Received: 22 October 2018 | Revised: 5 May 2019 | Accepted: 6 May 2019

DOI: 10.1002/ldr.3345

RESEARCH ARTICLE

WILEY

Changes in soil phosphorus and its influencing factors following afforestation in Northern China

Xiankun Li[1,2] | Yanan Li[3] | Shouzhang Peng[1,4] | Yunming Chen[1,4] | Yang Cao[1,4]

[1] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, PR China

[2] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, PR China

[3] College of Forestry, Northwest A&F University, Yangling 712100, PR China

[4] State Key Laboratory of Soil Erosion and Dry land Farming on Loess Plateau, Northwest A&F University, Yangling 712100, PR China

Correspondence
Y. Cao, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, Shaanxi, PR China.
Email: yang.cao@nwsuaf.edu.cn

Funding information
National Key R&D Program of China, Grant/Award Numbers: 2016YFC0501703 and 2017YFC0504605; National Nature Science Foundation of China, Grant/Award Numbers: 41601058 and 41201088; CAS "Light of West China" Program, Grant/Award Number: XAB2017A02

Abstract

Changes in soil carbon (C) and nitrogen (N) stocks following afforestation have been widely studied at different scales. However, soil phosphorus (P) dynamics following afforestation are poorly understood, especially at the regional scale. This paper studied the effects of prior land use (cropland, grassland, and barren land), tree species (conifer, broadleaf, shrub, and mixed), plantation age (young, middle, and old), and climate on soil total phosphorus and available phosphorus stocks change in the top 20 cm following afforestation based on a synthesis of 50 recent publications in northern China. We also considered possible confounding effects between these factors. The results showed that, overall, soil total phosphorus and available phosphorus stocks significantly decreased by 7.3% and significantly increased by 8.8%, respectively, following afforestation. Prior land use was found to be the most important driver in determining changes in soil P stocks. Compared with a significant decrease in P of afforestation of former cropland and grassland, afforestation of barren land caused no clear decrease in P. Tree species was found to have a limited effect on changes in soil P after afforestation, and broadleaf afforestation has a lower P demand than coniferous forests in the studied region. Plantation age did not affect the dynamics of P stocks. Our results showed confounding effects of precipitation, prior land use, and tree species, which impacted the estimates of the drivers of changes in P stocks. These results highlighted the importance of tree species selection and replication across sites that receive different amounts of precipitation.

KEYWORDS

afforestation, influencing factors, northern China, soil available phosphorus, soil total phosphorus

1 | INTRODUCTION

Afforestation, which is defined as tree planting on lands that historically have not contained forest cover, has expanded rapidly worldwide in recent decades. Accordingly, the area of planted forest increased from 168 to 278 M ha from 1990 to 2015 at the global scale (Keenan et al., 2015). However, long-term soil nutrient availability, which is essential for sustainable timer and/or carbon emission reduction, is not fully understood (Berthrong, Pineiro, Jobbagy, & Jackson, 2012), and the altered pools and cycles resulting from afforestation can in turn affect biomass production and ecosystem function (Yao, Shao, Jia, & Li, 2017). During the last two decades, soil carbon (C) and soil nitrogen (N) have been extensively studied at different scales and major influencing factors such as climate, prior land use, plantation age, tree species, and soil texture have been studied in depth (Barcena et al., 2014; Berthrong et al., 2012; Liu, Yang, Wang, Huang, & Li, 2018). However, levels of soil phosphorus (P), one of the most common limiting nutrients, can also regulate changes in soil C stocks following afforestation (Vitousek, Porder, Houlton, & Chadwick, 2010), mainly by controlling net primary productivity and C allocation in forest ecosystems, the decomposition rate of soil C, and the soil C sequestration process (Bronson et al., 2004; Shi et al., 2016). Therefore, improved knowledge of changes in soil P stocks following afforestation is necessary when evaluating current or potential soil productivity, which further back to suggestions for sustainable management of land resources, as well as for improved understanding of climate change and its feedback.

As the major nutritional constraint for primary production in terrestrial ecosystems, soil P is derived primarily from rock weathering; ecosystems begin their existence with a fixed amount of P, from which even very small losses cannot be easily replenished (Walker & Adams, 1958). To date, no consensus has been reached on whether afforestation is considered a 'soil degrader' or 'soil improver' (Attiwill & Adams, 1993; R. Wang & Wang, 2010). After afforestation, uptake of P and sequestration in biomass and litter likely drive the decrease of total phosphorus(TP; Vitousek et al., 2010). However, the enhanced primary vegetation productivity also increased the exogenous inputs (litter and rhizodeposition), and ultimately causing an increase in the source of soil P (Cao & Chen, 2017). To date, afforestation have been reported to either increase (Chen, He, et al., 2016; Zhang et al., 2019), decrease (Hu et al., 2018; Li et al., 2017), or have no effect (Shi et al., 2016; Wei et al., 2009) on total and available P. The current studies on changes in soil TP (available phosphorus [AP]) stocks following afforestation are mostly focusing on the plot scale, which fail to involve more affecting factors and extrapolate to a more convincing conclusion. For example, studies on P dynamics following grassland (GL) afforestation focused on the effect of the tree species, and the studied plantation ages were not dynamic (Chen, Condron, Davis, & Sherlock, 2000; Chirino-Valle, Davis, & Condron, 2016). Studies on the effects of temporal P dynamics following afforestation have also been limited to unique tree species and the same prior land-use type (Chen, Condron, Davis, & Sherlock, 2003; Liu et al., 2014; Wang & Wang, 2010). However, changes in soil P following afforestation can also be mediated by factors such as precipitation and temperature, local site properties, and even the spatial variation in the soil P content (Allen, Corre, Kurniawan, Utami, & Veldkamp, 2016; Liu, Shao, & Wang, 2013; Wei et al., 2009). In two global-scale reviews about P dynamics following afforestation, which included data from China (Deng et al., 2017; Shi et al., 2016), differences in vegetation, and soil type as well as broad differences in management regimens across regions may cause global-scale reviews to have limited value with respect to making inferences about regional areas (MacDonald, Bennett, & Taranu, 2012; Ringeval et al., 2017). In addition, the magnitudes and directions of P transformation are supposed to differ in regions with different condition, almost in each sections of P cycling (Figure 1). Therefore, combined with the limitation of plot-scale studies, a deeper understanding of changes in soil P in specific regions is necessary to provide more general but practical advice for tree planting activities and forest management based on local conditions and weather patterns.

Northern China, which predominantly consists of arid and semiarid areas, has been experiencing large-scale afforestation in recent decades, such as that associated with the 'Grain for Green' programme and the 'Three Norths Shelter Forest System' project. There is a need for further knowledge of changes in P after afforestation in this area, not only because the soil P concentration in northern China is lower on average than the global mean, resulting from low P inputs by weathering and strong losses by soil erosion and water runoff (Cao, Zhang, & Chen, 2017; Zhang, Zhang, Peng, Chen, & Cao, 2017), but also because northern China features by the climate of short rainy season and the growth and survival of vegetation in China's arid and semiarid regions are strongly limited by the availability of water (Deng, Yan, Zhang, & Shangguan, 2016). Although meta-analyses have been extensively used in quantitative reviews of changes in soil C and soil N after afforestation in this region, changes in soil P after afforestation are nonexistent or scarce. Based on 50 publications in northern China, this article aimed to synthesize the major changes in soil P stocks after afforestation by means of a

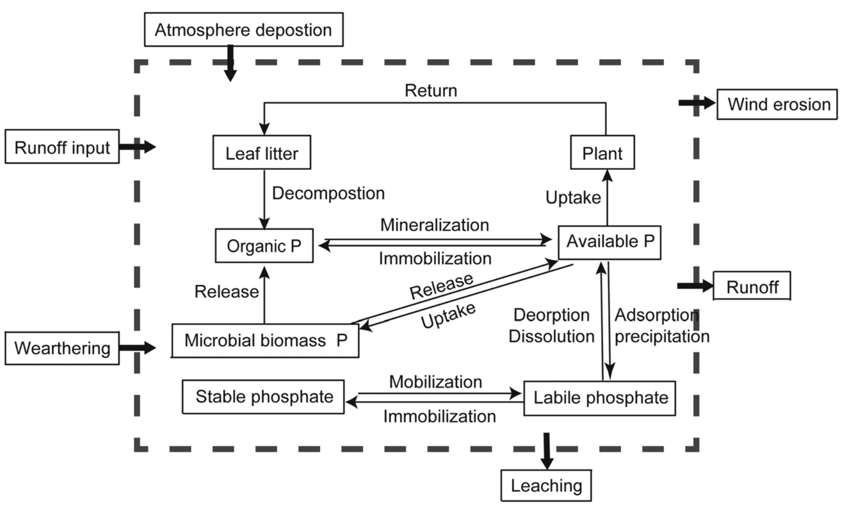

FIGURE 1 Schematic diagram of phosphorus cycling (Tiessen, Stewart, & Cole, 1984; Walbridge, Richardson, & Swank, 1991)

meta-analysis. We studied the major influencing factors, with focus on prior land use type, tree species, and plantation age, considering possible confounding effects of these factors and precipitation.

2 | MATERIALS AND METHODS

2.1 | Data selection and compilation

The literature available on the changes in soil total P and soil available P before November 2017 was collected. The sites span the northern China (Figure 2). We searched for articles that were published after the year 2000 and that report the impact of afforestation on soil P using the Web of Science and China National Knowledge Infrastructure (CNKI) databases. The searches included combinations of the terms 'tree plantation,' 'afforest*,' 'reforest*,' 'phosphorus,' and 'soil phosphorus,' as well as their Chinese meaning for the CNKI database. For inclusion of a study in the dataset, the following criteria had to be fulfilled: the study site was located in northern China; soil samples must have been collected, with the shallowest depth being 10 cm; the soil TP (AP) stocks were provided directly or could be calculated indirectly based on soil bulk density (BD), soil P concentration, and soil depth (if not reported, the BD could be replaced by the soil organic carbon [SOC] or soil organic matter [SOM] concentration); the experimental designs were paired site, chronosequential, or retrospective, and prior land use, tree species, time since conversion, mean annual temperature (MAT), mean annual precipitation (MAP), latitude, and longitude could be determined. We excluded soil texture and soil clay content, because only a small number of articles clearly presented these data. The raw data were obtained from tables or extracted from figures using Enguage Digitizer 4.1. When data were not provided in a publication, we tried to find the information in the study or contacted the author. In the end, 162 TP observations and 143 AP observations in the top 20 cm of the soil from 50 peer-reviewed articles were collected (Table S1 in the Supporting Information).

2.2 | Analysis procedure

2.2.1 | Data structure

Based on prior land use, the collected dataset was divided into cropland (CL), grassland (GL), and barren land (BL). Prior land use types such as savanna, fallow land, and bare mines were classified into the GL and BL categories, respectively, because of the small amounts (Liu et al., 2018). Tree species classifications included conifer, broadleaf, shrub, and mixed types. In accordance with the time since conversion, we divided the plantation age into young (<10 years), middle (10–30 years), and old (>30 years) (Zhang et al., 2013). Given the available data, we also classified the data into two groups by MAP (≤500 mm, >500 mm) (Zhang, Liu, Jia, & Qin, 2013) and MAT, based on the median, which was 7 (≤7°C, >7°C) (Table 1).

2.2.2 | Calculation of the main data

An empirical relationship was established based on the reported SOC concentration and soil BD values from the dataset. Any missing soil BD values were interpolated using the predicted values from the empirical function presented in Figure S1. For those studies that reported only SOM but without BD or SOC values, their SOC values

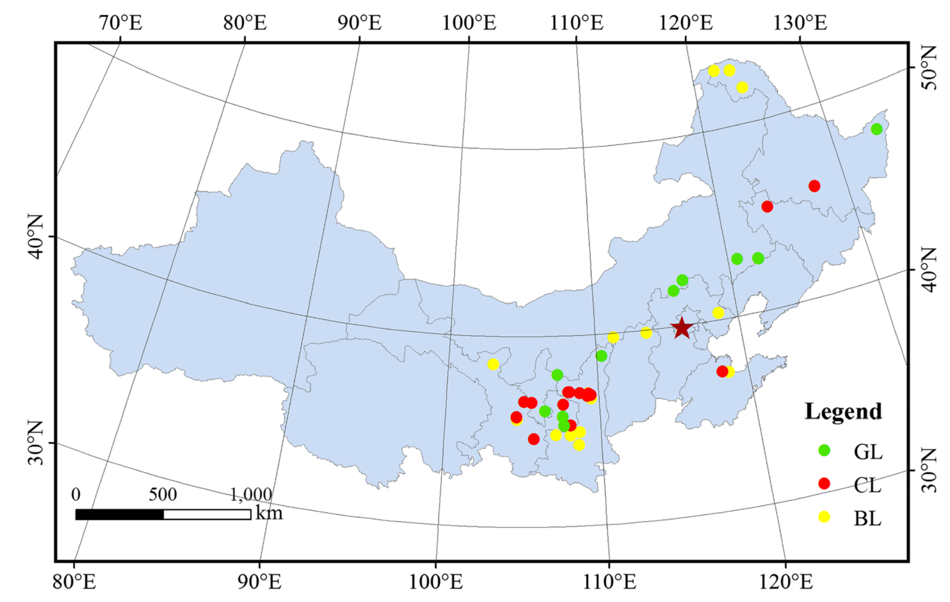

FIGURE 2 Locations of the study sites in this meta-analysis. Grassland (GL), cropland (CL), and barren land (BL) represent afforestation on grassland, afforestation on cropland and afforestation on barren land, respectively, the same below [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Method of classification of influencing factors and the corresponding numbers of observations collected in our dataset

Factor's classification	Numbers of observations (TP)			Numbers of observations (AP)		
	Total	Decrease	Increase	Total	Decrease	Increase
Prior land use						
Grassland	37	33	4	32	15	17
Cropland	90	59	31	80	37	43
Barrenland	35	21	14	31	16	15
Tree species						
Broadleaf	58	39	19	60	22	38
Conifer	43	32	11	33	19	14
Shrub	44	33	11	31	16	15
Mixed	17	9	8	19	11	8
Plantation age (year)						
0–10	53	38	15	47	22	25
10–30	91	63	28	79	39	40
>30	18	12	6	17	7	10
Precipitation (mm)						
≤500	78	62	16	64	40	24
>500	84	51	33	79	28	51
Temperature (°C)						
≤7	54	43	11	53	27	26
>7	108	70	38	90	41	49
Overall	162	113	49	143	68	75

were obtained through conversions of SOM to SOC by multiplying by 0.58, by using a previously reported formula (Guo & Gifford, 2002):

The soil TP and AP stocks were calculated using the following equation (Guo & Gifford, 2002):

$$\mathrm{Ps} = \mathrm{TP}\,(\mathrm{AP}) \times \mathrm{BD} \times \mathrm{D}/10,$$

where Ps is the soil total (available) phosphorus stocks (Mg ha^{-1}); TP (AP) is the soil TP or AP concentration (g/kg), respectively; BD is the soil BD (g/cm^3); and D is the soil thickness (cm).

We summed the TP (AP) stocks of different layers to represent the 20-cm stocks for those studies with two or more samplings below this layer. Three studies involved sampling depths that were shallower than 20 cm; because no significant general relationships between soil depth and P concentration and soil BD found in our dataset, unique linear relationships between depth and TP (AP) concentrations and BD were determined for each study based on the results of studies involving both similar climates and two sampling increments below 20 cm. We also used depths of 15 cm or 30 cm as 20 and 40 for comparison. Studies lacking enough available information to predict their stocks in top 20 cm were excluded. We also collected data from 20 to 40 cm and 40- to 60-cm soil layers and calculated their total stocks as deep as possible. Due to the low number of observations in the deep layers, we calculated mainly the P dynamics within the surface layer (20 cm).

2.2.3 | Meta-analysis

The size of the effect in each investigation was calculated as the response ratio $r = X_t/X_c$, where X_t and X_c represent the mean TP or AP stock of the treatment group and control group, respectively. The result was back transformed to a percentage change ([R − 1] * 100%) to represent the change in TP and AP stocks following afforestation. The values of effect size outside 3 standard deviations of the mean of each categorical variable were considered outliers and discarded according to the Pauta criterion (Shi et al., 2016). An unweighted meta-analysis was used to include additional studies because not all compiled studies reported the variance, and the definition of sample size differed among the studies (Deng et al., 2017).

The mean effect size, 95% confidence interval (CI), and between-group variance (Q_b) of each categorical variable were obtained by bootstrapping (4999 interactions) using MetaWin 2.1 (Rosenberg, Adams, & Gurevitch, 2000). The impacts of afforestation on TP and AP stocks were considered significant if the 95% CIs did not overlap with zero. The means of the different categorical variables were considered significantly different from one another if their 95% CIs did not overlap.

3 | RESULTS

3.1 | Changes in soil P following afforestation

Overall, due to afforestation, soil TP stocks significantly decreased by 7.3% following afforestation, and on average across all studies included, the soil AP stocks significantly increased by 8.8% (Figure 3). For indicating changes in soil P stocks after afforestation, the Q_b and p values of three major factors were tested. Among the factors taken into account, the Q_b of prior land use was the highest categorical variable for soil changes in TP stocks (Table 2), demonstrating that prior land use was the most influential factor in determining changes in soil TP stocks after afforestation. In contrast, the rest factors have limited effects on determining changes in soil AP stocks after afforestation.

3.2 | Factors affecting changes in soil P stocks following afforestation

3.2.1 | Prior land use

As indicated in Figure 3, afforestation on different prior land use showed different impact on TP (AP) stocks. Specifically, the TP stocks after CL afforestation decreased by 4.6%, and TP stocks after GL afforestation decreased more than CL did by 18.5%. However, BL afforestation only slightly deceased TP by 2.3%, and this decrease

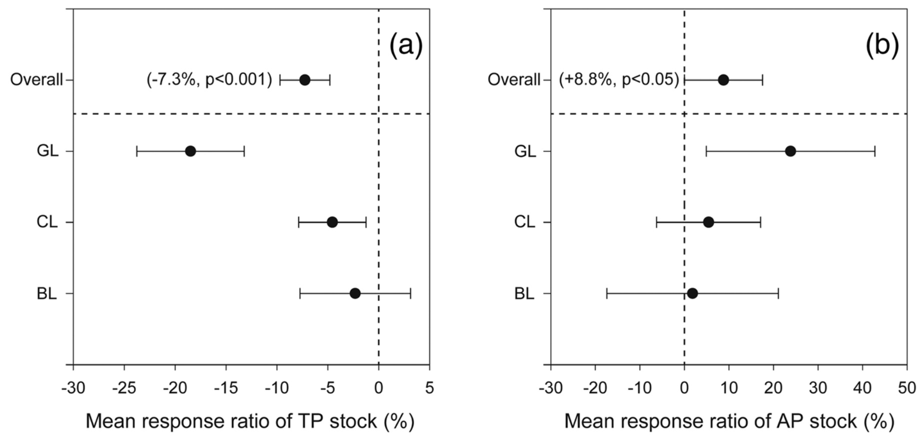

FIGURE 3 Mean response ratio of (a) total phosphorus (TP) and (b) available phosphorus (AP) after afforestation as influenced by prior land-use. Comparison between the non-forestry conditions and forest condition. The error bars represent 95% confidence intervals. The dotted line at zero represents that measurements of TP/AP were nonsignificant between two systems

TABLE 2 Between-group variance (Q_b) and p values for the categorical variables tested in the overall meta-analysis of total phosphorus (TP) and available phosphorus (AP) stocks response to afforestation

	TP stock		AP stock	
Factor	Q_b	P	Q_b	P
Prior land use	24.7713	<0.001	3.5025	0.17356
Tree species	8.6529	0.03428	3.1972	0.3622
Plantation age	1.3429	0.51096	2.6495	0.26587

was nonsignificant. Differences between prior land-uses were lower for AP stocks than for TP stocks. CL afforestation did not decrease but increase AP stocks by 5.4%, yet not significantly. BL afforestation exerted a smaller increase by 1.8%, and the variation of CIs was large. The significant increase of AP stocks was only found in GL afforestation by 23.8%.

3.2.2 | Tree species

As shown in Figure 4, except for a slight decrease (−1.9%) in mixed forests, the other three tree species caused significant reductions in TP stocks in northern China (Figure 3). The most pronounced decrease in TP stocks occurred in response to conifer forests (−13%), and a −6.4% decrease was found in shrub forests. The decrease in TP stocks in conifer forests differed to that in broadleaf (−4.9%), though the difference was not significant. Tree species was not important for indicating the changes of AP stocks after afforestation. The only significant increase of AP stock was found in broadleaf forest by 13.5%, and the other tree species were found no significant changes in AP stocks (Figure 4b).

3.2.3 | Plantation age

Due to afforestation, TP stocks were deprived by 5.4%, 7.9%, and 10.5% at young, middle, and old age, respectively (Figure 5a). Although

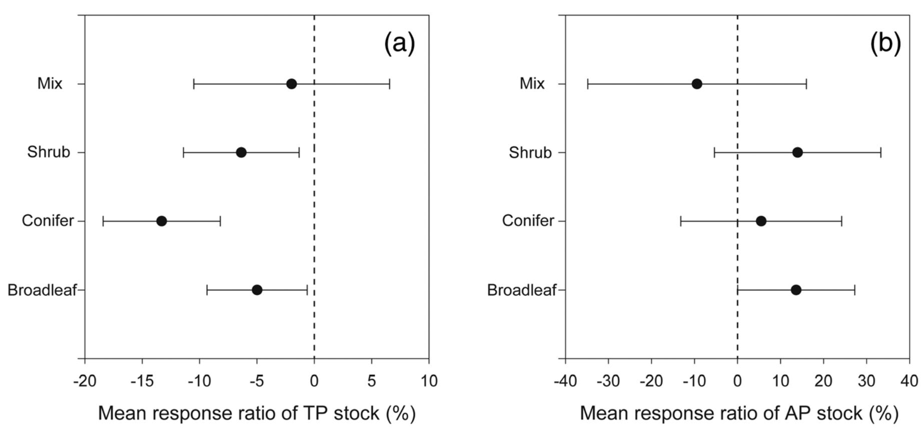

FIGURE 4 Mean response ratio of (a) total phosphorus (TP) and (b) available phosphorus (AP) after afforestation as influenced by tree species. Comparison between the non-forestry conditions and forest condition. The error bars represent 95% confidence intervals. The dotted line at zero represents that measurements of TP/AP were nonsignificant between two systems

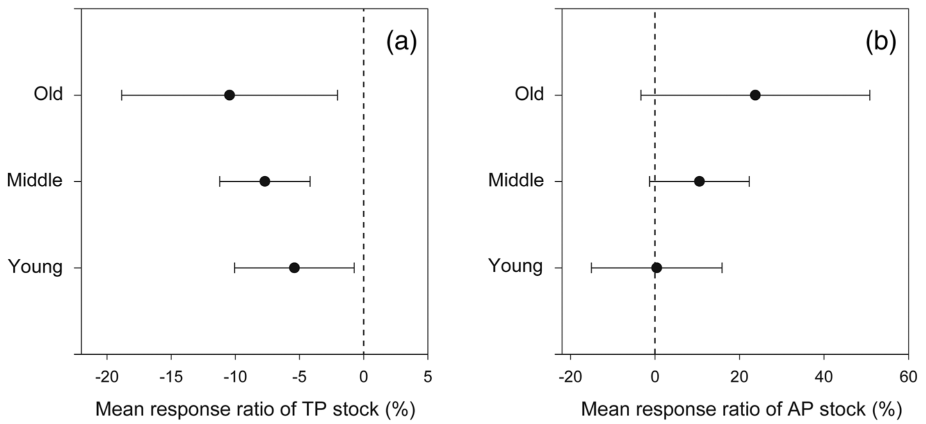

FIGURE 5 Mean response ratio of (a) total phosphorus (TP) and (b) available phosphorus (AP) after afforestation as influenced by plantation age. Comparison between the non forestry conditions and forest condition. The error bars represent 95% confidence intervals. The dotted line at zero represents that measurements of TP/AP were nonsignificant between two systems

TP stocks clearly decreased with time since conversion, afforestation-induced decrease in TP stocks did not differ significantly among plantation ages. In contrast, changes in AP stocks due to afforestation increased with plantation age. Young plantations presented a nonsignificant AP stock change of 0.4%, followed by higher increases in middle-age and old plantations (10.5% and 23.7%, respectively; Figure 5b). No significant differences in TP and AP stocks were found among plantation age classes.

3.2.4 | Climate

When the MAP and MAT are divided into two levels, the changes in TP stocks and AP stocks differ largely from each other (Figure 6). Significant differences were found in TP stocks between MAP≤500 and MAP>500 mm, with the former significantly reducing TP stocks by 11.8% and the latter by 3.0%. When the MAT≤7, TP stocks decreased by 13.9%, but when the MAT >7, TP stocks decreased by 4%. No significant difference in AP stocks was observed in response to MAP, although a significant increase (+19.7%) in AP stocks was observed when the MAP >500 mm. AP stocks were not affected by the MAT because both classes had similar effects.

3.2.5 | Confounding effects

We evaluated confounding effects by analyzing major interaction groups in separate analyses in an attempt to optimize the interpretation of the data (Table 3). Strong confounding was observed for MAP classes and prior land use types. For example, in the TP dataset that we collected, 90% of afforested GLs were in areas with low precipitation, and high-precipitation CLs represented more than 70% of the observations, meaning the effects of precipitation and prior land use types could not be separated. Precipitation and tree species planted were also confounded in some cases. Nearly a half of the observations from low-precipitation areas were afforested with conifers, and observations of broadleaf trees afforested in high-precipitation areas were predominant (62%). To avoid limitations from confounding effects, an interaction group that included fewer than five observations and originated from fewer than three studies was not determined. Confounding effects were also determined between these

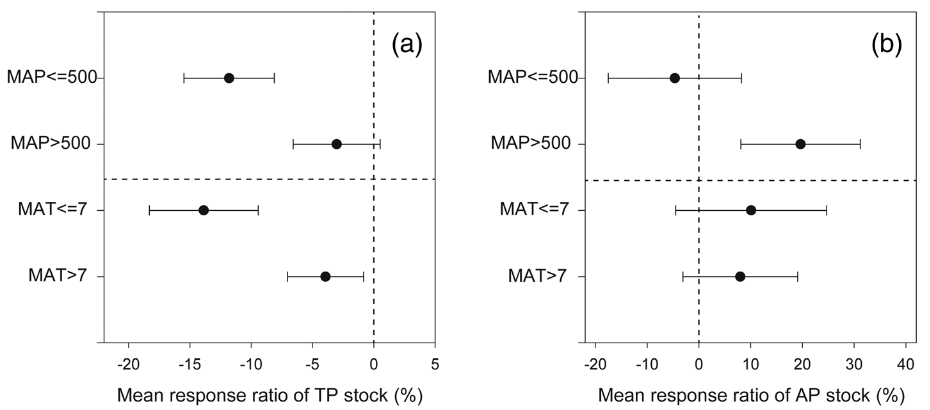

FIGURE 6 Mean response ratio of (a) total phosphorus (TP) and (b) available phosphorus (AP) after afforestation as influenced by mean annual precipitation (MAP) and mean annual temperature (MAT). Comparison between the non forestry conditions and forest condition. The error bars represent 95% confidence intervals. The dotted line at zero represents that measurements of TP/AP were nonsignificant between two systems

TABLE 3 Meta-estimates of TP and AP stock changes after afforestation for variable classes and the major in prior land-use (PLU), tree species (TS), and mean annual precipitation (low MAP and high MAP) in the 0- to 20-cm data set

	TP			AP		
Interection Group	K	PerChg		K	PerChg	
MAP:PLU						
Low MAP × CL	22	−7.7960	*	22	−39.8929	***
Low MAP × GL	34	−20.9797	***	30	22.6684	*
Low MAP × BL	22	−1.6226	ns	12	−8.3717	ns
High MAP × CL	68	−3.5063	*	58	22.6260	***
High MAP × BL	13	−3.4758	ns	19	8.2820	ns
High MAP × GL	3		nd	2		nd
MAP:TS						
Low MAP × Broadleaf	6	−6.6073	ns	11	−6.5207	ns
Low MAP × Conifer	38	−15.4738	***	26	5.5178	ns
Low MAP × Shrub	24	−8.9746	**	16	19.1225	ns
Low MAP × Mix	10	−7.7478	ns	11	−61.4316	***
High MAP × Broadleaf	52	−4.7996	*	49	18.1674	**
High MAP × Conifer	5		nd	7	5.4857	ns
High MAP × Shrub	20	−3.2351	*	15	8.4666	ns
High MAP × Mix	7	6.2767	ns	8	62.1207	*
PLU:TS						
CL × Broadleaf	44	−5.1215	**	42	18.2540	*
CL × Conifer	3		nd	7	0.7978	ns
CL × Shrub	26	−5.0279	*	17	−4.2621	ns
CL × Mix	17	−1.9730	ns	14	−18.9379	ns
GL × Broadleaf	4		nd	7	6.8384	ns
GL × Conifer	19	−26.6008	***	14	18.6116	ns
GL × Shrub	14	−13.6990	***	11	41.3201	**
GL × Mix	0		nd	0		nd
BL × Broadleaf	10	−7.6942	*	11	0.3582	ns
BL × Conifer	21	−2.2077	ns	12	−7.0237	ns
BL × Shrub	4		nd	3		nd
BL × Mix	0		nd	5	17.2698	ns

Note. The number of observations is denoted by 'k.' Not determined (nd) indicates that the interaction group did not fulfill the criteria and was therefore not analyzed. 'ns' refers to nonsignificant.

Abbreviations: AP: available phosphorus; TP: total phosphorus.

*Significant results at $p < .05$.

**Significant results at $p < .01$.

***Significant results at $p < .001$.

variables and plantation age (which was divided into <20 years and ≥ 20 years). For example, CL afforestation significantly reduced TP stocks in the young age group, whereas the old age group had no significant effect on TP stocks In contrast, GL afforestation caused no definitive decrease in TP stocks in the early age group, but a significant decline was observed in the old age group (Supplementary Table 2).

3.2.6 | Changes in the ratio of TP and AP after afforestation

As shown in Figure 7, we found that the ratio of TP to AP varied at different land use. The ratio of TP to AP reduced at CL and GL after afforestation, and the higher reduction was found in the former (324 to 224 at CL and 208 to 151 at GL, respectively). However, the decrease was not found at BL. In contrast, we found a slight increase at BL (130 to 124).

4 | DISCUSSIONS

4.1 | Changes in soil P following afforestation

Total P represents the ultimate soil reserves and reflects the size of the soil P pool. Available P represents the level P supplied to plants, which is an accurate indicator of the P supply in the soil (Wang & Wang, 2010). Our results argued that afforestation in northern China significantly reduced TP stocks, which is in general agreement with the findings from a previous global-scale study that argued that TP stocks in the top 20 cm significantly decreased (15%) in temperate continental areas (Deng et al., 2017). The lower decrease (7.3%) found in our study was probably caused by the large proportion of observations collected in our dataset were in arid and semiarid areas, because lower precipitation leads to less TP depletion, and fewer P uptake for plant issues; moreover, a dry climate in temperate and boreal forests reduces P losses through leaching (Chen, Li, & Yang, 2016; Zhang et al., 2005). However, our study challenges the finding of Shi et al. (2016), which demonstrated that changes in soil P concentrations were not significant. This inconsistency is probably attributable to Shi et al. (2016), who quantitatively reviewed the changes in P stocks within the top 30 cm. At different depths, soil P distribution, uptake for vegetation use and capture, and microclimate differs. Furthermore, reforestation articles included in the dataset increased the possibility of discrepancy. Our results showed that AP stocks significantly

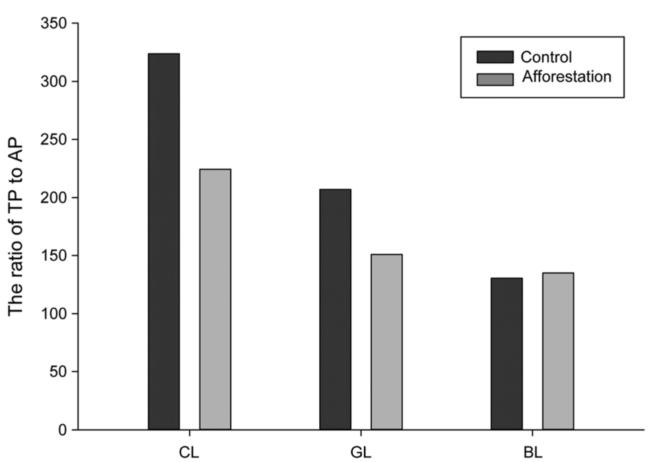

FIGURE 7 Ratio of soil total phosphorus (TP) to available phosphorus (AP) before afforestation and after afforestation

increased after afforestation, which contrasts with the results of Deng et al. (2017). Thus, compared with those of global-scale studies, the results of regional-scale studies on changes in soil P after afforestation may vary in direction and magnitude, which confirmed that the global-scale study had limited guidance for more reasonable and scientific management in northern China.

4.2 | Factors that influence changes in soil P following afforestation

4.2.1 | Prior land use

The highest Q_b of prior land use found in this article indicates that despite differences in geographical scales (global vs. regional), the effects of prior land use on change in soil P after afforestation are still prevalent. The difference in P between different land use categories appears to be a function of the forest environment and land use category in terms of their system components. With respect to CLs, first, P inputs are purported to be higher in CL ecosystems than in forest ecosystems. CL soils can be resupplied with P in the form of inorganic P via the application of fertilizers and manures, whereas in forest soils, P originates entirely from the weathering of parent material, which occurs at very slow rates (Gao, He, Yu, Chen, & Wang, 2014). Second, in addition to the uptake by vegetation, the reduction in AP can be greater in forest soils than in CL soils. AP can diminish along with losses of soil nutrients in the early plantation years due to soil erosion caused by strong disturbances to soils during plantation preparation. In CLs, grazing and tillage may increase P availability by stimulating the microbial decomposition of SOM and hence the release of nutrients, including P (Laganière, Angers, & Paré, 2010). In addition, slowly cycling P pools are smaller in forest soils than in CL soils, which can buffer the decrease in AP (De Schrijver et al., 2012). The acidic soil environment of forest soil may result in reduced P solubility and a consequent decrease in bioavailable P resulting from P reacting with aluminum (Al^{3+}) and iron (Fe^{3+}) to form amorphous aluminum and iron phosphates (Stevenson & Cole, 1999). Third, the continuous input of organic materials that have high C/P ratios from litter and root turnover in forest soils compared with agricultural soils may drastically increase microbial P immobilization and increase organic P accumulation (Chen, Condron, & Xu, 2008), which partly drives the decrease in AP stock in forest soils. Finally, forest cover can reduce the soil temperature in microclimates, thereby decreasing the amount of AP succumbing to microbial decomposition. For all the above mentioned reasons, the state of equilibrium is generally maintained at lower AP values in forest systems than in CL systems, and a significant reduction of 22% was observed on the global scale (Q. Deng et al., 2017); however, a decrease was not observed in our study. The nonsignificant change in AP stocks indicated that AP was maintained at high levels, most likely by efficient recycling of litter (Neufeldt, da Silva, Ayarza, & Zech, 2000). In addition, lower AP reduction induced by forming solids with calcium in arid and semiarid regions can be expected in forest than in CL because of the larger humidity and lower temperature induced by forest cover.

Unlike CL, which has relatively high soil P contents, BL is associated with relatively low soil nutrient availability. Afforestation of BL should increase the AP due to root growth and canopy development, which both increase SOM inputs and limit P leaching and soil erosion. However, our results showed no obvious increase in AP after afforestation of BL; abandoned lands with agricultural activities included in our dataset might be the main reason. It is likely that the higher initial soil P in abandoned CL than in BL (MacDonald et al., 2012) may lessen the increase in AP from organic matter inputs even to meet the same demands of trees. In contrast, GL maintains a permanent vegetation cover and a well-developed root system, which is similar to those in forest ecosystems. Although GL afforestation significantly increased AP stocks, which was much preferable for plant growth, in the long run, the significant decrease in TP stocks could also exhaust a large P content in the soil, which is purported to affect P recycling and transformation and cause P limitation. We suggest that the initial soil P stocks may strongly influence the changes in soil P stocks. However, further conclusions were limited by the small number of observations and relatively less balanced distribution of observations. Overall, our results suggested that, in northern China, afforestation on BL may be preferable for restoring sustainable productivity because there is no significant decline in TP stocks but a promising increase in AP stocks.

4.2.2 | Tree species

In northern China, tree species was not an important factor affecting soil P. This result is consistent with that of Deng et al. (2017), who reported that tree species had a relatively low importance among variables contributing to changes in P following afforestation. Specifically, broadleaf and conifer forests both significantly reduced soil TP stocks and AP stocks were not affected by conifer forests. These results are also generally in agreement with those of Deng et al. (2017) on a global scale. However, the significant increase in AP stocks following broadleaf afforestation was partly in contrast with the findings of a previous study (Shi et al., 2016), which suggested that N-fixers significantly reduced soil AP concentrations. Because more than 80% of the broadleaf trees were N-fixers in our dataset, the seeming inconsistencies drawn by our study likely arise because the majority of N-fixers in our study were of middle age and those in the study of Shi et al. (2016) were of young age. A plot scale study also found that black locust (N-fixers) increased available P stocks during the middle period (21 years) after afforestation (Qiu, Zhang, Cheng, & Yin, 2010).

Tree species purported to affect P dynamics via organic matter input, transfer, and P acquisition in combination with mycorrhizae. First, organic P input from litter may vary in quality and quantity. For example, due to biological differences in tree species, the concentrations of N and P in leaves of deciduous broad-leaved tree species are higher than those in evergreen coniferous tree species (Zeng et al., 2014), and the poorer substrate quality in conifer forests often leads to slower decomposition (Hobbie et al., 2006). This phenomenon, together with a larger annual litter production of broadleaf trees, should therefore lead to smaller soil depletion. Second, rooting characteristics in different tree species may affect P uptake and transfer.

Compared with that of conifers, the belowground biomass of broadleaf trees is higher (Laganière et al., 2010). On the Loess Plateau, both root length and root biomass have been reported to be greater for *Robinia pseudoacacia* L (a broadleaf species) than for *Pinus tabulaeformis* Carr (a coniferous species; Zhang, Chen, & Jiang, 2014). In addition, the root activities of different plant species selectively stimulate the growth of different microbial species in the rhizosphere, possibly due to differences in root exudation; thus, different organic acids and phosphatase enzymes excreted by soil microbes can affect P solubilization and thus the hydrolysis of organic P (Bais, Park, Weir, Callaway, & Vivanco, 2004; Chen et al., 2008). Third, tree species that differ in mycorrhizal associations may result in differences in P acquisitions. Associations with ectomycorrhizal fungi may have a competitive advantage over those with arbuscular mycorrhizal fungi in nutrient-poor landscapes due to the direct role of the former in breaking down leaf litter and their ability to secrete enzymes that break down complex substrates (Chen et al., 2008). Arbuscular mycorrhizal fungi generally do not have these capabilities but can still deliver up to 80% of their host tree's P requirements (Holste & Kobe, 2016).

Despite these differences in tree species, no significant differences in tree species were observed. The main reason for this phenomenon is that P depletion and mineralization are driven and controlled by demand for P, which is closely related to soil nutrient availability. Previous studies also found that similar soil P acquisition despite differences in the type of mycorrhizae associated with tree species and soil nutrient availability may be more important to tree species' nutrient acquisition than mycorrhizal fungi (Chirino-Valle et al., 2016; Holste & Kobe, 2016). Our results also suggested that the role of mycoriza in mediating AP stocks should be minor. In northern China, biological activity is primarily driven by water availability, as diffusion to the root surface is the major factor that limits P uptake. Physiological differences in tree species, such as root characteristics and mycorrhizal associations, will result in very little or no increase in plant P uptake from a drying soil (Suriyagoda, Ryan, Renton, & Lambers, 2014). In addition, the mycorrhizal AP uptake pathway is often reduced when the AP was maintained at high level (Breuillin et al., 2010), which was found in our study. Because plants in artificial ecosystems grow well in the soil, the lower P depletion of broadleaf trees compared with coniferous trees may suggest a low P requirement for P deficiency in northern China. Therefore, our results suggested that compared with coniferous forests, broadleaf forests have a lower P demand in northern China, which is reflected by the smaller P depletion in the latter.

4.2.3 | Plantation age

Despite a decreasing trend of TP and an increasing trend of AP with time since conversion, our study found no significant difference between plantation age classes. These results corroborated those of Deng et al. (2017) and Shi et al. (2016) on a global scale, both contended that plantation age had no consistent impact on total P. Two reasons may strongly account for this phenomenon. First, our results suggested that soil P depletion domains during the early period. This is reasonable because soil P depletion due to soil erosion caused by strong disturbance during site preparation occurred mainly during the young stages. In addition, the amount of P return from the organic P return is low due to relatively low litter production. As a result, AP stocks after afforestation were unlikely to increase during the young stage, as shown in our results. Second, P may be brought up from the deep layer, and forest ecosystems try to supply P concentrations near the surface while depleting total P at greater depths (Jobbagy & Jackson, 2001). In general, the major sources of P provided mainly by parent material located at the bottom of the soil (Walker & Adams, 1958). It has been reported that deep layer plays an important role in P supply as 60–80% total P and available P were recorded in deep-layer soils (20-80 cm; Wang et al.,2014; Zhang et al., 2014). Although our study focused on the surface soil (0–20 cm), our results showed that changes in TP stocks exhibited similar decreases at 20- and 40-cm depths, both cumulatively and separately (Figure S2). These results also support those of Wang et al. (2014), who reported similar temporal TP changing rates within 0- to 20-cm and 20- to 40-cm soil layers in regression slopes for different soil layers in this region at the site level (Wang, Wang, & Zu, 2014). As P movement in soil and plant uptake are reduced by drought, P remobilization and resorption become increasingly important in maintaining ecosystem balance in moisture-limited and P-limited environments (Suriyagoda et al., 2014). Additional conclusions were limited by the insufficient observations in deep layer.

4.2.4 | Climate and confounding effects

Climatic factor purported to affect changes in soil P after afforestation in terms of the source and transformation. It is well known that increased temperature accelerates the weathering of parent material from which soil P originates, and lower soil C and N contents and low P loss through leaching, and higher soil P content (Tian, Chen, Zhang, Melillo, & Hall, 2009). In addition, the decomposition rate is positively related to the temperature and precipitation (Wei et al., 2009). In this article, because soil AP exhibited similar trends across regions that have different temperatures, our study indicated that changes in soil P after afforestation were more constrained by precipitation than by temperature, which is a reasonable assumption for vegetation growth in arid and semiarid regions. It has long been recognized that MAP can negatively affect soil P availability by driving P loss and plant P uptake and enhancing soil weathered extent (Vitousek et al., 2010). However, our results showed that soil P depletion was lower in areas with high precipitation ($\geq$500) than in areas with low precipitation. Two reasons may strongly account for this phenomenon. First, initial P stocks are higher in areas with relatively high precipitation, and it has been reported that in Loess Plateau region where precipitation exceeds 500 mm, the soil P content is larger (Liu et al., 2013). Therefore, even the equilibrium P depletion for woody biomass in areas with low precipitation would strongly influence changes in soil P after afforestation. Second, the confounding effect of precipitation and prior land use enhanced the reduction in TP stocks after afforestation in area with low precipitation, where more than 40% of observations were GLs; and CLs represented more than 70% of the observations in areas with high precipitation.

Because we observed that the directions and magnitudes of changes in TP or AP stock in area with different climate were dominated by prior land use, and the role of weathering in changing TP and AP stocks was largely controlled by climate. We could infer that the role of weathering in changing soil TP and AP stocks were still minor compared with the role of prior land use change. Because our results showed that precipitation confounded with prior land use, our results concerning the effects of precipitation on changes in soil P after afforestation should be conservative. Previous studies also showed that climate on soil P varied among prior land uses (Liu et al., 2013). Moreover, besides the amount of AP in forming solid, climate would also affect aridity degree, soil particle size, and the sandy content of soil, which can also affect TP stocks and AP stocks (Hou et al., 2018). Afforestation increased the difficulty in clarifying the effect of these factors and their interactions. Overall, the effect of climate in affecting changes in TP stocks and AP stocks after afforestation still warrant future studies.

We also observed the interaction groups between tree species and precipitation. Because the effect of tree species in affecting changes of P stocks after afforestation was largely determined by the demand of P and the local nutrient availability, which are also related to climate, precipitation, in particular. Therefore, our study highlights the importance of tree species selection and replication across sites where precipitation differs to make management recommendations for reforestation success (Holste & Kobe, 2016).

5 | UNCERTAINTY

As with many other meta-analyses, our study also presents some uncertainties in applying meta-analysis. Due to insufficient observations, we consider treatments that share a single control as individual observations, which may reduce the accuracy of our results. However, a relatively stable vertical TP distribution could be expected irrespective of plantation age. Long-term weathering of parent material, together with an accumulation of P in the surface soil layer via translocation by plants, ultimately resulted in a relatively stable vertical TP distribution (Tian et al., 2009). In addition, unlike Barcena, T. G. (2014), we failed to use mass correction method for more increased accuracy because no soil BD values were available or could be generated from the available data. We suggest that future studies present a more detailed soil BD at different depths.

Notably, changes in P after afforestation were also mediated by initial P stocks and topographical features. A highly heterogeneous spatial distribution and a complex pattern among soil orders at different developmental stages should therefore affect the P content and its vertical distribution (Zhang et al., 2005), which can lead to underestimates of the effects of land use on changes in soil nutrients (Allen et al., 2016). Our study also indicated above that different initial stock may mediate the change of P afforestation and should vary in prior land use types. Soil textures is related to P source and P sorption. For example, soils that are relatively sandy contains less P and provide fewer binding sites for P. Stronger P sorption of clay soils may limit P uptake by trees. Topographical features such as slope and aspect are often strongly correlated with hydrologic and nutrient transport downslope and subsequently influence soil P heterogeneity. In addition, slope gradient also contributes to the rate of physical erosion (Chen, He, et al., 2016). Compared with other areas, slope farmlands with wind–water erosion crisscross regions and plantation establishments were purported to experience greater soil nutrient losses (Meng, Fu, Tang, & Ren, 2008; Wei et al., 2009), which may lead to lower soil fertilization of CL in some cases (Wang, Fu, Lü, & Chen, 2011). The 'Fertile island' theory has also been proposed to have an effect on estimating changes in soil nutrients caused by land use changes (Allen et al., 2016; Yao et al., 2017). Future studies should pay increased attention to the horizontal distribution of changes in P stocks, which, together with the vertical distribution, may offer improved understanding of changes in P dynamics following afforestation in these regions.

6 | CONCLUSIONS

In general, our study showed a significant decrease in TP stocks and a significant increase in AP stocks following afforestation in northern China. Prior land use was found to be the most important factor. Compared with afforestation of CL and GL, which resulted in significant decreases in TP, afforestation of BL resulted in no definitive decrease in P. Tree species has a limited effect on changes in TP stocks after afforestation; these nonsignificant differences are due mainly to changes in soil P controlled by P demand for tree growth and determined by soil nutrient availability and soil P, but we also found a lower P demand by broadleaf forests than by coniferous forests in northern China. Planation age also had a limited effect on changes in P stocks, which may be related to the large P depletion that occurred during the young stage, and afforestation may uplift P from deep layers. Our results showed confounding effects between precipitation, prior land use, and tree species planted, which had an impact on estimating the effects of afforestation. Therefore, our results highlighted the importance of tree species selection and replication across sites where precipitation differs. Future studies should combine vertical changes and horizontal P changes after afforestation to provide a more comprehensive understanding of changes in soil P and its influencing factors.

ACKNOWLEDGMENTS

This research was supported by National Key R&D Program of China (2017YFC0504605 and 2016YFC0501703), and CAS "Light of West China" Program (XAB2017A02), and the National Nature Science Foundation of China (41201088 and 41601058).

ORCID

Yang Cao https://orcid.org/0000-0001-7831-8068

REFERENCES

Allen, K., Corre, M. D., Kurniawan, S., Utami, S. R., & Veldkamp, E. (2016). Spatial variability surpasses land-use change effects on soil biochemical properties of converted lowland landscapes in Sumatra, Indonesia.

Geoderma, *284*, 42–50. https://doi.org/10.1016/j.geoderma.2016.08.010

Attiwill, P. M., & Adams, M. A. (1993). Nutrient cycling in forests. *New Phytologist*, *124*(4), 561–582. https://doi.org/10.1111/j.1469-8137.1993.tb03847.x

Bais, H. P., Park, S. W., Weir, T. L., Callaway, R. M., & Vivanco, J. M. (2004). How plants communicate using the underground information superhighway. *Trends in Plant Science*, *9*(1), 26–32. https://doi.org/10.1016/j.tplants.2003.11.008

Barcena, T. G., Kiaer, L. P., Vesterdal, L., Stefansdottir, H. M., Gundersen, P., & Sigurdsson, B. D. (2014). Soil carbon stock change following afforestation in Northern Europe: A meta-analysis. *Global Change Biology*, *20*(8), 2393–2405. https://doi.org/10.1111/gcb.12576

Berthrong, S. T., Pineiro, G., Jobbagy, E. G., & Jackson, R. B. (2012). Soil C and N changes with afforestation of grasslands across gradients of precipitation and plantation age. *Ecological Applications*, *22*(1), 76–86. https://doi.org/10.1890/10-2210.1

Breuillin, F., Schramm, J., Hajirezaei, M., Ahkami, A., Favre, P., Druege, U., … Reinhardt, D. (2010). Phosphate systemically inhibits development of arbuscular mycorrhiza in Petunia hybrida and represses genes involved in mycorrhizal functioning. *Plant Journal*, *64*(6), 1002–1017. https://doi.org/10.1111/j.1365-313X.2010.04385.x

Bronson, K. F., Zobeck, T. M., Chua, T. T., Acostamartinez, V., Pelt, R. S. V., & Booker, J. D. (2004). Carbon and nitrogen pools of Southern High Plains cropland and grassland soils. *Soil Science Society of America Journal*, *68*(5), 1695–1704. https://doi.org/10.2136/sssaj2004.1695

Cao, Y., & Chen, Y. (2017). Coupling of plant and soil C:N:P stoichiometry in black locust (Robinia pseudoacacia) plantations on the Loess Plateau, China. *Trees*, *31*(5), 1559–1570. https://doi.org/10.1007/s00468-017-1569-8

Cao, Y., Zhang, P., & Chen, Y. (2017). Soil C:N:P stoichiometry in plantations of N-fixing black locust and indigenous pine, and secondary oak forests in Northwest China. *Journal of Soils and Sediments*, *18*(4), 1478–1489. https://doi.org/10.1007/s11368-017-1884-0

Chen, C. R., Condron, L. M., Davis, M. R., & Sherlock, R. R. (2000). Effects of afforestation on phosphorus dynamics and biological properties in a New Zealand grassland soil. *Plant and Soil*, *220*(1–2), 151–163. https://doi.org/10.1023/A:1004712401721

Chen, C. R., Condron, L. M., Davis, M. R., & Sherlock, R. R. (2003). Seasonal changes in soil phosphorus and associated microbial properties under adjacent grassland and forest in New Zealand. *Forest Ecology and Management*, *177*(1–3), 539–557. https://doi.org/10.1016/s0378-1127(02)00450-4

Chen, C. R., Condron, L. M., & Xu, Z. H. (2008). Impacts of grassland afforestation with coniferous trees on soil phosphorus dynamics and associated microbial processes: A review. *Forest Ecology and Management*, *255*(3–4), 396–409. https://doi.org/10.1016/j.foreco.2007.10.040

Chen, L.-F., He, Z.-B., Zhu, X., Du, J., Yang, J.-J., & Li, J. (2016). Impacts of afforestation on plant diversity, soil properties, and soil organic carbon storage in a semi-arid grassland of northwestern China. *Catena*, *147*, 300–307. https://doi.org/10.1016/j.catena.2016.07.009

Chen, L. Y., Li, P., & Yang, Y. H. (2016). Dynamic patterns of nitrogen: Phosphorus ratios in forest soils of China under changing environment. *Journal of Geophysical Research – Biogeosciences*, *121*(9), 2410–2421. https://doi.org/10.1002/2016JG003352

Chirino-Valle, I., Davis, M. R., & Condron, L. M. (2016). Impact of different tree species on soil phosphorus immediately following grassland afforestation. *Journal of Soil Science and Plant Nutrition*, *16*(2), 477–489.

De Schrijver, A., Vesterdal, L., Hansen, K., De Frenne, P., Augusto, L., Achat, D. L., … Verheyen, K. (2012). Four decades of post-agricultural forest development have caused major redistributions of soil phosphorus fractions. *Oecologia*, *169*(1), 221–234. https://doi.org/10.1007/s00442-011-2185-8

Deng, L., Yan, W., Zhang, Y., & Shangguan, Z. (2016). Severe depletion of soil moisture following land-use changes for ecological restoration: Evidence from northern China. *Forest Ecology and Management*, *366*, 1–10. https://doi.org/10.1016/j.foreco.2016.01.026

Deng, Q., McMahon, D. E., Xiang, Y., Yu, C. L., Jackson, R. B., & Hui, D. (2017). A global meta-analysis of soil phosphorus dynamics after afforestation. *The New Phytologist*, *213*(1), 181–192. https://doi.org/10.1111/nph.14119

Gao, Y., He, N., Yu, G., Chen, W., & Wang, Q. (2014). Long-term effects of different land use types on C, N, and P stoichiometry and storage in subtropical ecosystems: A case study in China. *Ecological Engineering*, *67*, 171–181. https://doi.org/10.1016/j.ecoleng.2014.03.013

Guo, L. B., & Gifford, R. M. (2002). Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, *8*(4), 345–360. https://doi.org/10.1046/j.1354-1013.2002.00486.x

Hobbie, S. E., Reich, P. B., Oleksyn, J., Ogdahl, M., Zytkowiak, R., Hale, C., & Karolewski, P. (2006). Tree species effects on decomposition and forest floor dynamics in a common garden. *Ecology*, *87*(9), 2288–2297. https://doi.org/10.1890/0012-9658(2006)87[2288:TSEODA]2.0.CO;2

Holste, E. K., & Kobe, R. K. (2016). Tree species and soil nutrients drive tropical reforestation more than associations with mycorrhizal fungi. *Plant and Soil*, *410*(1–2), 283–297. https://doi.org/10.1007/s11104-016-3013-z

Hou, E. Q., Chen, C. R., Luo, Y. Q., Zhou, G. Y., Kuang, Y. W., Zhang, Y. G., … Wen, D. Z. (2018). Effects of climate on soil phosphorus cycle and availability in natural terrestrial ecosystems. *Global Change Biology*, *24*(8), 3344–3356. https://doi.org/10.1111/gcb.14093

Hu, Y. F., Shu, X. Y., He, J., Zhang, Y. L., Xiao, H. H., Tang, X. Y., … Yuan, S. (2018). Storage of C, N, and P affected by afforestation with Salix cupularis in an alpine semiarid desert ecosystem. *Land Degradation & Development*, *29*(1), 188–198. https://doi.org/10.1002/ldr.2862

Jobbagy, E. G., & Jackson, R. B. (2001). The distribution of soil nutrients with depth: Global patterns and the imprint of plants. *Biogeochemistry*, *53*(1), 51–77. https://doi.org/10.1023/A:1010760720215

Keenan, R. J., Reams, G. A., Achard, F., de Freitas, J. V., Grainger, A., & Lindquist, E. (2015). Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. *Forest Ecology and Management*, *352*, 9–20. https://doi.org/10.1016/j.foreco.2015.06.014

Laganière, J., Angers, D. A., & Paré, D. (2010). Carbon accumulation in agricultural soils after afforestation: a meta-analysis. *Global Change Biology*, *16*(1), 439–453. https://doi.org/10.1111/j.1365-2486.2009.01930.x

Li, D., Wen, L., Zhang, W., Yang, L., Xiao, K., Chen, H., & Wang, K. (2017). Afforestation effects on soil organic carbon and nitrogen pools modulated by lithology. *Forest Ecology and Management*, *400*, 85–92. https://doi.org/10.1016/j.foreco.2017.05.050

Liu, J. B., Zhang, Y. Q., Wu, B., Qin, S. G., Jia, X., & Feng, W. (2014). Changes in soil carbon, nitrogen, and phosphorus along a chronosequence of Caragana microphylla plantation, Northwestern China. *Polish Journal of Environmental Studies*, *23*(2), 385–391.

Liu, X., Yang, T., Wang, Q., Huang, F. R., & Li, L. H. (2018). Dynamics of soil carbon and nitrogen stocks after afforestation in arid and semi-arid regions: A meta-analysis. *Science of the Total Environment*, *618*, 1658–1664. https://doi.org/10.1016/j.scitotenv.2017.10.009

Liu, Z.-P., Shao, M.-A., & Wang, Y.-Q. (2013). Spatial patterns of soil total nitrogen and soil total phosphorus across the entire Loess Plateau region of China. *Geoderma*, *197-198*, 67–78. https://doi.org/10.1016/j.geoderma.2012.12.011

MacDonald, G. K., Bennett, E. M., & Taranu, Z. E. (2012). The influence of time, soil characteristics, and land-use history on soil phosphorus legacies: A global meta-analysis. *Global Change Biology*, *18*(6), 1904–1917. https://doi.org/10.1111/j.1365-2486.2012.02653.x

Meng, Q., Fu, B., Tang, X., & Ren, H. (2008). Effects of land use on phosphorus loss in the hilly area of the Loess Plateau, China. *Environmental Monitoring and Assessment*, *139*(1–3), 195–204. https://doi.org/10.1007/s10661-007-9826-8

Neufeldt, H., da Silva, J. E., Ayarza, M. A., & Zech, W. (2000). Land-use effects on phosphorus fractions in Cerrado oxisols. *Biology and Fertility of Soils*, *31*(1), 30–37. https://doi.org/10.1007/s003740050620

Qiu, L., Zhang, X., Cheng, J., & Yin, X. (2010). Effects of black locust (Robinia pseudoacacia) on soil properties in the loessial gully region of the Loess Plateau, China. *Plant and Soil*, *332*(1–2), 207–217. https://doi.org/10.1007/s11104-010-0286-5

Ringeval, B., Augusto, L., Monod, H., van Apeldoorn, D., Bouwman, L., Yang, X., … Pellerin, S. (2017). Phosphorus in agricultural soils: drivers of its distribution at the global scale. *Global Change Biology*, *23*(8), 3418–3432. https://doi.org/10.1111/gcb.13618

Rosenberg, M. S., Adams, D. C., & Gurevitch, J. (2000). *MetaWin Version 2: Statistical Software for Meta-analysis*. Sunderland: Sinauer Associates Inc.

Shi, S., Peng, C., Wang, M., Zhu, Q., Yang, G., Yang, Y., … Zhang, T. (2016). A global meta-analysis of changes in soil carbon, nitrogen, phosphorus and sulfur, and stoichiometric shifts after forestation. *Plant and Soil*, *407*(1–2), 323–340. https://doi.org/10.1007/s11104-016-2889-y

Stevenson, F. J., & Cole, M. A. (1999). The phosphorus cycle. In F. J. Stevenson & M. A. Cole (Eds.), *Cycles of soil: carbon nitrogen, phosphorus, sulfur, micronutrients* (pp. 279–329). New York: Wiley.

Suriyagoda, L. D. B., Ryan, M. H., Renton, M., & Lambers, H. (2014). Plant responses to limited moisture and phosphorus availability: A meta-analysis. *Advances in Agronomy*, *124*(124), 143–200. https://doi.org/10.1016/B978-0-12-800138-7.00004-8

Tian, H., Chen, G., Zhang, C., Melillo, J. M., & Hall, C. A. S. (2009). Pattern and variation of C:N:P ratios in China's soils: A synthesis of observational data. *Biogeochemistry*, *98*(1–3), 139–151. https://doi.org/10.1007/s10533-009-9382-0

Tiessen, H., Stewart, J. W. B., & Cole, C. V. (1984). Pathways of phosphorus transformations in soils of differing pedogenesis. *Soil Science Society of America Journal*, *48*(4), 853–858. https://doi.org/10.2136/sssaj1984.03615995004800040031x

Vitousek, P. M., Porder, S., Houlton, B. Z., & Chadwick, O. A. (2010). Terrestrial phosphorus limitation: Mechanisms, implications, and nitrogen-phosphorus interactions. *Ecological Applications*, *20*(1), 5–15. https://doi.org/10.1890/08-0127.1

Walbridge, M. R., Richardson, C. J., & Swank, W. T. (1991). Vertical distribution of biological and geochemical phosphorus subcycles in two southern Appalachian forest soils. *Biogeochemistry*, *13*(1). https://doi.org/10.1007/bf00002876

Walker, T. W., & Adams, A. F. R. (1958). Studies on soil organic matter: I. Influence of phosphorus content of parent materials on accumulations of carbon, nitrogen, sulfur, and organic phosphorus in grassland soils. *Soil Science*, *85*(6), 307–318. https://doi.org/10.1097/00010694-195806000-00004

Wang, H. M., Wang, W. J., Chen, H. F., Zhang, Z. H., Mao, Z. J., & Zu, Y. G. (2014). Temporal changes of soil physic- chemical properties at different soil depths during larch afforestation by multivariate analysis of covariance. *Ecology and Evolution*, *4*(7), 1039–1048. https://doi.org/10.1002/ece3.947

Wang, R., & Wang, C. (2010). Impacts of *Larix olgensis* afforestation on soil phosphorus dynamics. *Procedia Environmental Sciences*, *2*, 1669–1678. https://doi.org/10.1016/j.proenv.2010.10.178

Wang, W., Wang, H., & Zu, Y. (2014). Temporal changes in SOM, N, P, K, and their stoichiometric ratios during reforestation in China and interactions with soil depths: Importance of deep-layer soil and management implications. *Forest Ecology and Management*, *325*, 8–17. https://doi.org/10.1016/j.foreco.2014.03.023

Wang, Y., Fu, B., Lü, Y., & Chen, L. (2011). Effects of vegetation restoration on soil organic carbon sequestration at multiple scales in semi-arid Loess Plateau, China. *Catena*, *85*(1), 58–66. https://doi.org/10.1016/j.catena.2010.12.003

Wei, X., Shao, M., Fu, X., Horton, R., Li, Y., & Zhang, X. (2009). Distribution of soil organic C, N and P in three adjacent land use patterns in the northern Loess Plateau, China. *Biogeochemistry*, *96*(1–3), 149–162. https://doi.org/10.1007/s10533-009-9350-8

Yao, Y. F., Shao, M. A., Jia, Y. H., & Li, T. C. (2017). Distribution of soil nutrients under and outside tree and shrub canopies on a revegetated loessial slope. *Canadian Journal of Soil Science*, *97*(4), 637–649. https://doi.org/10.1139/cjss-2017-0013

Zeng, X., Zhang, W., Cao, J., Liu, X., Shen, H., & Zhao, X. (2014). Changes in soil organic carbon, nitrogen, phosphorus, and bulk density after afforestation of the "Beijing–Tianjin Sandstorm Source Control" program in China. *Catena*, *118*, 186–194. https://doi.org/10.1016/j.catena.2014.01.005

Zhang, C., Chen, L., & Jiang, J. (2014). Vertical root distribution and root cohesion of typical tree species on the Loess Plateau, China. *Journal of Arid Land*, *6*(5), 601–611. https://doi.org/10.1007/s40333-014-0004-x

Zhang, C., Tian, H., Liu, J., Wang, S., Liu, M., Pan, S., & Shi, X. (2005). Pools and distributions of soil phosphorus in China. *Global Biogeochemical Cycles*, *19*(1). https://doi.org/10.1029/2004gb002296

Zhang, G., Zhang, P., Peng, S., Chen, Y., & Cao, Y. (2017). The coupling of leaf, litter, and soil nutrients in warm temperate forests in northwestern China. *Scientific Reports*, *7*(1), 11754. https://doi.org/10.1038/s41598-017-12199-5

Zhang, W., Liu, W., Xu, M., Deng, J., Han, X., Yang, G., … Ren, G. (2019). Response of forest growth to C:N:P stoichiometry in plants and soils during Robinia pseudoacacia afforestation on the Loess Plateau, China. *Geoderma*, *337*, 280–289. https://doi.org/10.1016/j.geoderma.2018.09.042

Zhang, Y. Q., Liu, J. B., Jia, X., & Qin, S. G. (2013). Soil organic carbon accumulation in arid and semiarid areas after afforestation: A meta-analysis. *Polish Journal of Environmental Studies*, *22*(2), 611–620.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Li X, Li Y, Peng S, Chen Y, Cao Y. Changes in soil phosphorus and its influencing factors following afforestation in Northern China. *Land Degrad Dev*. 2019;30:1655–1666. https://doi.org/10.1002/ldr.3345