

# Decreased soil total phosphorus following artificial plantation in the Loess Plateau of China

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## ABSTRACT

Artificial plantation, established on non-forest lands in recent decades in China's Loess Plateau, play an important role in enhancing ecological restoration. However, soil phosphorus (P) dynamics following artificial plantation still remain unclear, especially at the regional scale. We aim to determine how do soil total P (TP) and available P (AP) change and how do drivers affect the dynamics of soil P following artificial plantation. Here we examined the effects of climate (precipitation and temperature), prior land use cover (cropland and barren land), current land use cover (forest, grassland, and shrubland), soil properties (soil organic carbon, bulk density, and pH), tree species, and plantation age on changes in soil TP and AP in top 100 cm following artificial plantation. Our examination was conducted based on a meta-analysis of 740 independent observations from 67 articles. The results showed that, across all the variations, TP concentrations significantly decreased by 17.5% in the top 100 cm soil layer following artificial plantation, with no significant change in AP. Concentration of TP in the 100 cm soil depth had a similar spatial pattern, characterized by a higher depletion in northwest area but lower depletion in southeast area. Climate, prior land use, tree species, and soil properties all played an important role on TP, while only tree species influenced AP response to artificial plantation. Our findings suggest that artificial plantation did not appear to directly induce P limitation because of the nearly unaltered AP in the regional scale. However, compared with lower TP depletion in southeast area, substantial declines in TP in northwest area may drive such region toward greater P limitation with the decrease of AP replenishment capacity in the future.

## 1. Introduction

Artificial plantation, the conversion of cultivated and uncultivated lands to plantation forests or grass, increases terrestrial biomass and contributes to ecosystem restoration and climate change mitigation (Canadell & Raupach, 2008; IPCC, 2013). Accordingly, the area of artificial plantation has increased in recent decades. From 1990 to 2015, the planted forest increased from 168 M ha to 278 M ha, while natural forest declined from 3961 M ha to 3721 M ha at the global scale (Keenan et al., 2015; Payn et al., 2015). In China, artificial plantation increased by 1.5 M ha y<sup>-1</sup> between 2010 and 2015 due to the 'Grain for Green' program and the 'Three Norths Shelter Forest System' project (Keenan

et al., 2015). However, the high growth rates of artificial plantation compared with prior land use cover can also lead to higher demand for soil nutrients, resulting in long-term limitations of soil nutrients (Lorenz and Lal, 2010; Goll et al., 2012).

In terrestrial ecosystems, soil P is often limiting (Elser et al., 2007), either because of the lower TP or the unavailable forms of soil P for plants (Walker & Syers, 1976), especially in the Loess Plateau of China (Liu et al., 2013). A deficit in AP may influence the plant net primary productivity, C allocation in terrestrial ecosystems, or the soil C sequestration process (Li et al., 2012; IPCC, 2013; Shi et al., 2016). However, much less has been known about the responses of soil P and its availability to the artificial plantation at the regional scale (Reed et al.,

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2015; Deng et al., 2017; Li et al., 2019). Given the widespread P limitation in the Loess Plateau of China (Zhang et al., 2005; Liu et al., 2013), improved understanding of changes in soil P and its drivers in artificial terrestrial ecosystems is urgently needed in such region.

To date, although several authors have analyzed the dynamics of soil P during the process of artificial plantation, a consensus on whether artificial plantation is considered a soil 'degrader' or 'improver' has yet to be achieved (Attiwill and Adams, 1993; Wang & Wang, 2010; Goll et al., 2012). After artificial plantation, the enhanced net primary productivity likely reduces the TP due to the plant nutrient uptake (Vitousek et al., 2010), but the accompanying exogenous inputs (such as litter and rhizodeposition) may cause an increase in the source of soil P (Cao & Chen, 2017). Consequently, artificial plantation has been reported to either increase (Chen 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 TP. Like other soil properties, soil P distributes heterogeneously after artificial plantation causing by various factors, including climatic variables at a global scale (Deng et al., 2017; Hou et al., 2018), prior or current land cover at a regional scale (Li et al., 2019), soil properties at a global scale (Macdonald et al., 2012), and vegetations at a local scale (Rodríguez et al., 2009; Chirino-Valle et al., 2016). For example, both high precipitation and temperature can facilitate rapid soil P leaching, mineralization and immobilization, causing changes in soil P forms (Vitousek et al., 2010; Siebers et al., 2017). While Deng et al. (2017) found that prior land cover and climate are most important factors for influencing soil TP and AP after afforestation at a global scale. Li et al. (2019) concluded that prior land cover, precipitation and tree species showed the confounding effects on changes in P stocks following afforestation in Northern China. Furthermore, the impact of these factors depends on spatial scale, which may be differences in vegetation, soil type and management regimens (Macdonald et al., 2012; Ringeval et al., 2017). Another explanation for the inconsistency was that soil P changes following artificial plantation vary with depth, but most reviews have not adequately considered sampling depth in their analyses (Zhang et al., 2005; Deng et al., 2017; Ringeval et al., 2017; Hou et al., 2018; Li et al., 2019). Therefore, a deeper understanding of changes in soil P in specific regions is necessary to provide more general but practical advice for artificial plantation and forest management based on local conditions.

In Northern China, Loess Plateau has been experiencing large scale artificial plantation in recent decades, such as the 'Grain for Green' project (converting cropland into grassland, shrubland or forest, we defined it as artificial plantation). To date, few studies have reported the soil P distribution and its drivers after artificial plantation across the entire Loess Plateau of China, especially for the deeper soils (Liu et al., 2013; Li et al., 2019), which could provide deep insights into mechanisms strengthening driver effects on soil P cycling. In this study, we compiled a database of soil TP and AP in paired (artificial plantation and nonplantation (control)) sites, with data from 740 independent observations, including climatic variables, land cover, vegetations, and key soil properties. Combining these variables, we determined the spatial pattern of soil P at different soil depths and quantified the relative importance of drivers in artificial plantation effect on soil P across the entire Loess Plateau. Specifically, we tested three hypotheses: (1) artificial plantation establishment would decrease TP while have no significant influence in AP; and (2) prior land cover and climate would contribute significantly to variation in P responses to afforestation.

## 2. Materials and methods

### 2.1. Data sources, data structure, and data preparation

Peer-reviewed literature related to soil TP and AP before July 2019 were searched using Web of Science, Google Scholar, and China National Knowledge Infrastructure databases. The searches included combinations of the terms 'phosphorus', 'soil phosphorus', 'tree', 'grass',

'shrub', 'plantation', 'afforest', 'reforest', 'land use'. The following criteria were used to select literature for synthesis: i) the study site was located in the Loess Plateau of China; ii) soil TP (AP) stocks were provided or could be calculated based on soil P concentration, bulk density (BD) and soil depth; iii) the experiments used paired sites, namely, there were information for both the plantation and prior land use sites. Our search was restricted to studies of unfertilized soils for the plantation sites. The raw data were obtained from tables or extracted from figures using GetData Graph Digitizer (version 2.24, Russian Federation). In total, the final dataset comprised 67 studies, including 740 independent observations at 86 sites (Fig. S1).

In the selected paper, the reported P (soil TP and AP) concentrations or stocks in the 0–100 cm soil layers were extracted. Although TP and AP in some studies were determined by different methods, resulting in measurement of different amount of the soil P in different studies, use of consistent methods within individual study ensured within-study comparability. In our study, AP was intended to represent the amount of soil P availability to plants, either 'labile' or 'available' P.

For the variables, the following information was selected for each paper: site, location (longitude and latitude), mean annual precipitation (MAP), mean annual temperature (MAT), elevation, climate type, prior land use cover, current land use cover, soil type, soil pH, soil BD (paired sites), soil organic carbon (SOC) (paired sites), sampling depths, species, plantation age.

In order to facilitate analysis, some variables were compiled. In our study, the climate type of all sites was classified as temperate continental semi-arid climate and temperate continental semi-humid climate, based on the Koppen classification as applied by Kottek et al. (2006). Prior land use cover was classified as 'degraded' (describing the site as degraded, bare land, overgrazed, wasteland before plantation) and 'nondegraded' (cropland before plantation). In our database, forest was the major current land use cover (50.7%), followed by grass (29.1%) and shrub (18.2%), with relatively small proportions for other vegetation (e.g., mixed-land use). Because of the deep loess in such region, loessial was the major soil type (71.4%), followed by cinnamon (13.5%), dark loessial (11.7%) and arenosols (3.3%), according to Chinese soil Taxonomic classification. Vegetations were compiled by three forms: i) leguminosae (63.9%), pinaceae (9.5%), cupressaceae (5.6%), rosaceae (4.9%), elaeagnaceae (4.6%), salicaceae (4.5%), asteraceae (3.9%), poaceae (2.9%), <10 observations was removed; ii) broadleaf (86.3%) and conifers (13.6%); iii) nitrogen fixation (65.1%) and non-nitrogen fixation (36.7%). We also recorded the plantation age, control and plantation BD, pH, SOC at each depth increment.

In our study, to test how soil TP and AP varied with sampling depth, the final dataset was separated into 5 subsets with 20 cm soil depth interval. These subsets included 0–20 cm (51.6%), 20–40 cm (19.1%), 40–60 cm (13.4%), 60–80 cm (8.0%), 80–100 cm (8.0%). In addition, to compare all studies, we selected 0–20 cm soil depth for all the analysis, except for the assessing the effect size of soil depth on soil TP and AP following plantation.

### 2.2. Data calculations

A mean response ratio (RR) was used to represent our metric of effect size. The RR value was calculated as the ratio of the mean value of soil P in the artificial plantation group (Pt) to that in the control group (Pc):

$$RR = \ln r = \ln \left( \frac{P_t}{P_c} \right) = \ln(P_t) - \ln(P_c)$$

where Pt and Pc represent the mean TP or AP concentration or stock of the plantation and control site, respectively.

The soil TP stock (Mg ha<sup>-1</sup>) and AP stock (kg ha<sup>-1</sup>) were calculated using the following equation:

$$Pstock = TPi(APi) \times BD \times Di/10$$

where  $TP_i$ ,  $AP_i$ ,  $BD_i$ ,  $D_i$  represent the TP concentration ( $g\ kg^{-1}$ ), AP concentration ( $mg\ kg^{-1}$ ), bulk density ( $g\ cm^{-3}$ ), the soil thickness (cm), respectively, of the  $i$ th layer of soil.

Where BD was not reported, we used soil organic matter (OM) content to estimate BD using the following equation (Post and Kwon, 2000):

$$BD = \frac{100}{\frac{OM\%}{0.244} + \frac{100-OM\%}{1.64}}$$

where OM% is the percentage of soil organic matter. If a study reported SOC instead of soil OM, we adapted the procedure slightly by using 0.58 (Mann, 1986). Moreover, report with no BD, SOC, or OM, we calculated BD at each soil layer using an empirical equation between the directly measured BD and soil layer for plantation and control sites (Deng et al., 2017). Our calculated BD using OM and directly measured BD was available even it was not able to capture large changes in BD with artificial plantation (Fig. S2).

### 2.3. Statistical analysis

An unweighted analysis rather than weighting method was used because of the differences of the variance and the definition of sample size among the studies (Deng et al., 2017). Where multiple samples were taken from the same stand at different times, or from adjacent stands of different ages in a chronosequence, we averaged the values for the different ages to avoid pseudoreplication. Because of the non-Gaussian distribution of the effect sizes, we used nonparametric approaches to test the hypothesis that the mean effect size is not equal to zero. To determine significance at the  $\alpha = 0.05$  level (significant if this bootstrapped interval did not include zero or do not overlap between categories), we conducted bootstrapping 95% confidence intervals (CI) based on 4999 random simulations.

Structural equation modeling (SEM) was also conducted to identify the relative importance of the potential pathways and drivers in mediating soil TP and AP using the data in the 0–20 cm soil depth (Grace, 2006). Before we performed SEM analysis, the necessary data manipulations were handled as follows: (1) Given the redundancy of some variables (i.e. degraded/non-degraded, prior land use cover, and current land use cover, climate type and MAP, elevation and MAT), only current land use cover, MAP, and MAT were adopted; (2) We considered SOC, BD, and soil depth as indicators of soil characteristic.

After data manipulations were complete, two priori models were established based on the relationships among these variables and hypothetical effects (Fig. S3). One model finally included MAP, MAT, soil characteristics, TP concentration, and AP concentration; and the other one included MAP, MAT, vegetation parameters, TP concentration, and AP concentration. The criteria for evaluation of the overall model fit, such as the Chi-square/degree values (CHI/DF), overall P value, and the root-mean-square error of approximation (RMSEA), were adopted. A good model fit was indicated by the smaller CHI/DF,  $0.05 \leq P \leq 1.00$ , and  $0 \leq RMSEA \leq 0.05$  (Grace, 2006). All SEM analyses were conducted using the R package 'lavaan' (Rosseel, 2012) in R 3.5.1 (R Core Team, 2018).

To evaluate the long-term effects of plantation, we used TP and AP concentration in plantation stands of different ages, rather than the stock because of their similar response to the artificial plantation. Bivariate relationships between the mean response ratio of TP and AP after plantation and MAP, MAT, elevation, SOC, pH was also determined in the 0–20 cm soil depth, using R 3.5.1 (R Core Team, 2018). In addition, the relationships between soil characteristics and  $\log_{10}$  transformed soil P were determined. Because of wide variation in AP among stands, we expressed TP concentration to examine the spatial variation of soil P at each soil layer by using interpolation method.

## 3. Results

### 3.1. Changes in soil P following artificial plantation

Overall, plantation soil showed less TP than the controls, whereas AP was unchanged for artificial plantation across all data (Table 1). Soil TP concentrations significantly decreased by 17.5% (95% CI –25.5%, –7.9%), and on average across all studies included, the soil TP stocks significantly decreased by 12.7% (95% CI –19.4%, –5.3%) following artificial plantation. However, AP concentrations and stocks did not change significantly.

### 3.2. Factors affecting changes in soil P

We selected the data of 0–20 cm soil layer for the analysis in this section. The SEM analysis confirmed that climate, key soil properties, and current land use cover were the most important drivers for determining changes in soil TP and AP (Fig. 1).

#### 3.2.1. Prior and current land use

Plantation on different prior and current land use showed different impact on TP and AP concentrations. Specifically, current land use particularly affected the change in TP (Fig. 1). Shrubland was associated with larger decreases in TP concentration (23.4%) and stocks (18.6%) than that of woodland and grassland (Fig. 2A). The three land use types were not important for AP, which did not change significantly in any land use types (Fig. 2A).

At nondegraded sites, TP concentrations and stocks decreased significantly by 22.3% and 19.4%, respectively, whereas TP concentrations and stocks did not change significantly at degraded sites (Figs. S4a, S4c). At both nondegraded and degraded sites, AP concentrations and stocks did not change significantly after plantation (Figs. S4b, S4d).

#### 3.2.2. Climate and topography

In our study, the climate factors included climate type, MAP, and MAT. MAP and MAT was the most important factors for mean response of TP concentrations, which significantly increased with the increasing MAP and MAT ( $P < 0.001$ , Figs. 1, 3), but not with change in mean response of AP concentrations. Otherwise, the two climate types identified in this study generally differed in their mean response of TP concentrations to plantation (Fig. 2B). Increasing elevation was significantly and negatively associated with increases in mean response of TP concentrations with artificial plantation, but not with change in AP (Fig. 3).

#### 3.2.3. Soil properties

Total P concentrations tended to undergo the largest changes for arenosol and cinnamon soils, significantly decreasing by 23.1% and 22.4%, but not for loessial and dark loessial (Fig. S7). For TP stocks, the largest decrease (38.9%) was found in arenosol soil, whereas it was nearly not affected by loessial and dark loessial soil. Soil types showed no effect on soil AP concentrations and stocks along with plantation (Fig. S7).

Soil OC and BD play an important role in mean response of TP and AP to plantation (Fig. 1). Although mean response of TP and AP concentrations exhibited weak relationships with SOC and pH (Fig. S5), but  $\log_{10}$  of TP and AP showed a significant relationship with SOC and pH ( $P < 0.001$ , Fig. S6).  $\log_{10}$  of AP concentrations showed a significant and positive relationship with soil BD ( $R^2 = 0.11$ ,  $P < 0.001$ ), whereas  $\log_{10}$  of TP concentrations exhibited a weak relationship with soil BD (Fig. S6).

#### 3.2.4. Vegetations

Vegetation factors, including species classes, conifers/broadleaf, nitrogen/non-nitrogen fixation, were ranked as the less important

**Table 1**

Soil total and available P with artificial plantation and corresponding control value, to a soil depth of 100 cm. Abbreviations: RR: mean response ratio.

Soil layer	Variables	Total P					Available P				
		Mean	Med	Min	Max	n	Mean	Med	Min	Max	n
0–20 cm	P conc, control (mg kg <sup>-1</sup> )	603	582	390	1010	162	7.03	2.77	0.72	76.0	162
	P conc, plantation (mg kg <sup>-1</sup> )	490	484	240	910	162	5.19	1.92	0.34	92.5	162
	P stock, control (kg ha <sup>-1</sup> )	1698	1695	991	3300	162	18.9	7.62	1.83	193	162
	P stock, plantation (kg ha <sup>-1</sup> )	1479	1462	398	2693	162	14.6	5.64	0.86	232	162
	RR in P conc (%)	-17.6	-17.9	-74.3	52.5	162	4.90	-26.9	-95.2	19.1	162
	RR in P stock (%)	-11.9	-12.8	-87.9	66.2	162	3.72	-18.5	-95.3	18.8	162
20–40 cm	P conc, control (mg kg <sup>-1</sup> )	566	538	365	764	60	5.53	1.19	0.47	19.3	60
	P conc, plantation (mg kg <sup>-1</sup> )	463	421	254	972	60	5.01	1.19	0.41	49.3	60
	P stock, control (kg ha <sup>-1</sup> )	1652	1698	904	1990	60	15.9	3.64	1.48	59.9	60
	P stock, plantation (kg ha <sup>-1</sup> )	1457	1444	804	2577	60	12.7	2.55	0.63	131	60
	RR in P conc (%)	-18.7	-20.9	-46.1	48.9	60	-4.38	-12.9	-69.6	64.8	60
	RR in P stock (%)	-11.4	-12.8	-34.0	51.7	60	-7.42	-25.2	-74.0	71.8	60
40–60 cm	P conc, control (mg kg <sup>-1</sup> )	534	497	263	726	42	3.84	1.53	0.32	18.1	52
	P conc, plantation (mg kg <sup>-1</sup> )	463	408	216	878	42	3.25	1.28	0.19	17.2	52
	P stock, control (kg ha <sup>-1</sup> )	1481	1583	702	1934	42	10.8	4.09	1.03	47.2	52
	P stock, plantation (kg ha <sup>-1</sup> )	1407	1436	635	2488	42	9.66	3.37	0.65	53.6	52
	RR in P conc (%)	-12.4	-17.2	-34.9	50.6	42	4.31	-2.86	-66.0	125	52
	RR in P stock (%)	-5.13	-7.02	-27.1	29.1	42	6.41	-17.7	-65.9	148	52
60–80 cm	P conc, control (mg kg <sup>-1</sup> )	512	417	378	732	25	4.58	1.25	0.46	21.1	17
	P conc, plantation (mg kg <sup>-1</sup> )	482	425	298	783	25	4.48	0.99	0.18	22.3	17
	P stock, control (kg ha <sup>-1</sup> )	1412	1126	984	1996	25	11.2	3.41	1.51	49.7	17
	P stock, plantation (kg ha <sup>-1</sup> )	1311	997	647	2374	25	6.81	2.36	0.61	29.5	17
	RR in P conc (%)	-7.11	-6.11	-23.1	8.56	25	-4.8	-12.8	-59.8	77.5	17
	RR in P stock (%)	-10.3	-11.4	-42.1	20.7	25	-6.7	-25.8	-59.8	65.4	17
80–100 cm	P conc, control (mg kg <sup>-1</sup> )	461	398	261	712	25	3.81	1.03	0.66	17.2	17
	P conc, plantation (mg kg <sup>-1</sup> )	420	383	135	711	25	2.61	0.94	0.22	11.2	17
	P stock, control (kg ha <sup>-1</sup> )	1297	1155	728	1985	25	9.67	2.88	2.19	42.3	17
	P stock, plantation (kg ha <sup>-1</sup> )	1303	1040	223	2275	25	6.66	2.59	0.74	28.1	17
	RR in P conc (%)	-8.18	-5.09	-48.1	49.2	25	6.53	-32.8	-66.4	101	17
	RR in P stock (%)	-0.71	0.11	-69.3	41.5	25	0.22	-26.1	-66.4	150	17
0–100 cm	P conc, control (mg kg <sup>-1</sup> )	531	520	261	1010	314	5.46	3.39	0.32	76.0	308
	P conc, plantation (mg kg <sup>-1</sup> )	436	430	135	972	314	4.56	2.90	0.18	92.5	308
	P stock, control (kg ha <sup>-1</sup> )	1251	1028	702	3300	314	11.9	6.78	1.03	193	308
	P stock, plantation (kg ha <sup>-1</sup> )	1111	915	223	2693	314	9.87	5.06	0.61	232	308
	RR in P conc (%)	-17.5	-19.1	-74.3	52.5	314	-3.6	-22.9	-95.2	101	308
	RR in P stock (%)	-12.7	-11.5	-87.9	66.2	314	-4.7	-24.5	-95.3	150	308

predictor of changes in TP and AP, except for plantation age (Fig. 1). Specifically, in case of broadleaf/conifers, broadleaf had lower mean response of TP concentrations compared to conifers (Fig. 2D), and similar pattern was found in nitrogen/non-nitrogen fixation (Fig. 2C) because of more than 80% of the broadleaf trees were nitrogen fixation trees in our dataset. In addition, there was tiny difference in TP and AP among species classes (Fig. S8). With the increase in plantation age, TP concentrations linearly decreased ( $R^2 = 0.16$ ,  $P < 0.001$ ), whereas AP concentrations was not significantly related to plantation age ( $P > 0.05$ , Fig. S9).

### 3.3. Spatial variation and vertical change in soil P

In Fig. 4, mean response of TP concentrations showed substantial spatial variation in each soil layer across the Loess Plateau region. Generally, mean response of TP concentrations in each soil layer had a similar overall spatial pattern, characterized by a northwest area with low mean response of TP concentrations values and a southeast area with higher values. However, some differences in the detailed spatial patterns can be detected among soil layers.

Within stands where soil P was sampled at different soil layers, mean response of TP concentrations and stocks tended to decrease more with artificial plantation in surface soil layers (Table 1). Mean response of TP concentrations and stocks in 20 cm soil layer intervals had a similar overall decreasing pattern with the increasing soil depths. Nevertheless, both AP concentrations and stocks did not change significantly among soil layers after planation (Fig. S10).

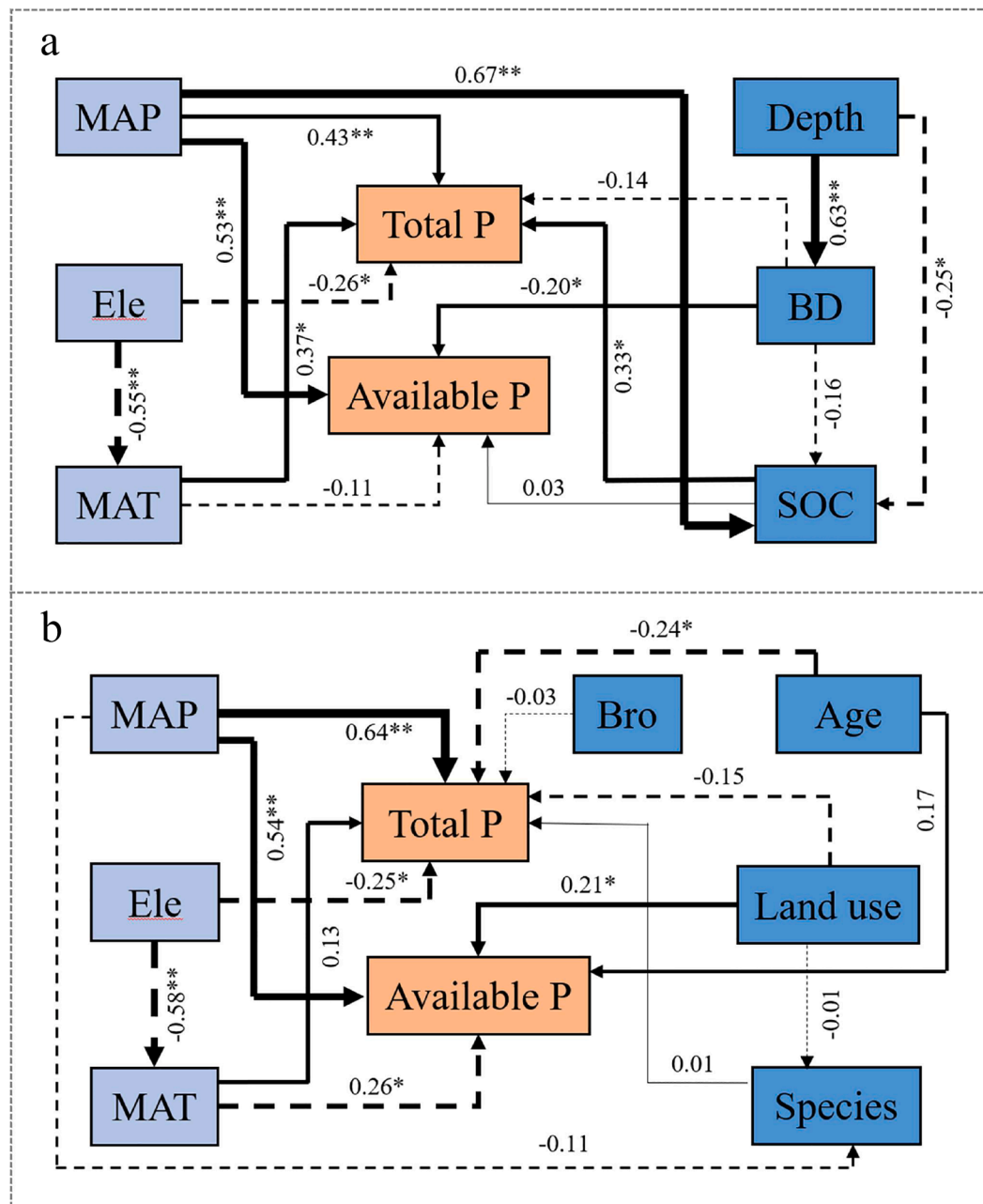
## 4. Discussion

### 4.1. Spatial patterns of soil P following artificial plantation

As previously reported by Li et al. (2019), there are a limited number of studies available on the effects of afforestation on soil P in Northern China, especially in the Loess Plateau. Our results showed artificial plantation led to an overall depletion of soil TP concentrations but with some unchanged AP concentrations in the 0–20 cm soil layer in the Loess Plateau, which is in general agreement with the findings from a previous regional scale in Northern China (Li et al., 2019) and in a global-scale study (Deng et al., 2017). The cessation of P fertilizer input with afforestation may be the main reason for resulting in lower soil P in planted forests than in agricultural soils (MacDonald et al., 2012). The lower decrease in soil P stocks (7.3%) reported by Li et al. (2019) was probably caused by the large proportion of observations collected in their dataset were in arid and semiarid areas (Chen et al., 2016). Additionally, although previous studies discussed the possible different drivers (including land use type, plantation age, and climate) of soil P changes (Liu et al., 2013; Deng et al., 2017; Li et al., 2019), they provided a partial picture of the soil P and preventing profound analysis of the relative contribution of the different potential drivers.

Our meta-analysis confirmed that artificial plantation on cropland use had typically greater overall influence on soil TP, but there were strong spatial differences for patterns of soil P components following artificial plantation. In our study, mean response of TP concentrations in each layer showed higher values in southeast area and lower values in northwest area (Fig. 4). It may be related to the abnormally severe soil erosion in northwest area and the consequent decline in soil fertility and land degradation (Tang, 1991; Moazed et al., 2010; Liu et al., 2013). In





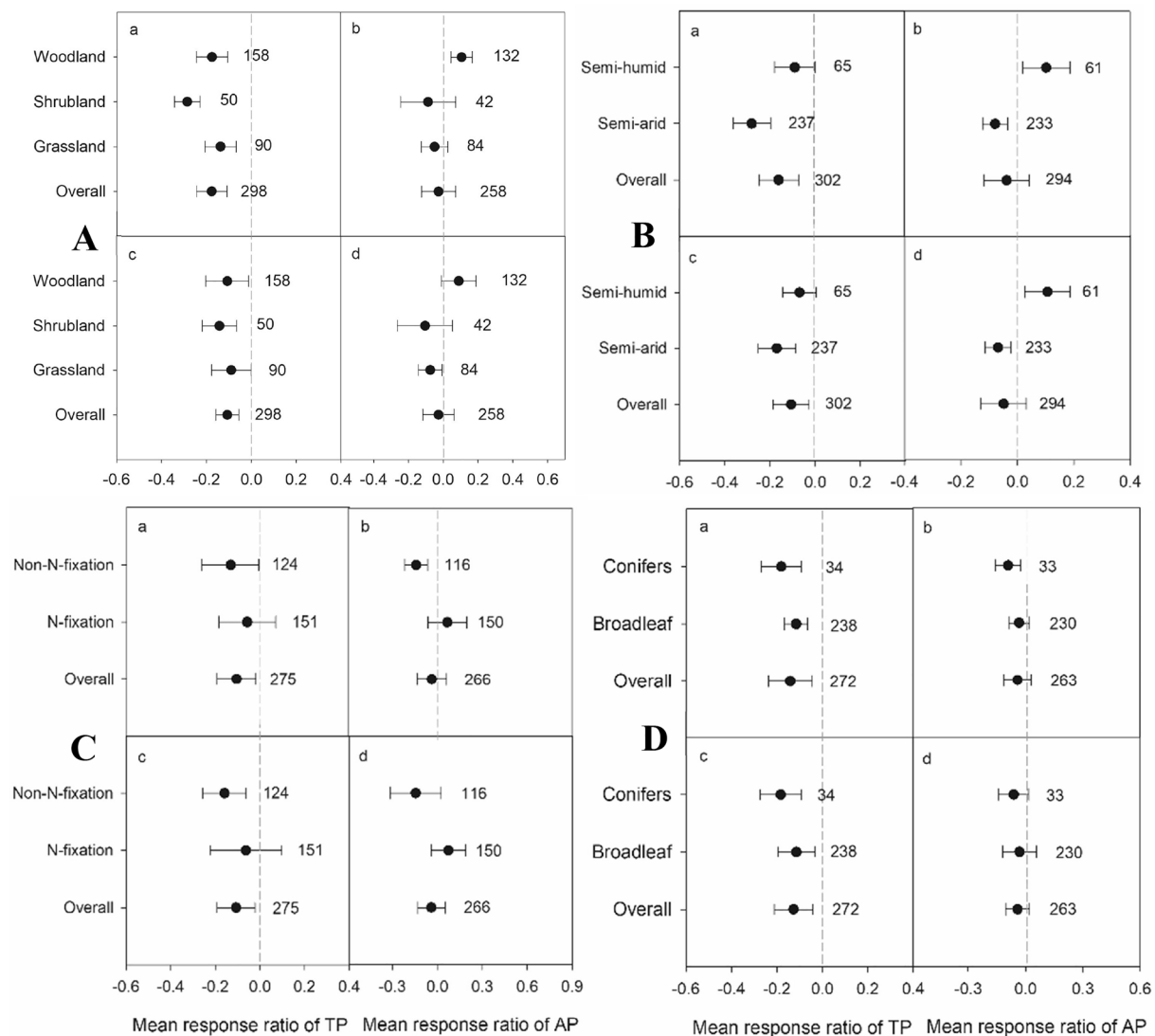
**Fig. 1.** Structural equation modeling variables effects on soil P. (a) Model on the effect of MAP, MAT, and soil characteristics soil P ( $\chi^2 = 0.85$ ,  $P = 0.42$ , RMSEA = 0.008), (b) Model on the effect of MAP, MAT, and vegetation parameters soil P ( $\chi^2 = 1.72$ ,  $P = 0.85$ , RMSEA = 0.025). Arrows width indicates the strength of standardized path coefficients. Paths with positive and negative relationships are presented as continuous and dashed lines, respectively. Numbers on arrows are standardized path coefficients. \*\* $P < 0.01$ ; \* $P < 0.05$ . Abbreviations: MAP: mean annual precipitation; MAT: mean annual temperature; Ele: elevation; Depth: soil depth; BD: soil bulk density; SOC: soil organic carbon; Bro: broadleaf or conifers; Age: stand age.

addition, limited input biomass and aeolian sandy soil with low background value, together with the massive loss of eroded surface soil can lead to low soil P in northwest area. Despite the significant influences on soil TP, our meta-analysis showed that artificial plantation did not significantly affect the AP. Considering the limited P inputs in plantation (Lacrau et al., 2005), this finding suggests that artificial plantation promoted soil P mineralization. To meet greater P demands, trees may invest more C and other resources in root exudates and microbial symbioses that degrade clay minerals or organic P compounds (Chen et al., 2008). Soil P vertical distribution patterns in 0–100 cm soil layers also showed that the higher mean response of TP concentrations were found in the northwestern part, where the severe soil erosion and low vegetation coverage is located (Tang, 1991; Liu et al., 2013).

## 4.2. Effect of drivers on soil P change

### 4.2.1. Climate

According to previous studies, climatic factor purported to affect changes in soil P after afforestation in terms of the source and transformation (MacDonald et al., 2012; Deng et al., 2017; Hou et al., 2016; Li et al., 2019). Taken as a whole, the fact that MAP appeared as the main driver of soil TP after artificial plantation is a critical result for further modelling efforts and increases our understanding of the distribution of P in forest soils at regional scale. Generally, it has long been recognized that soil TP and AP are negatively affect by MAP through driving P loss and plant P uptake and leaching from topsoil to deeper soils (Lorenz & Lal, 2010; Vitousek et al., 2010). However, our results



**Fig. 2.** Mean response ratio of soil TP (AP) after artificial plantation as influenced by (A) current land use cover, (B) climate type, (C) nitrogen fixation or non-nitrogen fixation, and (D) tree species. The error bars represent 95% confidence intervals. The dotted line at zero represents that no change in total or available P after artificial plantation. (a, b) and (c, d) represent mean response ratio of soil P concentration and stock, respectively.

showed that soil P depletion was lower in southeast areas with high precipitation than in northwest areas with low precipitation after artificial plantation (Fig. 4), indicating the relatively greater ability to promote soil P mineralization in wetter sites than in drier sites. There are two reasons may explain this phenomenon. First, initial soil P density ( $0.43 \text{ kg m}^{-2}$ ) are higher in areas with relatively high precipitation than that of ( $0.23 \text{ kg m}^{-2}$ ) in areas with relatively low precipitation (Liu et al., 2013), and in our study area, the higher soil P distributes in these areas where MAP exceeds 500 mm (Liu et al., 2013). Therefore, even the equilibrium P depletion for tree biomass in areas with low MAP would strongly influence changes in soil P content after artificial plantation. In addition, in wetter areas, there may be more secondary minerals or clay minerals, which can strongly retain P. Second, according to Li et al. (2019), the confounding effect of MAP and prior land use cover enhanced the reduction in soil TP concentrations after artificial plantation in area with low MAP.

We confirmed that climate influenced soil P dynamics after artificial plantation, as climate type was identified as an important predictor for the change in soil TP (Fig. 1). In our study, semi-arid climate type showed more sensitive characteristic than that of semi-humid climate type (Fig. 2B). This was also supported by the significant positive relationship between mean response of TP concentration and MAT (Fig. 3).

It is well known that increased MAT accelerates the weathering of parent material, together with an accumulation of P in the surface soil layer, resulting in higher soil P content in area with high MAT and semi-humid (Tian et al., 2009). Considering that declines in soil TP pool will weaken the capacity to generate the new AP, P limitation may be a major issue in areas with low MAP and MAT (Vitousek et al., 2010). Moreover, low temperature may limit the ability of rhizospheric microorganism to degrade organic P compounds, resulting in decreasing the soil AP (Fig. 2B, 3).

#### 4.2.2. Prior land use

The history of land use cover was found to be an important factor determining the dynamics of soil P after artificial plantation (Figs. 1, S4). The mean response of TP concentration is significantly lower in nondegraded lands than in soils of degraded lands after artificial plantation, which usually have relatively low vegetation coverage and soil P may lose due to erosion (Deng et al., 2017). The different responses of soil TP to plantation with degraded/nondegraded could be explained by the following two reasons: First, the long-term application of phosphate fertilizer in the farmland system resulted in the rapid increase in soil TP, which was similar to the research results of Shi et al. (2016). Farmland soils could be resupplied with P in the form of inorganic P via the

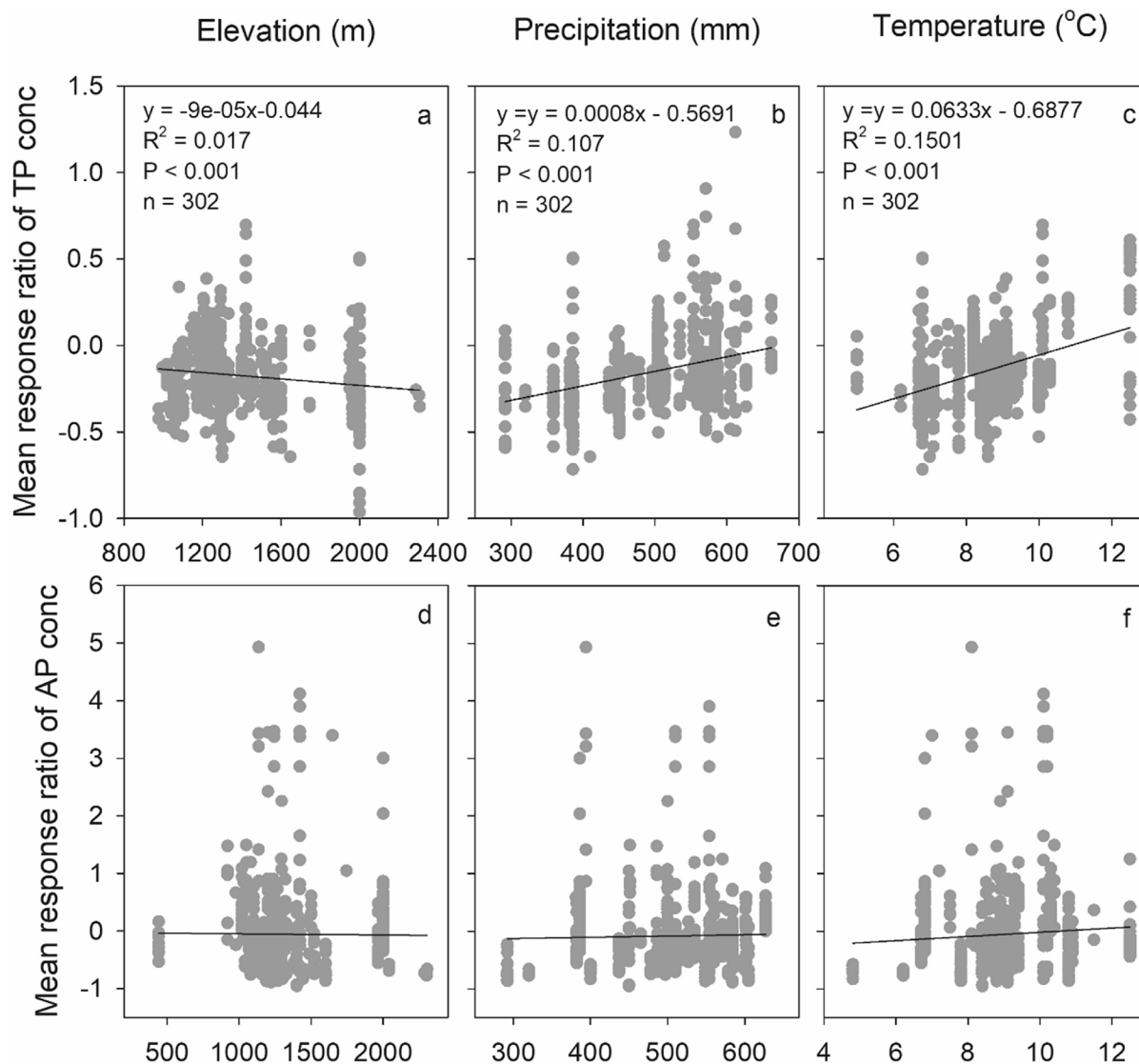


Fig. 3. Relationships between the mean response ratio of soil TP (AP) and elevation, precipitation, and temperature after artificial plantation.

application of fertilizers and manures, whereas in degraded soils, P originates entirely from the weathering of parent material, which occurs at very slow rates (Li et al., 2019). Second, the farmland tillage destroyed the soil aggregate structure, improved the ventilation condition, promoted the organic phosphorus mineralization and the increase of the inorganic phosphorus content. In addition, available P 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 (Deng et al., 2017).

The reduced soil TP concentration in nondegraded lands does not necessarily indicate P limitation; rather, it may simply reflect the less P inputs after artificial plantation (MacDonald et al., 2012). Phosphate fertilization is often used in fields to increase soil fertility and maintain high crop yields, which may contribute to the conversion of AP in the soil (McLauchlan, 2006). Farming also increases the availability of P by stimulating the decomposition of soil organic matter by microorganisms, which eventually releases nutrients including phosphorus (McLauchlan, 2006; Laganière et al., 2010). Generally, conversion between farmland and other land use cover usually results in the changes of labile P, especially in nondegraded lands. However, compared to nondegraded lands, these decreases may be smaller in the case of plantation than for degraded lands in our study areas, suggesting a

balance between increased P availability due to afforestation and the reduction associated with discontinuation of tillage (MacDonald et al., 2012).

#### 4.2.3. Tree species and plantation age

Compared with climate and land use cover, the vegetation driver (tree species and plantation age) had a smaller effect on soil P after artificial plantation (Fig. 1). This result is also consistent with that of Li et al. (2019), who reported that conifers showed a more sensitive change than that of broadleaves, probably explained by the two reasons. First, organic P input from plant litter vary in quality and quantity for the two species. For example, due to biological differences between the two species, the P content in plant residue for the broadleaves are higher than those in conifers (Zeng et al., 2014). Second, due to the higher belowground biomass of broadleaf, the root characteristics of broadleaf may increase the P uptake and transfer (Laganière et al., 2010). On the Loess Plateau, it has been reported that the root biomass of *R. pseudoacacia* (broadleaf) is greater than that of *P. tabulaeformis* (conifer) (Zhang et al., 2014).

In our study, the more decrease in AP concentrations following non-nitrogen fixation than that of nitrogen fixation species plantation was consistent with the findings of a new research (Shi et al., 2016). In the

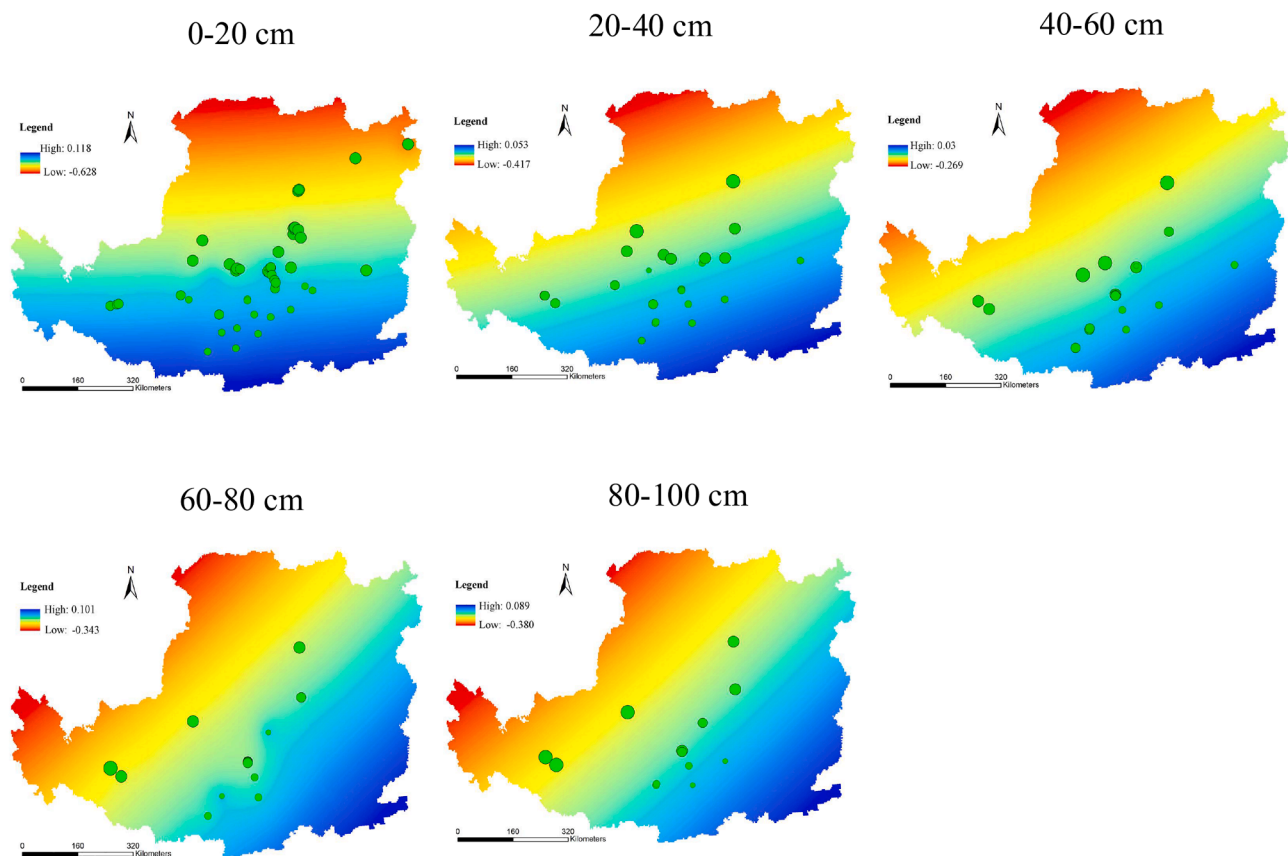


Fig. 4. Spatial distribution maps of mean response ratio of soil total phosphorus (P) in each soil layer across the Loess Plateau, China.

environment dominated by leguminous trees, legumes make more root phosphatase activity through biological nitrogen fixation, thus consuming more AP (Nasto et al., 2017; Png et al., 2017). Thus, the increasing consumption of AP affects the fixation of N by plants through feedback action, thus affecting the amount of N in the ecosystem, while the increase of phosphatase activity affects the AP concentrations in the ecosystem (Vitousek et al., 2010; Marklein & Houlton, 2012). In addition, a significantly decreasing trend of TP concentration and an increasing trend of AP with time since conversion was found in our study, suggesting that soil P depletion domains during the entire afforestation period. This is reasonable because soil P depletion due to soil erosion caused by strong disturbance occurred during the entire afforestation stages. These results were partly inconsistent with those of Deng et al. (2017) and Shi et al. (2016) on a global scale, both reported that plantation age had no significant impact on TP since afforestation. Tree species differences may explain this discrepancy, thus some more research based on tree species needs to be done on large scales in the future.

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 (Li et al., 2019). Previous studies also found that similar soil P acquisition despite differences in the type of mycorrhiza associated with tree species and soil nutrient availability may be more important to tree species' nutrient acquisition than mycorrhizal fungi (Holste and Kobe, 2016). In addition, 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 in such area (Suriyagoda et al., 2014).

#### 4.3. Implication and uncertainty

According to Paris Agreement in 2015, Chinese government promised that forest will increase by 4.5 billion  $\text{m}^3$  by 2030. Under such conditions, the soil P dynamic after afforestation should be further explored. In this paper, we considered the soil TP and AP dynamics, which showed different response mechanisms for various driving factors. The result showed that a significant decrease in soil TP but not AP, especially in northwest area, where the severe soil erosion and low vegetation coverage is located (Tang, 1991; Liu et al., 2013). The continued decrease in soil TP content may cause some ecosystem problems, such as the loss of soil nutrient (Cao and Chen, 2017; Goll et al., 2012) and the slow plant growth caused by P limit (Png et al., 2017; Zhang et al., 2019). Therefore, how to properly handle the relationship between afforestation and soil P requires further research.

Some uncertainties may be associated with the approach of our data integration, but this uncertainty will not significantly affect our main results. Chief sources of this uncertainty mainly include the variation in the methods used to determine TP and AP in the dataset, the failing to use mass correction method for more increased accuracy of soil BD, and the limited number of studies reporting from deeper soil layers within individual stands. In addition, a highly spatial heterogeneity of soil parent material should affect the vertical distribution of soil P, which can lead to misestimates of the effects of land use on changes in soil nutrients (Allen et al., 2016). 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 (Chen et al., 2008). Topographical features, including slope and aspect, are often strongly correlated with nutrient transport and subsequently influence soil P heterogeneity (Liu et al., 2013). Future studies should pay more attention to the spatial-temporal changes in P stocks, especially the vertical distribution, which may contribute to a better understanding of changes



in P dynamics after afforestation at regional scales.

## 5. Conclusions

In general, our meta-analysis showed a significant decrease in soil TP but minimum effects on soil AP after artificial plantation in the Loess Plateau of China. Across the entire Loess Plateau, soil TP depletion was higher in northwest areas with low precipitation than in southeast areas with high precipitation, indicating the P limitation could be a major issue in drier plantations as a result of commonly low-P soils. Soil TP depletion occurred in each soil layer characterized by a northwest area with larger P depletion and a southeast area with lower value. The random forest and SEM analysis showed that climate, including MAP and MAT, was the most important factor influencing soil P response. Artificial plantation established on barren land has a larger capacity to accumulate soil P than artificial plantation established on cropland. We observed significant reduction of P availability after artificial plantation in cropland with nitrogen fixation species, which may further limit plant growth. We also found a significant decrease of AP for broadleaves than for conifers because of 80% of broadleaves belongs to nitrogen fixation species. Plantation age had a limited effect on changes in soil P concentrations, suggesting a future P depletion along with the artificial plantation process. Taken together, our findings strengthened the importance of tree species selection across sites where precipitation differs. Moreover, to provide a more comprehensive understanding of changes in soil P and its influencing factors, further studies should combine vertical and horizontal P changes after artificial plantation in such region.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geoderma.2020.114882>.

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