Exogenous phosphorus compounds interact with nitrogen availability to regulate dynamics of soil inorganic phosphorus fractions in a meadow steppe

Heyong Liu [a,b], Ruzhen Wang [b,*], Hongyi Wang [b], Yanzhuo Cao [b,c], Feike A. Dijkstra [d], Zhan Shi [b], Jiangping Cai [b], Zhengwen Wang [b], Hongtao Zou [a,*], Yong Jiang [b]

[a] *College of Land and Environment, Shenyang Agricultural University, Shenyang 110866, China*

[b] *Erguna Forest-Steppe Ecotone Ecosystem Research Station, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China*

[c] *Key Laboratory of Regional Environment and Eco-Remediation, College of Environment, Shenyang University, Shenyang 110044, China*

[d] *Centre for Carbon, Water and Food, School of Life and Environmental Sciences, The University of Sydney, Sydney, NSW 2006, Australia*

[*] Correspondence to:

Dr. Ruzhen Wang, Tel: +86 24 83970603; *E–mail address:* ruzhenwang@iae.ac.cn

Dr. Hongtao Zou, Tel: +86 24 88487155; *E–mail address:* zouhongtao2001@163.com

Abstract

Here we investigated the effects of P compounds (KH_2PO_4 and $Ca(H_2PO_4)_2$) with different addition rates of 0, 20, 40, 60, 80 and 100 kg P ha^{-1} yr^{-1} and NH_4NO_3 addition (0 and 100 kg N ha^{-1} yr^{-1}) on soil labile inorganic phosphorus (IP) (dicalcium phosphate, Ca_2-P), moderate-cycling IP and recalcitrant IP fractions in a calcareous grassland of northeastern China. Soil moderate-cycling IP fractions, not readily available to plants but transforming into soil available P quickly, include variscite (Al-P), strengite (Fe-P) and octacalcium phosphate (Ca_8-P); recalcitrant IP fractions include hydroxylapatite (Ca_{10}-P) and occluded P (O-P). Soil labile and moderate-cycling IP fractions and total P significantly increased with increasing P addition rates, with higher concentrations detected for KH_2PO_4 than for $Ca(H_2PO_4)_2$ addition. Combined N and P treatments showed lower soil labile IP and moderate-cycling IP fractions compared to ambient N conditions due to enhanced plant productivity. Moderate-cycling IP was mainly regulated by P addition and plant P uptake to further enhance labile IP and total P concentrations with KH_2PO_4 and $Ca(H_2PO_4)_2$ addition. Soil labile IP was also directly and negatively affected by soil pH and plant P uptake with $Ca(H_2PO_4)_2$ addition. $Ca(H_2PO_4)_2$ addition significantly increased the soil recalcitrant IP (Ca_{10}-P) fraction, while KH_2PO_4 addition showed no impact on it. A significant positive correlation was detected between soil labile IP, moderate-cycling IP fractions and soil Olsen-P which illustrated that labile IP and moderate-cycling IP fractions were important sources for soil available P. Our results suggest that moderate-cycling IP fractions are essential for grassland P biogeochemical cycling and chemical form of P fertilizer should be considered during fertilization management for maintaining soil available P.

Key words semi-arid steppe; nitrogen enrichment; fertilization management;

mineral-bound phosphorus; occluded phosphorus

1. Introduction

Phosphorus (P) is an essential nutrient affecting terrestrial plant productivity and ecosystem functions (Luo et al., 2015). Soil inorganic P (IP) could occupy 50%-90% of soil total P (Jiang and Gu, 1989; Feng et al., 2016) and mainly includes adsorbed and mineral forms of phosphate (Hinsinger, 2001). Soil mineral-bound phosphate falls into two groups: those containing calcium (Ca-P) and those containing iron and aluminum (Chen et al., 2002), which are the leading sources of plant available P (Meena et al., 2018). The detailed classification of these two groups includes soil variscite (Al-P), strengite (Fe-P), dicalcium phosphate (Ca_2-P), octacalcium phosphate (Ca_8-P), hydroxylapatite (Ca_{10}-P) and occluded P (O-P) (Zhao et al., 2019). Soil IP is dominated by Al-P and Fe-P in acidic soils and by Ca-P fractions in calcareous soils (Baumann et al., 2017). The solubility of soil Ca-P fractions decreases in the order Ca_2-P > Ca_8-P > Ca_{10}-P (Jiang and Gu, 1989). Although these element-bound P fractions are not readily available to plants, soil Al-P, Fe-P, Ca_2-P and Ca_8-P can be converted to free phosphates serving as important buffering pools for available P (Herlihy and McGrath, 2006; Zhao et al., 2019). Based on P transforming dynamics, soil IP could be fractionated into soil labile (Ca_2-P) / available P (Olsen-P), moderate-cycling P fractions (Al-P, Fe-P and Ca_8-P) and recalcitrant P fractions (Ca_{10}-P and O-P). But the category is not universal which mainly depends on the sensitivity of soil IP fractions in different studies (Schrijver et al., 2012 *vs.* Zhao et al., 2019). Soil Olsen-P could be directly absorbed and utilized by plants, which includes all water-soluble P, some of the adsorbed and soluble IP, and mineralizable organic P (Tang et al., 2009; Cao et al., 2012). Ca_2-P, chemically similar to Olsen P, includes water-soluble P, citrate-soluble P and partially surface-adsorbed P (Shen et al., 2004; Zhao et al., 2019). Soil recalcitrant IP is relatively stable and unavailable for plants,

which is mainly converted from the fixation of labile and moderate-cycling IP (Shen et al., 2004; Zhao et al., 2019). Therefore, soil IP transformation is crucial for nutrient cycling in terrestrial ecosystems.

Adding P to soil is an effective way to enhance soil available P and sustain plant productivity (Marklein and Houlton, 2012). However, P addition changes ecosystem P cycling (Herlihy and McGrath, 2006) and the reactions between free phosphate and cations in soil thereby influencing the concentration and transformation of soil IP fractions (Walker and Syers, 1976). As such, chronic P input can result in insoluble phosphate accumulation and decrease P use efficiency without providing additional benefits for plant growth (Maistry et al., 2015). This could then increase the risk of soil P leaching losses (Shen et al., 2004). Therefore, exploring the effect of P addition on soil IP fractions is important for understanding soil available P supply and P dynamics in terrestrial ecosystems (Sigua et al., 2017).

Biogeochemical P dynamics can also be influenced by the chemical form of applied P (Margenot et al., 2017). Frequently-used P compounds include $Ca(H_2PO_4)_2$ (slow-release P fertilizer) and KH_2PO_4 (fast-release P fertilizer) (Mortvedt et al., 1999), which have played critial roles in agricultural ecosystems (Nguyen et al., 2012). Both P fertilizers can convert into various inorganic P fractions including soil Fe-P (especially in paddy soils with high Fe^{2+}) (Sah et al., 1989) and soil Al-P, which can account for 33% of the total soil P in weathered soils (Margenot et al., 2017). Soil Ca_2-P and Ca_8-P could be also formed with P addition, especially in calcareous soils with pH higher than 7 (Al-Khateeb et al., 1986). In a previous study it was found that long-term application of $Ca(H_2PO_4)_2$ increased soil IP fractions (Al-P, Fe-P, Ca_2-P, Ca_8-P and O-P) and total P (TP) concentrations in a calcareous soil (Wang et al. 2010); and other one showed that long-term $Ca(H_2PO_4)_2$ addition decreased soil P

availability due to fixation of P to the soil constituents (Xiong et al., 2018). KH_2PO_4 addition was suggested to enhance the reaction of phosphate with Fe and Al oxides and with hydroxyl ions under lower soil pH conditions (Shuman, 1988). While these studies provided insight into the relationships between P addition and IP fractions (Condron and Goh, 1989), little is known about the effects of different P compound additions on soil IP fractions and P availability.

Nitrogen enrichment can influence soil chemical properties thereby affecting soil P transformations, and consequently above-ground biomass and foliar P concentrations (Crowley et al., 2012). For instance, N addition often decreases soil pH and promotes the release of P from Fe and Al oxides (Gustafsson et al., 2012; Yang et al., 2014), and can result in redistribution of soil IP fractions (Zhao et al., 2019). Nitrogen addition could also promote the mineralization of soil organic P by increasing phosphatase activities (Olander and Vitousek, 2000). The effect of combined N and P addition on ecosystem P dynamics may further depend on their relative amounts added to the soil. For instance, inorganic P solubility and availability were particularly large when P was applied with N (Ross et al., 1995), while N and P applied at higher N:P ratios increased plant P use efficiency and leaf phosphatase activity (Hogan et al., 2010). It is well known that variation in N:P input ratios can also alter plant litter N:P ratios (Vitousek et al., 2010; Güsewell, 2004; Sun et al., 2018), thereby further affecting N and P availability through litter decomposition. However, it remains unclear how applications of N and P added at different ratios will affect soil IP fractions.

The meadow steppe in northern China is an important part of the Eurasian grassland ecosystem (Kang et al., 2007). With the intensive environmental stresses of overgrazing and enhanced outputs of animal products from a sharply rising population,

Inner Mongolia grassland ecosystems have potentially become more nutrient-limited, predominantly by N and P (Kang et al., 2007; Gong et al., 2011). Hence, N and P additions are necessary to enhance ecosystem productivity in the meadow steppe. The purpose of our study was to monitor the effects of various levels of KH_2PO_4 and $Ca(H_2PO_4)_2$ with and without N addition on concentrations of soil IP fractions, available P and TP. We hypothesized that 1) soil labile IP (Ca_2-P) and moderate-cycling IP fractions (Al-P, Fe-P and Ca_8-P) would significantly increase with KH_2PO_4 and $Ca(H_2PO_4)_2$ addition, while soil recalcitrant IP fractions (Ca_{10}-P and O-P) would not be affected, because of different solubility in IP fractions; 2) addition of soluble KH_2PO_4 would be more efficient in increasing soil labile IP, moderate-cycling IP fractions, recalcitrant P fractions and total P (TP) than less-soluble $Ca(H_2PO_4)_2$, because of faster conversion of KH_2PO_4 into labile and moderate-cycling IP fractions and consequentially promoting the formation of recalcitrant fractions; 3) the concentrations of soil IP fractions would be lower under combined P and N additions than that under P addition alone due to facilitation of plant P uptake with N addition.

2. Materials and methods

2.1. Study sites and experimental design

The study site (119º 22′ E, 50º 10′ N, elevation 523 m a.s.l.) is located in the Erguna Forest-Steppe Ecotone Research Station of Inner Mongolia, China. This area belongs to a temperate continental monsoon climate. The mean annual precipitation and mean annual temperature is 375 mm and -3 ℃, respectively. Rainfall of the site is mainly concentrated during the period from June to August and the average growing season is about 150 days. The soil is a Chernozem according to the Food and Agricultural

Organization of the United Nations classification (WRB, 2014), and the soil chemical characteristics of the site are reported in Table 1. The dominant plant species include *Stipa baicalensis, Leymus chinensis* and *Carex duriuscula*. The relative biomass proportion of the three dominant species combined to the total aboveground biomass was 50.29%-74.75% and 72.43%-91.92% in the plots without and with N addition, respectively.

The experiment, established in 2014, was arranged in a randomized block design with 24 treatments and five replicates. Phosphorus addition included two compounds, *i.e.,* KH_2PO_4 and $Ca(H_2PO_4)_2$, and were applied at six levels: 0, 20, 40, 60, 80 and 100 kg P ha^{-1} yr^{-1}. Half of the plots were applied with 100 kg N ha^{-1} yr^{-1} in the form of NH_4NO_3. P and N were added in the middle of May. All treatment plots were balanced for K using potassium chloride (KCl) to maintain the same amount of K input as in the treatment with 100 kg P ha^{-1} yr^{-1} of KH_2PO_4 addition (132 kg K ha^{-1}). To balance for Cl along with KCl addition, $CaCl_2$ was applied to maintain equal Cl inputs for all plots (121 kg Cl ha^{-1}). Calcium was not balanced in this calcareous soil, where Ca is already abundant. In this study we chose the same control plots for the KH_2PO_4 and $Ca(H_2PO_4)_2$ treatment, so that in total, there were 110 plots of 8 m $\times$ 8 m, separated by 1-m wide buffer zones. The initial pH of KH_2PO_4 and $Ca(H_2PO_4)_2$ solutions were 4.91 and 4.50, respectively.

2.2. Sample collection

In August 2016, aboveground biomass was harvested by clipping all living tissues using a 1 m $\times$ 1 m quadrat placed randomly within each plot. The plants were sorted to species and oven-dried at 65 ℃ for 48 h, then weighed and ground. Soil samples were taken from the surface (10 cm depth) using a 5-cm diameter soil auger. Five soil cores were collected from each plot and mixed into one composite sample. Each

sample was air-dried and passed through a 2-mm sieve to remove litter and detritus. A subsample of the air-dried soil was ground using a ball mill to pass through a 0.15-mm sieve for further analyses of IP fractions and TP.

2.3. Soil chemical analyses

Soil pH was measured in a 1:5 soil-to-water slurry with a pH meter (S210 SevenCompact™, Mettler, Germany). Soil IP fractions were extracted according to the sequential fractionation scheme proposed by Chang and Jackson (1957) which is modified to suit for calcareous soils (Jiang and Gu, 1989). Briefly, soil Ca_2-P was determined by shaking 0.5 g soil with 25 ml 0.25 M $NaHCO_3$ (pH 7.5), and then centrifuged at 3500 rpm for 8 min to measure soil Ca_2-P. The remaining soil was washed two times with 25 ml 95% C_2H_5OH and extracted with 25 ml 0.5 M NH_4Ac (pH = 4.2) to determine soil Ca_8-P (Jiang and Gu, 1989). After this, the soil was shaken with 25 ml 1 M NH_4Cl and centrifuged at 3500 rpm to discard the supernatant. The remaining soil was then shaken with 25 ml 0.5 M NH_4F (pH 8.2) and centrifuged at 3500 rpm for 8 min to analyze the soil Al-P fraction in the supernatant. The remaining soil was washed two times with 25 ml saturated NaCl, and then sequentially shaken with 25 ml mixture of 0.1 M NaOH and Na_2CO_3 for 2 h at 25 ℃, and then centrifuged at 4500 rpm for 10 min to measure soil Fe-P in the supernatant. The remaining samples were washed as above and extracted with 25 ml mixture of 0.3 M Na_3(citrate)-$Na_2S_2O_4$ and 0.5 M NaOH to measure soil O-P. Finally, the remaining samples were shaken with 0.25 M H_2SO_4 for 1 h at 25 ℃, and centrifuged at 3800 rpm for 10 min to determine soil Ca_{10}-P. The P concentration in all the extractants was determined by the molybdenum blue colorimetric method at wavelength of 700 nm with a UV-VIS spectrometer (UV-1700, Shimadzu) (Murphy and Riley, 1962). Soil total IP (TIP) concentration was defined as the sum of soil labile IP (Ca_2-P),

moderate-cycling IP (Al-P, Fe-P and Ca_8-P) and recalcitrant IP (Ca_{10}-P and O-P). Total

organic P (TOP) was calculated as the difference between TP and TIP concentrations.

The potential limitation of the extraction methods is that they may not be very specific

in separating the different forms of P minerals, as a small amount of other phosphate

dissolved in the extractants (Jiang and Gu, 1989).

Soil TP concentration was determined after digestion with 8 ml 85% HNO_3 +4 ml

72% $HClO_4$ +1 ml 40% HF (Sommers and Nelson, 1972), and Olsen-P was extracted

from air-dried soil with 0.5 M $NaHCO_3$ (pH 8.5) (Olsen et al., 1954). Plant TP

concentration was determined by acid digestion using H_2SO_4-H_2O_2 (Thomas et al.,

1967). Soil TP, Olsen P and plant TP were analyzed by the molybdenum blue

colorimetric method at 700 nm.

2.4. Statistical analyses

Plant P uptake of three dominant species was calculated using the following equation:

$$P\ uptake = \sum_{i}^{n} P_i \times B_i\ ,$$

where P_i is TP concentration of species i, and B_i is the biomass of species i. All the

data were shown as mean $\pm$ standard error. The Kolmogorov-Smirnov test was

performed to determine whether data had a normal distribution. Three-way ANOVAs

were conducted to determine the effects of N addition (N), P addition rate (P_r), P

compounds (P_t) and their interactions on soil IP fractions and Olsen-P concentration.

For each P compound and N treatment, the effect of P addition rates on

moderate-cycling IP fractions and plant P were determined using polynomial contrasts,

the effect of P addition rates on plant biomass, soil pH, soil recalcitrant IP fractions,

Olsen-P and TP were analyzed using Duncan's multiple range tests. Student t-test was

used to determine the difference between two P compounds within each P addition

rate and N treatment (without and with N) and between N treatments within each P

compound and addition rate. For moderate-cycling IP fractions, one-way analysis of covariance (ANCOVA) was employed to distinguish the slopes between the two N treatments (without N $vs.$ with N) for each P compound and between the two P compounds (KH_2PO_4 $vs.$ $Ca(H_2PO_4)_2$) for each N treatment. Pearson correlations were used to test the relationships between soil variables. All the above statistics were carried out using SPSS 16.0 (SPSS Inc., Chicago, USA).

Structural equation models (SEM) were built to clarify direct and indirect N and P addition effects on soil IP fractions through the changes in plant P uptake and soil pH. Chi-square test, Akaike information criteria (AIC) and the root mean square error of approximation (RMSEA) were used to evaluate the fit of the model. The SEM analyses were performed using AMOS 7.0 (Amos Development Co., Greene, Maine, USA). Statistical significance was accepted at $P < 0.05$.

3. Results

3.1. Aboveground plant biomass and soil pH

Nitrogen addition significantly increased aboveground biomass production (Fig. 1a,b). Aboveground biomass production did not show a clear trend in response to different levels of P addition, either as KH_2PO_4 or as $Ca(H_2PO_4)_2$ (Fig. 1a,b). Nitrogen addition significantly increased plant P uptake of the three dominant species *Stipa baicalensis*, *Leymus chinensis* and *Carex duriuscula* for both P compounds (Fig. 1c,d). Plant P uptake increased with increasing P addition rates with significantly higher overall KH_2PO_4 effect than $Ca(H_2PO_4)_2$. KH_2PO_4 addition showed no impact on soil pH (Fig. 1e), while $Ca(H_2PO_4)_2$ decreased soil pH without N addition (Fig. 1f).

3.2. Soil labile and moderate-cycling inorganic phosphorus fractions

For both KH_2PO_4 and $Ca(H_2PO_4)_2$ additions, soil Al-P and Fe-P concentrations

significantly increased with increased P addition rates (Fig. 2a, b, c, d). Soil Al-P and Fe-P concentrations were higher with KH_2PO_4 than with $Ca(H_2PO_4)_2$ addition, especially at higher P rates (Fig. 2; Table S1). This resulted in significant interactive $P_t \times P_r$ effects on soil Al-P and Fe-P concentrations (Table 2). Significant interactive $P_r \times N$ and $P_t \times P_r \times N$ effects were also found on soil Al-P. For instance, Al-P concentration was higher with KH_2PO_4 addition than $Ca(H_2PO_4)_2$ at P addition level of 60 kg P ha^{-1} yr^{-1} when N was not added, but it was higher for P addition levels of 60, 80 and 100 kg P ha^{-1} yr^{-1} when N was added. Nitrogen addition decreased both soil Al-P and Fe-P concentrations, particularly at higher levels of P addition (Fig. 2; Table 2 and S1).

Addition of both P compounds significantly increased soil Ca_2-P and Ca_8-P concentrations with and without N addition (Fig. 3a, b, c, d). With KH_2PO_4 addition, soil Ca_2-P and Ca_8-P concentrations were higher than with $Ca(H_2PO_4)_2$ addition (Fig. 3; Table S1). Nitrogen addition significantly decreased soil Ca_2-P and Ca_8-P concentrations for both P compounds in some P addition levels (Fig. 3; Table S1). Therefore, significant $P_t \times P_r$ interactive effects were detected on soil Ca_2-P and Ca_8-P and $P_r \times N$ interactive effect on soil Ca_2-P (Table 2).

3.3. Soil recalcitrant inorganic phosphorus fractions

$Ca(H_2PO_4)_2$ addition significantly increased soil Ca_{10}-P concentration, while KH_2PO_4 addition showed no impact (Fig. 4a, b). Soil Ca_{10}-P concentration was higher with $Ca(H_2PO_4)_2$ addition than with KH_2PO_4 addition for all levels except for 60 kg P ha^{-1} yr^{-1} without N addition and for 40, 60 and 100 kg P ha^{-1} yr^{-1} with N addition (Fig. 4a, b; Table S2). There was no main N addition and $N \times P_r$ interactive effect on soil Ca_{10}-P for both P compounds (Table 2). Nitrogen addition had also no significant effect on soil O-P with KH_2PO_4 addition but significantly decreased it with $Ca(H_2PO_4)_2$

addition at 60 and 80 kg P ha^{-1} yr^{-1} (Fig. 4c, d). Soil O-P showed a hump-shaped relationship along the P addition gradient with KH_2PO_4 when added with N, and with $Ca(H_2PO_4)_2$ independent of N addition. Soil O-P concentration was lower with $Ca(H_2PO_4)_2$ addition than with KH_2PO_4 addition for 60 and 80 kg P ha^{-1} yr^{-1} with N addition (Fig. 4c, d; Table S2). The relative proportions of soil O-P and Ca_{10}-P to soil TIP decreased while the proportions of soil Al-P, Ca_2-P, and Ca_8-P increased with increasing P addition rates for both P compounds (Fig. S1).

3.4. Soil Olsen-P and total P

For both P compounds, P addition significantly increased soil Olsen-P concentration regardless of N addition (Fig.5a, b). Soil Olsen-P concentration increased more strongly with increased levels of KH_2PO_4 addition than with $Ca(H_2PO_4)_2$ addition, resulting in significantly higher soil Olsen-P with KH_2PO_4 addition in the 100 kg P ha^{-1} yr^{-1} treatment with and without N addition (Fig. 5a, b). KH_2PO_4 addition increased soil TP irrespective of N addition, while $Ca(H_2PO_4)_2$ addition only increased soil TP without N addition (Fig. 5c, d).

3.5. Correlation between soil inorganic fractions with soil characteristics

For both P compounds, soil Al-P, Fe-P, Ca_2-P and Ca_8-P had significantly positive correlations with each other. In addition, soil TP and Olsen-P were all positively correlated with soil Al-P, Fe-P, Ca_2-P, and Ca_8-P ($P < 0.01$) (Table 3). Soil Ca_{10}-P had significantly positive correlations with soil Fe-P and Ca_8-P for both P compounds (Table 3). Soil TOP had significantly positive correlations with soil TP (Table 3). Furthermore, soil TIP concentration was positively correlated with the level of P addition for both P compounds (Fig. S2).

The SEM suggested that P addition had a positive impact on plant P uptake and soil moderate-cycling IP both with KH_2PO_4 (Fig. 6a) and with $Ca(H_2PO_4)_2$ addition

(Fig. 6b). N addition had a positive impact on plant P uptake under both P compounds addition (Fig. 6a ,b). Plant P uptake had a negative impact on soil moderate-cycling IP both with KH_2PO_4 (Fig. 6a) and with $Ca(H_2PO_4)_2$ addition (Fig. 6b), while soil pH also negatively influenced soil labile IP with $Ca(H_2PO_4)_2$. Soil moderate-cycling IP fractions drove the increase in soil labile IP concentration for both P compounds, with a higher contribution for KH_2PO_4 addition (Fig. 6a,b). Soil moderate-cycling IP contributed to the increase of soil TP under both P compounds (Fig. 6a, b).

4. Discussion

4.1. Effect of P additions rates on soil IP fractions

With increasing P addition levels, the increase in soil labile IP and moderate-cycling IP fractions was consistent with our first hypothesis and the findings from previous studies (Wang et al., 2010; Zhao et al., 2019). Soil IP fractions can be affected by nutrient addition, soil type and soil chemical properties (Daly et al., 2001; Stroia et al., 2011). The positive linear correlation of soil TIP concentration and P addition rates (Fig. S2) indicates that applied P was fixed mainly into inorganic forms (Chauhan et al., 1981) and converted to various soil P fractions (Piegholdt et al., 2013). Most of the applied P transformed into soil moderate-cycling IP fractions as seen from the decrease in the relative proportion of soil recalcitrant IP fractions (Fig. S1). Indeed, applied P fertilizer can be quickly bound by P-fixing constituents, *e.g.*, Fe/Al oxides and clay minerals (Devau et al., 2011). In calcareous soils, precipitation is the main process retaining applied P in soils, especially precipitation with Ca at relatively high soil pH (Wang et al., 2010). Likely, the amount of P from input processes (exogenous P and weathering) was higher than the amount from output processes (plant uptake, erosion and leaching losses), which can then cause P accumulation in the soil as

insoluble soil P fractions (Song et al., 2017). Therefore, both the monopotassium phosphate and monocalcium phosphate fertilizers transformed into soil labile IP and moderate-cycling IP fractions and contributed to the increase in soil Al-P, Fe-P, Ca_2-P and Ca_8-P concentrations (Fig. 7).

5   Inconsistent with our first hypothesis, we found significant changes in soil recalcitrant P fractions (Ca_{10}-P and O-P), which accounted for 21%-73% of soil TIP (Fig. S1) and potentially played an important role in supplying soil available P in this meadow steppe (Fig. 7). The significant increase of soil Ca_{10}-P with $Ca(H_2PO_4)_2$ addition was not expected; and it was inconsistent with a previous study from a

10   calcareous soil showing unchanged soil Ca_{10}-P after 21-years of superphosphate application (Wang et al., 2010). In this calcareous soil, $Ca(H_2PO_4)_2$ addition enhanced the transformation of soil Ca_2-P and Ca_8-P into more stable soil Ca_{10}-P fractions for reasons that are not clear. In return, soil Ca_{10}-P can be a potential P sink of soil moderate-cycling IP pools because of its significant correlation with soil Fe-P under

15   both chemical P forms (Table 3). Soil O-P showed a hump-shaped relationship with P addition for both P compounds when N was also supplied, while no relationship was found for KH_2PO_4 without N addition (Fig. 4c, d). This is in contrast to a 21-year long study where increased levels of $Ca(H_2PO_4)_2$ significantly increased soil O-P (Wang et al., 2010). The discrepancy might be due to 1) differences in soil type affecting soil P

20   dynamics differently (a Calcarid Regosol in the Wang et al. (2010) study and a Chernozem in this study); 2) different P compounds having different effects on soil O-P cycling; 3) N addition interacting with P to affect plant P uptake and soil O-P transformations (Marklein and Houlton, 2012; Zhang et al., 2004). Thus, P addition effects on soil O-P and other soil recalcitrant P fractions were complex, particularly

25   when N was also added.

The significant increase in soil Olsen-P with P addition levels was consistent with previous studies (Karaca et al., 2002; Zhou et al., 2018). Significant increase in soil Olsen-P most likely was a consequence of inputs of P going into this pool surpassing output processes of mineral fixation, leaching and plant uptake. Dissolution of exogenous P compounds could be the primary input process, which then directly contributed to the increase in soil Olsen-P concentration. Moreover, the soil IP pools, especially soil Fe-P, Al-P, Ca_2-P and Ca_8-P, can also be an important source of bioavailable P (Zhang et al., 2012). Significantly positive correlations between soil moderate-cycling IP fractions and soil labile IP (Table 3; Fig. 6) suggest that soil moderate-cycling IP fractions contributed strongly to enhance soil P availability (Fig. 7). Indeed, soil moderate-cycling IP fractions could release soil available P more easily than recalcitrant IP fractions (Zhang et al., 2012).

4.2. Effects of compound-specific P additions

Consistent with our second hypothesis, soil labile IP and moderate-cycling IP fractions of Al-P, Fe-P, and Ca_8-P tended to be higher with soluble KH_2PO_4 addition than with less-soluble $Ca(H_2PO_4)_2$ addition with significant increases in some P addition levels (Fig. 2 & Fig. 3). Compared to $Ca(H_2PO_4)_2$, KH_2PO_4 is more effective in elevating soil phosphate levels to form soil labile IP and moderate-cycling IP fractions by rapidly interacting with Fe- and Al-oxides and $CaCO_3$ (Havlin et al., 2005). The decrease in soil pH contributed to the increase in labile IP with $Ca(H_2PO_4)_2$ addition (Fig. 6b). Lower soil pH could accelerate soil recalcitrant IP fractions converting into soil labile IP, moderate-cycling IP and Olsen P (Alt et al., 2013). Under the $Ca(H_2PO_4)_2$ treatment, significant negative relationships of soil O-P and Olsen P further support this argument (Table 3). On the other hand, plant P uptake instead of soil pH was more responsible for variations in soil moderate-cycling IP

fractions with KH_2PO_4 addition (Fig. 6a). Under both P compounds, soil moderate-cycling IP fractions contributed to the increase of soil labile IP across N treatments (Fig. 6), which suggested that higher plant growth and P demand (Fig. 1c,d) could enhance the conversion of soil moderate-cycling IP fraction into labile/available

5   P.

In contrast to our expectation, soil recalcitrant IP fractions of O-P and Ca_{10}-P were higher with $Ca(H_2PO_4)_2$ than with KH_2PO_4 addition (Fig. 4 & Fig. 7). This suggests that a higher proportion of $Ca(H_2PO_4)_2$ was converted into stable inorganic P forms than the more soluble KH_2PO_4. Additionally, lower soil O-P and Ca_{10}-P

10   concentrations could be caused by enhanced plant P uptake intensity under KH_2PO_4 addition which facilitated more soil recalcitrant IP fractions transforming into moderate-cycling IP and labile IP. Thus, $Ca(H_2PO_4)_2$ appears to be better than the KH_2PO_4 in maintaining soil recalcitrant IP fractions in the soil. Although soil recalcitrant IP fractions (O-P and Ca_{10}-P) are relatively stable, they play essential roles

15   in buffering the depletion of soil moderate-cycling P and maintaining soil available P levels (Seeling and Jungk, 1996; Vu et al., 2008).

As expected, more soluble KH_2PO_4 could result in higher labile IP (Fig. 7) in soil solution through dissolution. It is generally observed that this more soluble P fertilizer type dissolves in soil water at a shorter time and generates more free PO_4^{3-} (Chien et

20   al., 2011). Soil moderate-cycling IP fractions also contributed to elevated soil Olsen-P concentrations with stronger correlations under KH_2PO_4 addition (Table 3). Soil moderate-cycling IP factions showed a stronger direct and positive effect on soil labile IP with KH_2PO_4 addition than $Ca(H_2PO_4)_2$ addition, while plant P uptake showed both indirect negative (by negatively affecting soil moderate-cycling IP) and direct

25   negative effects on labile IP with $Ca(H_2PO_4)_2$ addition (Fig. 6). Based on the

correlation analyses between soil IP fractions and Olsen-P, we found that soil Ca_2-P and Al-P were the dominant soil IP fractions to improve soil P availability in the calcareous soil. Our results suggest that KH_2PO_4 was better than $Ca(H_2PO_4)_2$ in alleviating P limitations of soil microorganisms and plants by promoting the formation of soil labile IP and moderate-cycling IP fractions in the semi-arid steppe.

4.3. Nitrogen addition regulated P effects on soil inorganic P fractions

We predicted that the concentrations of soil IP fractions would be lower under combined P and N additions than under P addition alone because of increased plant P uptake with N addition (third hypothesis). We found some support for this, where combined P and N additions decreased most soil IP fractions compared to P addition alone, except for the soil Ca_{10}-P fraction. We also found a significant increase in plant biomass with combined P and N addition (Fig. 1a,b) and a negative correlation between plant P uptake and moderate-cycling IP fractions (Fig. 6a,b). Therefore, the decrease in soil moderate-cycling IP fractions with N addition could have been due to enhanced plant P uptake (Fig. 1c,d) as a result of increased plant biomass (Fig. 1a,b & Fig. 7). Under N addition, simultaneous increases in soil Olsen-P output (plant uptake) and input pathways (transformation from soil moderate-cycling IP fractions) may have resulted in mostly non-significant difference in soil Olsen-P concentrations between combined P and N addition and P addition alone (Fig. 5a, b). Nitrogen addition can potentially increase soil P availability by promoting solubilization of soil IP fractions in the short-term (Wang et al., 2016). However, long-term N deposition resulted in soil IP-exhaustion, thereby constraining the growth of plants (Olander and Vitousek, 2000; Yang et al., 2014). Previous research has also found that decades of N addition could accelerate PO_4^{3-} release (Malik et al., 2012; Stroia et al., 2011) and enhance conversion of soil recalcitrant IP fractions to soil labile IP and

moderate-cycling IP fractions as a result of soil acidification (Alt et al., 2013). Additionally, N addition was found to suppress acid and alkaline phosphatase enzymes resulting in the decrease of soil organic P mineralization in a similar semi-arid grassland (Tian et al. 2016). Therefore, combined N and P addition might decrease soil IP fractions by reducing the conversion of soil organic P to IP as compared to P addition alone. Our results clearly illustrate that N effects on soil IP fractions depended on P inputs, where combined N and P additions could accelerate conversion of soil moderate-cycling IP fractions into soil available P and enhance plant P uptake and biomass (Fig. 7).

5. Conclusions

Addition of P compounds significantly increased soil moderate-cycling IP fractions of Al-P, Fe-P, Ca_2-P and Ca_8-P, which may have contributed to higher available P (Olsen P) in the soil. Soil moderate-cycling IP fractions were higher with soluble KH_2PO_4 addition, but in contrast, soil recalcitrant fractions of Ca_{10}-P and O-P were higher with $Ca(H_2PO_4)_2$ addition. Combined N and P addition decreased soil IP fractions due to enhanced plant P uptake compared to P addition alone for both P compounds. Thus, N addition promoted the transformation of soil moderate and recalcitrant IP fractions into available forms. Soil moderate-cycling IP fractions had a greater contribution to soil P availability than soil recalcitrant P fractions. Our findings elucidated the interactive effects of N and P addition on soil IP dynamics and presented the first evidence for the relative roles of exogenous P compounds in regulating P availability in the meadow steppe grassland. Overall, P fertilization is necessary for promoting productivity and sustainable management of grasslands by maintaining soil P availability and pools under scenarios of ecosystem N enrichment.

Acknowledgments

We acknowledge Erguna Forest-Steppe Ecotone Ecosystem Research Station, Institute of Applied Ecology, Chinese Academy of Sciences for logistical support. The

5 study was financially supported by the National Natural Science Foundation of China (31770525 and 31870441), the National Key Research and Development Program of China (2016YFC0500707) and the Youth Innovation Promotion Association CAS (Y9QCH121YY).

10 **References**

Al-Khateeb, I.K., Raihan, M.J., and Asker, S.R.: Phase equilibrium and kinetics of orthophosphate in some Iraqi soils, Soil Sci., 141, 31-37, https://doi.org/10.1097/00010694-198601000-00006, 1986.

Alt, F., Oelmann, Y., Schöning, I., and Wilcke, W.: Phosphate release kinetics in

15 calcareous grassland and forest soils in response to H^+ addition, Soil Sci. Soc. Am. J., 77, 2060-2070, https://doi.org/10.2136/sssaj2013.02.0072, 2013.

Baumann, K., Glaser, K., Mutz, J., Karsten, U., MacLennan, A., Hu, Y.F., Michalik, D., Kruse, J., Eckhardt, K.U., Schall, P., and Leinweber, P.: Biological soil crusts of temperate forests: Their role in P cycling, Soil Biol. Biochem., 109, 156-166,

20 https://doi.org/10.1016/j.soilbio.2017.02.011, 2017.

Thomas, R.L., Sheard, R.W., and Moyer, J.R.: Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion, Agron. J., 59, 240-243, https://doi.org/10.2134/agronj1967.00021962005900030010x, 1967.

25 Cao, N., Chen, X., Cui, Z., Zhang, F.: Change in soil available phosphorus in relation

to the phosphorus budget in China, Nutr. Cycl. Agroecosyst, 94: 161-170,

10.1007/s10705-012-9530-0, 2012.

Chang, S.C., and Jackson, M.L.: Soil phosphorus fractions in some representative

soils, Eur. J. Soil Sci., 84, 133-144.

https://doi.org/10.1111/j.1365-2389.1958.tb01903.x, 1958.

Chen, C.L.M., Condron, M.R., and Davis, S.R.R.: Phosphorus dynamics in the

rhizosphere of perennial ryegrass (*Lolium perenne L.*) and radiata pine (*Pinus radiata D. Don.*), Soil Biol. Biochem., 34, 487-499,

https://doi.org/10.1016/S0038-0717(01)00207-3, 2002.

Chauhan, B.S., Stewart, J.W.B., and Paul, E.A.: Effect of labile inorganic phosphorus

status and organic carbon additions on the microbial uptake of phosphorus in

soils, Can. J. Soil Sci., 61, 373-385, https://doi.org/10.4141/cjss81-041, 1981.

Chien, S.H., Prochnow, L.I., Tu, S., and Snyder, C.S.: Agronomic and environmental

aspects of phosphate fertilizers varying in source and solubility: an update review,

Nutr. Cycl. Agroecosyst., 89, 229-255.

https://doi.org/10.1007/s10705-010-9390-4, 2011.

Condron, L.M., and Goh, K.M.: Effects of long-term phosphatic fertilizer applications

on amounts and forms of phosphorus in soils under irrigated pasture in New

Zealand, J. Soil Sci., 40, 383-395,

https://doi.org/10.1111/j.1365-2389.1989.tb01282.x, 1989.

Crowley, K.F., Mcneil, B.E., Lovett, G.M., Canham, C.D., Driscoll, C.T., Rustad, L.E.,

Denny, E., Hallett, R.A., Arthur, M.A., Boggs, J.L., Goodale, C.L., Kahl, J.S.,

McNulty, S.G., Olliinger, S.V., Pardo, L.H., Schaberg, P.G., Stoddard, J.L.,

Weand, M.P., and Weathers, K.C.: Do nutrient limitation patterns shift from

nitrogen toward phosphorus with increasing nitrogen deposition across the

Northeastern United States? Ecosystems, 15, 940-957,

https://doi.org/10.1007/s10021-012-9550-2, 2012.

Daly, K., Jeffrey, D., and Tunney, H.: The effect of soil type on phosphorus sorption

capacity and desorption dynamiacs in Irish grassland soils, Soil Use Manag., 17,

12-20, https://doi.org/10.1111/j.1475-2743.2001.tb00003.x, 2001.

Devau,N., Hinsinger, P., Le Cadre, E., and Gérard, F.: Root-induced processes

controlling phosphate availability in soils with contrasted P-fertilized treatments,

Plant Soil, 348, 203-218, https://doi.org/10.1007/s11104-011-0935-3, 2011.

Gong, X., Chen, Q., Dittert, K., Taube, F., and Lin, S.: Nitrogen, phosphorus and

potassium nutritional status of semiarid steppe grassland in Inner Mongolia,

Plant Soil, 340, 265-278, https://doi.org/10.1007/s11104-010-0577-x, 2011.

Feng, J., Turner, B. L., Lü, X., Chen, Z., Wei, K., Tian, J., Wang, C., Luo, W., and

Chen, L.: Phosphorus transformations along a large-scale climosequence in arid

and semiarid grasslands of northern China, Global Biogeochem. Cy., 30,

1264-1275, https://doi.org/10.1002/2015GB005331, 2016.

Gustafsson, J. P., Mwamila, L. B., and Kergoat, K.: The pH dependence of phosphate

sorption and desorption in Swedish agricultural soils, Geoderma, 189, 304-311,

https://doi.org/10.1016/j.geoderma.2012.05.014, 2012.

Güsewell, S.: N : P ratios in terrestrial plants: variation and functional significance,

New Phytol., 164, 243-266, https://doi.org/10.1111/j.1469-8137.2004.01192.x,

2004.

Havlin, J.L., Beaton, J.D., Tisdale, S.L., and Nelson, W.L.: Soil Fertility and

Fertilizers: An Introduction to Nutrient Management, seven ed. Prentice Hall,

New Jersey, 2005.

Herlihy, M., and Mcgrath, D.: Phosphorus fractions and adsorption characteristics in

grassland soils of varied soil phosphorus status, Nutr. Cycl. Agroecosyst., 77, 15-27, https://doi.org/10.1007/s10705-006-6687-4, 2006.

Hinsinger, P.: Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review, Plant Soil, 237, 173-195, https://doi.org/10.1023/A:1013351617532, 2001.

Hogan, E.J., Minnullina, G., Sheppard, L.J., Leith, I.D., and Crittenden, P.D.: Response of phosphomonoesterase activity in the lichen Cladonia portentosa to nitrogen and phosphorus enrichment in a field manipulation experiment, New Phytol., 186, 926-933, https://doi.org/10.1111/j.1469-8137.2010.03221.x, 2010.

Jiang, B., and Gu, Y.: A suggested fractionation scheme of inorganic phosphorus in calcareous soils, Fert. Res., 20, 159-165, https://doi.org/10.1007/BF01054551, 1989.

IUSS Working Group WRB: World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106, FAO, Rome, 2014.

Kang, L., Han, X., Zhang, Z., and Sun, O.J.: Grassland ecosystems in China: review of current knowledge and research advancement, Phil. Trans. R. Soc. B., 362, 997-1008, https://doi.org/10.1098/rstb.2007.2029, 2007.

Karaca, A., Naseby, D., and Lynch, J.: Effect of cadmium contamination with sewage sludge and phosphate fertiliser amendments on soil enzyme activities, microbial structure and available cadmium, Biol. Fertil. Soils, 35, 428-434, https://doi.org/10.1007/s00374-002-0490-4, 2002.

Luo, W., Elser, J.J., Lü, X., Wang, Z., Bai, E., Yan, C., Wang, C., Li, M., Zimmermann, N.E., Han, X., Li, H., Wu, Y., and Jiang, Y.: Plant nutrients do not covary with soil nutrients under changing climatic conditions, Global Biogeochem. Cy., 29,

1298-1308, https://doi.org/10.1002/2015GB005089, 2015.

Maistry, P.M., Muasya, A.M., Valentine, A.J., and Chimphango, S.B.M.: Increasing nitrogen supply stimulates phosphorus acquisition mechanisms in the fynbos species Aspalathus linearis, Funct. Plant Biol., 42, 52-62, https://doi.org/10.1071/FP14100, 2015.

Malik, M.A., Marschner, P., and Khan, K.S.: Addition of organic and inorganic P sources to soil – Effects on P pools and microorganisms, Soil Biol. Biochem., 49, 106-113, https://doi.org/10.1016/j.soilbio.2012.02.013, 2012.

Margenot, A.J., Sommer, R., Mukalama, J., and Parikh, S.J.: Biological P cycling is influenced by the form of P fertilizer in an Oxisol, Biol. Fertil. Soils, 53, 899-909, https://doi.org/10.1007/s00374-017-1226-9, 2017.

Marklein, A.R., Houlton, B.Z.: Nitrogen inputs accelerate phosphorus cycling rates across a wide variety of terrestrial ecosystems, New Phytol., 193, 696-704, https://doi.org/10.1111/j.1469-8137.2011.03967.x, 2012.

Meena, M.D., Narjary, B., Sheoran, P. Jat, H.S., Joshi, P.K., Chinchmalatpure, A.R., Yadav, G.M., Yadav, R.K., and Meena, M. K.: Changes of phosphorus fractions in saline soil amended with municipal solid waste compost and mineral fertilizers in a mustard-pearl millet cropping system, Catena, 160, 32-40, https://doi.org/10.1016/j.catena.2017.09.002, 2018.

Mortvedt, J.J., Follett, R.H.C., and Murphy, L.S.C.: Fertilizer technology and application. Meister Publishing Company, Willoughby, OH. 1999.

Nguyen, M.L., Rickard, S.D., Mcbride, and S.D.: Pasture production and changes in phosphorus and sulphur status in irrigated pastures receiving long-term applications of superphosphate fertilizer, New Zeal. J. Agr. Res., 32, 245-262, https://doi.org/10.1080/00288233.1989.10423460, 2012.

Olander, L.P., and Vitousek, P.M.: Regulation of soil phosphatase and chitinase activity by N and P availability, Biogeochemistry, 49, 175-190, https://doi.org/10.1023/A:1006316117817, 2000.

Olsen, S.R., Cole, C.V., Watanabe, F.S., and Dean, L.A.: Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA circular 939. U.S. Govt. Printing Office, Washington, DC. 1954.

Piegholdt, C., Geisseler, D., Koch, H., and Ludwig, B.: Long-term tillage effects on the distribution of phosphorus fractions of loess soils in Germany, J. Plant Nutr. Soil Sci., 176, 217-226, https://doi.org/10.1002/jpln.201200393, 2013.

Ross, D.J., Speir, T.W., and Kettle, H.A.: Soil: microbial biomass, C and N mineralization and enzyme activities in a hill pasture: influence of season and slow-release P and S fertilizer, Soil Biol. Biochem., 27, 1431-1443, https://doi.org/10.1016/0038-0717(95)00069-Q, 1995.

Sah, R.N., Mikkelsen, D.S., and Hafez, A.A.: Phosphorus behavior in flooded-drained soils. II. Iron transformation and phosphorus sorption, Soil Sci. Soc. Am. J., 53, 1723-1729, https://doi.org/10.2136/sssaj1989.03615995005300060019x, 1989.

Seeling, B., and Jungk, A.: Utilization of organic phosphorus in calcium chloride extracts of soil by barley plants and hydrolysis by acid and alkaline phosphatases, Plant Soil, 178, 179-184, https://doi.org/10.1007/BF00011581, 1996.

Schrijver, A.D., Vesterdal, L., Hansen, K., Frenne, P.D., Augusto, L., Achat, D.L., Staelens, J., Baeten, L., Keermaeker, L.D., Neve, S.D., and Verheyen, K.: Four decades of post-agricultural forest development have caused major redistributions of soil phosphorus fractions, Oecologia, 169, 221-234, https://doi.org/10.1007/s00442-011-2185-8, 2012.

Shen, J., Li, R., Zhang, F., Fan, J., Tang, C., and Rengel, Z.: Crop yields, soil fertility

and phosphorus fractions in response to long-term fertilization under the rice

monoculture system on a calcareous soil, Field Crops Res., 86, 225-238,

https://doi.org/10.1016/j.fcr.2003.08.013,   2004.

Shuman, L. M.: Effect of phosphorus level on extractable micronutrients and their

distribution among soil fractions, Soil Sci. Soc. Am. J., 52, 136-141,

https://doi.org/10.2136/sssaj1988.03615995005200010024x, 1988.

Sigua, G.C., Stone, K.C., Bauer, P.J., and Szogi, A.A.: Phosphorus dynamics and

phosphatase activity of soils under corn production with supplemental irrigation

in humid coastal plain region, USA, Nutr. Cycl. Agroecosyst., 109, 249-267,

https://doi.org/10.1007/s10705-017-9882-6, 2017.

Sommers, L.E., and Nelson, D.W.: Determination of total phosphorus in soils: a rapid

perchloric acid digestion procedure, Soil Sci. Soc. Am. J., 36, 902-904,

https://doi.org/10.2136/sssaj1972.03615995003600060020x, 1972.

Song, K., Xue, Y., Zheng, X., Lv, W., Qiao, H., Qin, Q., and Yang, J.: Effects of the

continuous use of organic manure and chemical fertilizer on soil inorganic

phosphorus fractions in calcareous soil, Sci. Rep., 7, 1164,

https://doi.org/10.1038/s41598-017-01232-2, 2017.

Stroia, C., Morel, C., and Jouany, C.: Nitrogen fertilization effects on grassland soil

acidification: consequences on diffusive phosphorus ions, Soil Sci. Soc. Am. J.,

75, 112-120, https://doi.org/10.2136/sssaj2009.0135, 2011.

Sun, X., Shen, Y., Schuster, M.J., Searle, E.B., Chen, J., Yang, G., and Zhang, Y.:

Initial responses of grass litter tissue chemistry and N:P stoichiometry to varied

N and P input rates and ratios in Inner Mongolia, Agr. Ecosyst. Environ., 252,

114-125, https://doi.org/10.1016/j.agee.2017.10.007, 2018.

Tang, X., Ma, Y., Hao, X., Li, X., Li, J., Huang, S., Yang, X.: Determining critical

values of soil Olsen-P for maize and winter wheat from long-term experiments in China, Plant Soil, 323:143-151, 10.1007/s11104-009-9919-y, 2009.Tian, J., Wei, K., Condron, L.M., Chen, Z., Xu, Z., and Chen, L.: Impact of land use and nutrient addition on phosphatase activitites and their relationships with organic

5   phosphorus turnover in semi-arid grassland soils, Biol. Fertil. Soils, 52, 675-683, https://doi.org/10.1007/s00374-016-1110-z, 2016.

Vitousek, P.M., Porder, S., Houlton, B.Z., and Chadwick, O. A.: Terrestrial phosphorus limitation: mechanism, implications, and nitrogen-phosphorus interactions, Ecol. Appl., 20, 5-15, https://doi.org/10.1890/08-0127.1, 2010.

10   Vu, D.T., Tang, C., and Armstrong, R.D.: Changes and availability of P fractions following 65 years of P application to a calcareous soil in a Mediterranean climate, Plant Soil, 304, 21-33, https://doi.org/10.1007/s11104-007-9516-x, 2008.

Walker, T.W., and Syers, J.K.: The fate of phosphorus during pedogenesis, Geoderma,

15   15, 1-19, https://doi.org/10.1016/0016-7061(76)90066-5, 1976.

Wang, J., Liu, W., Mu, H., and Dang, T.: Inorganic phosphorus fractions and phosphorus availability in a calcareous soil receiving 21-year superphosphate application, Pedosphere, 20, 304-310, https://doi.org/10.1016/S1002-0160(10)60018-5, 2010.

20   Wang, R., Creamer, C.A., Wang, X., He, P., Xu, Z., and Jiang, Y.: The effects of a 9-year nitrogen and water addition on soil aggregate phosphorus and sulfur availability in a semi-arid grassland, Ecol. Indic., 61, 806-814, https://doi.org/10.1016/j.ecolind.2015.10.033, 2016.

Xiong, L., Wang, P., and Kopittke, P.M.: Tailoring hydroxyapatite nanoparticles to

25   increase their efficiency as phosphorus fertilisers in soils, Geoderma, 323,

116-125, https://doi.org/10.1016/j.geoderma.2018.03.002, 2018.

Yang, K., Zhu, J., Gu, J., Yu, L., and Wang, Z.: Changes in soil phosphorus fractions after 9 years of continuous nitrogen addition in a *Larix gmelinii* plantation, Ann. Forest Sci., 72, 435-442, https://doi.org/10.1007/s13595-014-0444-7, 2014.

5 Zhang, B., Fang, F., Guo, J., Chen, Y., Li, Z., and Guo, S.: Phosphorus fractions and phosphate sorption-release characteristics relevant to the soil composition of water-level-fluctuating zone of Three Gorges Reservoir, Ecol. Eng., 40, 153-159, https://doi.org/10.1016/j.ecoleng.2011.12.024, 2012.

Zhang, T., Mackenzie, A.F., Liang, B., and Drury, C.F.: Soil test phosphorus and

10 phosphorus fractions with long-term phosphorus addition and depletion, Soil Sci. Soc. Am. J., 68, 519-528, https://doi.org/10.2136/sssaj2004.5190, 2004.

Zhao, F., Zhang, Y., Dijkstra, F. A., Li, Z., Zhang, Y., Zhang, T., Lu, Y., Shi, J., and Yang, L.: Effect of amendments on phosphorous atatus in soils with different phosphorous levels, Catena, 172, 97-103,

15 https://doi.org/10.1016/j.catena.2018.08.016, 2019.

Zhou, K., Sui, Y., Xu, X., Zhang, J., Chen, Y., Hou, M., and Jiao, X.: The effects of biochar addition on phosphorus transfer and water utilization efficiency in a vegetable field in Northeast China, Agr. Water Manag., 210, 324-329, https://doi.org/10.1016/j.agwat.2018.08.007, 2018.

Tables

Table 1 General characteristics of the soil from the experimental site before nitrogen and phosphorus manipulation. Selected parameters include sand, silt and clay fractions, soil pH, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total inorganic phosphorus (TIP), organic P, exchangeable Ca and Al, and available Fe and Mn. Data are means $\pm$ SE (n = 5).

Sand (%)	Silt (%)	Clay (%)	Soil pH	SOM (g kg^{-1})	TN (g kg^{-1})	TP (mg kg^{-1})	TIP (mg kg^{-1})	Organic P (mg kg^{-1})	Ca (cmol kg^{-1})	Al (cmol kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})
36.75 ± 0.93	39.61 ± 0.96	23.64 ± 0.78	6.68 ± 0.06	43.89 ± 1.14	1.83 ± 0.06	508.23 ± 21.30	105.05 ± 2.87	403.17 ± 22.95	13.41 ± 0.43	0.05 ± 0.01	36.76 ± 1.77	30.70 ± 0.93

Table 2 Results (F values) of three-way ANOVAs on the effect of phosphorus (P) fertilizer type (P_t), P addition rate (P_r), nitrogen (N) addition and their interactions on soil inorganic phosphorus fractions of variscite (Al-P), strengite (Fe-P), dicalcium phosphate (Ca_2-P), octacalcium phosphate (Ca_8-P), hydroxylapatite (Ca_{10}-P), occluded phosphate (O-P), Olsen-P, total inorganic phosphorus(TIP), soil total P (TP) with KH_2PO_4 and $Ca(H_2PO_4)_2$ addition.

	Al-P	Fe-P	Ca_2-P	Ca_8-P	Ca_{10}-P	O-P	Olsen-P	TIP	TP
P_t	32.4^{**}	76.7^{**}	59.9^{**}	101^{**}	98.1^{**}	0.60	21.5^{**}	60.4^{**}	2.90
P_r	268^{**}	97.3^{**}	73.8^{**}	62.6^{**}	6.30^{**}	3.88^{*}	25.0^{**}	192^{**}	7.70^{**}
N	37.1^{**}	18.2^{**}	11.1^{**}	21.9^{**}	5.20^{*}	0.00	1.90	36.8^{**}	3.80
$P_t \times P_r$	7.90^{**}	3.40^{*}	11.6^{**}	8.40^{**}	1.00	3.21^{*}	5.90^{**}	13.6^{**}	0.90
$P_t \times N$	0.40	0.10	5.30	6.20	0.10	19.7^{**}	1.80	0.00	6.00^{*}
$P_r \times N$	6.30^{**}	2.10	2.70^{*}	2.20	0.60	0.70	2.00	4.90^{**}	0.80
$P_t \times P_r \times N$	4.20^{**}	2.60^{*}	0.90	4.00^{**}	0.40	2.81^{*}	1.30	3.40^{**}	3.90^{**}

*, ** Significance level at 0.05 and 0.01, respectively

Table 3 Correlation analyses (R values) among soil inorganic fractions, Olsen-P, total phosphorus (TP) and organic P (TOP) with $Ca(H_2PO_4)_2$ and KH_2PO_4 addition in the meadow steppe.

		Fe-P	Ca$_2$-P	Ca$_8$-P	Ca$_{10}$-P	O-P	Olsen-P	TP	TOP
KH_2PO_4	Al-P	0.92**	0.93**	0.87**	0.25	0.15	0.70**	0.44**	-0.26*
addition	Fe-P		0.95**	0.86**	0.27*	0.19	0.59**	0.41**	-0.28*
	Ca$_2$-P			0.92**	0.23	0.12	0.63**	0.41**	-0.28*
	Ca$_8$-P				0.29*	0.10	0.57**	0.37**	-0.29*
	Ca$_{10}$-P					0.00	0.17	0.06	-0.17
	O-P						0.07	0.15	0.01
	Olsen-P							0.52**	0.04
	TP								0.74**
$Ca(H_2PO_4)_2$	Al-P	0.91**	0.92**	0.80**	0.47*	-0.04	0.48**	0.29*	-0.08
addition	Fe-P		0.94**	0.87**	0.49*	-0.03	0.46**	0.31*	0.01
	Ca$_2$-P			0.84**	0.42	-0.03	0.53**	0.32*	-0.06
	Ca$_8$-P				0.50*	0.05	0.34**	0.26**	0.02
	Ca$_{10}$-P					0.26*	0.11	0.17	-0.12
	O-P						-0.29*	-0.03	-0.03
	Olsen-P							0.34*	0.14
	TP								0.88**

*, ** Significance level at 0.05 and 0.01, respectively
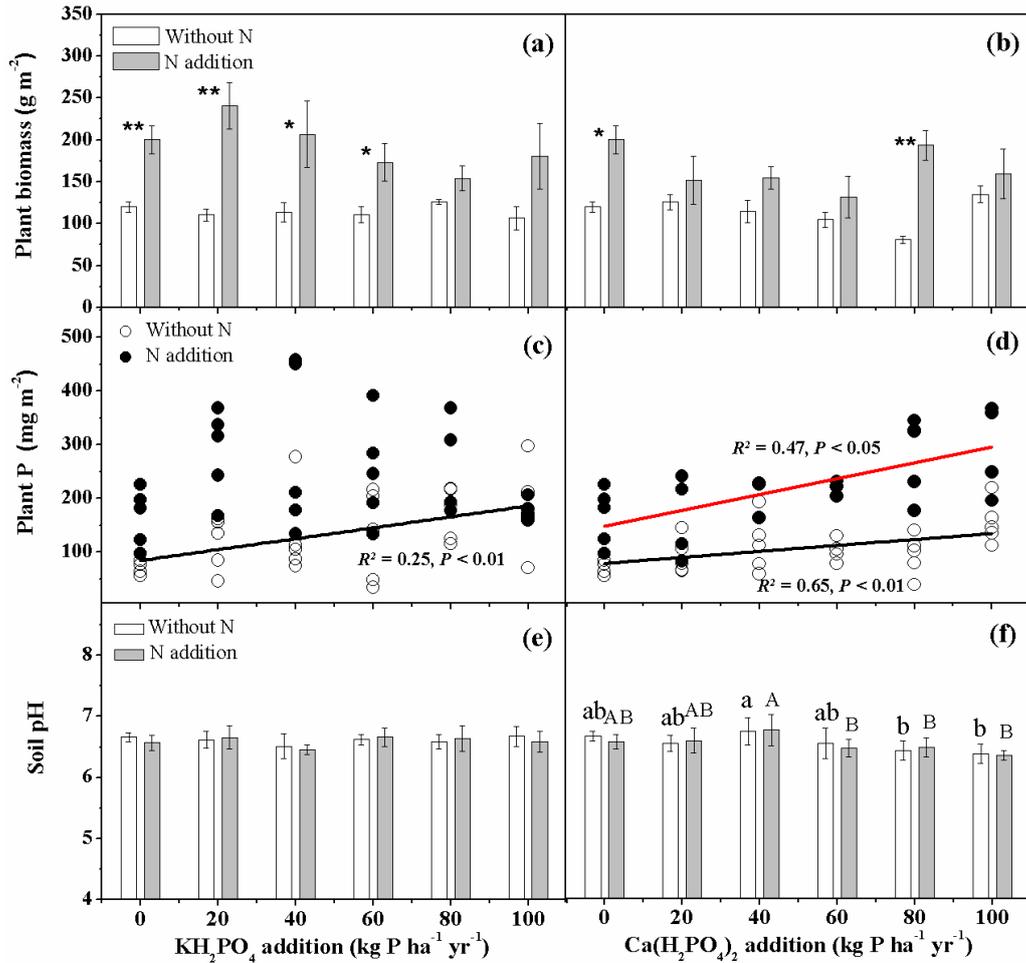
Fig. 1 Aboveground plant biomass (a, b), biomass-weighted phosphorus (P) uptake of three dominant plant species (c, d) and soil pH (e, f) as affected by KH_2PO_4 and $Ca(H_2PO_4)_2$ additions with and without N inputs. Data are represented as means $\pm$ SE for panels a, b, e and f. Letters indicate significant differences between P rates of KH_2PO_4 or $Ca(H_2PO_4)_2$ addition without N (lowercase letters) and with N addition (capital letters). Asterisks represent significance between N treatments within each P type and rate (* and ** for $P < 0.05$ and 0.01, respectively).
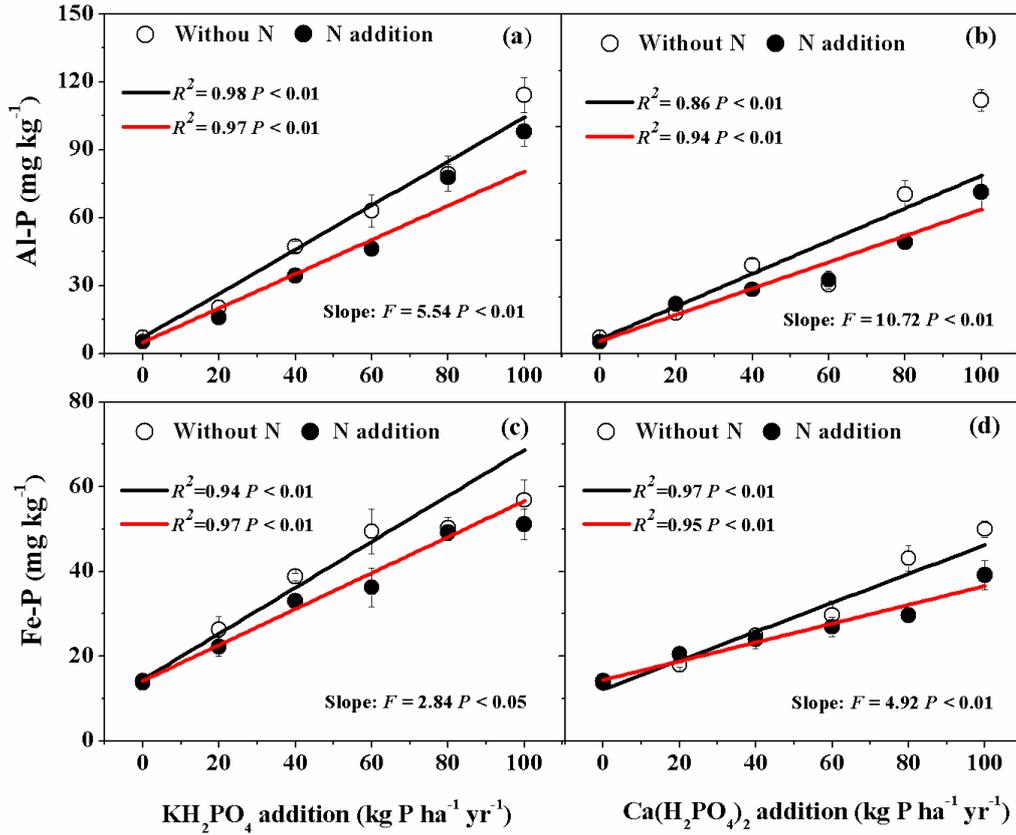
Fig. 2 Effects of phosphorus (P) and nitrogen (N) additions on soil variscite (Al-P) and strengite (Fe-P). Data are represented as means ± standard error. Phosphorus types include KH_2PO_4 and $Ca(H_2PO_4)_2$ at rates of 0, 20, 40, 60, 80 and 100 kg P ha^{-1} yr^{-1}. Fitted lines are based on linear regression models. The black and red line represent without N and N addition, respectively. Significance was labeled for slopes of the black and red lines.
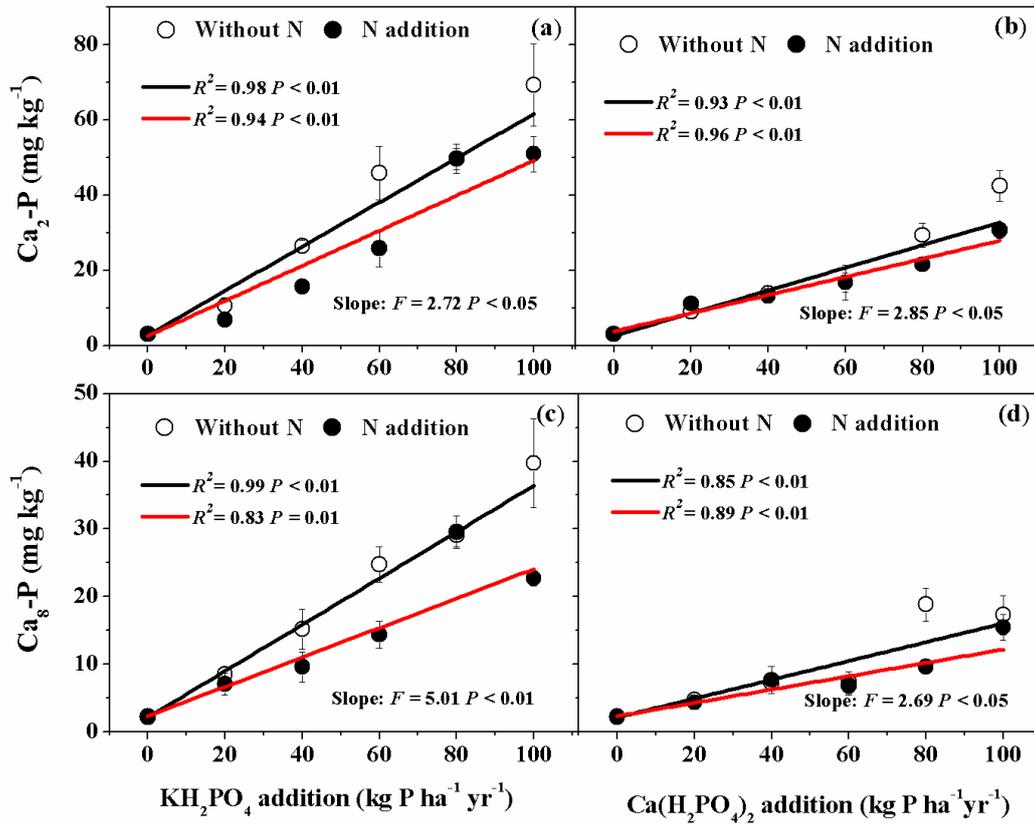
Fig. 3 Effects of phosphorus (P) and nitrogen (N) additions on soil dicalcium phosphate (Ca_2-P) and octacalcium phosphate (Ca_8-P). Phosphorus types include KH_2PO_4 and $Ca(H_2PO_4)_2$ at rates of 0, 20, 40, 60, 80 and 100 kg P ha^{-1} yr^{-1}. Data are represented as means ± standard error. Fitted lines are based onlinear regression models.The black and red line represent without N and N addition, respectively. Significance was labled for slopes of the black and red lines.

Fig. 4 Effects of phosphorus (P) and nitrogen (N) additions on soil hydroxylapatite (Ca_{10}-P) and occluded P (O-P). Phosphorus types include KH_2PO_4 and $Ca(H_2PO_4)_2$ at rates of 0, 20, 40, 60, 80 and 100 kg P ha^{-1} yr^{-1}. Data are represented as means ± standard error. Letters indicate significant differences between P rates of KH_2PO_4 or $Ca(H_2PO_4)_2$ addition without N (lowercase letters) and with N addition (capital letters). Asterisks represent significance between N treatments within each P type and rate (* and ** for $P < 0.05$ and 0.01, respectively).
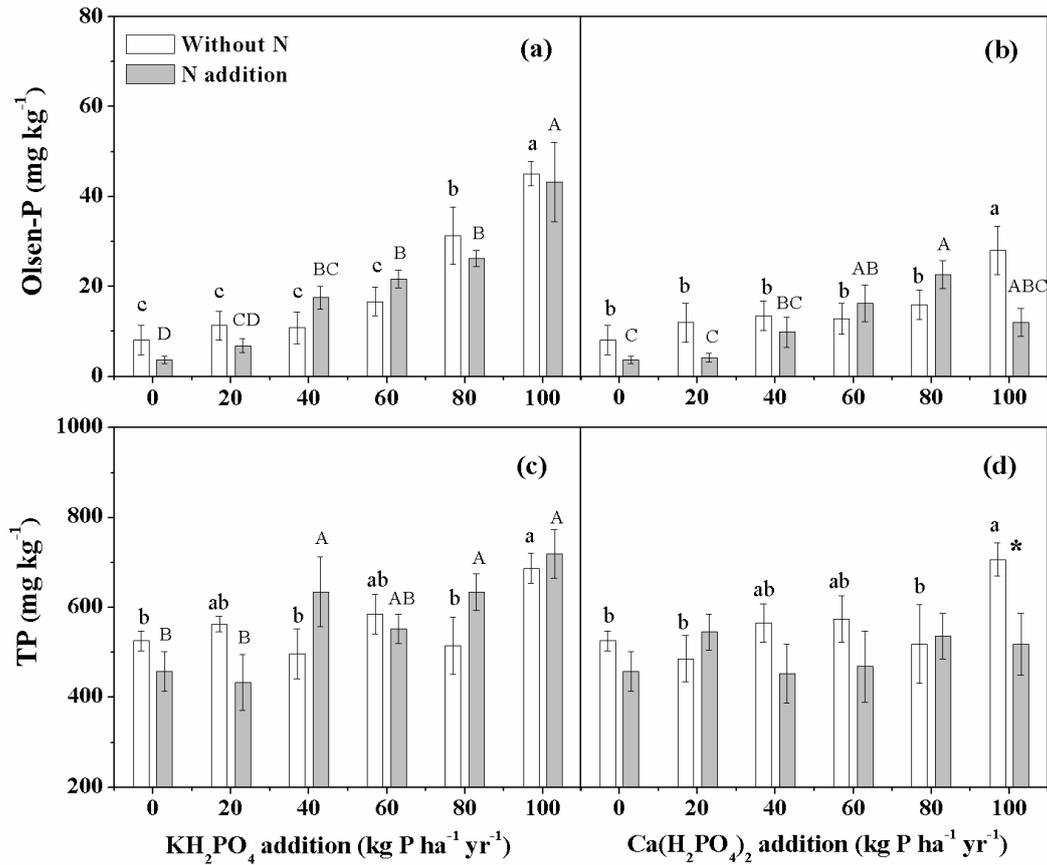
Fig. 5 Effects of phosphorus (P) and nitrogen (N) additions on soil Olsen-P and total P (TP) in the meadow steppe. Phosphorus types include KH_2PO_4 and $Ca(H_2PO_4)_2$ at rates of 0, 20, 40, 60, 80 and 100 kg P ha^{-1} yr^{-1}. Data are represented as means $\pm$ standard error. Letters indicate significant differences between P rates of KH_2PO_4 or $Ca(H_2PO_4)_2$ addition without N (lowercase letters) and with N addition (capital letters). Asterisks represent significance between N treatments within each P type and rate (* and ** for $P < 0.05$ and 0.01, respectively).
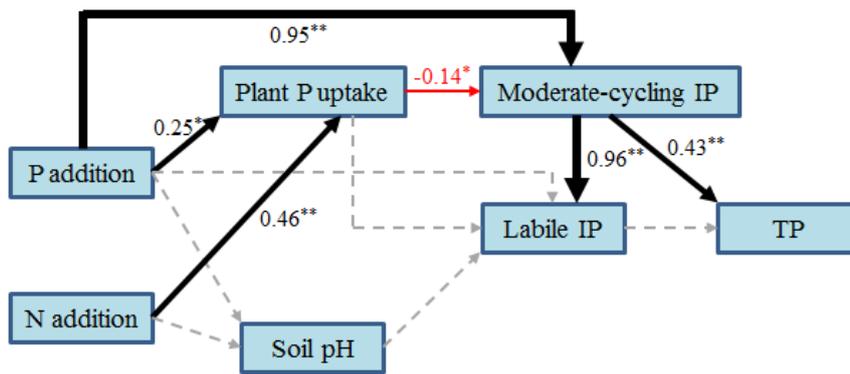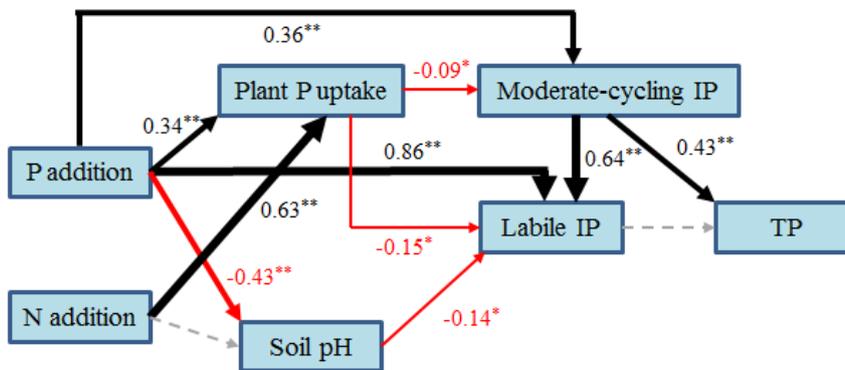
Fig. 6 Structural equation model of the relationships between soil pH, plant P uptake, soil moderate-cycling inorganic phosphorus (IP), labile P and TP under KH_2PO_4 (a, χ^2 = 23.44, P = 0.38, RMSEA = 0.03, AIC = 67.44) and $Ca(H_2PO_4)_2$ additions (b, χ^2 = 27.01, P = 0.08, RMSEA = 0.09, AIC = 79.01) across N treatments. Arrows indicate positive (black), negative (red) and neutral (grey-dotted) effects. Arrow width is proportional to the strength of the relationship. The number adjacent to each arrow is the standardized path coefficient with corresponding significance (*, ** for $P < 0.05$ and 0.01, respectively).
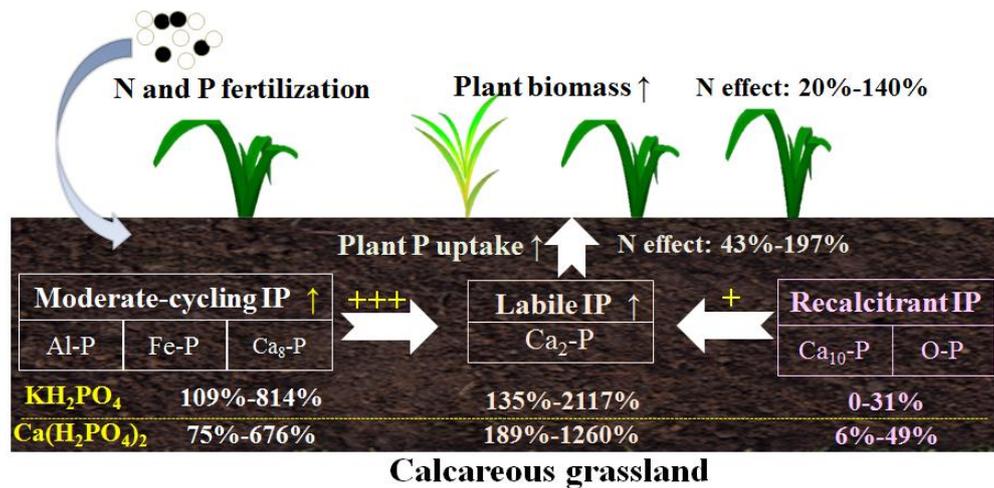
Fig. 7 Schematic diagram shows the effects of phosphorus (P) compound addition on soil inorganic P transformations in the calcareous grassland of Inner Mongolia. The percentages represent increase ("↑" in the diagram) of soil inorganic P fractions, plant P uptake and plant biomass as affected by fertilization across P addition rates. KH_2PO_4 addition had a larger impact on moderate-cycling IP (sum of Al-P, Fe-P and Ca_8-P) as compared to $Ca(H_2PO_4)_2$ (109%-814% *vs.* 75%-676%). However, recalcitrant P (sum of Ca_{10}-P and O-P) increased more with $Ca(H_2PO_4)_2$ addition relative to KH_2PO_4 (6%-49% *vs.* 0-31%). Nitrogen addition decreased moderate-cycling P by enhancing plant biomass and plant P uptake for both P compound additions across P addition rates. Therefore, moderate-cycling P showed a higher contribution to soil labile P than recalcitrant P as represented by '+++' and '+', respectively.