassland Research Station, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences (CAS), for their help in field work. This paper was financially supported by the National Natural Science Foundation of China(No. 41571106, 41622103), National Key Research and Development Plan (No. 2016YFC0500506), and Youth Innovation Promotion Association, CAS (No. 1100000036).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2021.105576.

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