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# Quantitative Evaluation of the Crop Yield, Soil-Available Phosphorus, and Total Phosphorus Leaching Caused by Phosphorus Fertilization: A Meta-Analysis

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**Abstract:** Phosphorus (P) leaching from excessive P application is the primary pathway of P losses in agricultural soils. Different P fertilizer practices have mixed effects on P leaching. We conducted a meta-analysis of the relevant literature regarding the response of crop yields, soil-available P (AP), and total P (TP) leaching to reduced P input (RP) and an inorganic-organic combination fertilizer (NPKM) for different agricultural land-use types. Compared to conventional P application (CP), RP (10~90% reduction) did not reduce crop yields in vegetable fields (experiments were 1~4 years) but significantly reduced cereal yields by 4.57%. Compared to chemical fertilizer (NPK), NPKM significantly increased cereal yields by 12.73%. Compared to CP, RP significantly reduced AP at 0~60 cm in vegetable and cereal fields. The greatest reduction occurred at 20~40 cm in vegetable fields (40.29%) and 0~20 cm in cereal fields (34.45%). Compared to NPK, NPKM significantly increased the AP at 0~60 cm in vegetable fields, with the greatest increase (52.44%) at 20~40 cm. The AP at 0~40 cm in cereal fields significantly increased under the NPKM treatment, with the greatest increase at 0~20 cm (76.72%). Compared to CP, RP significantly decreased TP leaching by 16.02% and 31.50% in vegetable and cereal fields, respectively. Compared to NPK, NPKM significantly increased TP leaching in vegetable fields (30.43%); no significant difference in leaching occurred in cereal fields. P leaching, in response to RP, was influenced by the P amounts applied (34.49%); soil organic matter (14.49%); and TP (12.12%). P leaching in response to NPKM was influenced by multiple factors: rainfall (16.05%); soil organic matter (12.37%); soil bulk density (12.07%); TP (11.65%); pH (11.41%). NPKM was more beneficial for improving yields in cereal fields with low soil fertility and lower P-leaching risks.

**Keywords:** P leaching; P transformation; P application; inorganic-organic combination fertilizer; cropping system types; fertilization



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## 1. Introduction

Phosphorus (P) is an essential nutrient required by crops [1] but the availability of P in soils is generally low due to the fixation of P by calcium ions and Fe- and Al-oxides in soil [2]. Crop yields are often maintained through continuous P fertilization in agricultural production [3]; however, long-term excessive P input has led to a P surplus in many areas, resulting in a rapid increase in soil-available P (AP) [4,5]. This poses a serious leaching risk when the surplus P exceeds the soil adsorption capacity [6], and can contribute to eutrophication of surface waters and groundwater [7]. Soil P-leaching losses are influenced by soil properties, climate, and management practices (e.g., cultivation and fertilization) [8,9], with fertilization measures being the most direct and effective way to minimize P-leaching losses [5]; therefore, it is important to clarify the effects of different P fertilizer measures on P leaching for the sake of both economic and environmental benefits.

P leaching is controlled by the amount and type of P fertilizer applied [10]. Many studies have shown that reducing P input reduces soil AP and P leaching [11], especially in areas with massive P surpluses. For instance, reducing P input in vegetable fields with high P accumulation is more beneficial for decreasing the total P (TP) leaching than it is in cereal fields [12]. The appropriate P fertilizer input rate is a key point, since excessive reductions in P input may lead to crop failure. For example, Qi et al. [13] indicated that P leaching were significantly reduced at a 40% reduction in the P application rate (120 kg/ha), yet crop yields were also significantly decreased; therefore, it is necessary to reduce P fertilizer inputs to maintain or increase crop yields and to reduce P-leaching risk.

Inorganic-organic combination fertilizers are an effective measure in agricultural production for increasing crop yields and improving soil physical and chemical properties and microbial communities [14,15]; however, long-term excessive input of both inorganic and organic P fertilizer leads to the accumulation of P in the soil [5] and causes P leaching from the soil. Most studies have shown that inorganic-organic combination fertilizers contribute more to higher crop yields and to P leaching than chemical fertilizers alone [16,17], with these studies also reporting that total P input was higher under inorganic-organic combination fertilizers than under chemical fertilizers alone. Organic fertilizer inputs not only directly influence soil-P transformation but also indirectly affect soil physicochemical properties [18]. In study designs that entail unequal P input between treatment groups with an inorganic-organic combination fertilizer and inorganic fertilizer only, it is difficult to distinguish whether P leaching is caused by excessive P input or by organic fertilizers improving soil physicochemical properties and increasing P mobility. Some studies have been conducted with equal amounts of P fertilizer inputs across treatment groups, with the effect of P leaching varying with the proportion of organic fertilizer. Zhang et al. [19] showed that, compared to chemical fertilizer alone, replacing 50% of the inorganic P input with organic fertilizer significantly reduced TP leaching by 21.3~48.8%; in contrast, Cui et al. [20] concluded that substituting 30% of P input with organic fertilizer increases TP concentrations and P losses. These inconsistent results suggest that the effects of organic fertilizer on P leaching from agricultural soils are influenced by many factors, including soil-P status and P input; therefore, it is essential to quantify and synthesize the effects of inorganic-organic combinations on crop yields and TP leaching at the same amount of P applied as chemical fertilizers alone.

P leaching is also influenced by water input (precipitation and irrigation) and soil properties [21]. Studies have shown that irrigation water inputs contribute 23.3% to TP leaching, which was second only to the input of manure (24.2%) [10]. The long-term application of an inorganic-organic combination fertilizer has a significant impact on the physical, chemical, and biological properties of the soil [22]. Organic fertilizer application can increase soil pH and soil organic matter (SOM) [23]. Previous studies have revealed the effects each of these two factors have on the soil-P-sorption capacity [24]. A ten-year experiment showed that soil pH decreased by 0.6 units with chemical fertilizer alone and, compared to unfertilised soil, increased by 0.7 units with an inorganic-organic combination fertilizer (pH 5.7) [18]. SOM enhances the availability of P by influencing the sorption/desorption of P in the soil by competing with phosphate for adsorption sites [25]. SOM also increases aggregate stability and decreases soil bulk density, which may increase the risk of P leaching [26]. Currently, there is a paucity of published research on the contributions of the above factors to P leaching. Therefore, a quantitative analysis of the contribution of these individual factors to P leaching as reported in multiple studies is essential to reduce the environmental risk of P leaching.

Here, we collected data from 106 studies about P application conducted across the main farmlands (vegetable and cereal fields). The data included the crop yields, soil AP, and TP leaching. In this study, the main objectives were (1) to quantify the amount of mineral P input on crop yields, the AP, and the P-leaching losses in the main farmlands; (2) to quantify the effects of the types of P input on crop yields, AP, and P-leaching losses in the main crop farmlands under equal amounts of P input; and (3) to identify factors that lead to differences in TP leaching between different P fertilization measures. The ultimate purpose of the study is to guide future P management and to control P-leaching losses in farmlands.

## 2. Materials and Methods

### 2.1. The Literature Search

We conducted a literature search using the Web of Science (http://apps.webofknowledge.com, accessed on 1 March 2022) and the China National Knowledge Infrastructure database (CNKI, http://www.cnki.net, accessed on 7 March 2022) to collect the peer-reviewed journal articles published from 2000 to 2022. The following keywords were used for the search: 'P loss or P leaching or available P or P accumulation or P surplus'. The originality of the data in the studies was determined by evaluating the titles and abstracts of the articles, and articles that appeared to have used original data were examined in detail. The procedure of identifying studies was conducted by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [27]. Data were further scrutinized and extracted from the published studies using the following inclusion criteria and protocols: (1) The study design needed to include a pairwise control (with conventional P (CP) application as the control group, and reduced-P input (RP) as the experimental group; or with chemical fertilizer alone (NPK) as the control group and inorganic-organic combination fertilizer as the experimental group (NPKM), and with equal P inputs in both the NPK and NPKM groups), such that the P treatments had the same indicators as the control; (2) The study needed to be a field trial and could not include any simulation trial results. Crop yield or soil-AP content (in the 0–60 cm soil layer at 20 cm intervals) or TP leaching at harvest time (obtained by collecting leachate in underground leaching trays, represented by the amount of leaching over the entire growing period) should be listed in the literature for each treatment; (3) If a given study reported multiple independent experiments (e.g., two experiments at separate locations, different fertilization treatments, or different crops), each was considered an individual study and was incorporated as an independent observation in the data set; (4) The study needed to report mean value (M), standard error (SE), or standard deviation (SD), and sample sizes (n); (5) The study needed to include data information on the experimental sites, crop species, and basic soil physicochemical properties typically included in the literature. M, SD, SE, and number of replicates could be collected from the study tables and figures by using GetData Graph Digitizer (version 2.25). Ultimately, 106 studies were included in our database, including 56 studies on yield and available P and 40 studies on TP leaching.

The data units in this paper were first standardized, and the crop yield, AP, and TP leaching data are presented for both the control and experimental groups in t/ha, mg/kg, and kg/ha, respectively. If SE was reported in the original study, it was converted to SD by the equation SE $\times \sqrt{n}$, and if the standard deviations were not provided in the study, we estimated the corresponding SD based on the ratios of the existing SD to the means. The P fertilizer reduction proportions, organic fertilizer proportions, P inputs, and soil depths reported in the studies were divided into subgroups to better analyse the effect of P fertilizer measures on crop yield, soil AP, and TP leaching.

### 2.2. Data Analysis

The natural logarithm of the response ratio (lnRR) of crop yield, AP, and TP leaching changes was calculated as Equation (1):

$$(\ln RR) = \ln\,(Xt/Xc) = \ln Xt - \ln Xc \quad (1)$$

where Xt is the mean value of each observation in the experimental groups for crop yield, AP, and TP leaching, and Xc represents the mean value of each observation in the control groups.

The sampling variance for each lnRR was calculated as Equation (2):

$$V = (SDt^2/Xt^2 \times n_t) + (SDc^2/Xc^2 \times n_c) \quad (2)$$

where $n_t$ and $n_c$, SDt and SDc, Xt and Xc are the pairs of sample sizes, standard deviations, and mean responses for the experimental and control groups, respectively.

The meta-analysis was performed by including the studies as random factors using the rma function in the R statistical software package metafor (setting the method as 'REML'), which was necessary to reduce data dispersion due to the original study experimental design or measuring method. Mean effect sizes and bias-corrected 95% confidence intervals (CIs) were generated using a bootstrapping procedure (4999 iterations). To facilitate data interpretation, the percentage of change in values for the experimental groups relative to that for the control groups was calculated by Equation (3):

$$\text{Effect size} = (\exp(\ln R) - 1) \times 100\% \quad (3)$$

where a positive value indicates an increase in experimental groups relative to control groups, while a negative value indicates a decrease. The effect of P fertilizer application was considered significant if the 95% CI did not overlap with zero; otherwise, no significant effect was deemed to exist.

Egger's test and funnel plots are the main methods for testing the quality of meta-analyses and their reliability was confirmed by the previous literature [28,29]. To evaluate the quality of the meta-analysis, the Egger's test (Table S1) and funnel plot (Figures S1–S3) were used in this paper. The results showed that there was no publication bias in the meta-analysis data (these indicators are explained and included in Supporting Information). The Leave1out function in the metafor R package was used for sensitivity analysis of the meta-analysis results, which showed that the conclusions of this study were reliable. 'Random Forest' package in R was used to evaluate the contribution of factors affecting the leaching of total phosphorus. The above data analyses were performed in R 4.1.0, and Origin 2019b was used for graphing.

## 3. Results

### 3.1. Data Composition

There is a limited amount of literature in our collected databases that includes both soil-available phosphorus content and total phosphorus leaching data; therefore, we differentiated the data types into AP content and TP leaching. The P input amounts for all fertilization treatments under different data types are summarized in Table 1. The average P input of the RP treatment was approximately 50% of the CP treatment, while treatment NPK and NPKM had the same P fertilizer input (Table 1); moreover, the average P inputs of all treatments in vegetable fields were higher than those in cereal fields (Table 1). We also established the response curve showing the top 0~20 cm soil layer AP in response to the proportion of P fertilizer reduction and the proportion of organic fertilizer (Figure 1). When the proportion of the P reduction and the organic fertilizer was ≤30%, the AP decreased sharply with the proportion of the increase (Figure 1). The AP changed slightly when the P reduction and the organic fertilizer proportion was 30~70%, and it dropped slightly when the proportion was ≥70% (Figure 1). These trends were used as the foundation for the meta-analysis of subgroup classifications.

**Table 1.** Inputs of P fertilizer under different P fertilization measures.

| Data Type | Land Type | CP/RP (kg/ha/yr) | | | | NPK/NPKM (kg/ha/season) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Max | Min | N | Mean | Max | Min | N |
| AP content | Vegetable fields | 411/193 | 891/540 | 72/30 | 62 | 161 | 284 | 53 | 46 |
| | Cereal fields | 125/61 | 300/150 | 20/10 | 92 | 67 | 135 | 25 | 55 |
| TP leaching | Vegetable fields | 269/165 | 985/779 | 25/24 | 131 | 187 | 548 | 40 | 32 |
| | Cereal fields | 219/113 | 466/433 | 15/15 | 53 | 116 | 174 | 60 | 15 |

Note: N indicates the sample size for each group of data.

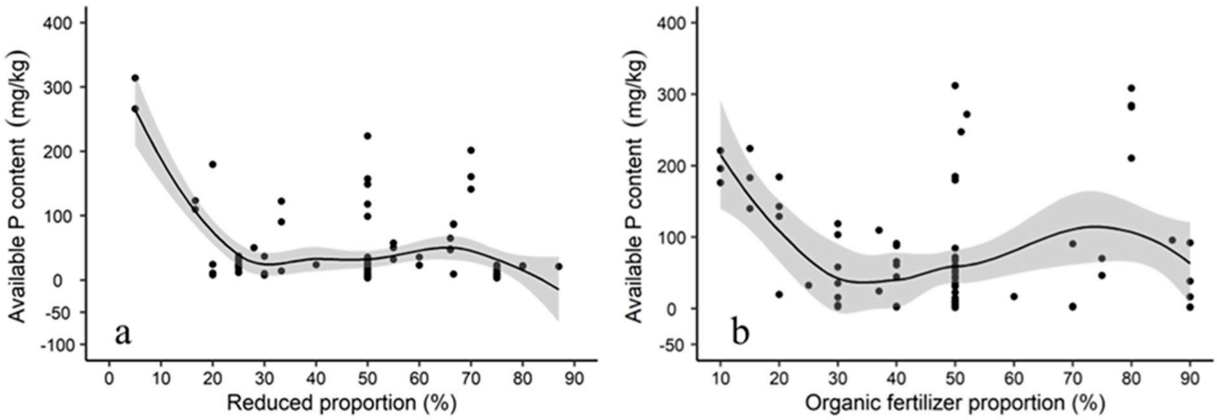


**Figure 1.** The response curves for available P in the top 0~20 cm soil layer in response to the proportions of P reduction (**a**) and organic fertilizer (**b**). Note: The gray areas represent 95% confidence intervals.

### 3.2. *Effect of P Fertilizer Measures on Crop Yields*

Compared with CP, RP was able to maintain vegetable yields but significantly reduced crop yields in cereal fields by 4.57% (Figure 2a, all effect sizes and their confidence intervals in this paper are provided in Supporting Information, Tables S2–S4). Vegetable yields were maintained by RP under different P input rates. Conversely, RP significantly reduced crop yield at P application amounts below 125 kg/ha in cereal fields. Notably, cereal yields could be maintained if the reduction in P input was less than 30% but a reduction in P input over 30% reduced cereal crop yields.

At the same P-fertilizer input rate, compared to the use of NPK, the use of NPKM significantly increased cereal yields by 12.73% and increased vegetable yields by 3.96%. NPKM had a positive effect on increasing the yield of cereal crops at different rates of P input. Significant increases of 14.94% were observed in cereal yields for organic fertilizer substitution proportions of 30~70% (Figure 2b).

### 3.3. *Effect of P Fertilizer Measures on the Soil-Available P*

RP significantly reduced the available P (AP) in the 0~60 cm soil layer of vegetable and cereal fields, primarily at depths of 20~40 cm (40.29%) in vegetable fields and the top 0~20 cm (34.45%) in cereal fields. The AP in the top 0~20 cm soil layer was significantly and positively correlated with P-leaching losses, so the data for the AP in the top 0~20 cm soil layer for CP and NPKM treatments were divided into the following subgroups: P inputs and the proportion of reduction, or organic P proportion. Regardless of the level of P input, RP reduced the AP in the top 0~20 cm soil layer of both vegetable and cereal fields, and the decrease in AP content was positively correlated with the proportion of reduction (Figure 3a).

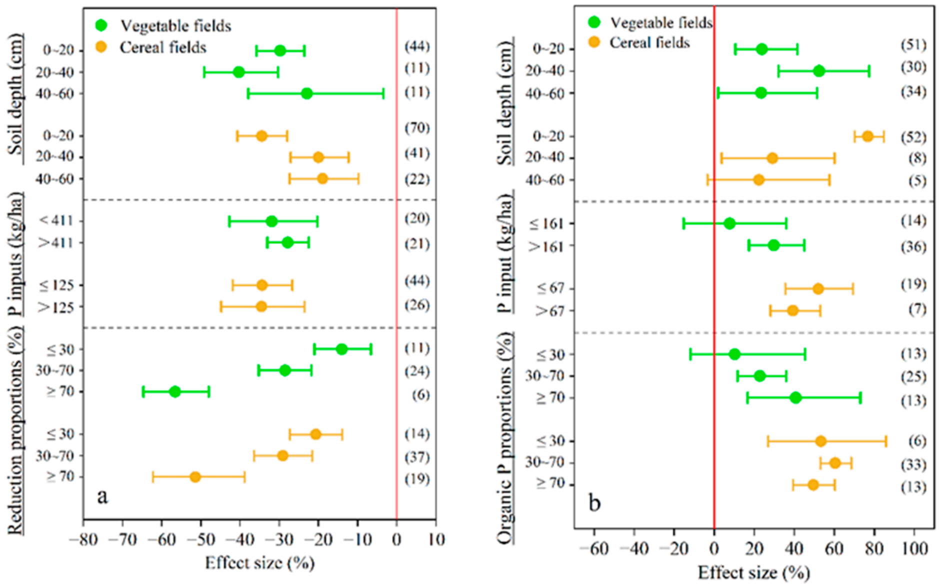


**Figure 2.** Effect of RP (**a**) and NPKM (**b**) on yields in vegetable and cereal fields. Note: The red vertical line in the figure represents 0, numbers in parentheses represent sample size, and the dotted lines separate the different subgroups, the same as below.

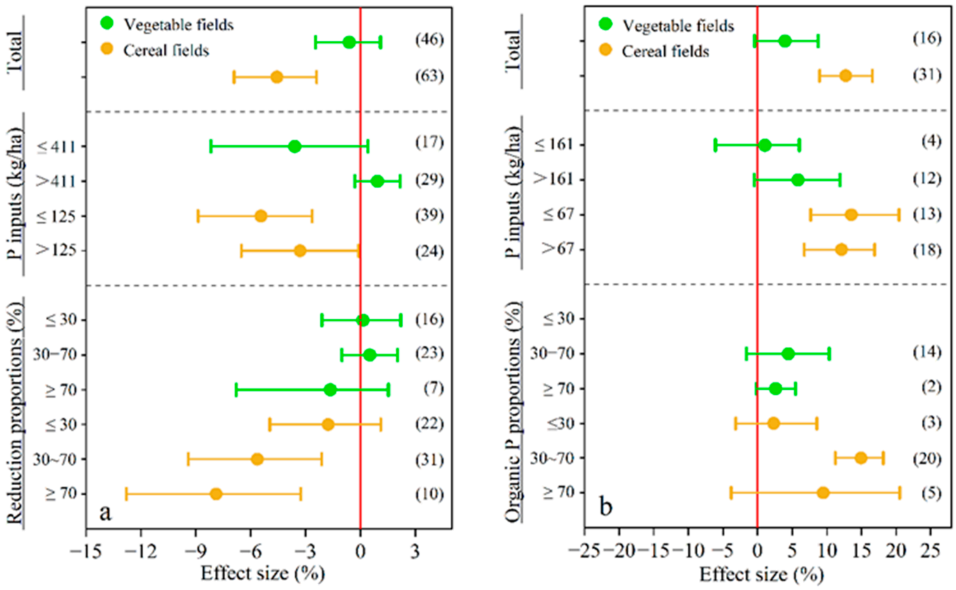


**Figure 3.** Effect of RP (**a**) and NPKM (**b**) on soil-available P in vegetable and cereal fields.

The use of NPKM significantly increased the AP in the 0~60 cm soil layer of vegetable fields and in the 0~40 cm soil layer of cereal fields, primarily at the depths of 20~40 cm in vegetable fields. The AP in the top 0~20 cm of soil in vegetable fields increased in response to NPKM application; however, when the total P input was ≤161 kg/ha, the change in AP was not significant. For cereal fields, the greatest increase in AP was found in the top 0~20 cm (76.72%) of soil, while the AP change was not significant at the depths of 40~60 cm. The proportion of organic fertilizer that was applied had different effects on the change in the AP in the top 0~20 cm of soil. The AP in vegetable fields increased significantly (by 22.79~40.76%) when organic fertilizer substitution was >30% but the change was not significant when the substitution was ≤30%. For cereal fields, the use of NPKM significantly increased AP at different P-input rates and organic fertilizer proportions (Figure 3b).

*3.4. Effect of P Fertilizer Measures on P-Leaching Losses*

Compared to CP, RP significantly reduced TP leaching in vegetable and cereal fields. In addition, TP leaching significantly decreased in vegetable and cereal fields under all P input conditions, and the proportion of P fertilizer reduction was positively correlated with the reduction in TP leaching in both vegetable and cereal fields (Figure 4a).

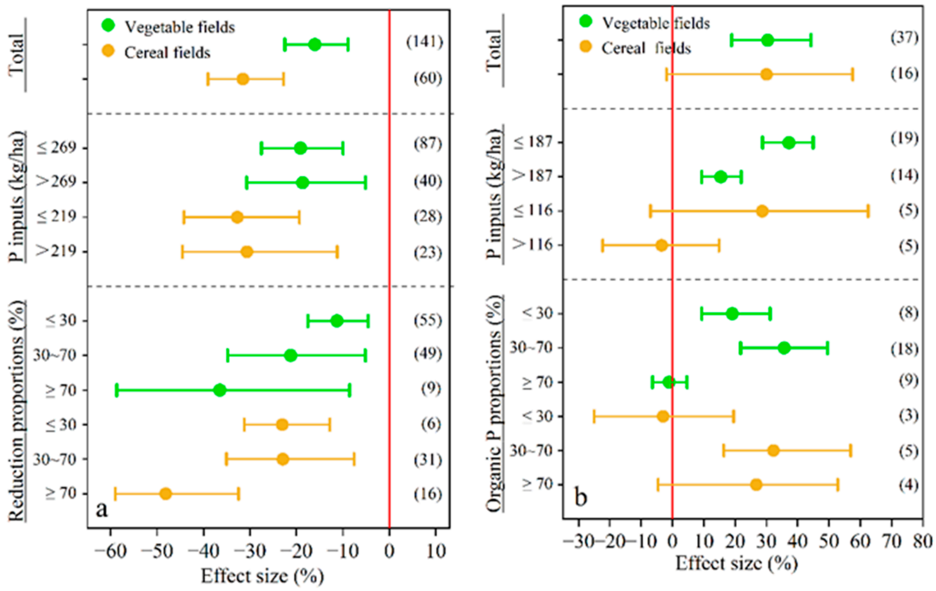


**Figure 4.** Effect of RP (**a**) and NPKM (**b**) on TP leaching in vegetable and cereal fields.

NPKM significantly increased TP leaching in vegetable fields but had no effect in cereal fields. Under any P input rate, organic fertilizer application increased TP leaching in vegetable fields but had no effect on TP leaching in cereal fields. At average P inputs, organic fertilizer substitution proportions <70% increased TP leaching in vegetable fields, while organic substitution proportions of 30~70% increased TP leaching in cereal fields (Figure 4b).

*3.5. Factors Affecting TP Leaching*

The results showed that the most important factor determining TP leaching under RP was the P input, accounting for 34.49% of the contribution to TP leaching. The importance of soil organic matter (SOM) and TP in explaining the variation in TP leaching rates was 14.49% and 12.12%, respectively (Figure 5a).

Rainfall was the most important factor affecting TP leaching when NPKM was used, explaining 16.05% of the variation in TP leaching rates. The importance of organic matter, soil bulk density, TP, pH, and total nitrogen in explaining the variation in TP leaching rates was 12.37%, 12.07%, 11.65%, 11.41%, and 10.44%, respectively, indicating that TP leaching under NPKM was influenced by a complex set of factors (Figure 5b).

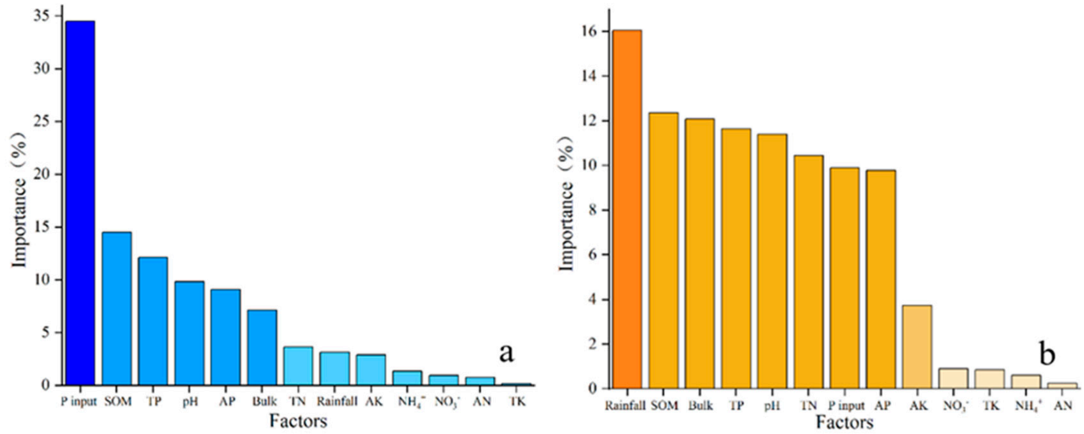


**Figure 5.** Differences in factors influencing TP leaching in RP (**a**) and NPKM (**b**). P input represents application amount of phosphorus fertilizer, SOM represents soil organic matter, TP represents total soil phosphorus, AP represents available soil phosphorus, Bulk represents soil bulk density, TN represents total soil nitrogen, Rainfall represents total rainfall in the season, AK represents available soil potassium, $NH_4^+$ represents soil ammonium nitrogen, $NO_3^-$ represents soil nitrate nitrogen, AN represents soil alkaline nitrogen, and TK represents total soil potassium. Note: Different colors represent the degree of importance, the darker the color, the more important it is.

## 4. Discussion

### *4.1. Effect of P Fertilizer Measures on Crop Yield*

This meta-analysis showed that compared to CP, RP maintained vegetable yields (trials with RP over the course of 1–4 years) but a trend towards yield reduction was observed when the reduction was more than 70% of the average P application; however, this yield reduction was not significant. P input was generally high in vegetable fields, with the maximum amount of P applied across all the studies reaching 891 kg/ha and the average amount of P applied being 411 kg/ha (Table 1). Long-term excess P input leads to a large surplus of P in vegetable fields, which promotes the accumulation of soil legacy P [30]. Some studies have reported that vegetables can reuse legacy P with no reduction in yields for several years after cessation of P input [31,32]. Therefore, a short-term reduction in P input in high-legacy-P vegetable soils would not only maintain crop yield but also save P fertilizer resources.

Cereal yields are significantly increased at the appropriate level of P input, while excessive P input is detrimental to cereal yield increases. For example, Hou et al. showed that the optimum rate of P fertilizer for annual maize is 88~97 kg/ha. When the P input was increased to 130~160 kg/ha, the crop yield declined. Therefore, optimum P input is crucial to ensure crop yield. The present meta-analysis showed that RP significantly reduced cereal yields by 4.57% at 20~125 kg/ha. Cereal yields were maintained by RP when P input was more than 125 kg/ha. P fertilizer reductions of more than 30% resulted in grain yield decreases of 5.64~7.89% of grain yields with average P input (125 kg/ha) (Figure 2a). In summary, vegetable fields have more potential than cereal fields for tolerating P reduction while maintaining crop yields.

Many studies have shown the generally positive effects of inorganic-organic combination fertilizers on crop yield [15], with the total P input of inorganic-organic combination fertilizer treatments being higher than that of chemical fertilizer alone in relevant studies [33]. Organic fertilizers provide some nutrients to plants and directly increase crop yields, especially with long-term excess inputs; meanwhile, organic fertilizers increase SOM by a series of interdependent processes and improve biological activity, soil structure, cation exchange, water holding capacity, and so on [34]. These changes can ultimately lead to an increase in crop yields [35]; however, it is difficult to distinguish the contribution of the amount or type of P fertilizer to yield enhancement.

The meta-analysis in this paper showed that NPKM increased cereal yields by 12.73% and vegetable yields by 3.96% (Figure 2b). The increase in crop yield in response to inorganic-organic combination fertilizers was not only related to P input but also depended on the soil fertility (specifically, the soil-available P (AP), total nitrogen, SOM, and pH) and on the rate of available nutrient supply from the soil for plants [36]. The more significant yield-increasing effects of organic fertilizer were observed in soils with low fertility, and this response decreased as soil fertility increased. Organic fertilizer addition produced a greater yield increase response, especially in soils of nearly neutral pH (pH between 6.6 and 7.3) and with low SOM (<10 g/kg) [36], which explains the better increase in yield with an inorganic-organic combination fertilizer in grain fields compared with vegetable fields. Some meta-analyses have concluded that compared to chemical fertilizers, inorganic-organic combination fertilizers did not increase grain yields [37]. The reason may be the relatively high soil fertility in the fields studied. Studies have shown that organic–combination fertilizers increase the SOM content, enhance microbial activity, and improve the soil structure [36,38].

### *4.2. Effects of Inorganic-Organic Combination Fertilizer on Soil-Available P and TP Leaching*

Many studies have shown that the input of soil P is typically much higher than the uptake of P by crops, resulting in the accumulation of massive P in the soil [39,40]. P moves downwards through the transport of water, creating a risk of leaching when the sorption saturation of the soil is exceeded. RP significantly reduces the AP in the 0~60 cm soil layer of vegetable and cereal fields, as shown in Figure 3a. Notably, RP mainly reduces the AP in the 20~40 cm soil layer of vegetable fields and in the 0~20 cm soil layer of grain fields. This finding probably indicates that the P adsorption capacity of vegetable field surface soil is saturated and that P, therefore, tends to move downwards [41]. The main reasons for the downward movement of P are the higher nutrient content and water usage in vegetable fields.

Zhang et al. [42] compared the effect of organic-inorganic fertilizer and chemical fertilizer on the P speciation in vegetable soils under equal P input rates, indicating that organic fertilizer substitution increased the proportion of soil active P. Many studies have shown that the AP of soils is significantly increased by organic fertilizer application [43,44]. Organic fertilizer application also consistently promotes P leaching, as the accumulated P can become a source of P leaching [45,46]. The results of our meta-analysis show that compared to NPK, NPKM increased the AP in the 0~60 cm of soil in vegetable fields and in the 0~40 cm in cereal fields. These results indicate that organic substitution management created a higher risk of P leaching in vegetable fields and a lower risk in cereal fields.

### *4.3. Effect of P Fertilizer Measures on TP Leaching and Influencing Factor Analysis*

P leaching is a slow process and can continue for many years before becoming an environmental threat. There is a wide body of evidence showing that the risk of P loss from agricultural soil is closely related to AP [47]. Figure 3a shows that RP significantly reduced the AP in the 0~60 cm of soil in both vegetable and cereal fields, thereby reducing TP leaching in these fields (Figure 4a). The P input rate was the main factor (34.49%) that reduced soil TP leaching (Figure 3a), which is consistent with the findings of previous studies [48]. We recommend that the minimum P input to vegetable fields be a 70% reduction in the average P application amount, with a suitable P application rate of 123~411 kg/kg based on what is needed for maintaining crop yield. The appropriate P input is 88~125 kg/kg based on the results from a 30% reduction in the average P application in cereal fields. At this recommended range of suitable P input, crop yield is maintained, and soil AP and TP leaching are significantly reduced.

The results in Figure 3b show that compared to NPK, NPKM significantly increased the AP in all soil layers from 0~60 cm in vegetable fields, which creates the possibility of P leaching. Although the AP in the 0~40 cm of soil increased in grain fields, there was no significant difference at depths of 40~60 cm. The leaching losses of TP in vegetable fields under NPKM treatment were significantly increased but there was no effect in grain fields (Figure 4b). This difference is due to the widespread long-term excess fertilization of vegetable fields, resulting in a large P surplus [49]. Notably, manure is mostly applied to vegetable fields, while crop straw or root stubble are typically applied to grain fields and at a lower application rate [50]. The accumulation of P from the long-term application of manure to vegetable fields inevitably poses an environmental risk.

### 4.4. Limitations of This Study and Future Research Directions

Over the past several decades, P input worldwide has been mainly aimed at increasing soil P levels and crop yields [51]. This has resulted in a significant accumulation of soil P in many areas, and the environmental risk of P leaching has gradually gained attention. It is, therefore, necessary to optimize P application measures that guarantee crop yields while reducing P losses and alleviating phosphate resource shortages; however, most of the relevant current research focuses only on the agronomic or the environmental effects of phosphate fertilizer application, which in our view should be viewed as closely linked rather than as disconnected. Crop yields, soil AP, and P leaching were all considered in our research, and these three aspects represent the 'fate' of P in the agroecosystem. The data on crop yields and AP included in our study were properly matched, with mostly small 95% confidence intervals for the results. This indicates a high reliability level and shows that our meta-analysis provides a foundation for the optimization of P fertilizer practices in agriculture.

There are delays in the beneficial effects of organic fertilizer application since the mineralization, and the release of nutrients from organic fertilizers is relatively slow and could take longer to have a noticeable effect. Many long-term locational fertilizer trials have reported that manure application increases AP and creates a high risk of P environmental pollution [5,52]; however, in these studies, the total P input tended to be significantly higher in the NPKM treatment than in the NPK treatment, so the corresponding conclusions were not scientifically rigorous and cannot reflect the true effect of inorganic-organic combination fertilizer. Coppi [53] reported that subsurface movement of P was not environmentally significant during 6 years of continuous equivalent-manure application compared to the non-manured control. Such long-term trials are necessary to determine the effects of organic fertilizers on crop yields and the environment, as these fertilizers may have a cumulative effect rather than producing a significant change in the short run [54]. Long-term locational monitoring trials with equivalent amounts of total P input are lacking, and the effect of organic fertilizer type and application timing on P leaching still requires further research.

The recommended P application rates, reduction proportions, and organic fertilizer application proportions presented in our paper are given based on the data sets we collected and may not be applicable to some specific situations. Such nuances can be resolved in detail in individual experiments but are difficult to sort out when aggregating larger data sets. Thus, combining meta-analysis with more detailed primary research is essential for a more complete understanding of the processes and mechanisms involved.

## 5. Conclusions

This meta-analysis quantified the effects of P inputs and types on crop yield, soil AP, and TP leaching in vegetable and cereal fields. Compared to CP, RP significantly reduced the AP and TP leaching from soils in vegetable and cereal fields, reducing the risk of P losses; meanwhile, vegetable yields were maintained in the RP treatment but cereal yields were significantly reduced.

Compared to NPK, NPKM increased the AP in the 0~60 cm soil layer in vegetable fields and in the 0~40 cm soil layer in cereal fields when equivalent P inputs were applied. Moreover, partial organic fertilizer substitution had a positive effect on cereal yields but significantly increased TP leaching in vegetable fields.

Taken together, the above results show that RP significantly reduces the AP and the risk of P leaching from agricultural soils; however, the soil fertility status needs to be fully considered when using RP, otherwise, soils with lower fertility (e.g., soil in cereal fields) can experience reduced crop yields. The inorganic-organic combination fertilizer had a positive effect on improving soil P availability and increased the risk of P leaching for soils with high fertility (such as those in vegetable fields). For cereal fields with low soil fertility, inorganic-organic combination fertilizer increased crop yields while posing a low environmental risk.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13092436/s1, Supporting Information (include Tables S1–S4, Figures S1–S3).

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