# Long-term natural succession improves nitrogen storage capacity of soil on the Loess Plateau, China

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**Abstract.** Land-use change resulting from natural succession enhances the nitrogen (N) accumulation capacity of terrestrial ecosystems. To explore those factors that foster changes in soil N storage under evolving conditions of vegetation succession, a study on N storage at differing stages along a 150-year chronosequence was conducted in the Ziwuling Forest Region in the central part of the Loess Plateau, China. A principal finding was the rapid increase in N storage in the 0–60 cm soil layer, which achieves a stable value after the shrub community stage (~50–60 years), leading to the overall long-term (~150 years) accumulation of soil stored N in the post-abandonment secondary forest. Soil N accumulated mainly in the pioneer stage and showed a significant increase before the shrub community stage ($P < 0.05$). The N storage in the 0–60 cm soil layer changed from 5.8 to 8.4 Mg ha$^{-1}$ during the transition from abandoned farmland (~3–5 years) to climax community (*Quercus liaotungensis* Koidz forest) (~150 years). The N storage values were higher in the upper (<20 cm) than the deeper soil layers (>20 cm). In the topsoil (0–20 cm), N storage values showed a markedly positive correlation with soil organic carbon (SOC), total soil N and fine roots. In the deeper soil layers (20–40 and 40–60 cm) there was a correlation only with TN. Soil bulk density, soil water content and soil pH were not the determining factors behind N storage values in the topsoil (0–20 cm), although they did show negative, positive and negative correlations, respectively. In addition, they showed no consistent correlations in the lower soil layer (<20 cm). The results suggest that changes to N storage values were the result of the accumulation of SOC, total N and primary productivity during the process of forest succession, and this capacity is positively related to post-abandonment forest succession on the Loess Plateau, China.

**Additional keywords:** China, natural succession, nitrogen storage, Ziwuling Forest Region.

## Introduction

Nitrogen (N) is a key nutrient for all living organisms and is the most common limiting element for plant production in the terrestrial biosphere (Galloway *et al*. 2004). Therefore, it plays an important role in regulating both the structure (Gundale *et al*. 2006) and function (Cleveland *et al*. 2006) of terrestrial ecosystems. Identifying a terrestrial N sink, where the element accumulates and is held for a long period, has long been one of the most important issues in the field of biogeochemistry. Studies have shown that soil has the potential to function as such a long-term N sink (Burke *et al*. 2002; Chapuis-Lardy *et al*. 2007).

Soil is the largest N reservoir in the terrestrial biosphere, containing more than vegetation (Yang *et al*. 2007). Consequently, the dynamics of soil N storage could determine whether terrestrial ecosystems function as N

sources or sinks (Tian *et al*. 2006). The role N plays in the biogeochemical cycle of carbon (C) is crucial because C–N interactions are essential in determining whether terrestrial C sinks can be sustained over the long term (Luo *et al*. 2004, 2006). Carbon dioxide enrichment experiments indicate that N limitation directly influences terrestrial C sequestration (Hu *et al*. 2001; Schlesinger and Lichter 2001), a process fundamental to either mitigating or deferring global warming. Thus, there is a need to identify and describe biogeochemical cycles, not only globally, but especially those processes and system variables relevant at the regional spatio-temporal scale, because it is at the regional scale that landscape policies are implemented.

Luo *et al*. (2004) reported that N dynamics is a key parameter in the regulation of long-term terrestrial C sequestration. For example, increased N deposition could have the effect of

**Abbreviations:** Afs, Abandoned farmland stage; Hs, herbaceous community stage; Ss, shrub community stage; Pas, pioneering arbour community stage; Mfs, mixed forest community stage; Cs, climax community stage.

attenuating atmospheric $CO_2$ by stimulating the accumulation of forest biomass (Giardina *et al*. 2003). Therefore, elucidating the N dynamics in soils has important implications both for the sustainable management of land resources regionally and predictions of future C and N cycling globally.

The Loess Plateau, China, is an area suffering severe soil and water losses (Liu *et al*. 2007). Many studies report that secondary succession can recover the properties of degraded soil and maintain soil fertility (Feldpausch *et al*. 2004; Jia *et al*. 2005; Wang *et al*. 2011*a*; Deng *et al*. 2013*a*). For this reason, understanding secondary forest succession processes in the central region of the Loess Plateau is becoming increasingly important (Jia *et al*. 2005; Deng *et al*. 2013*a*). To improve the frail natural ecosystems of the Loess Plateau and alleviate degradation, the Chinese government launched a series of conservation programs aimed at restoring agricultural land to forest and grassland; this is the case for the study area, where farmland had already been abandoned and the process of natural secondary succession was under way. With regard to these ecosystem functions, the retention of C and N in soil is crucial (Prietzel and Bachmann 2012). Consequently, succession in the Ziwuling secondary forest has received significant attention from Chinese scientists (Zou *et al*. 2002; Jia *et al*. 2005; Wang *et al*. 2010; Deng *et al*. 2013*a*). Several studies have focused on changes to aboveground vegetation during secondary forest succession in the centre of the Loess Plateau (Zou *et al*. 2002; Wang *et al*. 2010). Deng *et al*. (2013*a*) studied soil C-storage responses to forest succession in the Ziwuling Forest Region of the Loess Plateau. However, there is little available information on soil N storage dynamics at different stages of natural regeneration in the area.

We hypothesised that natural regeneration significantly affects soil N conditions in the central region of the Loess Plateau. To test our hypothesis and evaluate N dynamics during succession from managed to natural communities in semi-arid regions, the objectives of this study were: (*i*) to estimate soil N storage along a long-term natural regeneration gradient, and (*ii*) to discuss the contributing factors and mechanisms controlling soil N storage.

## Materials and methods

The Ziwuling Forest Region (33°50′–36°50′N, 107°30′–109°40′E; 1100–1756 m a.s.l.) is in the hinterland of the Loess Plateau. The study area has landforms typical of hilly-gully loess topography and a mid-temperate, continental monsoon climate. The study was conducted on the Lianjiabian Forest Farm of the Heshui General Forest Farm of Gansu (35°03′–36°37′N, 108°10′–109°18′E; 1211–1453 m a.s.l.) covering a total area of 23 000 km². The area's mean annual temperature is 10°C (1960–2010) and the mean annual rainfall 587 mm (1960–2010) (Deng *et al*. 2013*a*). The region's soils are largely loessial, having developed from primitive or secondary loess parent materials (Cheng *et al*. 2012), which are evenly distributed 50–130 m above red earth consisting of calcareous cinnamon soil (Jia *et al*. 2005). Soil pH ranges from 7.92 to 8.31 (Deng *et al*. 2013*a*). The area is covered in species-rich, uniform forests with a forest canopy density of 80–95% (Deng *et al*. 2013*a*), and the distribution of ground

litter was uniform. The region's natural biomes are deciduous broadleaf forests of which the climax vegetation is the *Quercus liaotungensis* Koidz forest. Throughout the region, *Populus davidiana* Dode and *Betula platyphylla* Suk communities dominate the pioneer forests; *Sophora davidii* (Franch.) Skeels, *Hippophae rhamnoides* (Linn.), *Rosa xanthina* Lindl and *Spiraea pubescens* Turcz are the main shrub species; and *Bothriochloa ischaemun* (Linn.) Keng, *Carex lanceolata* Boott, *Potentilla chinensis* (Ser), *Lespedeza dahurica* (Laxm.) Schindl and *Stipa bungeana* Trin are the main herbaceous species.

The post-abandonment secondary forests regenerated naturally on abandoned farmland after many local inhabitants emigrated from the Ziwuling Forest Region during a national conflict in 1842–1866. Chen (1958), who investigated the vegetation recovery of the Ziwuling Forest Region in the 1950s, determined that *P. davidiana* made up 70% of the vegetation cover after about a century. Zou *et al*. (2002) investigated the vegetation succession three times (1962, 1982 and 2000). They found that *Q. liaotungensis* forests had replaced *P. davidiana* forests within ± 50 years. Thus, the recovery period for *Q. liaotungensis* forests was ~150 years (Wang *et al*. 2010). In the 20 or more years ranging from 1940 to the 1960s, famine, war and disasters led some people to immigrate and reclaim land in the region. The process of human emigration and immigration, in which arable land has been abandoned more than once in different areas, has yielded different successional stages on the degraded sloping land. Based on previous research, we chose six communities that were at different stages of succession in the Ziwuling Forest Region. Two methods were used to determine the ages of the communities. For the shrub and herbaceous communities with <60 years of succession, we verified the length of time both by visiting local elders and by referring to land contracts between farmers and the government. For the forest community, which had >60 years of recovery, we determined the length of time by boring tree rings and checking related written sources (Wang *et al*. 2010).

### Experiment design and sampling

A field survey was undertaken between 15 July and 5 August 2005. Five sampling areas were randomly chosen from each of the six vegetation communities (Table 1), representing 3–5, 20–25, 50–60, 90–100, 120–130 and 150 years of natural succession. The size of the plots varied, with the communities being 20 m by 20 m in the forest communities, 5 m by 5 m in the shrub communities, and 2 m by 2 m in the herbaceous communities. The plots were not more than 5 km apart and the largest relative elevation difference between two plots was <120 m. Most of the plots were facing north, with a slope gradient of <20°.

Soil samples were taken at five points, i.e. the four corners and centre, of the soil sampling sites in the six successional stages as described above. Sampling, using a soil-drilling sampler, was done in three soil layers: 0–20, 20–40, and 40–60 cm. In each plot, the ground litter was first removed but not measured; the soil samples were then taken at the five sampling points and mixed together to effectively form one soil sample for each soil layer. After removing the stones, leaves,

**Table 1.   Geographical and vegetation characteristics at different succession stages in the Ziwuling Forest Region of the Loess Plateau**

Afs, Abandoned farmland stage; Hs, herbaceous community stage; Ss, shrub community stage; Pas, pioneering arbour community stage; Mfs, mixed forest community stage; Cs, climax community stage. H, S, F: Herb, shrub, forest, respectively

| Succession stage (year) | Quadrat size (number) | Latitude (N) | Longitude (E) | Cover (%) | Altitude (m) | Aspect | Slope (°) | Dominant species |
|---|---|---|---|---|---|---|---|---|
| Afs (3–5) | 2 m by 2 m (5) | 36°05′05.4″ | 108°31′57.4″ | 62 | 1357 | Half-north facing | 3–6 | *Lespedeza bicolor* |
| Hs (20–25) | 2 m by 2 m (5) | 36°05′19.6″ | 108°31′36.5″ | 95 | 1330 | Half-north facing | 14–16 | *Bothriochloa ischaemum, Lespedeza dahurica* |
| Ss (50–60) | 5 m by 5 (5) | 36°04′57.9″ | 108°31′53.1″ | 85 | 1346 | North facing | 12–22 | S: *Sophora davidii*, H: *Carex lanceolata*: or S: *Hippophae rhamnoides*, H: *Carex lanceolata* |
| Pas (90–100) | 20 m by 20 m (5) | 36°02′54.5″ | 108°31′44.8″ | 90 | 1432 | Half-north facing | 12–16 | S: *Spiraea schneideriana*, H: *Carex lanceolata* |
| Mfs (120–130) | 20 m by 20 m (5) | 36°04′14.1″ | 108°27′58.6″ | 90 | 1440 | Half-north facing | 12–15 | F: *Populus davidiana* + *Quercus liaotungensis*, S: *Spiraea schneideriana*, H: *Carex lanceolata*; |
| Cs (150) | 20 m by 20 m (5) | 36°02′56.1″ | 108°32′13.6″ | 95 | 1427 | North facing | 20–22 | F: *Quercus liaotungensis*, S: *Rosa hugonis*, H: *Carex lanceolata* |

roots and large pieces of debris, the soil samples were sieved through a 2-mm screen, air-dried and stored at room temperature for determination of physical and chemical properties. The bulk density (BD) of the different soil layers was measured using a steel soil bulk sampler, 5.0 cm in diameter and 5.0 cm high (three replicates), at points adjacent to the soil sampling plots. Thus, one pit was dug to 60 cm depth in the centre of the plot and three soil BD samples were taken. The original volume of each soil core and its dry mass after oven-drying at 105°C for 48 h were measured.

To measure roots, soil sampling was repeated three times in three soil layers (0–20, 20–40, and 40–60 cm) in the centre of each plot using a 9-cm-diameter root auger. The majority of the roots found in the soil samples were isolated using a 2-mm sieve. The remaining fine roots taken from the soil samples were isolated by spreading the samples in shallow trays, overfilling the trays with water, and allowing the outflow from the trays to pass through a 0.5-mm mesh sieve. No attempts were made to distinguish between living and dead roots. All of the roots thus isolated were oven-dried at 65°C for 48 h. The fine roots (FR; diameter <2 mm) were then isolated using a vernier caliper and weighed to within 0.01 g.

*Physical and chemical analysis*

Because the occurrence of coarse particles in the loessial soils of the study region is rare, they were considered negligible (Liu *et al*. 2011), so soil BD was calculated depending on the inner diameter of the core sampler, sampling depth and the oven-dried weight of the composite soil samples (Jia *et al*. 2005). Soil organic C (SOC) was assayed by dichromate oxidation (Kalembasa and Jenkinson 1973) and soil total N (TN) concentration was assayed using the Kjeldahl method (Jackson 1973). Soil water content was measured gravimetrically and expressed as a percentage of soil water to dry soil weight. Soil pH was measured in distilled water mixed 5 : 1 (by mass) with dry soil using a Delta 320 pH meter (Mettler-Toledo Instruments (Shanghai) Ltd, China) equipped with a calibrated combined glass electrode.
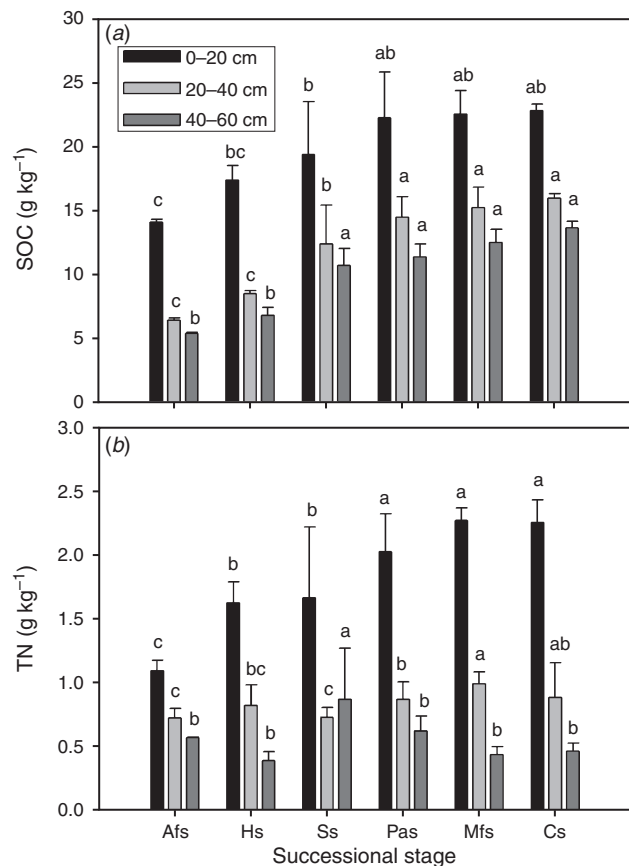


**Fig. 1.**   Changes in (*a*) soil organic carbon (SOC) and (*b*) total nitrogen concentration (TN) in three soil layers with the vegetation succession gradient at 0–60 cm soil depth. Bars are mean and capped lines are s.e.; sample size, *n* = 5. Letters above the bars are for comparison in the same soil layer at the different restoration stages; bars with the same letter are not significantly different at *P* = 0.05. Afs, Abandoned farmland stage; Hs, herbaceous community stage; Ss, shrub community stage; Pas, pioneering arbour community stage; Mfs, mixed forest community stage; Cs, climax community stage.

### Calculation of soil N storage

Because our soil samples did not contain any coarse fraction (>2 mm), the study used the following equation to calculate soil N storage (Rytter 2012):
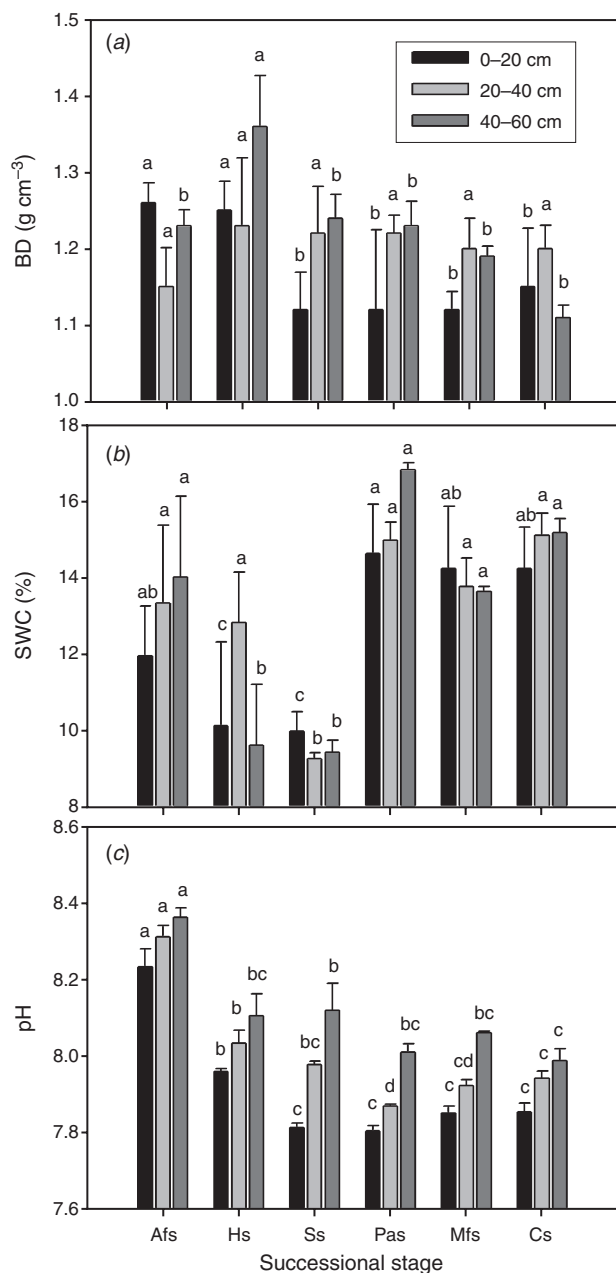
$$Ns = BD \times TN \times D/10$$



**Fig. 2.** Changes in (*a*) soil bulk density (BD), (*b*) soil water content (SWC), and (*c*) soil pH in three soil layers with the vegetation succession gradient at 0–60 cm soil depth. Bars are mean and capped lines are s.e.; sample size, $n = 5$. Letters above the bars are for comparison in the same soil layer at the different restoration stages; bars with the same letter are not significantly different at $P = 0.05$. Afs, Abandoned farmland stage; Hs, herbaceous community stage; Ss, shrub community stage; Pas, pioneering arbour community stage; Mfs, mixed forest community stage; Cs, climax community stage.

where Ns is soil N storage (Mg ha$^{-1}$), BD is soil bulk density (g cm$^{-3}$), TN is soil total N concentration (g kg$^{-1}$), and D is soil thickness (cm).

### Statistical analyses

One-way ANOVA was used to analyse the mean of the same soil layers taken from across the different successional stages. Differences were evaluated at $P = 0.05$. When significance was observed ($P < 0.05$), a least significant difference (l.s.d.) post-hoc test was used to carry out multiple comparisons. GLM (generalised linear model) was adopted to determine whether there were significant correlations between soil N storage and the soil properties measured in the study. All statistical analyses were performed using the software program SPSS, ver. 17.0 (SPSS Inc., Chicago, IL, USA).

## Results

### Soil organic carbon and total nitrogen

Along the vegetation succession gradient, the SOC increased quickly and tended to be stable after the pioneering arbour
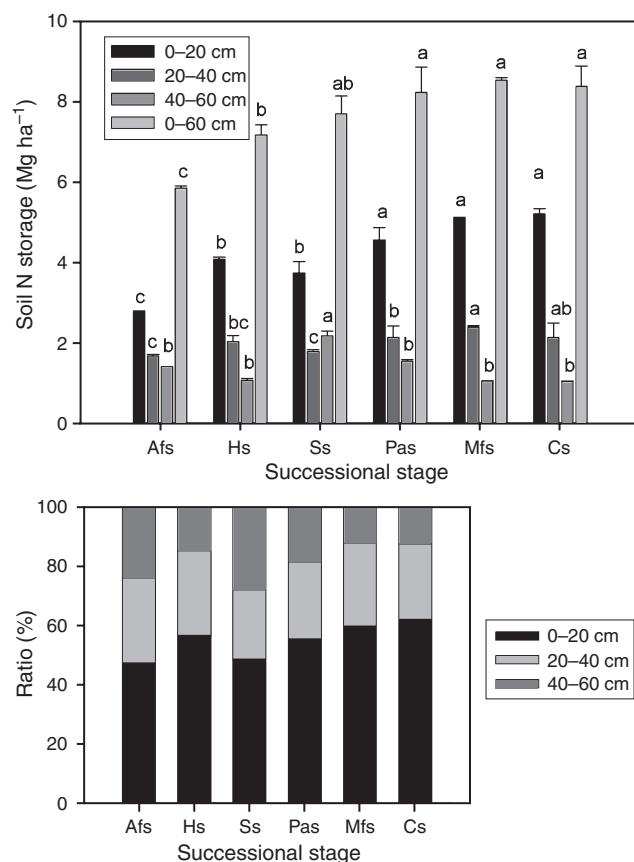


**Fig. 3.** Changes in (*a*) soil N storage and (*b*) the ratio of N storage in each soil layer changes with the vegetation succession gradient at 0–60 cm soil depth. Bars are mean and capped lines are s.e.; sample size, $n = 5$. Letters above the bars are for comparison in the same soil layer at the different restoration stages; bars with the same letter are not significantly different at $P = 0.05$. Afs, Abandoned farmland stage; Hs, herbaceous community stage; Ss, shrub community stage; Pas, pioneering arbour community stage; Mfs, mixed forest community stage; Cs, climax community stage.

community stage (Pas; >90–100 years) (Fig. 1*a*). Before Pas (<50–60 years), the SOC in the 0–20, 20–40, and 40–60 cm soils increased significantly along with vegetation succession ($P < 0.05$) (Fig. 1*a*). The highest and the lowest SOC contents were in the climax community stage (Cs; ~150 years) and the abandoned farmland stage (Afs; 3–5 years). A similar trend was observed for TN. The TN in the 0–20 cm soil increased with vegetation succession, becoming nearly constant (Fig. 1*b*) following Pas (>90–100 years). The TN in the 20–40 cm soil increased slowly, and tended to be stable after the mixed forest community stage (Mfs; >120–130 years) (Fig. 1*b*); the TN in the 40–60 cm soil remained almost unchanged, except in the shrub community stage (Ss; 50–60 years) (Fig. 1*b*), which may due to the occurrence of the $N_2$-fixing species *S. davidii* and *H. rhamnoides* (Table 1).

### Soil bulk density

With vegetation succession, BD varied mainly in the topsoil layer (0–20 cm) (Fig. 2*a*), where it decreased significantly with vegetation succession ($P < 0.05$) (Fig. 2*a*). In the early stages of vegetation succession (Afs and Hs), BD did not significantly vary ($P > 0.05$), and tended to be stable after Ss (50–60 years) (Fig. 2*a*). The BD in the 20–40 layers showed no significant difference in the six restoration stages ($P > 0.05$) (Fig. 2*a*). The BD in the 40–60 cm layers at Hs was significantly higher than other stages.

### Soil N storage

In the long term (~150 years), N storage in the 0–60 cm soil layer increased rapidly and tended to be stable after Ss (50–60 years), and achieved its highest value at roughly Mfs (120–130 years) (Fig. 3*a*). The soil N accumulated mainly in the early succession stages, and significantly increased before Ss ($P < 0.05$). From Afs to Cs, the N storage values in the 0–60 cm soil were 5.8, 7.2, 7.7, 8.2, 8.5 and 8.4 Mg ha$^{-1}$, respectively. The N storage was greater in the upper than the lower soil layers (Fig. 3*b*). The N storage in the 0–20 cm soil increased with vegetation succession, and that in the 20–40 cm soil was higher in the latter stages than the early stage. The N storage in the 40–60 cm soil layer showed a similar trend to TN in the 40–60 cm soil layer, which was nearly unchanged, except at Ss (50–60 years) (Fig. 3*a*).
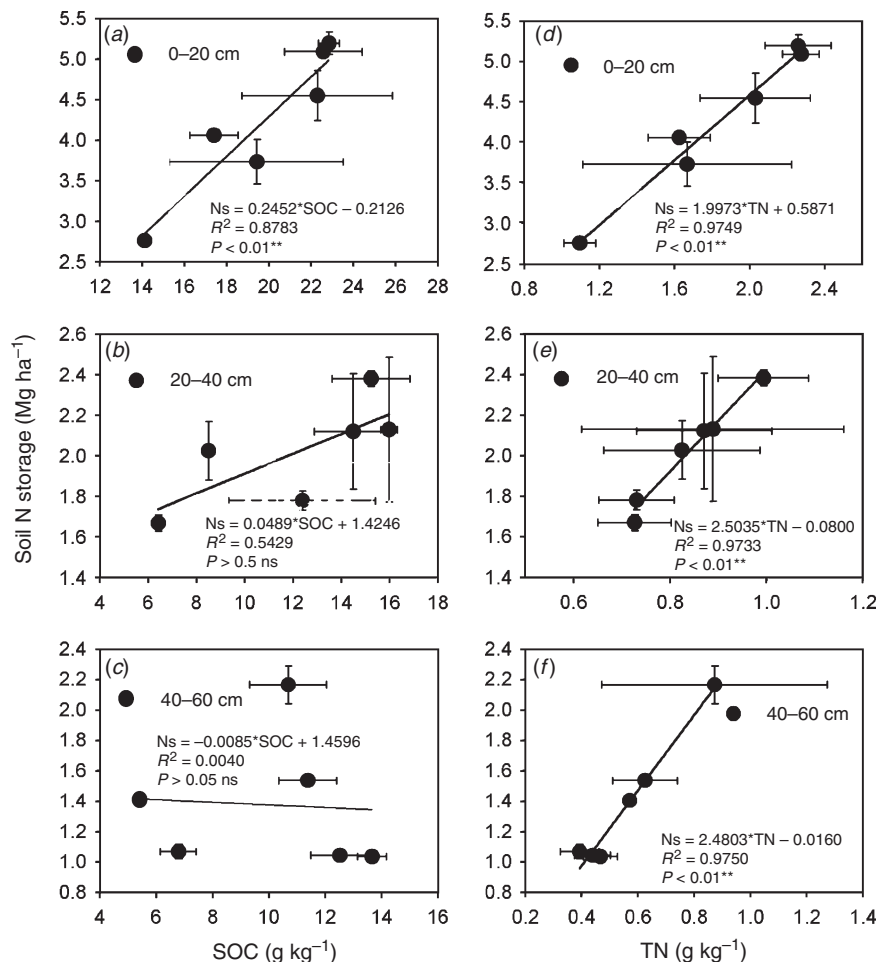


**Fig. 4.** Relationship between soil N storage (Ns) and (*a–c*) soil organic carbon (SOC) and (*d–f*) total N concentration (TN) in three soil layers with the vegetation succession gradient at 0–60 cm soil depth. Capped horizontal and vertical lines are the SE.

## Discussion

Soil organic C is an essential contributor to soil physical and chemical properties (Schoenholtz *et al.* 2000). It is also a key element in the process of trapping atmospheric $CO_2$ in terrestrial ecosystems through primary production (Post and Kwon 2000). Changes in land use caused by vegetation restoration probably enhance the C sequestration capacity of terrestrial ecosystems on the Loess Plateau (Deng *et al.* 2013*a*), and soil C and N show significant positive correlations in the process of the vegetation restoration (Deng *et al.* 2013*b*).

In our study, the N storage in the 0–60 cm soil layer significantly increased ($P < 0.05$), especially in the 0–20 cm soil (Fig. 3), indicating the accumulation of N through natural regeneration. These results agree with those of Wang *et al.* (2011*b*), who studied changes to the physicochemical properties of topsoil during natural succession on abandoned farmland. The accumulation of nutrients and organic matter in surface soils results from complex interactions between biotic processes moderated by plants and soil biota and abiotic processes driven by environmental processes (Hooper *et al.* 2000). Storage of N was largely determined by organic C in the soil. There was a

marked correlation between the N storage value and SOC in the 0–20 cm soil layer (Fig. 4*a*), but the correlation was not significant in the deeper layers (Fig. 4*b, c*). The altered size, composition and dynamics of microbial communities and altered vegetation biomass along the vegetation succession gradient may influence the biogeochemical cycles of soil C and other nutrients (Cleveland *et al.* 2004; Wang *et al.* 2011*a*). The varied distribution of N storage in the different soil layers may be due to differences in the SOC in those soil layers.

Aboveground vegetation plays an important role in regulating the biogeochemistry of ecosystems through C-fixing and use of nutrients, and by preventing the loss of nutrients through disturbance (Bormann and Sidle 1990; Li *et al.* 2007). It is also clear from these results that vegetation succession has a great impact on N storage. In our study, there was a markedly positive correlation between N storage and the TN in the soil ($P < 0.001$) (Fig. 4*d–f*), indicating that TN is the determining factor in Ns. Deng *et al.* (2013*a*) found that soil C storage tended to be stable at the latter stage of forest succession (>50 years) in the Ziwuling Forest Region, indicating a strong correlation between soil C and N storage. Deng *et al.* (2013*b*)
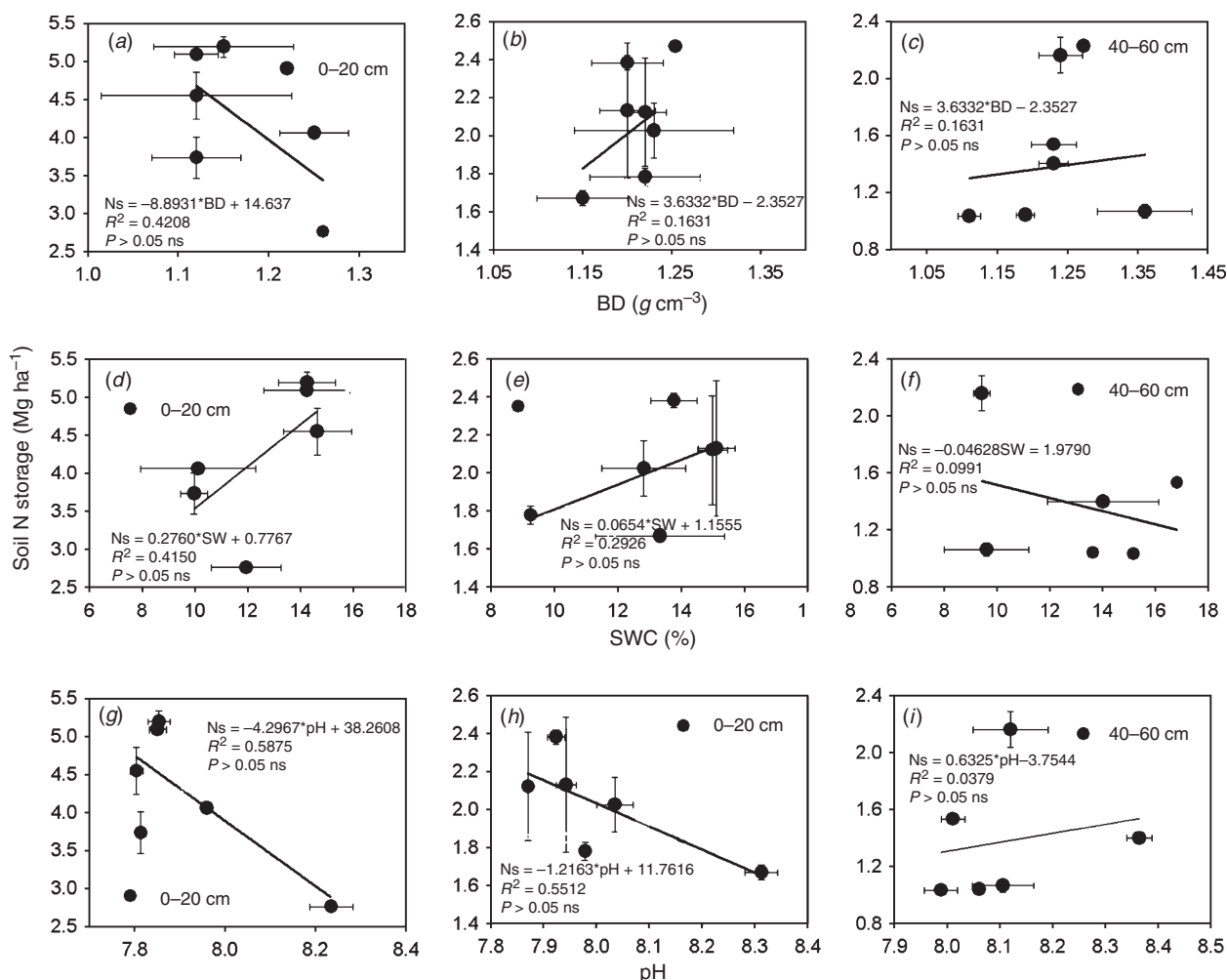


**Fig. 5.** Relationship between soil N storage (Ns) and (*a–c*) soil bulk density (BD), (*d–f*) soil water content (SWC), and (*g–i*) soil pH in three soil layers with the vegetation succession gradient at 0–60 cm soil depth. Capped horizontal and vertical lines are the SE.

also found that soil C storage and N storage were significantly and positively correlated. In addition, Luo *et al.* (2004) reported that long-term terrestrial C sequestration is related to soil; therefore, we should focus on long-term soil N dynamics to predict terrestrial C sequestration on the Loess Plateau. In addition, in deeper soil layers (40–60 cm), SOC increased but TN was almost unchanged following natural succession, indicating that soil organic matter (SOM) input more than decomposition, and the input and uptake of N in the SOM are balanced in the process of vegetation succession.

Soil BD, soil water content (SWC) and pH were not the determining factors behind the N storage values although they had non-significant positive, positive and negative correlations, respectively (Fig. 5). Generally, soil depth is fixed, meaning that N storage values are determined by TN and soil BD. With vegetation succession, 0–20 cm soil BD did not significantly vary ($P > 0.05$) in the early stages of vegetation succession (Afs and Hs), but BD significantly decreased until Ss ($P < 0.05$) and then tended to be stable after Ss (50–60 years) (Fig. 2*a*); meaning that our findings agree with Wang *et al.* (2011*a*). The N storage value was negatively correlated with BD (Fig. 5*a*), leaving TN itself to act as the key factor affecting N storage during the process of restoration (Figs 1 and 4).

On the Loess Plateau, porosity is a key attribute of soil structure affecting the soil reservoir under conditions of natural vegetation recovery (Zhao *et al.* 2010). Soil moisture is an indicator of SOM accumulation (Deng *et al.* 2013*a*), and SOM determines SOC and TN in the soil. Therefore, a markedly positive correlation between N storage, SOC and TN strongly suggests that soil moisture is a reflection of the N storage value. However, the study did not indicate significant relationships between SWC and N storage along the vegetation succession gradient (Fig. 5*d–f*), although the SWC was higher

in the latter stage (>50–60 years) than earlier (<50–60 years) (Fig. 2*b*). This demonstrated instead that SWC in the soil was not the key factor influencing N storage in the Ziwuling Forest Region. Rather, as Deng *et al.* (2013*a*) point out, SWC is more likely related to the annual rainfall, which is close to 600 mm in the Ziwuling Forest Region, in the south of the Loess Plateau, where the climate is relatively humid compared with the other, drier regions of the Loess Plateau. Wang *et al.* (2011*b*) reported that soil pH decreased after farmland was converted to forest, and our findings were similar (Fig. 2*c*), in that the N storage value was non-significantly negatively correlated with pH (Fig. 5*g, h*). The BD, SWC and pH are not the determining factors behind the N storage values. However, in the topsoil (0–20 cm), they did show stronger negative, positive and negative correlations, respectively, which indicates that vegetation restoration can increase N storage and improve the physicochemical properties of topsoil. There was little correlation in the 40–60 cm soil (Fig. 5*c, f, i*), indicating that these mechanisms did not function in the lower soils (Figs 2, 5).
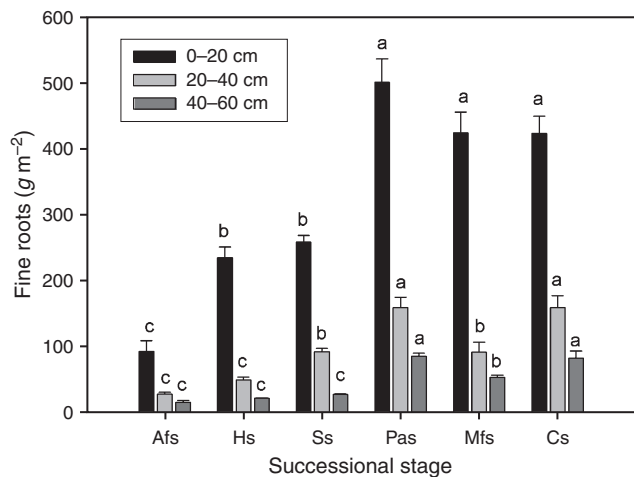


**Fig. 6.** Changes in fine roots in three soil layers with the vegetation succession gradient at 0–60 cm soil depth. Bars mean and capped lines are s.e.; sample size, *n* = 5. Letters above the bars are for comparison the same soil layer at the different restoration stages; bars with the same letter are not significantly different at *P* = 0.05). Afs, Abandoned farmland stage; Hs, herbaceous community stage; Ss, shrub community stage; Pas, pioneering arbour community stage; Mfs, mixed forest community stage; Cs, climax community stage.
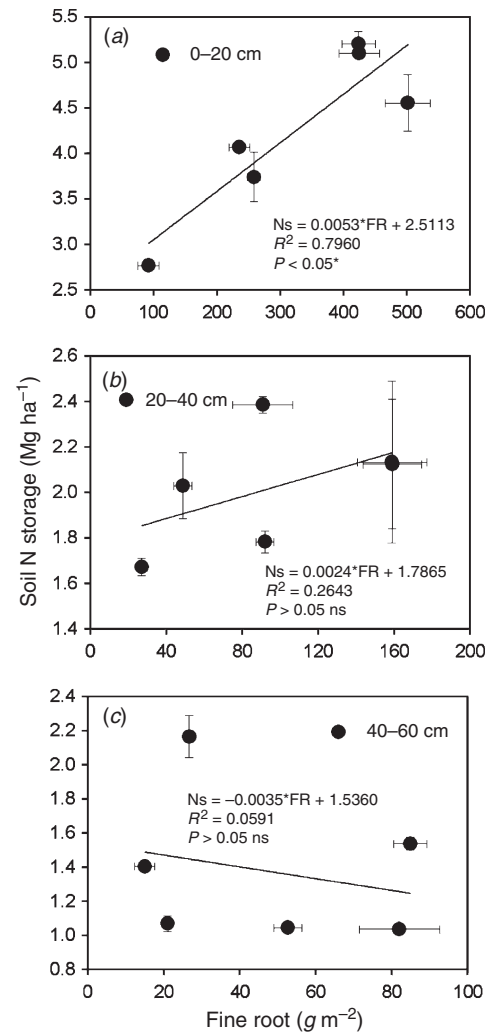


**Fig. 7.** Relationship between soil N storage (Ns) and fine roots in three soil layers with the vegetation succession gradient at 0–60 cm soil depth. Capped horizontal and vertical lines are the SE.

There may be a range of potential mechanisms through which N storage values in the topsoil are increased through natural regeneration. A prime candidate is the return of soil N from increased aboveground biomass and litter. As soil N input is mainly derived from the decomposition of litter (Wang *et al.* 2011*b*), primary productivity is the main driver of soil N accumulation and results primarily in an increase in N storage in the topsoil (Wang *et al.* 2011*b*). We also found a marked increase in fine roots in the topsoil (0–20 cm) (Fig. 6), with which N storage showed a significant positive correlation ($P < 0.05$) (Fig. 7*a*). In addition, an increased N input by rhizodeposition (dead roots, mycorrhizae, and exudates) is an important element of soil N accumulation (Langley and Hungate 2003; Prietzel and Bachmann 2012). Fine roots are easy to turnover, and their dynamics controls a dominant flux of C from vegetation into soils (McCormack *et al.* 2013), which in turn leads into N dynamics because of the strong positive correlative relationship between C and N (Luo *et al.* 2004, 2006). Because fine roots increased with vegetation succession (Fig. 6), their turnover (dead roots) increased. In addition, changes in the vegetation composition and dominant plant functional group affect N sequestration in the soil (De Deyn *et al.* 2008; Mareschal *et al.* 2010). In agreement with Deng *et al.* (2013*b*), natural regeneration had a direct effect on the dominant vegetation species, vegetation cover, height, and above- and belowground biomass, and thus has a positive effect on soil N. Increased atmospheric deposition, and/or subsoil mining, also increased soil N storage (Feldpausch *et al.* 2004).

## Conclusions

The impact of long-term vegetation succession on the soil N pool was significantly different from grassland to forest. The N storage value increased with the length of vegetation succession. Over the long term (~150 years), N storage in secondary forest succession in the soil at 0–60 cm increased rapidly and tended to be stable after the shrub communities stage (Ss) (~50–60 years). Soil N accumulated mainly in the early succession stages; it had significantly increased before Ss. The results suggest that changes in N storage values were the result of the accumulation of SOC and TN and primary productivity during forest succession. This capacity has been shown positively correlated with forest succession on the Loess Plateau, China. In light of this important finding, it is clear that restored soil can play an extensive role in N-sink efforts. Further study is now required to understand what drives changes in N storage over the long-term, the time-frame in which the process of sequestration occurs. The combined mechanisms of increased primary productivity, litter decomposition, rhizodeposition, changes in vegetation composition and microbial communities, increased atmospheric deposition, and subsoil mining were likely responsible for increasing the storage of soil N along this vegetation gradient.

## Acknowledgements

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