Ecosystem C:N:P stoichiometry and carbon storage in plantations and a secondary forest on the Loess Plateau, China

Yang Cao [a,b], Yunming Chen [a,b,*]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling 712100, Shaanxi, China
[b] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, Shaanxi, China

A B S T R A C T

Establishing plantations and protecting secondary forests are important measures to enhance carbon (C) sequestration in terrestrial ecosystems. We compared the C: nitrogen (N): phosphorous (P) stoichiometry of major ecosystem components and the C storage partitioning patterns in three ∼40-year-old forests of a fast-growing, N-fixing black locust plantation (*Robinia pseudoacacia*), an indigenous Chinese pine plantation (*Pinus tabuliformis Carrière*), and a secondary oak forest (*Quercus liaotungensis*) on the Loess Plateau, China. The concentrations of C, N, and P in tree tissues, herbs, litter and soils were measured by sampling. The tree tissues biomass was calculated using published species-specific allometric equations and the soil C stock of each soil layer is based on the soil layer depth, its bulk density, and C concentrations. Results showed that N concentrations of tree tissues, herbs, and litter in the N-fixing *R. pseudoacacia* stands were significantly higher than those in the *P. tabuliformis* and *Q. liaotungensis* stands. However, there were no significant differences in soil C and N concentrations between N-fixing and non-N-fixing stands. Soil P concentration was higher only in the *R. pseudoacacia* and *P. tabuliformis* plantations when compared to the secondary *Q. liaotungensis* forest. Leaf N:P ratios indicated soil P limitation in the *R. pseudoacacia* plantation and the secondary *Q. liaotungensis* forest (N:P ratios >16), while both N and P limitation were found in the *P. tabuliformis* plantation (N:P ratios = 14). No shrub vegetation was found in the plantations. Litter C storage was significantly lower in the *R. pseudoacacia* stands than in the *P. tabuliformis* and *Q. liaotungensis* stands. The ecosystem C storage of the secondary *Q. liaotungensis* forest (359 t ha^{-1}) was higher than that of the *P. tabuliformis* (298 t ha^{-1}) and *R. pseudoacacia* (214 t ha^{-1}) plantations. The majority of C storage was in the soil pool, accounting for 76.75%, 60.37%, and 67.93% in the *R. pseudoacacia* plantation, *P. tabuliformis* plantation, and the secondary *Q. liaotungensis* forest, respectively. These results indicate that the secondary *Q. liaotungensis* forest and indigenous *P. tabuliformis* plantation enhance C storage more substantially than the fast-growing *R. pseudoacacia* plantation in the long-term on the Loess Plateau.

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1. Introduction

Forests play an important role as terrestrial carbon (C) sinks because they store large quantities of C in vegetation biomass and soil (Schimel et al., 2001). Therefore, acquiring new C stocks through afforestation and protection of C stocks in existing forests have become important measures used to enhance the C sequestration capacity in terrestrial ecosystems and mitigate global warming (Laclau 2003; Chen et al., 2009; Bonner et al., 2013; He et al., 2013).

Establishing plantations on abandoned and degraded agricultural lands has been recommended in The Kyoto Protocol as an effective measure to reduce atmospheric C dioxide (Montagnini and Porras 1998; Li et al., 2005). However, some studies have challenged the effectiveness of plantations in this respect (Schulze et al., 2000; Schlesinger and Lichter 2001). Secondary forests provide important ecosystem services, such as stabilizing topsoil, improving soil chemistry, sequestering C, producing timber and non-timber forest products, improving landscape hydrology, and conserving biodiversity (Corlett 1995; Finegan 1996; Schlesinger and Lichter 2001; Bonan 2008; Chazdon et al., 2009). Most studies on the different ecological processes between plantations and secondary forests on forest biomass C and soil C dynamics have been conducted in tropical, subtropical, and subalpine forests; however, many questions regarding those dynamics remain unan-

swered (Cuevas et al., 1991; Chen et al., 2004; Li et al., 2005; Bonner et al., 2013; He et al., 2013; Marin-Spiotta and Sharma 2013; Sang et al., 2013; Zhang et al., 2013; Ma et al., 2014). Little is known about the differences in ecological processes between forests and plantations in temperate regions, especially disturbed forests on the Loess Plateau, China. This knowledge gap leads to the current debate on whether plantations or secondary forests are more effective in sequestering atmospheric C dioxide (Corlett 1995; Schulze et al., 2000; Silver et al., 2000; Law et al., 2003; Bonner et al., 2013). To help resolve these controversies, studying existing afforested stands and secondary forests is very important, as there are practical references for evaluating the C sequestration capacity of secondary forests and plantation stands on the Loess Plateau, China.

China's Loess Plateau is one of the regions in the world most heavily impacted by soil erosion (Shi and Shao 2000), and deforestation has been attributed as the main cause of soil erosion in the region (Zheng 2006). In 1999, the Grain for Green Program, a project to control soil erosion has been launched, which is known to be the largest ecological restoration project on the Plateau (Jiao et al., 2012). Fast-growing tree and shrub species are usually planted for vegetation restoration. A representative tree species is the black locust (Robinia pseudoacacia), which is a fast-growing nitrogen (N)-fixing species and was introduced to China from Europe (Shan et al., 2002; Cierjacks et al., 2013; Tsunekawa et al., 2014), with more than 70 000 ha planted on the Plateau since the last few decades (Qiu et al., 2010). Another widely planted species on the Loess Plateau is the conifer Chinese pine (P. tabuliformis Carrière) which is an indigenous species that is widely spread across central and northern China. Large areas of P. tabuliformis plantations are found in the Huanglongshan Mountain of the Loess Plateau (Tsunekawa et al., 2014). Natural vegetation on the Loess Plateau is mainly distributed in the Huanglongshan Mountain and Qiaoshan Mountain forest districts on the southeast part of the region and the dominant native tree species is oak forest (Quercus liaotungensis). The implementation of the Natural Forest Protection Project, with the Loess Plateau being listed as one of the key areas of focus for the ecological environment, made Q. liaotungensis forest natural rehabilitation become the most important strategy for the future re-vegetation of the region (Zhou et al., 2013).

Afforestation and conservation efforts of forest resources in recent decades through the implementation of the Grain for Green Project and the Natural Forest Protection Project have led to significant increases in the forest cover area in the Loess Plateau, which has consequently enhanced the C sequestration capacity of forest and plantation stands (Zhou et al., 2013). Numerous studies have drawn upon the efforts of the Grain for Green Program to estimate the amount of soil C storage in the region and determine which factors drive changes in soil C stocks (Qiu et al., 2010; Chang et al., 2011; Fu et al., 2011; Deng et al., 2013a; Deng et al., 2014a; Shen and Zhang 2014). However, these studies gave little attention to studying the C stock of secondary forests under the Natural Forest Protection Project, as well as to comparing the C sequestration capacities between secondary forests and plantations on the Loess Plateau (Jia et al., 2005; Wei et al., 2012; Deng et al., 2013b; Deng et al., 2014b).

Understanding the different roles of plantations and secondary forests as C reservoirs is crucial for improving predictions of current and future effects of changes in land use and land cover on the global and regional C cycle (Chen et al., 2004; Li et al., 2005; Bonner et al., 2013; Marin-Spiotta and Sharma 2013). Therefore, in the present study, we conducted a comparative field study with three 40-year-old forest types of the R. pseudoacacia and P. tabuliformis plantations, and the secondary Q. liaotungensis forest in the Huanglongshan Mountain of the Loess Plateau, China. We quantified C, N, and phosphorous (P) concentrations in major ecosystem components (tree tissues, understory, litter, and soil) in these three tree species stands. The objectives of this study were to compare the concentrations of C, N, and P, and their ratios in components of tree tissues (leaves, branches, stem, bark, fine and coarse roots), understory (shrub and herb plants), litter, and soil (0–100 cm depths), and to compare their C storage partitioning patterns in these three main forest types. The comparison was made on the basis of similarities in topography, soil texture, stand age, and management history. The results of this study regarding the differences in C:N:P stoichiometry and C storage partitioning patterns within different forest types may be useful in developing a comprehensive understanding of the ecological restoration process in this region. We hypothesized that: (1) concentration of C, N, and P and its ratios in various ecosystem components varied in the three forest types; and (2) the secondary Q. liaotungensis forests would have more C storages than in plantations of R. pseudoacacia and P. tabuliformis on the Loess Plateau, China.

2. Materials and methods

2.1. Site description

The study sites were in the Huanglongshan Mountain, which is located in the northern Shaanxi Province of the southeast Loess Plateau, China (35°28′49″−36°02′01″N, 109°38′49″−110°12′47″E). The area is a transition region of warm temperate to semi-humid and semi-arid climate. The average annual temperature is 8.6 °C and the average annual precipitation is 612 mm. The major soil in the area is cinnamon, which is a cambisol according to the FAO classification system. Huanglongshan Mountain has been the main native distribution area of secondary Q. liaotungensis forests and large-area R. pseudoacacia and P. tabuliformis plantations established since the 1950s (Wei et al., 2013).

2.2. Sample collection and analyses

In July 2011, three independent replicate stands of R. pseudoacacia plantations, P. tabuliformis plantations, and secondary Q. liaotungensis forests (each around 40 years old) were randomly chosen from the entire area of the Huanglongshan Mountain. The adjacent plantations of R. pseudoacacia and P. tabuliformis were planted and the secondary Q. liaotungensis forest had naturally regenerated on abandoned cultivated lands. These lands had been cleared of the native Q. liaotungensis forests, and were not irrigated or fertilized before cultivation (Tateno et al., 2007). To minimize between-site variability, all of the stands are characterized by similar stand age, elevation, soil texture, and topography (Table 1). A 20 m × 20 m plot was randomly selected within each stand, and diameter at breast height (DBH, at 1.3 m height) and tree height of all trees was measured. Based on DBH and tree height, the tree tissue (leaves, branches, stems, and roots) biomass of different tree levels was calculated using published species-specific allometric equations within or nearby the study area (Xiao 1990; Zhang 1990; Zhang and Chen, 1992). The concentrations of C, N, and P in tree tissues were estimated by sampling leaves, branches, stems, barks, and fine and coarse roots from five trees closest to the mean values of tree height and DBH at each plot. A destructive harvesting method was used to measure the biomass in the leaf, stem, and root portions of the shrub layer and the above- and under-ground portions of the herb layer from five 1 m × 1 m quadrates selected randomly at each plot (Deng et al., 2013a). Litter biomass was collected from these five subplots. All samples including tree tissues, shrubs, herbs, and litter were weighed and oven-dried at 65 °C to a constant weight in the lab and reweighed to obtain wet-to-dry

Table 1
Site properties and stand characteristics for three forest types in the study area.

Forest types	Black locust plantation	Chinese pine plantation	Secondary oak forest
Altitude (m)	1000–1200	1000–1200	1100–1500
Slope aspect	Southeast	Southwest	South
Slope gradient (°)	24–26	24–26	24–27
Shrubs			*Ostryopsis davidiana Decaisne, Spiraea pubescens, Rosa xanthina*
Herbaceous	*Artemisia selengensis, Calamagrostis epigejos L., Artemisia argyi*	*Carex lanceolate, Artemisia sacrorum, Artemisia argyi*	*Carex lanceolata, Artemisia sacrorum, Aster tataricus L. f*
DBH (cm)	16.08(0.61)	17.49(0.59)	18.74(0.59)
Tree height (m)	9.95(0.19)	10.37(0.32)	10.49(0.23)
Stem density (trees ha^{-1})	950(81)	1183(82)	975(43)
Age (year)	38–39	38–39	40–43

mass conversion factors. The dried samples were ground and used to determine plant nutrient concentrations.

In each sample plot, five soil columns of 100 cm depth were randomly sampled by a soil auger (5 cm in diameter). Each soil column at the 0–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, and 50–100 cm in depth was collected separately and after removing the plant roots, fauna, and debris by hand, the soil was air dried at a room temperature of about 20 °C, and was then ground and passed through a 0.25-mm sieve for measurement of soil nutrient concentrations. Soil volumetric rings (100 cm^3) were used to collect undisturbed soil samples at different layers and taken to the laboratory to measure soil bulk density by use of the cutting ring method.

The C concentrations in the vegetation, litter, and soil samples were measured by the dichromate oxidation method; total N was determined using the kjeldahl procedure; and total P was determined colorimetrically after the digestion with H_2SO_4 and $HClO_4$. All samples were analyzed at the central laboratory of the Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources (Yangling, China).

2.3. Data calculation and analysis

Total ecosystem carbon storage was based on the combination of tree, shrub-herb layer, litter, and soil pools. Leaf, branch, stem, and root C concentrations were multiplied by tree component biomass from the species-specific allometric equations to partition carbon stock among the tree components, and summed for each tree and site level to calculate the stand level tree biomass C stock. For shrub-herbs and litter, C concentrations of shrubs, herbs, and litter were multiplied by the component mass at the plot level to calculate the stand level C stock (Cao and Chen 2015). The soil C stock of each soil layer is based on the soil layer depth, its bulk density, and C concentrations. Furthermore, the calculated results for all layers (0–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, and 50–100 cm) were summed to estimate the total stock of soil C to a depth of 100 cm.

All comparisons in concentrations of C, N, and P, ratios of C:N, C:P, and N:P, and C storage among the different forest types were performed using ANOVAs, followed by multiple comparisons (LSD tests). And sample data were transformed to meet the assumptions of normality and homogeneity when needed. All statistical analyses were performed with SPSS (version 20.0, SPSS Inc., Chicago, IL, USA) and the accepted significance level was set at α = 0.05.

3. Results

3.1. C, N, and P concentrations in various ecosystem components

The C concentrations were significantly different between tree tissues in *P. tabuliformis* and *Q. liaotungensis* species (Table 2). For the *P. tabuliformis* species, the highest C concentrations were found in stems (469 g kg^{-1}), which differed significantly from the lower C concentration values observed in the coarse roots (422 g kg^{-1}). For *Q. liaotungensis*, the highest C concentration was observed in leaves (437 g kg^{-1}) while the lowest value was in the branches (389 g kg^{-1}). The highest and the lowest N and P concentrations in tree tissues among these three species were all found in leaves and stems, respectively (Table 2). The C concentrations of the tree tissues (i.e. branch, stem, fine and coarse roots) in the *P. tabuliformis* species were significantly higher than those in *R. pseudoacacia* and *Q. liaotungensis* species (Table 2). In contrast, the N and P concentrations of the tree tissues in *R. pseudoacacia* species were higher than those in *P. tabuliformis* and *Q. liaotungensis* species (Table 2).

Shrub plants were only found in *Q. liaotungensis* stands. N and P concentrations were higher in the shrub leaves (32 and 1.2 g kg^{-1}, respectively) than in the shrub roots (11 and 0.2 g kg^{-1}, respectively). In the herb layer, above-ground concentrations of C and P in *P. tabuliformis* and N and P in *R. pseudoacacia* stands were significantly higher than those in below-ground portions of the herb layer (Table 2). N and P concentrations of the above- and below-ground part of the herb layer and litter in *R. pseudoacacia* stands were higher than those in *P. tabuliformis* and *Q. liaotungensis* stands, and there were no significant differences between *P. tabuliformis* and *Q. liaotungensis* stands (Table 2). Moreover, there was no significant difference between C concentrations of the above- and below-ground herb layer and litter within the three forest types (Table 2).

The highest C and N concentrations were in the surface 0–10 cm soil layer in all three forest types, and the values significantly decreased with soil depth, while soil P concentration remained stable with soil depth (Table 2). Soil C concentration was higher in the secondary *Q. liaotungensis* forest than in the *R. pseudoacacia* and *P. tabuliformis* plantations at 0–10 cm, 30–50 cm, and 50–100 cm depths. There were no significant differences in soil N concentrations among forest types with the exception at a 30–50 cm soil depth. Soil P concentration was significantly higher in the *R. pseudoacacia* plantation than in the secondary *Q. liaotungensis* forest at all five depths.

3.2. C:N:P stoichiometry in various ecosystem components

The C:N ratio was higher in stems than in other types of tree tissues for each forest type, and C:N ratios were significantly lower in tree tissues of *R. pseudoacacia* than in tree tissues of *P. tabuliformis* (Table 3). Leaves contained the lowest C:P ratios among other tree tissues for each forest type. C:P ratios were significantly lower in tree tissues of *R. pseudoacacia* than in those of *P. tabuliformis* and *Q. liaotungensis* but did not differ among tree tissues between the *P. tabuliformis* and *Q. liaotungensis* stands (Table 3). The N:P ratios of *P. tabuliformis* did not differ among tree tissues, but N:P ratios were significantly higher in bark (52 and 26, respectively) than in

Table 2
Concentrations of C, N, and P in various ecosystem components in the three forest types on the Loess Plateau, China.

Ecosystem pool	C concentration (g kg^{-1})			N concentration (g kg^{-1})			P concentration (g kg^{-1})		
	Robinia	Pinus	Quercus	Robinia	Pinus	Quercus	Robinia	Pinus	Quercus
Tree									
Leaves	429(17)	451(5)	437(8)	37.9(0.2)a	12.6(0.3)c	20.5(0.3)b	1.8(0.05)a	0.9(0.07)b	1.0(0.05)b
Branch	418(5)b	462(9)a	389(5)c	13.7(1.0)a	5.4(0.3)b	6.7(0.3)b	0.9(0.2)	0.4(0.03)	0.5(0.1)
Stem	427(11)b	469(11)a	412(9)c	6.8(2.0)	2.4(0.5)	2.6(0.3)	0.5(0.05)a	0.2(0.04)b	0.1(0.02)b
Bark	428(11)	434(7)	421(1)	25.8(0.6)a	2.7(0.1)c	6.0(0.1)b	0.6(0.2)	0.2(0.02)	0.2(0.01)
Fine root	426(4)b	449(7)a	410(3)b	33.3(4.6)a	6.5(0.3)b	6.8(0.3)b	1.4(0.5)a	0.3(0.02)b	0.3(0.03)b
Coarse root	395(5)b	422(9)a	395(1)b	37.0(1.6)a	8.3(0.5)b	3.9(0.4)c	1.0(0.1)	0.5(0.1)	0.3(0.03)
Shrub									
leaves		442(5)			32(1)			1.2(0.1)	
stem		438(3)			13(0.5)			0.4(0.04)	
root		435(3)			11(0.7)			0.2(0.02)	
Herb									
aboveground	350(49)	419(21)	337(15)	26(3)a	18(4)ab	9(1)b	1.9(0.2)a	1.1(0.2)b	0.6(0.07)b
belowground	302(50)	246(19)	287(35)	16(1)a	8(0.5)b	10(1)b	1.1(0.1)a	0.6(0.1)b	0.6(0.09)b
Litter	327(18)	385(23)	389(8)	23(2)a	10(1)b	13(0.2)b	1.8(0.7)	0.6(0.1)	0.6(0.02)
Soil									
0–10 cm	38.0(5.1)b	47.3(3.9)b	69.1(3.4)a	2.3(0.4)	2.2(0.2)	2.6(0.1)	0.6(0.02)a	0.6(0.03)ab	0.5(0.01)b
10–20 cm	19.8(4.0)	23.3(2.4)	34.5(4.1)	1.3(0.3)	1.7(0.2)	1.1(0.1)	0.6(0.01)a	0.6(0.03)a	0.4(0.01)b
20–30 cm	13.1(2.2)	16.9(2.8)	24.3(2.8)	0.9(0.2)	1.3(0.2)	0.8(0.1)	0.6(0.01)a	0.5(0.03)a	0.4(0.01)b
30–50 cm	9.1(0.9)b	9.8(0.7)b	18.5(1.5)a	0.6(0.1)b	1.0(0.1)a	0.5(0.05)b	0.6(0.02)a	0.5(0.03)ab	0.4(0.02)b
50–100 cm	7.4(0.3)b	6.5(0.5)b	11.7(0.6)a	0.5(0.03)	1.0(0.1)	0.4(0.03)	0.6(0.02)a	0.4(0.03)b	0.4(0.03)b

Notes: Data in parentheses represent S.E. (n = 3). Values in a line followed by the different letters denote significant differences (P<0.05) among the three forest types. No letters at the table indicated that there was no significant among the three forest types.

Table 3
Ratios of C:N, C:P, and N:P in various ecosystem components in the three forest types on the Loess Plateau, China.

Ecosystem pool	C:N			C:P			N:P		
	Robinia	Pinus	Quercus	Robinia	Pinus	Quercus	Robinia	Pinus	Quercus
Tree									
Leaves	11(0.5)c	36(0.9)a	21(0.5)b	232(13)b	513(42)a	435(28)a	21(0.5)a	14(1)b	20(0.9)a
Branch	30(2)c	85(4)a	59(3)b	524(87)b	1187(85)a	866(163)ab	17(2)	14(0.5)	15(2)
Stem	74(19)b	214(37)a	162(24)ab	857(101)	3326(720)	3340(712)	13(3)	15(0.9)	20(1)
Bark	17(0.8)c	159(7)a	70(2)b	867(211)b	2665(409)a	1796(113)ab	52(12)a	17(3)b	26(1)ab
Fine root	13(2)b	70(3)a	61(2)a	503(99)b	1535(141)a	1281(134)a	38(6)a	22(2)b	21(2)b
Coarse root	11(0.4)c	51(2)b	101(9)a	365(110)b	906(191)ab	1597(167)a	35(11)	18(3)	16(0.3)
Shrub									
leaves		14(1)			376(21)			27(1)	
stem		34(2)			1068(92)			31(2)	
root		38(2)			2008(173)			52(4)	
Herb									
aboveground	13(0.2)b	26(6)ab	37(4)a	181(14)b	414(76)ab	592(59)a	14(1)	16(1)	16(1)
belowground	19(2)b	31(3)a	30(2)ab	288(54)	398(46)	497(77)	15(1)	13(2)	17(2)
Litter	16(1)b	39(4)a	30(1)a	244(74)b	604(75)a	634(4)a	16(4)	16(1)	21(1)
Soil									
0–10 cm	17(0.9)b	18(0.9)b	31(2)a	59(7)b	94(6)b	118(11)a	3.5(0.6)	3.8(0.6)	5.2(0.2)
10–20 cm	15(2)b	21(0.4)a	20(0.4)a	32(6)	56(4)	63(10)	2.2(0.5)	3.2(0.5)	2.6(0.2)
20–30 cm	15(0.3)b	20(0.5)a	19(0.2)a	22(4)b	41(6)ab	47(7)a	1.5(0.2)	2.5(0.4)	2.0(0.2)
30–50 cm	14(0.6)b	19(0.6)a	18(0.7)a	16(3)b	24(1)ab	36(5)a	1.2(0.2)	2.0(0.3)	1.3(0.1)
50–100 cm	15(1)	18(1)	19(4)	13(1)b	16(18)ab	32(4)a	0.9(0.1)b	1.7(0.3)a	0.8(0.1)b

Notes: Data in parentheses represent S.E. (n = 3). Values in a line followed by the different letters denote significant differences (P<0.05) among the three forest types. No letters at the table indicated that there was no significant among the three forest types.

branches (17 and 15, respectively) for *R. pseudoacacia* and *Q. liaotungensis* stands. N:P ratios were significantly greater in the leaves, bark, and fine roots of *R. pseudoacacia* than in those of *P. tabuliformis* (Table 3).

In the shrub layer of *Q. liaotungensis* stands, C:N, C:P, and N:P ratios were significantly lower in leaves than in stems and roots. C:N, C:P, and N:P ratios did not differ between above- and below-ground components in the herb layer (Table 3). C:N and C:P ratios of the above- and below-ground parts of the herb layer and litter were lower in *R. pseudoacacia* stands than in *P. tabuliformis* and *Q. liaotungensis* stands but did not differ between the *P. tabuliformis* and *Q. liaotungensis* stands (Table 3). Furthermore, the N:P ratios in the herb layer and litter did not differ among *R. pseudoacacia*, *P. tabuliformis,* and *Q. liaotungensis* stands.

Soil C:N ratios at a 0–10 cm depth were lower in the *R. pseudoacacia* and *P. tabuliformis* plantations than in the secondary *Q. liaotungensis* forest but did no differ between the *R. pseudoacacia* and *P. tabuliformis* plantations. Soil C:N ratios at 10–20 cm, 20–30 cm, and 30–50 cm soil depths were lower in the *R. pseudoacacia* plantation than in the *P. tabuliformis* plantation and secondary *Q. liaotungensis* forest but did no differ between the *P. tabuliformis* plantation and *Q. liaotungensis* forest (Table 3). There were no significant differences between soil C:N ratios among forest types at the 50–100 cm soil depth. Soil C:P ratios were significantly lower in the *R. pseudoacacia* plantation than in the secondary *Q. liaotungensis* forest among most soil depths with the exception among forest types at the 10–20 cm soil depth (Table 3). There was no significant difference among forest types on soil N:P ratios among soil depth except at 50–100 cm (Table 3).

3.3. Ecosystem C storage partitioning patterns in different forest types

The C storage in the tree biomass of the *R. pseudoacacia*, *P. tabuliformis,* and *Q. liaotungensis* stands were 52, 115, and 100 t ha^{-1}, respectively (Table 4). Among the tree components, the C storage in leaves was greater in the *P. tabuliformis* stand (14.9 t ha^{-1}) than in the *R. pseudoacacia* (4.9 t ha^{-1}) and *Q. liaotungensis* (4.5 t ha^{-1}) stands. Stems had the highest C storage, which was significantly greater in the *P. tabuliformis* stand (52.5 t ha^{-1}) than in the *R. pseudoacacia* (14.6 t ha^{-1}) and *Q. liaotungensis* (35.2 t ha^{-1}) stands (Table 4). Only the *Q. liaotungensis* stand had shrub vegetation and the C storage in shrubs was 0.95 t ha^{-1}. The C storage in litter was much higher in the *P. tabuliformis* (10.13 t ha^{-1}) and *Q. liaotungensis* (6.9 t ha^{-1}) stands than in the *R. pseudoacacia* (0.58 t ha^{-1}) stand.

The total C stored in the soil (0–100 cm depth) was 161, 173, and 251 t ha^{-1} in the *R. pseudoacacia*, *P. tabuliformis,* and *Q. liaotungensis* stands, respectively (Table 4). In the three stands, soil C was mainly stored at the surface soil layer and deceased as soil depth increased (Table 4). The C storage was higher in the secondary *Q. liaotungensis* forest than in the *R. pseudoacacia* and *P. tabuliformis* plantations at depths of 0–10 cm, 30–50 cm, 50–100 cm, and 0–100 cm.

The total ecosystem C storage was highest in the secondary *Q. liaotungensis* forest at 359 t ha^{-1}; those stored in the plantations of *P. tabuliformis* and *R. pseudoacacia* were 298 and 214 t ha^{-1}, respectively (Table 4). In the three stands, the C storage is ranked in the following order: soil > tree > litter > shrubs and herb plants. The proportion of the shrubs and herb plants to the ecosystem C storage was less than 1%. Litter accounted for the ecosystem C storage of 0.28%, 3.39%, and 1.92% in the *R. pseudoacacia*, *P. tabuliformis* and *Q. liaotungensis* stands, respectively, while Trees accounted for 24.42%, 38.57%, and 28.05%. Soil C storage were 3.1, 1.5, and 2.5 fold higher than tree C storage, and accounted for the ecosystem C storage of 75.12% in the *R. pseudoacacia* stands, 57.98% in the *P. tabuliformis* stands, and 69.58% in the *Q. liaotungensis* stands (Table 4).

4. Discussion

Knowledge of the C stock pools stored in various forest types can facilitate optimal decision-making regarding C management (He et al., 2013). As a contribution to the current existing knowledge, we compared the C:N:P ratios of major ecosystem components and the C storage partitioning patterns between a fast-growing N-fixing *R. pseudoacacia* plantation, an indigenous *P. tabuliformis* plantation, and a secondary *Q. liaotungensis* forest on the Loess Plateau, China. The results showed that concentration of C, N, and P and its ratios in various ecosystem components varied in the three forest types; and the secondary *Q. liaotungensis* forests had more C storages than in plantations of *R. pseudoacacia* and *P. tabuliformis*.

4.1. Tree tissues C:N:P characteristics among forest types

Conifer tree *P. tabuliformis* species have higher C concentrations than deciduous tree *R. pseudoacacia* and *Q. liaotungensis* species, which is a result of a relatively higher degree of lignifications in conifer tissues and a relatively higher concentration of non-structural carbohydrates in deciduous tissues (Lamlom and Savidge 2003; Thomas and Martin 2012). Generally, leaves of N-fixing plants contain a higher concentration of N than P, and thus a higher N:P ratio than that of non-N-fixing plants (Killingbeck 1996; Rice et al., 2004; Wright et al., 2004; Vergutz et al., 2012; Li et al., 2014). Our study showed that all tree tissues of N-fixing *R. pseudoacacia* had both higher N and P concentrations and N:P ratios than non-N-fixing *P. tabuliformis* and *Q. liaotungensis* tree species. However,

the indigenous N-fixing shrub, Chinese sea-buckthorn, on the loess Plateau did not have higher P concentrations than co-occurring non-N-fixing plants (Li et al., 2014).

The higher C:N and C:P and lower N:P ratios in the stems of the three forest types are mainly attributed to the higher proportion of C-enriched compounds such as lignin (Agren 2008; Li et al., 2013). The lower C:N and C:P ratios in fast-growing N-fixing *R. pseudoacacia* species are accounted for by higher N and P accumulate rates compared with the C accumulate rate, which constrains tree growth (Elser et al., 2007; Vitousek et al., 2010). Decreased plant C:N and C:P ratios have been observed with increasing plantation age (Agren 2008; Li et al., 2013). An increasing number of studies have used the N:P ratio of leaves to indicate soil nutrient limitation at the plant community level, i.e., N:P ratios <14 suggest N limitation, N:P ratios >16 suggest P limitation and N:P ratios between 14 and 16 suggest both N and P limitation (Gusewell 2004; Reich and Oleksyn 2004; Richardson et al., 2008). In this study, leaf N:P ratios in the conifer tree *P. tabuliformis* stands indicated both N and P limitation; whereas, leaf N:P ratios in the N-fixing tree *R. pseudoacacia* and secondary *Q. liaotungensis* stands indicated P limitation in both stands. Zheng and Shangguan (2007) studied leaf nutrients in southern to northern ranges on the Loess Plateau and their results also indicated that the flora of the Loess Plateau is P-limited.

4.2. Understory and litter C:N:P characteristics among forest types

Although all herbs are not N-fixing plants, N and P concentrations in herbs were higher in the N-fixing *R. pseudoacacia* stands than in the non-N-fixing tree *P. tabuliformis* and *Q. liaotungensis* stands. This may indicate that non-N-fixing herb plants can absorb more N with the help of symbiotic N-fixing bacteria of co-occurring N-fixing plants. Moreover, C concentrations were lower in herb plants than in overstory trees in all three forest types. This is consistent with previous reports that trees can synthesize and accumulate more organic matter, thereby resulting in higher C concentration than that found in understory components (Cleveland et al., 2011; He et al., 2013). In addition, a recent study found that the P concentrations were significantly lower in overstory than in understory plants in subtropical China (Fan et al., 2015). This has been exemplified by records of a decrease in leaf P concentration with increasing plant size (Han et al., 2005; Elser et al., 2010).

Litter plays an important role in nutrient cycling between plants and soils in terrestrial ecosystems. The nutrient characteristic of litter depends on litter type, decomposition rate, micro-environment, and litter productivity. It is generally accepted that litter C concentrations in broadleaf forests is lower than that in coniferous forests (He et al., 2013). However, in our study, litter N concentration was only significantly higher in the N-fixing tree *R. pseudoacacia* stand than in the non-N-fixing *P. tabuliformis* and *Q. liaotungensis* stands, but did not differ between coniferous *P. tabuliformis* and broadleaved *Q. liaotungensis* stands. As a consequence, the C:N and C:P ratios of litter in the N-fixing tree *R. pseudoacacia* stand were lower than in *P. tabuliformis* and *Q. liaotungensis* stands. Our results are consistent with previous studies on the litterfall production between *R. pseudoacacia* plantations and indigenous *Q. liaotungensis* forests on the Loess Plateau (Tateno et al., 2007). Moreover, Tateno et al. (2007) found that the annual N cycling via litterfall was higher in the *R. pseudoacacia* plantation than in the secondary *Q. liaotungensis* forest.

4.3. Soil C:N:P characteristics among forest types

N-fixing species have been widely used as fertilizing plants to supplement N stores, increase rates of N cycling and availability, and increase primary productivity in the recovery of degraded min-

Table 4
C stock (t ha^{-1}) and percentage (%) in various ecosystem components in the three forest types on the Loess Plateau, China.

Ecosystem pool	Black locust plantation		Chinese pine plantation		Secondary oak forest	
	Carbon storage	percentage	Carbon storage	percentage	Carbon storage	percentage
Tree biomass	52(7)	24.42	115(20)	38.57	100(25)	28.05
Leaves	4.5(0.7)b	2.12	14.9(2)a	4.97	4.9(0.5)b	1.36
Branch	18.8(3.4)	8.82	19.0(3)	6.35	31.5(10)	8.78
Stem	14.6(1.7)b	6.84	52.5(9)a	17.59	35.2(7)b	9.81
Bark	3.7(0.4)	1.75	9.1(2)	3.04	9.6(2)	2.68
Root	10.4(1.4)	4.89	19.8(4)	6.62	19.5(5)	5.42
Shrub					0.95(0.2)	0.27
Herb	0.37(0.04)	0.18	0.22(0.03)	0.06	0.66(0.2)	0.18
Litter	0.58(0.04)b	0.28	10.13(1.7)a	3.39	6.9(0.6)a	1.92
Soil total	161(14)b	75.12	173(10)b	57.98	251(13)a	69.58
0–10 cm	46(6)b	21.54	55(4)b	18.44	75(4)a	20.87
10–20 cm	25(5)	11.74	27(3)	9.05	37(1)	10.29
20–30 cm	17(3)	8.11	21(3)	7.03	27(3)	7.51
30–50 cm	22(4)b	10.32	24(1)b	8.04	43(6)a	11.96
50–100 cm	50(2)b	23.41	46(3)b	15.42	68(2)a	18.95
Net ecosystem	214(12)c	100	298(10)b	100	359(6)a	100

Notes: Notes: Data in parentheses represent S.E. (n = 3). Values in a line followed by the different letters denote significant differences (P < 0.05) among the three forest types. No letters at the table indicated that there was no significant among the three forest types.

ing land, deforested land, and agroforestry systems (Deans et al., 1999; Uselman et al., 2000; Rice et al., 2004; Macedo et al., 2008; Wang et al., 2010). For example, soil organic matter and N concentrations in the 0–5 cm soil depth were 40–50% and 20–50% higher in the N-fixing forests than in the non-N-fixing forests in the restoration of degraded lands in southern China (Wang et al., 2010). However, our study showed that soil P concentrations were only significantly higher in the *R. pseudoacacia* and *P. tabuliformis* plantations than in secondary *Q. liaotungensis* forest, and we did not find higher soil C and N concentrations in N-fixing species when compared to non- N-fixing species. Tateno et al. (2007) also found no significant differences in soil N between *R. pseudoacacia* and *Q. liaotungensis* forests on the Loess Plateau, and suggested that *R. pseudoacacia* stands should be gradually converted to indigenous tree species in the long-term. Although the soil C:N and C:P ratios showed similar patterns in plants and litter, those in the *R. pseudoacacia* plantation were lower than in the *P. tabuliformis* plantations and *Q. liaotungensis* forest; further contrasting results between the higher N concentrations in leaves and litter and the lower soil N concentrations supply are needed to understand how soil nutrient availability influences plant nutrients for the N-fixing *R. pseudoacacia* plantations on the Loess Plateau.

4.4. Ecosystem C storage partitioning patterns among forest types

In the tropics and subtropics, biomass C accumulation was higher in plantations than in secondary forests (Corlett 1995; Silver et al., 2000; Bonner et al., 2013). However, we found no significant difference in biomass C storage between plantations and the secondary forest in this study. Previous studies have shown that *R. pseudoacacia* is a suitable species for afforestation in the study area due to its adaptability to grow in dry, sandy soil, and its high survival and remarkable growth rates (Shan et al., 2002; Du et al., 2007; Jin et al., 2011; Cierjacks et al., 2013; Yan et al., 2013). Shen and Zhang (2014) reported that *R. pseudoacacia* plantations reach their highest annual net tree biomass C storage capacities just after five years of afforestation. *R. pseudoacacia* was selected for afforestation on the Loess Plateau mainly because of its rapid growth, which results in a "dry soil horizon" of *R. pseudoacacia* plantations, followed by the wilting of the top of the crown and the deaths of individual trees (Hou et al., 1999; Wei et al., 2005; Shangguan 2007; Chen et al., 2008).

Due to the lack of shrub plant biomass and few herbaceous plants in the *R. pseudoacacia* and *P. tabuliformis* plantations, the C

storage in the shrub-herb composition of the plantations was significantly lower than that of the secondary *Q. liaotungensis* forest. There were few seedlings and little understory vegetation in the plantations due to scarce precipitation during the prior autumn; whereas many seedlings and abundant understory vegetation were evident in the secondary *Q. liaotungensis* forest (Tateno et al., 2007; Tsunekawa et al., 2014). Therefore, the presence of few to no shrub plants in plantations has become a limitation factor in assessing the ecological success of restoration efforts by afforestation on the Loess Plateau (Jiao et al., 2012). C storage in litter is accounts for an estimated 5% of all forest ecosystem C stocks worldwide (Domke et al., 2016). However, in this study, C storage in litter only accounted for 0.21%, 2.82%, and 2.75% of total C storage in *R. pseudoacacia*, *P. tabuliformis,* and *Q. liaotungensis* stands, respectively. Moreover, the litter C storage in the *R. pseudoacacia* plantation was significantly lower than that in the *P. tabuliformis* plantation and secondary *Q. liaotungensis* forest. A possible explanation is that the *R. pseudoacacia* plantation might be more susceptible to soil erosion, and thus a considerable amount of *R. pseudoacacia* leaves are removed by surface soil erosion and wind, resulting in thinner and more fragmented litter in the *R. pseudoacacia* plantation on the Loess Plateau (Tateno et al., 2007).

Our study agrees with previous studies that soil acts as the main carbon pool for the three forest types. Several studies have demonstrated that tree species can have a major effect on the soil C pool (Paul et al., 2002; Berthrong et al., 2009; Laganiere et al., 2010; Li et al., 2012). Soil C storage was significantly higher in the secondary *Q. liaotungensis* forest than in the plantations of *R. pseudoacacia* and *P. tabuliformis* at all soil depths. The results of a study on the changing soil C stocks in China's Grain for Green Program highlighted that planting a broadleaf forest had a greater effect on soil C stocks than planting a conifer forest (Deng et al., 2014a). However, in this study, there was no significant difference in soil C storage between the *R. pseudoacacia* and *P. tabuliformis* plantations at all soil depths. Instead, the secondary *Q. liaotungensis* forest had a significantly higher C storage than the plantations of *R. pseudoacacia* and *P. tabuliformis*.

4.5. Relationships between C:N:P characteristics and biomass production

The results of our analysis on the relationships between the characteristics of the C, N, P concentrations and their ratios and biomass production are consistent with previous reports which

show that these relationships are generally weak (Gusewell 2004). However, any clear weak relationships have only been observed occasionally. One example was observed in wetlands forests, where there was a decline in litter biomass production with an increasing N:P ratio (Lockaby and Conner 1999). The biomass of aboveground plant components was negatively correlated to C and P concentration but that of the belowground components was negatively correlated to the N concentration at the Tibetan Plateau in China (Hong et al., 2016). The biomass production of road verges correlated negatively with tissue N:P ratios (Schaffers 2002). Understory biomass was positively related to N:P ratios, while overstory growth was negatively related to a N:P ratio that was observed in Eucalyptus plantations in subtropical China (Fan et al., 2015). Agren (2004) reported that the N:P ratio was enhanced at low growth rates and declined at high growth rates.

Most studies have focused on the impacts of forest types on C storage capacity in tropical, subtropical, subalpine, temperate, and boreal forests (Chazdon et al., 2009; Laganiere et al., 2010; He et al., 2013; Sang et al., 2013; Zhang et al., 2013). However, potential positive or negative effects of forest types on C sequestration should be evaluated to ensure long-term sustainability. To highlight long-term changes in C storage, it is necessary to monitor and assess the effects of different forests on stand structure, biomass production, plant diversity, and plant-soil biogeochemical cycles.

5. Conclusion

Understanding the different roles of plantations and secondary forests in temperate regions, especially disturbed forests on the Loess Plateau, China, as C reservoirs is crucial for improving predictions of current and future effects of changes in land use and land cover on the global and regional C cycle. Our results showed that the N-fixing tree *R. pseudoacacia* had higher N and P concentrations and N:P ratios, and lower C:N and C:P ratios in tree tissues, herbs, and litter than the non-N-fixing *P. tabuliformis* and *Q. liaotungensis* tree species. In contrast, soil C and N concentrations in the *R. pseudoacacia* plantation were not higher than those in the *P. tabuliformis* plantation and secondary *Q. liaotungensis* forests. The C storage of the soil and total ecosystem were significantly higher in the secondary *Q. liaotungensis* forests than in plantations of *R. pseudoacacia* and *P. tabuliformis*. These results indicate that in the long-term, the secondary *Q. liaotungensis* forests and indigenous *P. tabuliformis* plantations may enhance C storage more substantially than fast-growing *R. pseudoacacia* plantations on the Loess Plateau, China. Thus, in the semi-aried environment of the Loess Plateau, the secondary forests can fulfill important ecosystem service roles and natural revegetation without intensive human interference should be advocated as a more adaptive and appropriate type for ecological restoration. In addition, more measures and technological approaches for afforestation are needed and indigenous *P. tabuliformis* plantations should also get more attention in the restoration project.

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References

Agren, G.I., 2004. The C:N:P stoichiometry of autotrophs – theory and observations. Ecol. Lett. 7, 185–191.

Agren, G.I., 2008. Stoichiometry and nutrition of plant growth in natural communities. annual review of ecology. Evol. Syst. 39, 153–170.

Berthrong, S.T., Jobbagy, E.G., Jackson, R.B., 2009. A global meta-analysis of soil exchangeable cations, pH, carbon, and nitrogen with afforestation. Ecol. Appl. 19, 2228–2241.

Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320, 1444–1449.

Bonner, M.T.L., Schmidt, S., Shoo, L.P., 2013. A meta-analytical global comparison of aboveground biomass accumulation between tropical secondary forests and monoculture plantations. For. Ecol. Manage. 291, 73–86.

Cao, Y., Chen, Y., 2015. Biomass, carbon and nutrient storage in a 30-year-old Chinese cork oak (Quercus variabilis) forest on the south slope of the Qinling Mountains, China. Forests 6, 1239–1255.

Chang, R.Y., Fu, B.J., Liu, G.H., Liu, S.G., 2011. Soil carbon sequestration potential for grain for green project in Loess Plateau, China. Environ. Manage. 48, 1158–1172.

Chazdon, R.L., Peres, C.A., Dent, D., Sheil, D., Lugo, A.E., Lamb, D., Stork, N.E., Miller, S.E., 2009. The potential for species conservation in tropical secondary forests. Conserv. Biol. 23, 1406–1417.

Chen, C.R., Xu, Z.H., Mathers, N.J., 2004. Soil carbon pools in adjacent natural and plantation forests of subtropical Australia. Soil Sci. Soc. Am. J. 68, 282–291.

Chen, H.S., Shao, M.G., Li, Y.Y., 2008. Soil desiccation in the Loess Plateau of China. Geoderma 143, 91–100.

Chen, X.G., Zhang, X.Q., Zhang, Y.P., Wan, C.B., 2009. Carbon sequestration potential of the stands under the Grain for Green Program in Yunnan Province, China. For. Ecol. Manage. 258, 199–206.

Cierjacks, A., Kowarik, I., Joshi, J., Hempel, S., Ristow, M., von der Lippe, M., Weber, E., 2013. Biological flora of the british isles: robinia pseudoacacia. J. Ecol. 101, 1623–1640.

Cleveland, C.C., Townsend, A.R., Taylor, P., Alvarez-Clare, S., Bustamante, M.M.C., Chuyong, G., Dobrowski, S.Z., Grierson, P., Harms, K.E., Houlton, B.Z., Marklein, A., Parton, W., Porder, S., Reed, S.C., Sierra, C.A., Silver, W.L., Tanner, E.V.J., Wieder, W.R., 2011. Relationships among net primary productivity, nutrients and climate in tropical rain forest: a pan-tropical analysis. Ecol. Lett. 14, 1313–1317.

Corlett, R.T., 1995. Tropical secondary forests. Prog. Phys. Geogr. 19, 159–172.

Cuevas, E., Brown, S., Lugo, A., 1991. Above– and belowground organic matter storage and production in a tropical pine plantation and a paired broadleaf secondary forest. Plant Soil 135, 257–268.

Deans, J.D., Diagne, O., Lindley, D.K., Dione, M., Parkinson, J.A., 1999. Nutrient and organic-matter accumulation in Acacia senegal fallows over 18 years. For. Ecol. Manage. 124, 153–167.

Deng, L., Shangguan, Z.P., Sweeney, S., 2013a. Changes in soil carbon and nitrogen following land abandonment of farmland on the Loess Plateau, China. PLoS One 8.

Deng, L., Wang, K.B., Chen, M.L., Shangguan, Z.P., Sweeney, S., 2013b. Soil organic carbon storage capacity positively related to forest succession on the Loess Plateau, China. Catena 110, 1–7.

Deng, L., Liu, G.b., Shangguan, Z.p., 2014a. Land-use conversion and changing soil carbon stocks in China's 'Grain-for-Green'Program: a synthesis. Global Change Biol.

Deng, L., Wang, K.B., Shangguan, Z.P., 2014b. Long-term natural succession improves nitrogen storage capacity of soil on the Loess Plateau, China. Soil Res. 52, 262–270.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., Russell, M.B., Smith, J.E., 2016. Estimating litter carbon stocks on forest land in the United States. Sci. Total Environ. 557, 469–478.

Du, S., Yamanaka, N., Yamamoto, F., Otsuki, K., Wang, S., Hou, Q., 2007. The effect of climate on radial growth of Quercus liaotungensis forest trees in Loess Plateau, China. Dendrochronologia 25, 29–36.

Elser, J.J., Bracken, M.E.S., Cleland, E.E., Gruner, D.S., Harpole, W.S., Hillebrand, H., Ngai, J.T., Seabloom, E.W., Shurin, J.B., Smith, J.E., 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecol. Lett. 10, 1135–1142.

Elser, J.J., Fagan, W.F., Kerkhoff, A.J., Swenson, N.G., Enquist, B.J., 2010. Biological stoichiometry of plant production: metabolism, scaling and ecological response to global change. New Phytol. 186, 593–608.

Fan, H.B., Wu, J.P., Liu, W.F., Yuan, Y.H., Hu, L., Cai, Q.K., 2015. Linkages of plant and soil C:N:P stoichiometry and their relationships to forest growth in subtropical plantations. Plant Soil 392, 127–138.

Finegan, B., 1996. Pattern and process in neotropical secondary rain forests: the first 100 years of succession. Trends Ecol. Evol. 11, 119–124.

Fu, B.J., Liu, Y., Lu, Y.H., He, C.S., Zeng, Y., Wu, B.F., 2011. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. Ecol. Complexity 8, 284–293.

Gusewell, S., 2004. N:P ratios in terrestrial plants: variation and functional significance. New Phytol. 164, 243–266.

Han, W.X., Fang, J.Y., Guo, D.L., Zhang, Y., 2005. Leaf nitrogen and phosphorus stoichiometry across 753 terrestrial plant species in China. New Phytol. 168, 377–385.

He, Y.J., Qin, L., Li, Z.Y., Liang, X.Y., Shao, M.X., Tan, L., 2013. Carbon storage capacity of monoculture and mixed-species plantations in subtropical China. For. Ecol. Manage. 295, 193–198.

Hong, J.T., Wang, X.D., Wu, J.B., 2016. Variation in carbon, nitrogen and phosphorus partitioning between above- and belowground biomass along a precipitation gradient at Tibetan Plateau. J. Mountain Sci. 13, 661–671.

Hou, Q., Han, R., Han, S., 1999. The preliminary research on the problems of soil drying in artificial forest and grass land in the Loess Plateau. Soil Water Conserv. China 5, 11–14.

Jia, G.M., Cao, J., Wang, C.Y., Wang, G., 2005. Microbial biomass and nutrients in soil at the different stages of secondary forest succession in Ziwulin, northwest China. For. Ecol. Manage. 217, 117–125.

Jiao, J.Y., Zhang, Z.G., Bai, W.J., Jia, Y.F., Wang, N., 2012. Assessing the ecological success of restoration by afforestation on the chinese loess plateau. Restor. Ecol. 20, 240–249.

Jin, T.T., Liu, G.H., Fu, B.J., Ding, X.H., Yang, L., 2011. Assessing adaptability of planted trees using leaf traits: a case study with Robinia pseudoacacia L. in the Loess Plateau, China. Chin. Geog. Sci. 21, 290–303.

Killingbeck, K.T., 1996. Nutrients in senesced leaves: keys to the search for potential resorption and resorption proficiency. Ecology 77, 1716–1727.

Laclau, P., 2003. Biomass and carbon sequestration of ponderosa pine plantations and native cypress forests in northwest Patagonia. For. Ecol. Manage. 180, 317–333.

Laganiere, J., Angers, D.A., Pare, D., 2010. Carbon accumulation in agricultural soils after afforestation: a meta-analysis. Global Change Biol. 16, 439–453.

Lamlom, S.H., Savidge, R.A., 2003. A reassessment of carbon content in wood: variation within and between 41 North American species. Biomass Bioenergy 25, 381–388.

Law, B.E., Sun, O.J., Campbell, J., Van Tuyl, S., Thornton, P.E., 2003. Changes in carbon storage and fluxes in a chronosequence of ponderosa pine. Global Change Biol. 9, 510–524.

Li, Y., Xu, M., Zou, X.M., Shi, P.J., Zhang, Y.Q., 2005. Comparing soil organic carbon dynamics in plantation and secondary forest in wet tropics in Puerto Rico. Global Change Biol. 11, 239–248.

Li, D.J., Niu, S.L., Luo, Y.Q., 2012. Global patterns of the dynamics of soil carbon and nitrogen stocks following afforestation: a meta-analysis. New Phytol. 195, 172–181.

Li, H., Li, J., He, Y.L., Li, S.J., Liang, Z.S., Peng, C.H., Polle, A., Luo, Z.B., 2013. Changes in carbon, nutrients and stoichiometric relations under different soil depths, plant tissues and ages in black locust plantations. Acta Physiol. Plant. 35, 2951–2964.

Li, X.W., Sun, K., Li, F.Y., 2014. Variation in leaf nitrogen and phosphorus stoichiometry in the nitrogen-fixing Chinese sea-buckthorn (Hippophae rhamnoides L. subsp sinensis Rousi) across northern China. Ecol. Res. 29, 723–731.

Lockaby, B.G., Conner, W.H., 1999. N: P balance in wetland forests: productivity across a biogeochemical continuum. Bot. Rev. 65, 171–185.

Ma, Z.Q., Hartmann, H., Wang, H.M., Li, Q.K., Wang, Y.D., Li, S.G., 2014. Carbon dynamics and stability between native Masson pine and exotic slash pine plantations in subtropical China. Eur. J. For. Res. 133, 307–321.

Macedo, M.O., Resende, A.S., Garcia, P.C., Boddey, R.M., Jantalia, C.P., Urquiaga, S., Campello, E.F.C., Franco, A.A., 2008. Changes in soil C and N stocks and nutrient dynamics 13 years after recovery of degraded land using leguminous nitrogen-fixing trees. For. Ecol. Manage. 255, 1516–1524.

Marin-Spiotta, E., Sharma, S., 2013. Carbon storage in successional and plantation forest soils: a tropical analysis. Global Ecol. Biogeogr. 22, 105–117.

Montagnini, F., Porras, C., 1998. Evaluating the role of plantations as carbon sinks: an example of an integrative approach from the humid tropics. Environ. Manage. 22, 459–470.

Paul, K.I., Polglase, P.J., Nyakuengama, J.G., Khanna, P.K., 2002. Change in soil carbon following afforestation. For. Ecol. Manage. 168, 241–257.

Qiu, L.P., Zhang, X.C., Cheng, J.M., Yin, X.Q., 2010. Effects of black locust (Robinia pseudoacacia) on soil properties in the loessial gully region of the Loess Plateau, China. Plant Soil 332, 207–217.

Reich, P.B., Oleksyn, J., 2004. Global patterns of plant leaf N and P in relation to temperature and latitude. Proc. Natl. Acad. Sci. U. S. A. 101, 11001–11006.

Rice, S.K., Westerman, B., Federici, R., 2004. Impacts of the exotic, nitrogen-fixing black locust (Robinia pseudoacacia) on nitrogen-cycling in a pine-oak ecosystem. Plant Ecol. 174, 97–107.

Richardson, S.J., Allen, R.B., Doherty, J.E., 2008. Shifts in leaf N:P ratio during resorption reflect soil P in temperate rainforest. Funct. Ecol. 22, 738–745.

Sang, P.M., Lamb, D., Bonner, M., Schmidt, S., 2013. Carbon sequestration and soil fertility of tropical tree plantations and secondary forest established on degraded land. Plant Soil 362, 187–200.

Schaffers, A.P., 2002. Soil, biomass, and management of semi-natural vegetation – Part I. Interrelationships. Plant Ecol. 158, 229–246.

Schimel, D.S., House, J.I., Hibbard, K.A., Bousquet, P., Ciais, P., Peylin, P., Braswell, B.H., Apps, M.J., Baker, D., Bondeau, A., Canadell, J., Churkina, G., Cramer, W., Denning, A.S., Field, C.B., Friedlingstein, P., Goodale, C., Heimann, M., Houghton, R.A., Melillo, J.M., Moore, B., Murdiyarso, D., Noble, I., Pacala, S.W., Prentice, I.C., Raupach, M.R., Rayner, P.J., Scholes, R.J., Steffen, W.L., Wirth, C., 2001. Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. Nature 414, 169–172.

Schlesinger, W.H., Lichter, J., 2001. Limited carbon storage in soil and litter of experimental forest plots under increased atmospheric CO2. Nature 411, 466–469.

Schulze, E.D., Wirth, C., Heimann, M., 2000. Climate change – managing forests after Kyoto. Science 289, 2058–2059.

Shan, C., Liang, Z., Hao, W., 2002. Review on growth of locust and soil water in Loess Plateau. Acta Botanica Boreali-Occidentalia Sinica 23, 1341–1346.

Shangguan, Z.P., 2007. Soil desiccation occurrence an its impact on forest vegetation in the Loess Plateau of China. Int. J. Sustain. Dev. World Ecol. 14, 299–306.

Shen, J.P., Zhang, W.H., 2014. Characteristics of carbon storage and sequestration of Robinia pseudoacacia forest land converted by farmland in the Hilly Loess Plateau Region. Acta Ecol. Sin. 34.

Shi, H., Shao, M.G., 2000. Soil and water loss from the Loess Plateau in China. J. Arid Environ. 45, 9–20.

Silver, W.L., Ostertag, R., Lugo, A.E., 2000. The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. Restor. Ecol. 8, 394–407.

Tateno, R., Tokuchi, N., Yamanaka, N., Du, S., Otsuki, K., Shimamura, T., Xue, Z., Wang, S., Hou, Q., 2007. Comparison of litterfall production and leaf litter decomposition between an exotic black locust plantation and an indigenous oak forest near Yan'an on the Loess Plateau, China. For. Ecol. Manage. 241, 84–90.

Thomas, S.C., Martin, A.R., 2012. Carbon content of tree tissues: a synthesis. Forests 3, 332–352.

Tsunekawa, A., Liu, G., Yamanaka, N., Du, S., 2014. Restoration and Development of the Degraded Loess Plateau, China. Springer.

Uselman, S.M., Qualls, R.G., Thomas, R.B., 2000. Effects of increased atmospheric CO2, temperature, and soil N availability on root exudation of dissolved organic carbon by a N-fixing tree (Robinia pseudoacacia L.). Plant Soil 222, 191–202.

Vergutz, L., Manzoni, S., Porporato, A., Novais, R.F., Jackson, R.B., 2012. Global resorption efficiencies and concentrations of carbon and nutrients in leaves of terrestrial plants. Ecol. Monogr. 82, 205–220.

Vitousek, P.M., Porder, S., Houlton, B.Z., Chadwick, O.A., 2010. Terrestrial phosphorus limitation: mechanisms, implications, and nitrogen-phosphorus interactions. Ecol. Appl. 20, 5–15.

Wang, F.M., Li, Z.A., Xia, H.P., Zou, B., Li, N.Y., Liu, J., Zhu, W.X., 2010. Effects of nitrogen-fixing and non-nitrogen-fixing tree species on soil properties and nitrogen transformation during forest restoration in southern China. Soil Sci. Plant Nutr. 56, 297–306.

Wei, X., Liu, S., Zhou, G., Wang, C., 2005. Hydrological processes in major types of Chinese forest. Hydrol. Processes 19, 63–75.

Wei, J., Cheng, J.M., Li, W.J., Liu, W.G., 2012. Comparing the effect of naturally restored forest and grassland on carbon sequestration and its vertical distribution in the Chinese Loess Plateau. PLoS One 7.

Wei, X.R., Shao, M.G., Gale, W.J., Zhang, X.C., Li, L.H., 2013. Dynamics of aggregate-associated organic carbon following conversion of forest to cropland. Soil Biol. Biochem. 57, 876–883.

Wright, I.J., Reich, P.B., Westoby, M., Ackerly, D.D., Baruch, Z., Bongers, F., Cavender-Bares, J., Chapin, T., Cornelissen, J.H.C., Diemer, M., Flexas, J., Garnier, E., Groom, P.K., Gulias, J., Hikosaka, K., Lamont, B.B., Lee, T., Lee, W., Lusk, C., Midgley, J.J., Navas, M.L., Niinemets, U., Oleksyn, J., Osada, N., Poorter, H., Poot, P., Prior, L., Pyankov, V.I., Roumet, C., Thomas, S.C., Tjoelker, M.G., Veneklaas, E.J., Villar, R., 2004. The worldwide leaf economics spectrum. Nature 428, 821–827.

Xiao, Y., 1990. Comparative studies on biomass and productivity of Pinus tabulaeformis plantations in different climatic zones in Shaanxi Province. Acta Phytoecologica et Geobotanica Sinica 14, 237–246.

Yan, M.J., Yamamoto, M., Yamanaka, N., Yamamoto, F., Liu, G.B., Du, S., 2013. A comparison of pressure-volume curves with and without rehydration pretreatment in eight woody species of the semiarid Loess Plateau. Acta Physiol. Plant. 35, 1051–1060.

Zhang, B., 1990. Study on Biomass and Productivity of Quercus lidotungensis Stands in Ziwuling Forest Region of Shaanxi Province. J. Northwest For. Univ. 5, 1–7.

Zhang, L., Chen, C., 1992. Biomass and production of Robinia pseudoacacia plantation in Hongxing tree farm of Changwu county, Shaanxi province. Shaanxi For. Sci. Technol. 3, 13–17.

Zhang, Y.D., Gu, F.X., Liu, S.R., Liu, Y.C., Li, C., 2013. Variations of carbon stock with forest types in subalpine region of southwestern China. For. Ecol. Manage. 300, 88–95.

Zheng, S., Shangguan, Z., 2007. Spatial patterns of leaf nutrient traits of the plants in the Loess Plateau of China. Trees – Struct. Funct. 21, 357–370.

Zheng, F.L., 2006. Effect of vegetation changes on soil erosion on the Loess Plateau. Pedosphere 16, 420–427.

Zhou, P., Wen, A.B., Zhang, X.B., He, X.B., 2013. Soil conservation and sustainable eco-environment in the Loess Plateau of China. Environ. Earth Sci. 68, 633–639.