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ORIGINAL PAPER

Nutrients of green and senesced leaves of a *Robinia pseudoacacia* plantation along a latitudinal gradient on the Loess Plateau, China

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Abstract Plantations have been widely established to improve ecosystem services and functioning. Black locust, *Robinia pseudoacaci*a L. is a common, widely planted species to control soil erosion on the Loess Plateau. Previous studies have focused on economic values but the interactions between soil and plant carbon (C), nitrogen (N) and phosphorus (P) remain unknown. Investigating variations of soil, green and senesced leaf C, N and P levels in *R. pseudoacacia* along a latitudinal gradient is useful to understanding its ecological functions. The results show that soil C, N and senesced leaf N and P significantly decreased with an increase in latitude, but there were no significant changes in the senesced leaf C and soil P. The resorption efficiency of N was related with latitude and soil N levels, and the relation between green leaf N and soil N was significant. These relations suggest that soil N was the key in affecting green leaf N levels. At higher latitudes, senesced leaves had lower N levels associated with higher N resorption efficiency to maintain a stable N content in green leaves. With a decrease of soil N, *R. pseudoacacia* can enhance N resorption efficiency to meet the demand of growth. Thus, it is an important species for reforestation, especially in nutrient-poor environments.

Keywords Green leaves · Senesced leaves · Resorption efficiency · *Robinia pseudoacacia* · Loess plateau · Vegetation restoration

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Introduction

Vegetation restoration is widely implemented globally to improve land cover, reduce soil erosion, and enhance ecosystem services and functioning. Reforestation is regarded as an effective method for restoring vegetative cover. Previous studies showed that reforestation improved soil quality, site biodiversity, carbon fixation, and climate regulation (Sun et al. 2015; Zethof et al. 2019; Zheng et al. 2020). For example, after nearly 30 years of vegetation restoration, forest cover and vegetation index have increased on the Loess Plateau (Li et al. 2017, 2015). These increases in vegetation cover could be attributed to planting of *Robinia pseudoacacia* on the Loess Plateau.

R. pseudoacacia is a fast-growing species and widely planted although it is sometimes considered an invasive species (Vítková et al. 2017). *R. pseudoacacia* is a useful species for reforestation and ecological restoration, and is widely planted throughout China since the 1970s for soil and water conservation. Several studies have been carried out on improving soil moisture under *R. pseudoacacia* plantations (Zhang et al. 2003), reducing soil water depletion, enhancing root distribution (Zhong et al. 2006), improving soil microbial diversity (Zhang et al. 2008), and increasing soil nutrients (Ji et al. 2012; Qiu et al. 2010). The species has the ability of nitrogen fixation by bacteria through root nodules and is easily propagated (Vítková et al. 2017). It uses nutrients from senesced leaves to grow in nutrient-poor soils. Although *R. pseudoacacia* has been studied by numerous researchers (Cierjacks et al. 2013; Kowarik and Schepker 1998; Rice et al. 2004), most studies have focused on its economic value rather than its ecological function (Vítková et al. 2017). Relatively little attention has been given to strategies for enhancing interactions among soil nutrients, and green and senesced leaves to improve soil moisture.

Foliar resorption is a common process to avoid loss of nutrients, an important mechanism for nutrient conservation and a strategy for adapting to low nutrient environments (Aerts 1996). Nutrient resorption plays a critical role in the development of different soil environments, making vegetation less dependent on soil nutrients (Tang et al. 2013). This resorption mechanism also affects plant growth and the limitation of nutrients. Previous studies have shown that plant species, climate and soil conditions were the main factors affecting nutrient levels of green and senesced leaves (Chen et al. 2013; Reich and Oleksyn 2004; Tang et al. 2013). At a regional level, green leaf nutrients show a biogeographical pattern which also influence the distribution of nutrient resorption efficiency (Yuan and Chen 2009). N and P (phosphorous) resorption efficiencies were significantly related with latitude and climate factors (Yuan and Chen 2009). A global study reported that green leaf nutrients and their resorption efficiency significantly increased with latitude (Vergutz et al. 2012).

Regarding the effect of latitude on soil and plant nutrients (Reich and Oleksyn 2004), the resorption efficiency of nutrients might be used to evaluate the potential for sustainable regional *Robinia pseudoacacia* plantations based on changes in the contents in green and senesced leaves. A specific objective was to examine the distribution of C, N and P through the soil–green leaf–senesced leaf system and evaluate the following hypotheses: (1) C, N and P contents in the soil would show more variability compared to green and senesced leaf samples along a latitudinal gradient; and, (2) the resorption efficiency of *Robinia pseudoacacia* would increase along with an increase in latitude across the northern Loess Plateau.

Material and methods

Study area

The Loess Plateau (ca. 640,000 km^2), one of the world's most seriously eroded area, is located along the upper and middle catchments of the Yellow River (Fu et al. 2000). From south to north, mean annual precipitation (MAP) varies from around 800 mm to approximately 100 mm. Along a latitude gradient, mean annual temperature (MAT) decreases from 15 to–7 °C (Zhao et al. 2013). In response to the implementation of China′s "Green for Grain" project, numerous plantations have been established, including ones using *R. pseudoacacia.* Therefore, we selected 20-year-old *R. pseudoacacia* plantations from north to south in 14 counties on the Loess Plateau, northwest Shaanxi province (Fig. 1). The study area is within a typical temperate zone (34°42′39.79″–38°48′35.17″N, 108°40′31.6″–110°21′54.57″E). Three sampling sites were selected in each county as replicates.

Soil sampling

All the sampling sites were > 10 km from settlements to eliminate anthropogenic disturbances. In each site, one 20 m × 20 m plot was used for sampling. Ten soil cores (10 cm) were taken in each plot to form a comprehensive soil sample. Stones, roots, decayed materials were removed and the soil samples sieved through 0.15-mm sieve for the analysis of soil C, N, and P.

Green leaf and senesced leaf sampling

Five healthy *R. pseudoacacia* trees of similar height and age were randomly chosen in each plot. Green leaves were picked from the east, north, west and south sides of the crowns, with an evenly distributed amount from each direction. Green leaves from five trees on each site were mixed into one paper bag. Green leaves were collected mid-August when biomass peaked with the highest levels of nutrients (Zeng et al. 2016b). At the end of the growing season, senesced leaves were collected from the same tree and site (Delgado-Baquerizo et al. 2016).

Measurement of total C, N, and P

Green and senesced leaves were oven-dried at 65 °C to a consistent weight, and ground with a ball mill. Total N in plants and soils were determined by the Kjeldahl acid-digestion method (Sparks et al. 1996). Plant and soil samples were digested with H_2SO_4 and H_2O_2 and the P content in plant material determined by a spectrophotometer at 700 nm (Thomas et al. 1967) and in soil samples by a spectrophotometer (Parkinson and Allen 1975). A modified Mebius method was used to measure the organic carbon contents (Nelson and Sommers 1982).

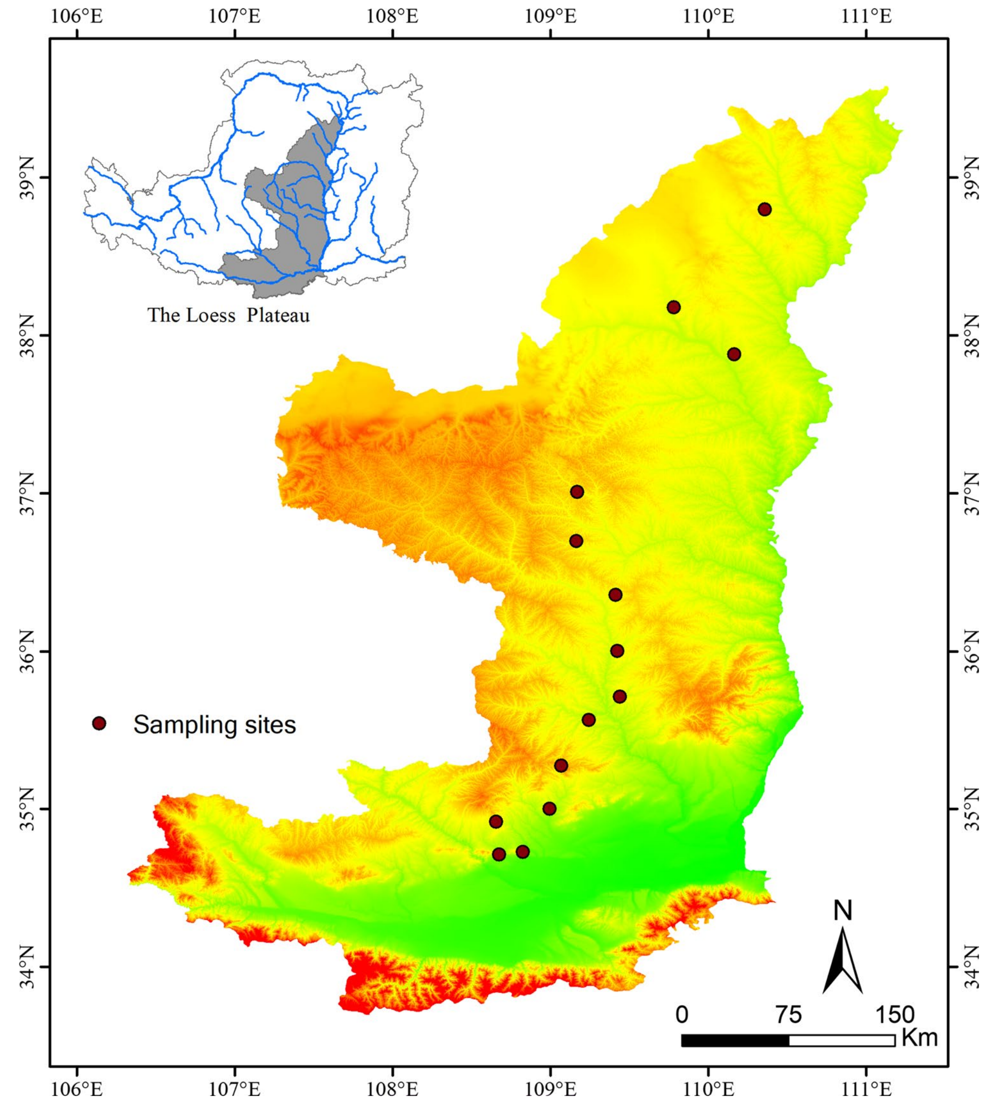

Fig. 1 Geographic information of sampling sites on the Loess Plateau

Statistical analysis

The resorption efficiency (RE) was calculated using Eq. (1) (Zeng et al. 2016b):

$$RE = \frac{\text{Green leaf content} - \text{Senesced leaf content}}{\text{Senesced leaf content}} \times 100\% \tag{1}$$

The statistical package for the social sciences (SPSS 20.0) was used for statistical analyses. The ratio of the standard deviation to the mean of each variable expressed variations of C, N and P. General linear models were used to study the relationships between levels of C, N and P, the resorption efficiency, and latitude. Pearson relation analysis was determined to explore the relations between C, N and P contents in soil, and in green and senesced leaves.

Results

C, N and P contents in soil, and in green and senesced leaves

Latitude had significant effects on soil C and N ($p < 0.05$) but not on P (Fig. 1). Soil C, N and P levels ranged from 2.4 to 24.6 g kg^{-1}, 0.2 to 2.1 g kg^{-1}, and 0.5 to 1.8 g kg^{-1}, respectively. Average C, N and P levels were 10.8 g·kg^{-1}, 1.1 g·kg^{-1} and 1.2 g kg^{-1}, respectively (Table 1). Higher coefficients of variation were observed in soil C (69%) and soil N (63%). The distribution of soil C and total N were spatially consistent, declining linearly with an increase in latitude ($p < 0.05$). The association between latitude and soil P content was significant ($p < 0.05$).

Table 1 Total C, N and P levels of *Robinia pseudoacacia* forest soil, and green and senesced leaves

Components	Elements contents (g/kg)	Max	Min	Mean	SD	CV (%)
Soil	C	24.6	2.4	10.8	7.4	69
	N	2.2	0.2	1.1	0.7	63
	P	1.8	0.5	1.2	0.3	25
Green leaf	C	485	423	455	17.6	4
	N	27.3	18.0	21.8	2.6	12
	P	3.0	1.9	2.4	0.4	15
Senesced leaf	C	216	149	187	20.6	11
	N	20.9	15.0	17.3	1.9	11
	P	2.1	1.4	1.8	0.2	10

Max Maximum value; *Min* Minimum value; *Mean* Average mean value; *SD* Standard deviation; *CV* Coefficient of variation

Green leaf C, N, and P levels (g kg^{-1}) ranged from 429 to 485 g kg^{-1}, 18 to 27 g kg^{-1}, and 1.9 to 3.0 g kg^{-1}, respectively. The coefficients of variation for C, N and P were 4%, 12% and 15%, respectively. The CV for green leaf P (15%) was higher than that of green leaf N (12%). Senesced leaf C, N, and P contents were 149–216 g kg^{-1}, 15–21 g kg^{-1}, and 1.4–2.1 g kg^{-1}, respectively, and the coefficients of variation were 11%, 11% and 10%, respectively. Overall, the coefficients of variation for soil nutrients were greater than for plant nutrients. There were no significant relationship of green leaf C, N, P and senesced leaf C to latitude. Senesced leaf N and P levels significantly decreased linearly with an increase in latitude ($p < 0.05$) (Fig. 2).

Association between soil and plant C, N and P levels

Pearson correlation analysis revealed that soil C was significantly related with soil N levels (Table 2). Correlation between carbon content and green leaf N content was negative ($p < 0.05$). Phosphorous levels in senesced leaves

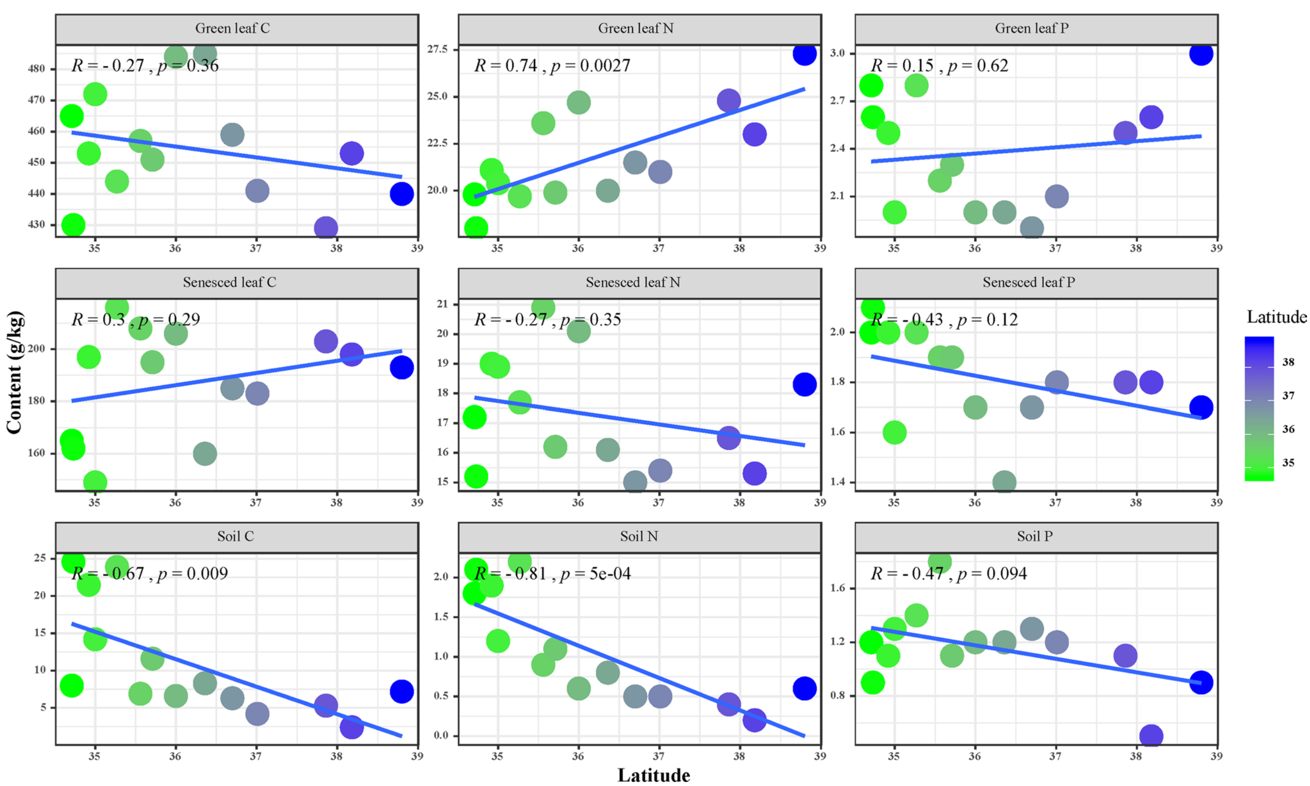

Fig. 2 Linear regressions of C, N and P contents in soil and green and senesced leaves to latitude

Table 2 Pearson relations between C, N, and P levels in soil and in green and senesced leaves

	Soil C	Soil N	Soil P	Green leaf C	Green leaf N	Green leaf P	Senesced leaf C	Senesced leaf N	Senesced leaf P
Soil C	1	**0.900****	0.086	−0.236	**−0.579***	0.286	−0.095	0.092	**0.580***
Soil N		1	0.218	−0.137	**−0.656***	0.375	−0.178	0.147	**0.652***
Soil P			1	0.242	−0.107	−0.386	0.053	0.529	−0.086
Green leaf C				1	−0.062	**−0.566***	−0.277	0.355	**−0.631***
Green leaf N					1	0.144	0.511	0.397	−0.418
Green leaf P						1	0.236	−0.021	0.485
Senesced leaf C							1	0.301	0.074
Senesced leaf N								1	−0.165
Senesced leaf P									1

* indicates the significant relation at 0.05 level; ** indicate the significant relation at 0.01 level

Bold values indicate significant correlations

were significantly related with soil C and N. Soil N was negatively correlated with green leaf N and senesced leaf P levels ($p < 0.05$). Correlations between senesced leaf and soil C, N and P levels were insignificant.

Resorption efficiency for N and P by latitude

N resorption efficiency ranged from 7 to 34% and was positively related to latitude (Fig. 3), and P resorption efficiency ranged from 20 to 45%, but the relationship with latitude was insignificant. Average resorption efficiency for N and P were 20% and 23%, respectively. Soil N was significantly related

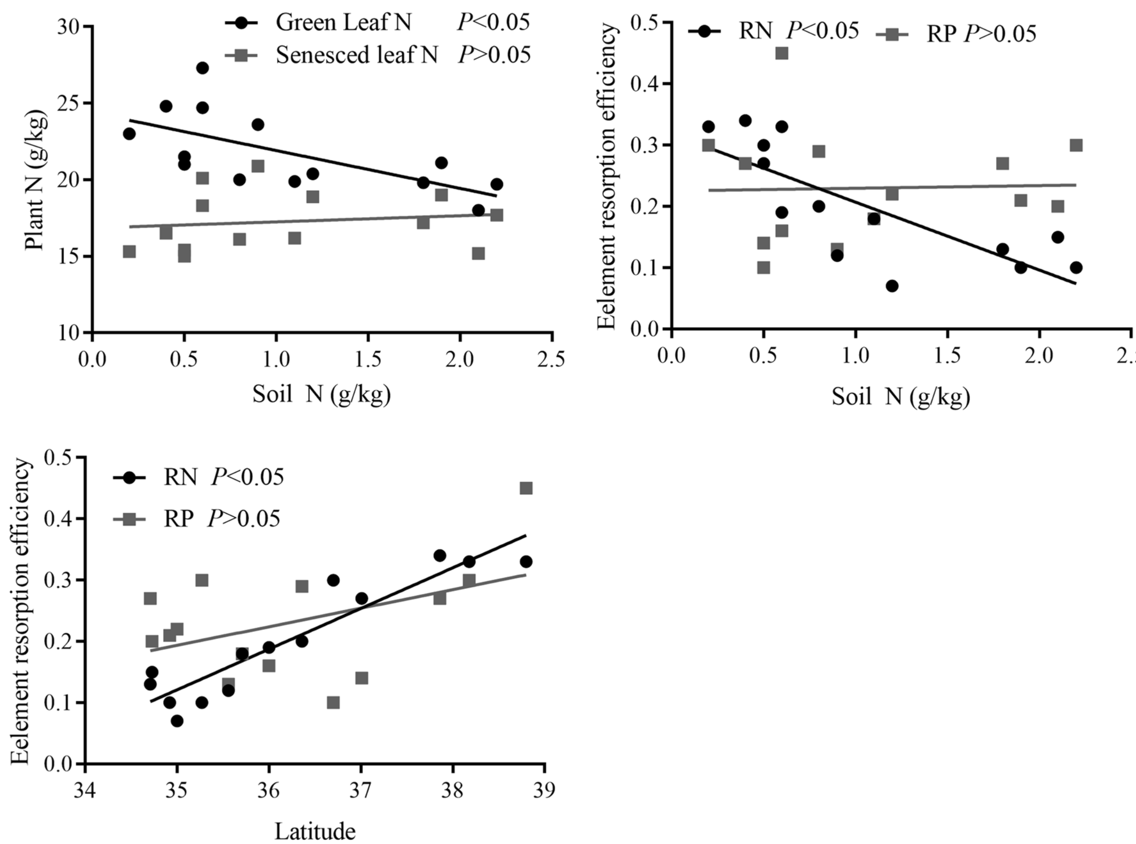

Fig. 3 Associations between resorption efficiency, latitude and N content in soil, and between N content in green and senesced leaves and soil nitrogen; RN, N resorption efficiency; RP, P resorption efficiency

with N resorption efficiency and green leaf N content, however, the correlation between soil N, P resorption efficiency, and green leaf P content were insignificant.

Discussion

Variations of C, N and P levels with latitude

The data are partially in accord with the first hypothesis that soil C and N levels (except P) are significantly decreased with increasing latitude, which has also been observed on the Loess Plateau by Deng et al. (2014). Sources of soil nitrogen are mainly derived from organic matter through litter decomposition (Dang et al. 2007). Decomposition and plant productivity processes are closely related with climate and thereby influence the accumulation and distribution of soil organic matter (SOM) and N levels (Yang et al. 2013). On the Loess Plateau, average annual rainfalls and temperatures decrease from south to north (Zhao et al. 2013), which results in slower litter decomposition rates in northern regions. This results in decreasing SOM and plant productivity from south to north. The coefficient of variation for phosphorous was lowest in terms of spatial variation compared to soil C and total N. Being relatively immobile, phosphorous is not easily leached out from soils and the spatial distribution of total P in soil is homogeneous. There were a large number of factors (e.g., parent material, organisms and geochemical processes) affecting soil P content. Climate factors such as temperature and rainfall may play an important role in promoting P leaching and its loss in soil (Sharpley et al. 1997; Simard et al. 2000). However, this study did not find that latitude affected soil phosphorous levels (Fig. 2). On the Loess Plateau, soil parent material may be the main sources of phosphorous (Mage and Porder 2013). Weathering and subsequent leaching of parent minerals resulted in the sources of soil P (Walker and Syers 1976).

Soil C and N are generally high in hot and humid regions because of high plant productivity and low P levels due to leaching (Veldkamp et al. 2008). Reich and Oleksyn (2004) indicated that phosphorous was the main limiting element in soils of the tropics; however, in the present study, soil P levels were relatively stable.

Latitude influences climate, depending on the distance from the equator and this is because the poles (90° N and 90° S) receive less sunlight than the equator. The higher the latitude, the lower the temperature. In the sites in this study, changes of soil total C and N may be attributed to hydrothermal conditions. Temperature and rainfall decrease with increase in latitude. However, the soil undergoes a transformation from "loess" to "sandy loess" beyond a specific latitude (Zeng et al. 2016a). Increasing proportions of sand in the soil with latitude decreases the soil's nutrient contents.

Variations of C, N and P in green and senesced leaves along a latitude gradient

The data show that green leaf C (454 mg g^{-1}) was slightly lower than the global level (464 mg g^{-1}) (Elser et al. 2000), but N (21.36 mg g^{-1}) and P (2.08 mg g^{-1}) levels were slightly higher than the global level (20.6 mg g^{-1} and 2.0 mg g^{-1}). This may be attributed to climatic and hydrothermal conditions on the Loess Plateau.

Within ecosystems, the relative inputs of above- and below-ground biomass strongly control the quantity and quality of dead leaves being decomposed (He et al. 2016). This determines the dynamics of labile organic matter and associated nutrient release in the ecosystem which contributes to plant nutrition (Freschet et al. 2013). Therefore, senesced leaves play important roles in the soil–plant interface. N and P are important elements that can limit plant growth as they are involved in basic physiological and biochemical processes. With increasing latitude, *R. pseudoacacia* senesced leaf N and P significantly decreased but no variation was observed in C levels. Precipitation, temperature and soil type may cause these variations. The soil on the Loess Plateau in Shaanxi Province is sandy loess and nutrient levels gradually decrease from south to north. Sandy loess is prone to wind and water erosion and does not adequately preserve nutrients, leading to a poor growth environment for *R. pseudoacacia* in the northern areas on the plateau. With decreasing soil nutrients, the senesced leaf N and P contents decline with increasing latitude.

Green leaf nitrogen levels were relatively stable as a result of higher resorption efficiency in higher latitudes. These levels were negatively correlated with soil N, explained by the higher resorption efficiency and the function of N fixation for *R. pseudoacacia* (Boring and Swank 1984). Nutrient resorption efficiency is a conservation mechanism, especially in lower nutrient environments (Aerts 1996). Increasing N resorption efficiency resulted in the stability of green nitrogen contents which is in agreement with the results of Yuan and Chun (2009). Generally, plants in lower nutrient environments have higher resorption efficiencies (Vitousek 1982) and lower nutrient concentrations in senesced leaves (Killingbeck 1996). In the present study, green leaf nitrogen levels were negatively related to N resorption efficiency, suggesting that the green leaves had a higher nutrient status associated with a lower resorption efficiency (Kobe et al. 2005). In this study, N resorption efficiency (20%) was lower than reported by Han et al. (2013). They reported that nitrogen fixing species such as *R. pseudoacacia* had lower nitrogen resorption efficiency than other species. Soil nutrient levels also influence plant nutrient resorption efficiency

(Tang et al. 2013; Yuan et al. 2005). The significant correlation between soil N and N resorption efficiency indicates that soil nitrogen levels affect green leaf N content.

Soil N levels in this study were lower than the average for China, which suggests that the growth of *R. pseudoacacia* on the Loess Plateau was limited by nitrogen. More precisely, in higher latitude areas with lower soil N, nitrogen resorption efficiency and the ability of N fixation to meet nutrient demands was enhanced. This adaptive strategy resulted in a linear decrease of nitrogen levels in senesced leaves. Senesced leaf N contents declined with an increase in latitude. Thus, this result would provide useful insights into nutrient limitation strategy for reforestation under different latitudes.

Conclusions

This study indicates that changes in soil–plant associations are influenced by climate and the soil environment. Spatial variations in soil C and N, senesced leaf N and P contents declined significantly with an increase in latitude. Latitude had no effect on green leaf C, N and P levels. However, latitude affected green leaf nitrogen resorption efficiency with lower soil nitrogen, showing that it significantly affected green leaf nitrogen levels. These results highlight the importance of resorption efficiency in regulating *R. pseudoacacia* plantations over different latitudes on the Loess Plateau.

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