Ecological Engineering 58 (2013) 249–254

Contents lists available at ScienceDirect

Ecological Engineering

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

Successional changes in soil stoichiometry after land abandonment in Loess Plateau, China

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ARTICLE INFO

Article history:
Received 20 November 2012
Received in revised form 10 May 2013
Accepted 23 June 2013
Available online 27 July 2013

Keywords:
Loess Plateau
Nitrogen
Nutrient stoichiometry
Nutrient limitation
Phosphorus
Potassium
Soil nutrients
Succession
Vegetation restoration

ABSTRACT

Soil nutrient stoichiometry plays a substantial role in terrestrial carbon and nutrient cycling, but how it changes with time since land abandonment remains poorly unclear. By using a chronosequence since land abandonment (0, 5, 10, 15, 20 and 25 years, respectively) in Loess Plateau, China, here, we studied the successional changes in soil nitrogen (N), phosphorus (P), potassium (K) and their stoichiometric ratios. Along this chronosequence, soil organic matter, total and available N increased over time and were highest at 20-year-old age. However, soil P generally decreased with time since land abandonment. Consequently, the ratios of soil N:P increased but P:K decreased following abandonment, indicating that plant growth in this region were limited more by P than by N over time. Our results suggest that soil nutrient stoichiometry is actually impacted by land abandonment in Loess Plateau and such an adjustment of nutrient stoichiometry over time could lead to potential changes in species composition and nutrient cycles in this region.

1. Introduction

Abandoning unproductive land in Loess Plateau, China, has become a trend in the past two decades due to the rural–urban migration in areas where new economic/political opportunities are offered to rural people. In 2010, abandoned land in Loess Plateau was estimated to be 287×10^4 ha, accounting for 34% of all agricultural land in this region. Along with other human activities such as deforestation and over-exploitation, the abandonment of agricultural land in this region has been identified as a major issue for vegetation restoration and reconstruction (An et al., 2011; Zha and Tang, 2003).

Abandoning agricultural land represents a change of land use and cover, which can affect ecosystem functioning. Negative consequences could include: (1) soil and fertility loss, erosion and desertification, (2) reduction of water stocks, (3) biodiversity loss and reduced population of adapted species, (4) reduction of landscape heterogeneity vs. promotion of vegetation homogenization, (5) loss of cultural and esthetic values (Chen et al., 2010; Hartley et al., 2012; Kawada and Wuyunna, 2011; McGrath et al., 2001; Wang, 2006; Wang et al., 2013; Wen et al., 2005; Zhu et al., 2009). Previous studies suggest that surface runoff, soil loss, species diversity, soil moisture, and microbial activity changed greatly after abandonment of agricultural land (Du et al., 2007; Fu et al., 2006; Hou et al., 2002; Jia et al., 2010; Jiang et al., 2009; Peng and Wang, 2012; Raiesi, 2012; Shi and Shao, 2000; Uri et al., 2011; Wang, 2002; Zhang et al., 2013). For example, species richness and plant diversity increase after vegetation restoration (Zhang et al., 2011). However, the impact of abandoning agricultural land on soil characteristics remains unclear, especially in Loess Plateau. Due to the large size, sensitivity to disturbance, high soil carbon (C) contents, and predicted climate changes in Loess Plateau (Xin et al., 2007; Yao et al., 2005), it is crucial to study soil properties related to C and nutrient cycling.

Abandoned lands in Loess Pleteau may undergo secondary succession (passive restoration) (Benayas et al., 2008; Cuesta et al., 2012; Jiao et al., 2011; Wen et al., 2007; Zhao et al., 2010); during which time, cycling dynamics of soil nutrients, including nitrogen (N) and phosphorus (P), may change dramatically, affecting plant production, successional patterns, and ecosystem processes

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http://dx.doi.org/10.1016/j.ecoleng.2013.06.036

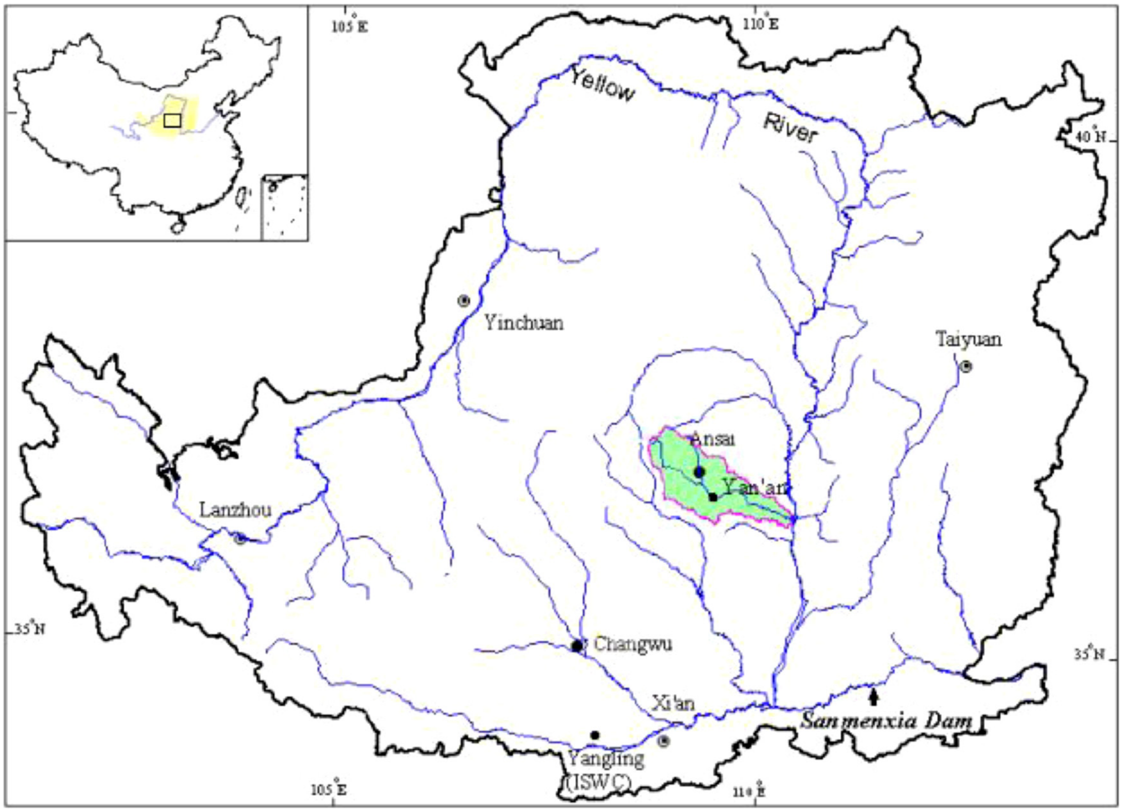

Fig. 1. The location of study area on the Loess Plateau. The yellow and green shades refer to Loess Plateau and the study sites, respectively.

(Bond-Lamberty et al., 2006; Conrad and Tischew, 2011; Deluca et al., 2002; Osman and Barakbah, 2011; Peltzer et al., 2010; Yuan and Chen, 2012a; Zornoza et al., 2009). Soil C:N:P stoichiometry, particularly the N:P ratio, is a powerful tool for us to advance our understanding of biological processes and nutrient cycling in terrestrial ecosystems (Cleveland and Liptzin, 2007; Tian et al., 2010; Yuan and Chen, 2012b; Yuan et al., 2011). At present, there are no studies addressing how soil N:P stoichiometry changes with succession, thus limiting our understanding of the role of soil nutrient stoichiometry in ecosystem nutrient cycling.

Soil N:P dynamics shall reflect directly the changes in N and P availability, which are influenced by both biotic and abiotic factors. To date, the generality of how soil N:P varies with secondary succession remains unclear. Currently there is no agreement on how soil N changes with secondary succession. Previous studies have found that it increases or decreases (Bond-Lamberty et al., 2006; Deluca et al., 2002). We still did not know whether the observed patterns of successional N dynamics in forest ecosystems could apply to abandoned successional lands. Furthermore, some studies showed that soil acidity and P decreases following land abandonment (Mulder and Elser, 2009), but this issue is still in debate (Vitousek et al., 2010). Due to the changes in species composition, production, and soil characteristics (Li et al., 2013; Yuan and Chen, 2012a, 2013), it is anticipated that soil N:P stoichiometry will change accordingly after land abandonment in Loess Plateau.

Our objective in this study was to determine how soil N, P and their ratio varied with secondary succession, in secondary abandoned lands of Loess Plateau, China. Given that both soil N and P might increase or decrease over time (Bond-Lamberty et al., 2006; Deluca et al., 2002), we hypothesized that soil N:P ratio changes (although the direction is unpredicted) following abandonment irrespective of how soil N and P vary with time since land abandonment.

2. Materials and methods

2.1. Study sites

This study was conducted in Yanhe watershed of the Loess Plateau at N 36°23′–37°17′and E 108°45′–110°28′ in northern Shaanxi Province (Fig. 1). The study area is characterized as a semi-arid climate by heavy seasonal rainfall with periodic local flooding and drought. Mean annual temperature is 9 °C and mean annual precipitation is 497 mm (from 1970 to 2000) with distinct wet and dry seasons (Fig. 2). The rainy season starts in July and

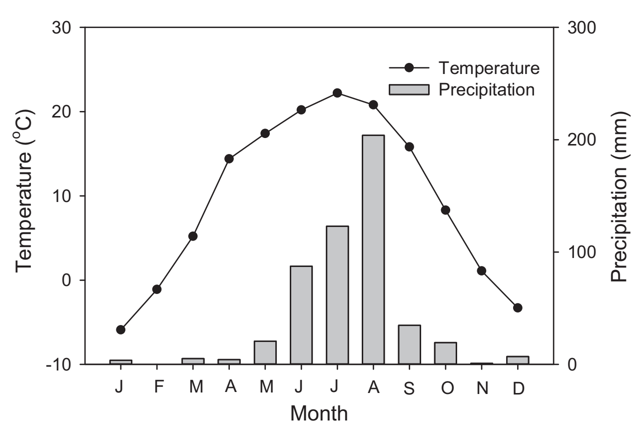

Fig. 2. Mean monthly temperature and precipitation in the study area.

Table 1
General properties of selected studied sites.

Age (year)	Slope (°)	Altitude (m)	Species
0	2–25	1076–1508	*Artemisia scoparia, Bothriochloa ischaemun*
5	8–29	1148–1624	*Artemisia scoparia, Bothriochloa ischaemun, Leymus secalinus, Lespedeza daurica, Stipa bungeana*
10	6–29	1392–1567	*A. scoparia, B. ischaemun, L. secalinus, L. daurica, S. bungeana*
15	18–26	1180–1363	*A. sacroru, B. ischaemun, L. daurica, P. Chinensis, S. bungeana*
20	5–35	1108–1587	*A. sacrorum, C. squarrosa, P. acaulis, S. bungeana*
25	24–35	1205–1369	*A. scoparia, B. ischaemun, L. daurica, S. bungeana*

continues up to October. The rainfall in August accounts for 23% of the annual precipitation. The annual reference evapotranspiration is approximately 1000 mm. Soils are described as Calcaric Cambisols according to the FAO classification system. The study area is composed of forest-steppe and temperate grassland. Typical vegetation includes herbs (*Artemisia sacrorum*, *A. giraldii*, *Lespedeza davurica*) and grasses (*Bothriochloa ischaemun*, *Leymus secalinus*, *Stipa bungeana*) (Li and Shao, 2003).

2.2. Study approach and sampling design

A chronosequence approach, albeit disputed because of the space for time substitution assumption, is useful for studying long-term changes in ecosystem structure and function over the life of a stand. The method used in this study was as recommended by Walker et al. (2010). Six age classes (0, 5, 10, 15, 20 and 25 years since abandonment) (Table 1) were selected in 2006, all of which had similar soil and climatic conditions. Before abandonment, crops of *Zea mays* were grown without grazing or fertilization. The age class was replicated five times, resulting in a total of thirty sampling stands (Fig. 3).

Within a 40 m × 40 m plot, the soils from each of these sites were simultaneously and randomly sampled in August 2009 with a metallic tube (20 cm high and 3 cm in diameter) at the 0–20 cm soil layer and analyzed for soil organic matter (SOM), total N (N_{total}), P (P_{total}) and potassium (K_{total}), available N (N_{avail}), P (P_{avail}) and K (K_{avail}). Composite samples of about 1 kg soils were collected with five sub-samples at each sampling plot and then air-dried and sieved through 1 mm sieve. SOM was determined on the basis of oxidation with potassium dichromate in a heated oil bath. N_{total} was measured according to the semi micro Kjeldahl method. P_{total} was digested with perchloric acid and sulfuric acid and determined using colorimetry. K_{total} was digested with hydrofluoric acid and perchloric acid. N_{avail} was analyzed by the Alkali diffusion method. P_{avail} was extracted with sodium bicarbonate and measured with colorimetry. K_{avail} in soils was extracted with ammonium acetate. All measurements were made at the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, China.

2.3. Data analysis

Statistical tests were performed with R 2.15.3. Soil nutrient data were transformed logarithmically to meet the assumptions of normality and homogeneity when needed. One-way analysis of variance was used to test the effect of age of abandonment on soil SOM, N, P, K, and their ratios. Post hoc multiple comparisons were computed using Duncan's test with library '*laercio*' in R. All R codes are shown in the Appendix.

3. Results

Soil organic matter (SOM), total N and P changed significantly over time since land abandonment (Fig. 4). Along the age sequence, SOM ranged from 5.53 to 8.02% and it was greatest in 20-year-old stand after abandonment. There were no significant differences among 0, 5, 10 and 15-year-old stands (Fig. 4A). Soil total N ranged from 0.36 to 0.50%. Similarly, it did not differ significantly before 20-year-old age but greater thereafter (Fig. 4B). By contrast, soil total P was highest in 0-year-old stands with no significant differences among the rest stands (Fig. 4A).

Along the chronosequence, soil available N, P and K varied with the age since abandonment (Fig. 5). Soil available N ranged from 23.2 to 31.9 mg kg^{-1} and demonstrated similar age-related patterns to total N, both of which were highest at Year 20 (Fig. 5A). The age-related trend of soil P availability was more apparent, being highest at Year 0 since abandonment (Fig. 5B). Similar to soil available N, the availability of K was highest at 20-year-old but lowest at 10-year-old age (Fig. 5C).

Both soil total and available N:P ratios differed significantly among six age classes (Fig. 6). The ratios of soil total N to P, ranging from 6.6 to 9.6, presented a mean value of 7.9. Those values were highest at 20-year-old and lowest at 15-year-old age (Fig. 6A). The

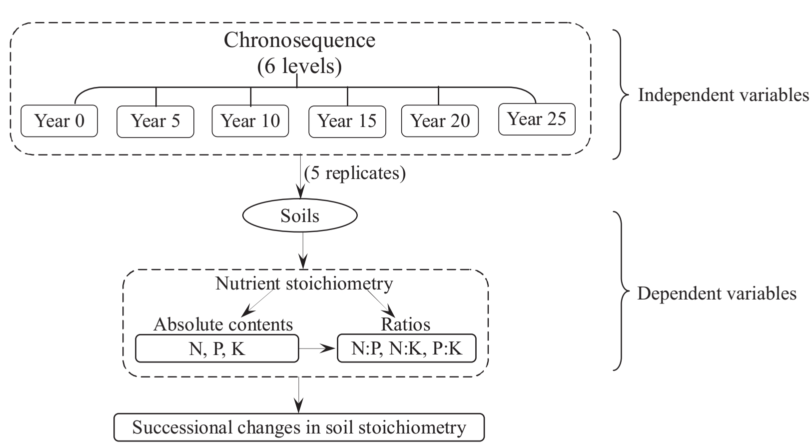

Fig. 3. The study approach and sampling design for this study.

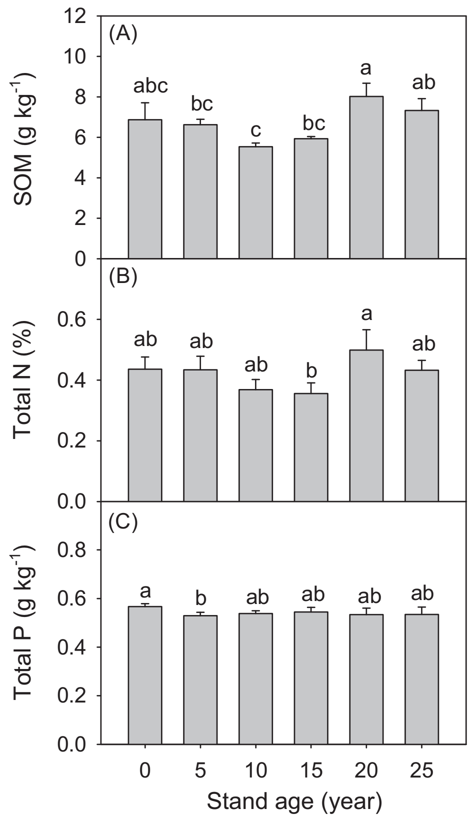

Fig. 4. Mean (±1SE) soil organic matter (SOM), total nitrogen and phosphorus after land abandonment over time.

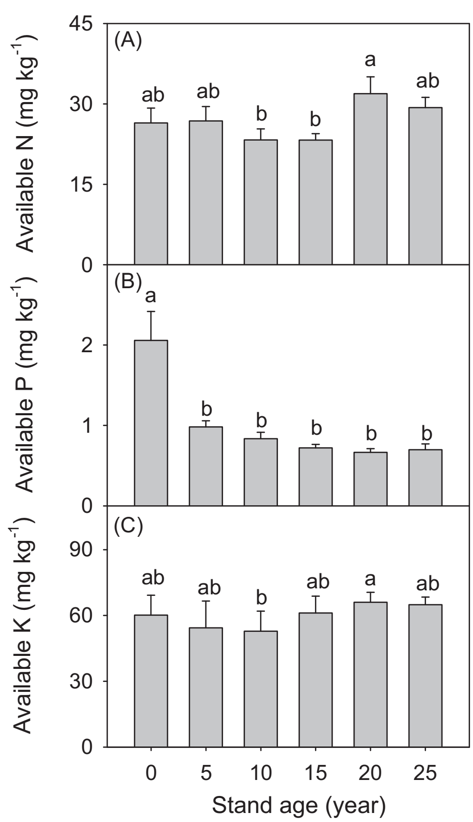

Fig. 5. Mean (±1SE) availability of soil nitrogen, phosphorus and potassium after land abandonment.

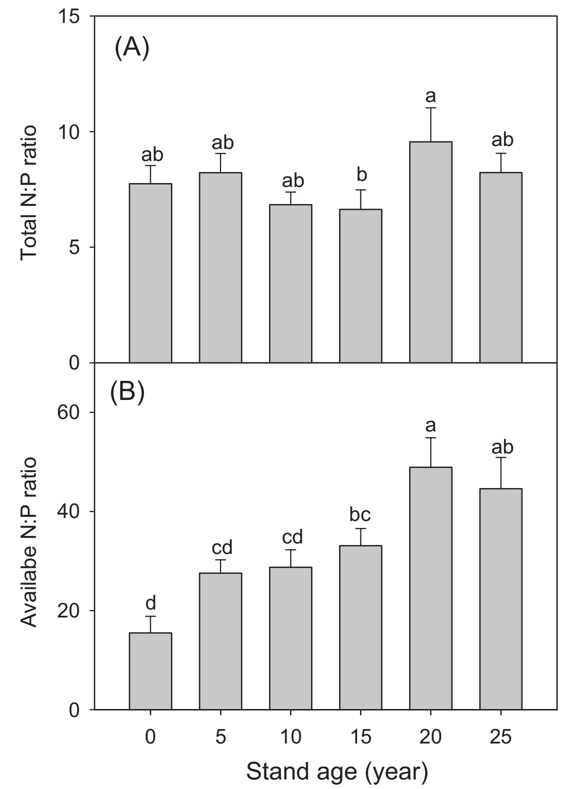

Fig. 6. Mean (±1SE) ratios of soil nitrogen to phosphorus after land abandonment.

trend of available N:P ratios, ranging from 15.5 to 48.9, generally increased with age (Fig. 6B). Along the age sequence, the ratios of soil available N:P increased 2.2 times.

Availability-based N:K and P:K ratios also varied with the age since abandonment (Fig. 7). The ratio of soil N:K was highest at 5-year-old and lowest at 15-year-old age (Fig. 7A). Soil available P:K ratio decreased over time ($P < 0.001$, Fig. 7B).

4. Discussion

Along the age sequence of land abandonment, we found significant shifts in soil N, P, K and their ratios, particularly soil P (Figs. 3–6), implying an impact of land abandonment on soil nutrient stoichiometry. The age-related patterns of soil available N, P, K and their ratios were more obvious than soil total nutrients. Soil available P generally decreased while N:P ratios increased following land abandonment. These successional changes in soil nutrient stoichiometry support our hypothesis that age after abandonment has a potential influence on soil nutrient cycles and thus plant growth. In our chronosequence, soil N:P ratios increased from 0-year-old to 20-year-old age and leveled off thereafter (Fig. 6), indicating an increasing P limitation for plant growth following land abandonment.

The increases in both soil total and available N status after land abandonment (Figs. 3–4) were similar to studies in secondary forests (Bond-Lamberty et al., 2006; Yuan and Chen, 2010), suggesting that the soil N changes in abandoned agricultural lands of Loess Plateau have similar patterns and likely samilar underlying mechanisms to secondary forests. First, the increasing soil N following land abandonment could be attributed to a favorable growth conditions after abandonment for the vegetation recovery and growth, especially herbaceous species (Jiao et al., 2011), which result in vegetation recovery and accumulations of plant litters and animal

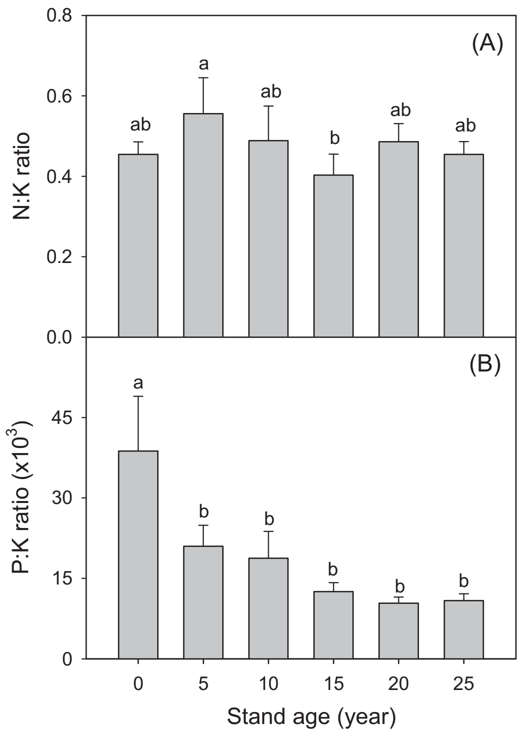

Fig. 7. Mean (±1SE) ratios of soil nitrogen to potassium and phosphorus to potassium after land abandonment.

debris. Second, through removing organic substrates in soil surface, and consequently N mineralization rate, agricultural activity generally reduces C and N mineralization, and thus soil organic matter stocks increase (Chen et al., 2005), reflected by N availability in soils as shown in our study. Thirdly, biological inputs of N fixation and accumulative atmospheric N deposition over time could contribute to the increasing soil N in soils.

Following land abandonment, soil P has been found to increase (Wang et al., 2011) or do not change (Wen et al., 2005). In our study, soil available P decreased with time since abandonment, although the pattern of soil total P did not. This short-term changes in soil P were consistent with the long-term patterns with soil age (Lambers et al., 2008b; Vitousek et al., 2010), indicating some similar factors driving short- and long-term variations in soil P availability (Conrad and Tischew, 2011; Osman and Barakbah, 2011). Further study is needed to identify those drivers that are directly and/or indirectly responsible for the age-related variations in soil P availability.

Age-related trends of soil available N, P and K were more distinct than the total contents of the same soil nutrients. The possible reason for the differences could be that total amount of nutrients often does not reflect plant-available nutrients in soils. For example, humus content in many studies is often not correlated to nutrient availability (Lambers et al., 2008a). Our results suggest that nutrient availability is a better predictor than total nutrients in reflecting soil nutrient stoichiometry and in understanding the relationships between stoichiometry and abandoned ages, and thus plant growth.

The similar trends in SOM and soil N contents along the sequence are interesting since it is possible to hypothesize that the changes in SOM along the sequence may also translate into some similar changes in soil C content. If the soil C content follows the changes in SOM content and changes in soil N content along the sequence, it may reveal a stronger coupling between C and N cycles than C and P or N and P cycles.

Comparing the patterns of soil total and available N, P and their ratios, the increasing soil available N:P ratio following land abandonment (Fig. 6) could be a direct reflection of decreasing soil P availability (Fig. 5). In the present study, the trend of soil total N:P ratio, however, was not so distinct as available nutrient-based N:P ratio, again suggesting nutrient availability is better than total nutrients in determining soil nutrient stoichiometry. Interestingly, our results demonstrated lower soil N:K and P:K ratios at older age (Fig. 7). Through plant osmotic control and improvement in stomatal function, K plays a major role in the plant–water relationship. The variations in soil N:K and P:K stoichiometry were expected to impact plant K uptake associated water stress during plant growth. In addition, the changes in soil nutrient stoichiometry could be caused by different plant species which have different nutrient use strategies (Yuan et al., 2006) in the sampling sites.

In this chronosequence, the soil N:P ratios increased 2.2 times after land abandonment (Fig. 6). The total soil N:P ratios did not exceed the Redfield ratio of 16, the threshold postulated for P limitation in plankton (Redfield, 1934). However, along the age sequence the significant increase in available soil N:P ratios, most above 16, indicated increasing P limitation for plant growth at older age after land abandonment. According to the N:P thresholds proposed by Koerselman and Meuleman (1996), these results suggest that N and P co-limited plant growth in those old abandoned lands, supporting the idea that P becomes increasingly limiting relative to N over time not only in forests (Wardle et al., 2004) but also in abandoned agricultural lands, at least in Loess Plateau.

Overall, our study reveals that soil nutrient stoichiometry is affected by land abandonment in Loess Plateau. Specifically, younger recently abandoned sites contained less organic matter, N and K but more P than the older sites. Consequently, the ratios of N:P increased but P:K decreased with time since land abandonment. These results add evidences that time since land abandonment impacts soil nutrient stoichiometry, ultimately influencing plant growth and nutrient cycles. To better understand how land abandonment influence ecosystem processes, further study is needed to address the ecological age-related factors driving those patterns of soil nutrient stoichiometry.

Acknowledgments

Thanks to Rebecca L. MacDonald for editing English. This study was sponsored by the Knowledge Innovation Program of the Chinese Academy of Sciences (KZCX2-EW-406), the National Natural Sciences Foundation of China (41271043), Key NSFC Program (41030532), Key Deployment Project of the Chinese Academy of Sciences (KZZD-EW-04-03), the Western Light Project of Chinese Academy of Sciences (2009y236) and Innovation Program of Northwest A&F University (QN2011073).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2013.06.036.

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