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Agronomic Responses of Major Fruit Crops to Fertilization in China: A Meta-Analysis

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Abstract: With increasing application of nitrogen (N), phosphorus (P), and potassium (K) fertilizers, especially in China's fruit crops, the agronomic responses of fruit crops to fertilization may be reduced with time. Thus, the quantification of these responses would be useful for establishing nutrient recommendation and fertilizer management for fruit crops. Here, a meta-analysis including 552 paired data for agronomic response and 1283 sets for amounts of optimal fertilization from 293 field studies in China were performed to systemically quantify these variations of yield response (YR), relative yield (RY), agronomic efficiency (AE), and partial factor productivity (PFP) in response to the application of N, P, or K fertilizer under different groups including fruit crop types, time, and regions. The results showed that the average YRs to N, P or K fertilizer were 7.6, 5.2, or 5.9 t ha^{-1}, indicating related RYs of 78.0%, 82.9%, or 82.4%, respectively. All of the RYs for N, P, or K application in studies after 2000 were higher and less variable than those before 2000. Higher RYs were also shown for deciduous fruit trees when compared with evergreen fruit trees. The average AEs of N, P, and K fertilizer in China's fruit crops were 29.1, 32.4 and 20.2 kg kg^{-1}, all of them were negatively correlated with fertilizer rate. Due to a higher yield response and less fertilizer rate, annual crops (mainly watermelon and melons) had significantly higher AE than that of perennial crops. The average PFPs of N, P, and K fertilizer in China's fruit crops were 129, 205, and 113 kg kg^{-1}, all of which showed a declining trend with time. These findings demonstrated that the building-up of soil indigenous nutrient supply (indicated by RY) together with improving fruit varieties, as well as pest management and other forms of management could make external fertilization less important for increasing the yield of fruit crops in China. A rational nutrient management is therefore crucial for balancing yield and environmental concerns in countries like China, India, and other countries where fertilizers are often overused.

Keywords: fruit; yield response; relative yield; agronomic efficiency; fertilization

1. Introduction

China is the world's largest fruit producer, but with an excessive input of nitrogen (N), phosphorus (P), and potassium (K) fertilizers. The production of pear, litchi, peach, and apple in China accounts for more than 50% of their global production, and the production of citrus, grapes, bananas, and pineapples accounts for 6–19% of their world's total production [1]. In addition, the planting area of fruit in China has been expanding, and the proportion of fruit planting area to total planting area has increased from 1.8% in 1980 to 8.4% in 2014 [2]. With the expansion of fruit planting areas, the amount of fertilizer per unit area of fruit has also increased [1]. The increasing demand and consumption of fertilizer for fruit crops have gradually become the primary forms of contribution to the increase of fertilizer consumption in China. Fertilizer application rates appear to be much higher in fruit crops than in cereal crops, due to the growth and development characteristics of fruit trees [2,3]. The phenomenon of excessive or imbalanced fertilization has become very common [4,5], due to the lack of knowledge about rational fertilization of fruit growers in China. Such excessive applications of fertilizer have led to low fertilizer use efficiency, serious environmental problems such as greenhouse gas emissions, surface water eutrophication, and ground water nitrate contamination [6–9]. Therefore, a scientific and reasonable fertilizer recommendation method is necessary for the requirements of both high yield and friendly environment [10].

Numerous studies had been conducted for methods of crop nutrient management [11,12], for example, soil testing has been applied as a way of fertilizer recommendation to increase crop yield and nutrient use efficiency in China [13]. However, there were fewer applications for fruit crops. In addition, the soil testing needs a large number of field sampling and laboratory analyses, which were labor intensive and expensive. Therefore, in the small-farm farming mode without systematic soil testing and professional fertilization recommendation, the Nutrient Expert (NE) has been developed and achieved inspiring results in wheat, maize, and other staple crops in China and other countries [14–16].

The core method of fertilizer recommendation in the Nutrient Expert was based on yield response, agronomic efficiency, and indigenous nutrient supply. The yield response to fertilizer NPK was the yield gap between NPK plots that receive ample nutrients and omission plots when one of these nutrients was omitted ($Y_{OPT\text{-}N}$, $Y_{OPT\text{-}P}$, and $Y_{OPT\text{-}K}$) [17]. The yield response was closely related to natural factors such as climate, soil fertility (or soil nutrient), and fertilization rates, crop nutrient management, and cultivation measures [18,19]. The yield response could reflect indigenous nutrient supply, which determined the yield in the omission plots based on soil fertility [20,21]. The soil indigenous nutrient supply (N, P, and K) was identified as a "black box" that could be provided from irrigation water, rainfall, atmospheric deposition, soil mineralization, crop residues, and so on, and was considered as one of the important factors when making fertilizer recommendations [16,22,23]. Some agronomic indicators, including agronomic efficiency (AE) and partial factor productivity (PFP), were often used to describe fertilizer use efficiency [24,25]. There have been numerous studies on nutrient use efficiency [26–29]. The agronomic efficiency of fertilizer N, P, and K (AE-N, AE-P and AE-K) were the yield increase per unit of fertilizer N, P, and K applied. The partial factor productivity of fertilizer N, P, and K (PFP-N, PFP-P and PFP-K) were the yield per unit of fertilizer N, P, and K applied [30]. Fertilizer recommendations based on yield response and fertilizer use efficiency has been shown to be very successful for maize and wheat in China [16].

When soil testing is not available in the field, fertilizer recommendation based on yield response and agronomic efficiency is another preferred way, which provides scientific principle for the optimal nutrient management practices, is indicative of the supply and plant demand for nutrients and to achieve balanced crop nutrition [31,32]. Therefore, the analysis of yield response (YR), agronomic efficiency (AE), partial factor productivity of fertilizer (PFP) and indigenous nutrient supply of the fruit crops under different scenarios will be helpful to efficiently use the nutrient resources from the soil and environment, and help to determine the attainable yield of the fruit crops [33].

With the increasing application of N, P, and K fertilizers in China's fruit crops [1], the agronomic responses of major fruit crops to fertilization may have been reduced over the last four decades. However, the yield response, fertilizer use efficiency, and indigenous nutrient supply could be different with large variations across different fruit producing regions and eras, due to different types of fruit crops, climates, soils, and nutrient management. Thus, the hypotheses of this study were: (i) continued excessive fertilization had led to soil nutrient surplus in fruit cropping systems and enhanced nutrient supply capacity, both of them could reduce yield response and fertilizer use efficiency with time; (ii) yield response of fruit crops to fertilization would be different among fruit crop types due to their growth characteristics including storage capacities for nutrients and productivity, as well as different climate conditions in fruit producing areas. A meta-analysis was therefore conducted to quantify the yield response of fruit crops to fertilization, and provide a basis for the establishment of the NE nutrient recommendation and nutrient management for fruit production.

2. Materials and Methods

2.1. Data Collection

A survey of peer-reviewed papers published before 2019 was conducted using the ISI-Web of Science (Thomson Reuters, New York, NY, USA) and the China Knowledge Resource Integrated dataset (CNKI). Keywords used in the searches included "fruit (apple, citrus, watermelon, and so forth)" and fertilization (nitrogen, phosphorus, and potassium). Data in graphical forms were digitized using the GetData v2.22 software (http://getdata-graph-digitizer.com/). In the context of agronomic response, there was few field trials based on farmers' fertilization practice; thus, field studies with optimal fertilization conditions were used to quantify agronomic responses of fruit crops to fertilization in China.

To minimize bias, the following criteria were used to select studies for the meta-analysis: (i) The collected data are from field trials only, excluding pot and greenhouse experiments; (ii) The data are representative of the entire growth period of the fruit crops; (iii) Tested treatments include optimal fertilizer management (OPT) or a series of nutrient omission treatments (OPT-N, OPT-P, or OPT-K); (iv) Fertilizer sources are from traditional fertilizer products (e.g., urea, calcium superphosphate, compound fertilizer, etc.); (v) The plantations of fruit crops have been under good management and not subjected to pests or diseases as ascertained in references (see appendix). Basing on these criteria, 552 paired data for yields and 1283 sets for optimal fertilization information were collected from 293 articles. The distribution of experimental sites was shown in Figure S1.

In the aspect of uncertainty, a large dataset provided a good basis for conducting a meta-analysis. Nevertheless, the studies were conducted in 22 different fruit crops and often had different objectives. A few studies had rather extreme treatment values (e.g., a very high yield with a low fertilizer input), probably for experimental purposes. Such extreme treatments might affect the outcome of this study. In addition, differences in sample size may also affect the results.

2.2. Data Analysis

Meta-analysis was used to quantify the yield response, relative yield, agronomic efficiency, and partial factor productivity of fertilizer in fruit crops. Since half of the collected data lacked the coefficient of variation, non-weighted methods were used for analysis [34].

Attainable Yield (Y_{OPT}) in this study was defined as the actual yield derived in the field under the optimal nutrient management practices. Yield response to fertilizer N, P, and K were defined as the yield gap between attainable yield and the yield from omission plots when one of the nutrients was omitted.

Soil indigenous nutrient supply could also be evaluated by relative yield when nutrient uptake was not available [15–17]. Relative yield (RY) was defined as the ratio between nutrient-limited yield ($Y_{OPT\text{-}i}$) and yield (Y_{OPT}) that could be achieved from an ample nutrients (N, P, K) supply. The nutrient efficiency parameters included agronomic efficiency (AE) and the partial factor productivity of the fertilizer (PFP). These could be estimated from the following equations:

$$YR_i\ (\mathrm{t\ ha^{-1}}) = Y_{OPT} - Y_{OPT\text{-}i} \tag{1}$$

$$RY_i\ (\%) = Y_{OPT\text{-}i}/Y_{OPT} \tag{2}$$

$$AE_i\ (\mathrm{kg\ kg^{-1}}) = (Y_{OPT} - Y_{OPT\text{-}i})/F_i \tag{3}$$

$$PFP_i\ (\mathrm{kg\ kg^{-1}}) = Y_{OPT}/F_i \tag{4}$$

where i represented N, P, or K, F was the amount of fertilizer applied (kg ha^{-1}), Y_{OPT} was the yield with OPT (t ha^{-1}), and $Y_{OPT\text{-}i}$ was the yield (t ha^{-1}) in a control treatment with no N, P, or K. In this study, the differences in yield and nutrient use efficiency in China's fruit crops were quantified for four groups according to each classification criterion (Table 1). Compared with perennial fruit crops, the annual fruit crops finish their life cycles within one year. Thus, the fruit crops could be divided into perennial versus annual based on their life cycle differences (group 1). As the largest proportions of fruit crops, woody fruit species could be divided into evergreen versus deciduous based on their differences in winter defoliation (group 2). Traditionally China is geographically divided into south China and north China (group 3). The former has a tropical and subtropical monsoon climate with a high annual rainfall (>1000 mm) and annual temperatures (16.5–18.5 °C), while the latter has a temperate monsoon or continental climate with low annual rainfall (<500 mm) and annual temperatures (7.0–9.5 °C) [35]. In addition, the inherent soil productivity (terms of soil indigenous nutrient supply in this study) indicated by on-farm cereal trials without fertilization in 2000s has been significantly improved compared to in the 1980s [36]. Therefore, field trials with fruit crops were also divided into trials conducted before and after 2000, with the aim to understand the historical change in soil indigenous nutrient supply that was indicated by relative yield.

2.3. Statistical and Sensitivity Analyses

To test the robustness of our meta-analysis, we performed a sensitivity analysis of the response ratio (RR, the effect of fertilizer rate on yield) [37]: RR = In ($Y_{OPT}/Y_{OPT\text{-}i}$). Using the Kolmogorov-Smirnov test method, the results showed that the RR distribution of fruit crops under N, P, and K fertilizers was not a typical normal distribution ($p < 0.05$) (Figure 1). Therefore, the nonparametric test of independent samples was used to compare the difference within two sub-groups of each indicator (YR, RY, AE, and PFP of N, P, and K) by using the Kruskal-Wallis one-way ANOVA with a SPSS 20.0 version (SPSS Inc., Chicago, IL, USA) [38]. The Mean effect size and corrected bias (i.e., the 95% confidence intervals (CI) for each category) generated using the boot-strapping (10,000 iterations) were calculated with a SPSS 20.0 version and a Sigmaplot 12.5 (Systat, San Jose, CA, USA) software based on a mixed-effected model.

Table 1. Data grouping and sample number in each group.

Grouping Characteristic	Sub-Group	Group Criterion	Sample Number (*n*) for YR, RY and AE				Sample Number (*n*) for PFP			
			Y_{OPT-N}	Y_{OPT-P}	Y_{OPT-K}	Total	PFP-N	PFP-P	PFP-K	Total
Life cycle	Annual [1]	Melons, watermelons, strawberries [2]	54	33	47	134	121	116	121	358
	Perennial	Apple, apricot, banana, cherry, citrus, dragon fruit, grape, jujube, kiwi, loquat, lychee, mango, papaya, peach, pear, persimmon, pineapple, plum, pomegranate	151	111	156	418	310	308	307	925
Woody fruit species	Evergreen	Citrus, dragon fruit, loquat, lychee, mango, papaya	40	27	37	104	86	86	86	258
	Deciduous	Apple, apricot, cherry, grapes, jujube, kiwi, peach, pear, persimmon plum, pomegranate	99	70	99	268	203	201	200	604
Geography and climate	South	Provinces: Anhui, Fujian, Guangdong, Guangxi, Guangzhou, Guizhou, Hainan, Hangzhou, Hubei, Hunan, Jiangsu (southern part), Jiangxi, Nanjing, Sichuan, Wuhan, Yunnan, Zhejiang Independently administered municipal districts: Chongqing, Shanghai	85	62	90	237	210	208	207	625
	North	Provinces: Gansu, Hebei, Heilongjiang, Henan, Jiangsu (northern part), Ningxia, Shaanxi, Shandong, Shanxi, Xi'an, Independently administered municipal districts: Beijing, Inner Mongolia, Liaoning, Xinjiang	120	82	113	315	221	216	221	658
Historical change	<2000	Field trials conducted before 2000	9	13	25	47	43	43	43	129
	>2000	Field trials conducted after 2000	196	131	178	505	388	381	385	1154

[1] Represents the compared two sub-groups; [2] Represents the contents of the sub-group. YR—yield response; RY—relative yield; AE—agronomic efficiency; PFP—partial factor productivity of fertilizer.

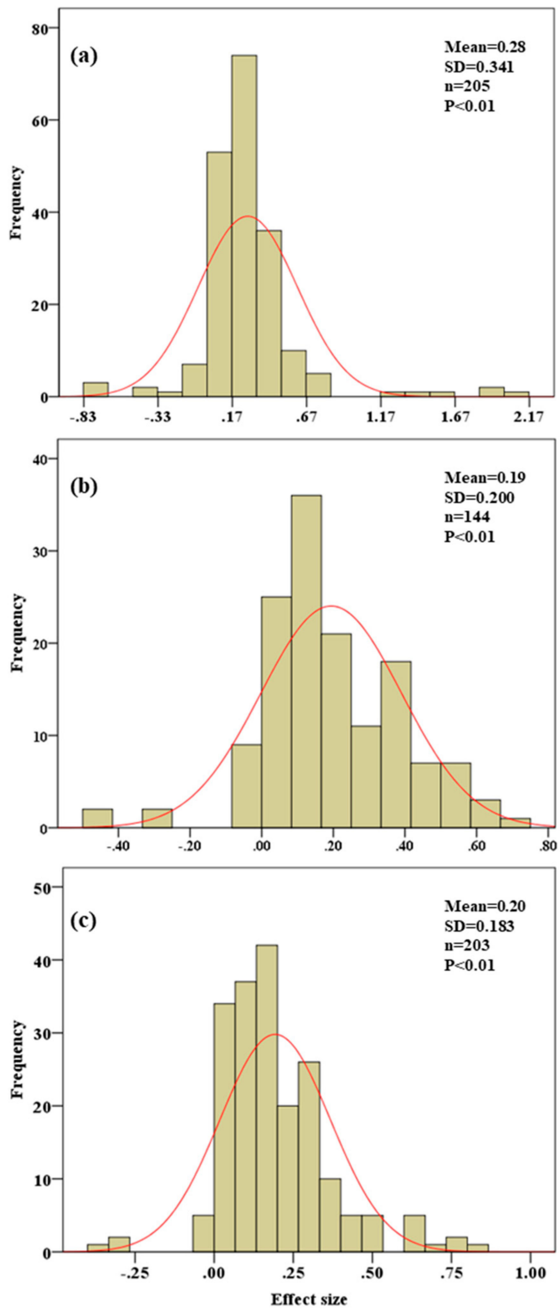

Figure 1. Frequency distribution of the response ratio (RR, the effect of fertilizer rate on yield) among all observations in the overall dataset. RR = ln (Yield treatment/Yield control), where yield treatment and yield control were the yield of plots with optimal nitrogen, phosphorus and potassium nutrient and nutrient omission, respectively. The RRs of nitrogen (**a**), phosphorus (**b**), and potassium (**c**) in the fruit crop system were shown.

3. Results

3.1. Yield Response and Relative Yield of Fruit Crops in China

The dataset showed that the average YR-N was 7.6 with CI of 7.7–10.0 t ha^{-1}, which was significantly higher than that of YR-P (5.2 with CI of 6.00–8.39 t ha^{-1}) and YR-K (5.9 with CI of 5.6–7.9 t ha^{-1}) in Chinese fruit crops (Figure 2a). Correspondingly, the average RY-N, RY-P and RY-K of the fruit crops in China were 78.0% with CI of 74.7–79.4%, 82.9% with CI of 80.8–86.1% and 82.4% with CI of 81.3–85.1%, respectively (Figure 2b).

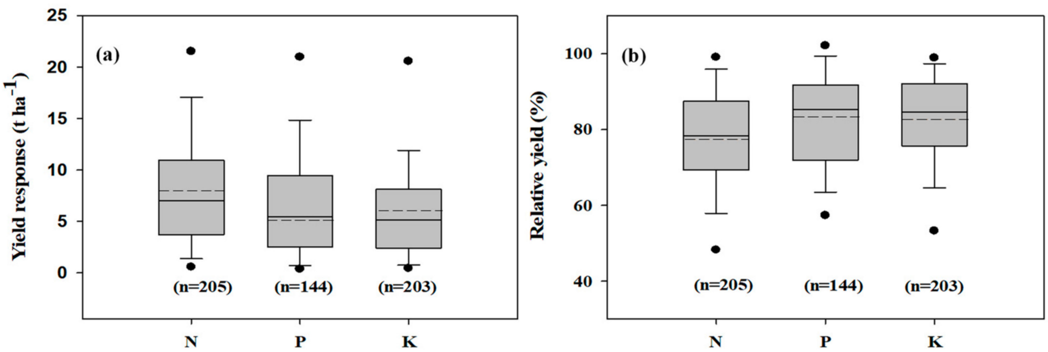

Figure 2. Yield response (**a**) and relative yield (**b**) of fruit crops under optimal fertilization conditions collected from 293 research articles. Black solid and dotted lines indicate medians and means, respectively. Box boundaries indicate upper and lower quartiles, whisker caps indicate 95th and fifth percentiles, and circles indicate outliers. The number of data points was given below each box.

The relative yield (RY) of fruit crops varied in different types, planting regions, and planting years (Figure 3). The average value of RY-N (80.7%) in deciduous fruit crops was significantly higher than that in evergreen fruit crops (72.6%), the average values of RY-P (86.0%) and RY-K (85.4%) were significantly higher than the RY-P (76.1%) and RY-K (77.2%) of evergreen fruit crops, respectively. The relative yields of N, P, and K in annual fruit crops were 78.2%, 80.0%, and 84.6%, respectively; while those of perennial fruit crops were 76.2%, 84.3%, and 82.8%, respectively. The average values of RY-N, RY-P, and RY-K in fruit crops of south China were 77.9%, 82.6%, and 83.5%, all of them had no significant differences with those in north China. For the times of trials conducted, the sample numbers before 2000 were reduced but with a larger variation when compared with those after 2000; the averages of RY-N (78.7%), RY-P (83.6%), and RY-K (82.4%) after 2000 were higher than those before 2000.

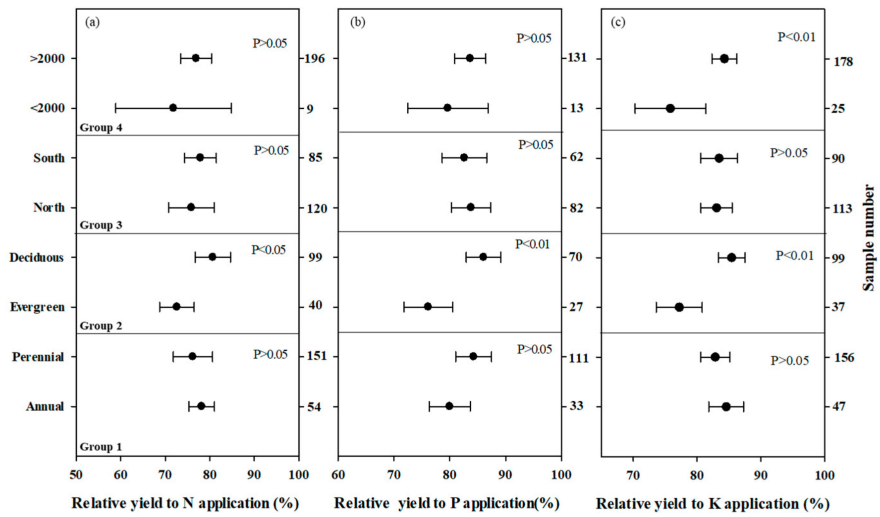

Figure 3. Relative yield to nitrogen (N) (**a**), phosphorus (P) (**b**), potassium (K) (**c**) application of fruit crops under optimal fertilization conditions collected from 293 literatures. Box circles indicate means, and the horizontal lines on the left and right sides represent the upper and lower limits of the 95% intelligence interval. Each group of data was determined with an F-test ($p < 0.05$).

3.2. *Optimal Fertilization Characteristics of Fruit Crops in China*

Under optimal fertilization conditions, the average application rates of N, P (as P_2O_5), and K (as K_2O) in Chinese fruit crops were 353 with CI of 327–381 kg ha^{-1}, 201 with CI of 184–219 kg ha^{-1}, and 320 with CI of 285–355 kg ha^{-1}, respectively (Figure 4). The average application rate of N, P_2O_5, K_2O in deciduous fruit crops was lower than that in evergreen fruit crops. Similarly, the average application rate of N, P_2O_5, and K_2O fertilizer in annual fruit crops were lower than that in perennial fruit crops. The application rates of N, P_2O_5, and K_2O for fruit crops in south China were similar to that in north China. The dataset also showed that the fertilizer application rates of N, P_2O_5, and K_2O in fruit crops had less variation after 2000, but generally higher rates than that before 2000 (Figure 5).

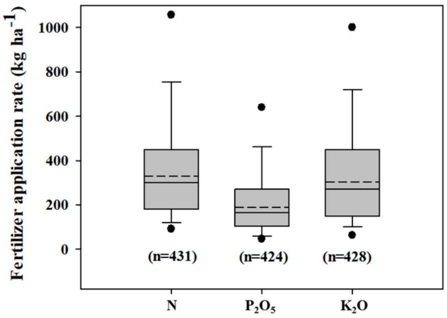

Figure 4. Application rate of nitrogen (N), phosphorus (as P_2O_5), and potassium (as K_2O) fertilizer in China's fruit crops under optimal fertilization conditions collected from 293 research articles. Black solid and dotted lines indicate medians and means, respectively. Box boundaries indicate upper and lower quartiles, whisker caps indicate 95th and 5th percentiles, and circles indicate outliers. The number of data points were given below each box.

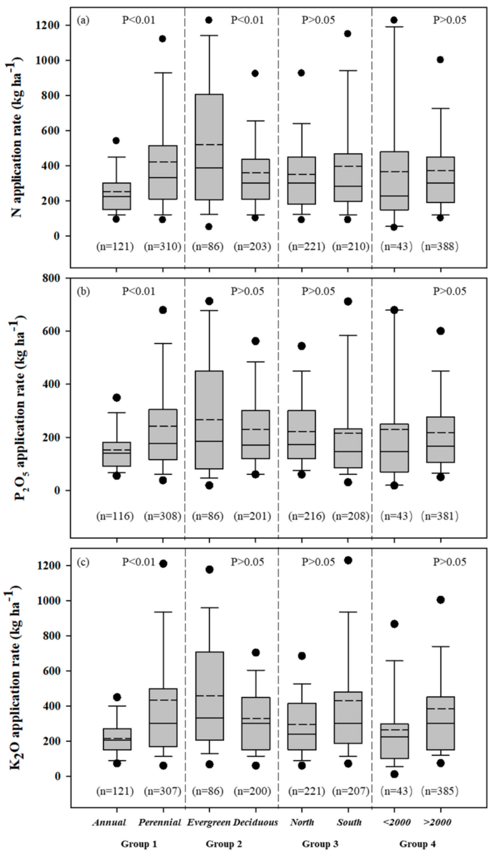

Figure 5. Application rate of nitrogen (N) (**a**), phosphorus (as P_2O_5) (**b**) and potassium (as K_2O) (**c**) fertilizers in China's fruit crops under optimal fertilization conditions collected from 293 research articles. Black solid and dotted lines indicate medians and means, respectively. Box boundaries indicate upper and lower quartiles, whisker caps indicate 95th and 5th percentiles, and circles indicate outliers. The number of data points was given below each box. Each group of data was determined with a F-test ($p < 0.05$).

3.3. Agronomic Efficiency of Fruit Crops in China

The average agronomic efficiency of nitrogen (AE-N), phosphorus (AE-P) and potassium (AE-K) in China's fruit crops was 29.1 with CI of 13.3–35.6 kg kg^{-1}, 32.4 with CI of 26.7–41.1 kg kg^{-1}, and 20.2 with CI of 17.0–23.6 kg kg^{-1}, respectively (Figure 6). There was a significant and negative relationship between the fertilizer rate and AE for all datasets. And such correlations could be well matched by exponential equations with high regression coefficients (Figure 7).

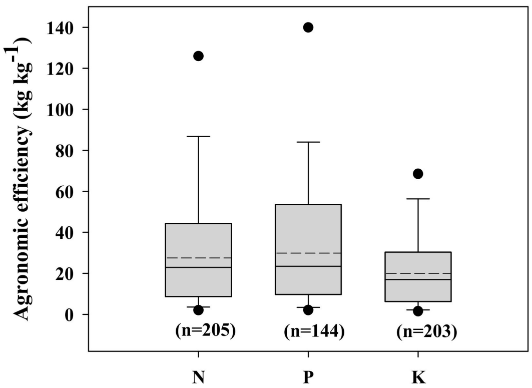

Figure 6. Agronomic efficiency nitrogen (N), phosphorus (P), and potassium (K) of China's fruit crops under optimal fertilization conditions collected from 293 literatures. Black solid and dotted lines indicate medians and means, respectively. Box boundaries indicate upper and lower quartiles, whisker caps indicate 95th and 5th percentiles, and circles indicate outliers. The number of data points was given below each box.

There was a significant difference in agronomic efficiency under different fruit crop groups (Figure 8). The average AE-N (50.3 kg kg^{-1}), AE-P (76.2 kg kg^{-1}) and AE-K (39.7 kg kg^{-1}) of annual fruit crops were significantly higher than AE-N (27.3 kg kg^{-1}), AE-P (20.3 kg kg^{-1}), and AE-K (17.0 kg kg^{-1}) of perennial fruit crops. The AE-N, especially AE-P and AE-K of deciduous fruit crops, was slightly higher than that of evergreen fruit crops. Meanwhile, the AE-N, AE-P, and especially AE-K of fruit crops in south China were lower than that of fruit crops in north China. The dataset also showed that the average AE-N (28.6 kg kg^{-1}) of fruit crops after 2000 was lower than that before 2000, meanwhile the AE-P and AE-K also showed a declining trend over time (Figure 8).

3.4. Partial Factor Productivity of Fertilizer in Fruit Crops in China

The dataset showed that partial factor productivity of nitrogen (PFP-N), phosphorus (PFP-P) and potassium (PFP-K) in China's fruit crops were 129 with CI of 115–144 kg kg^{-1}, 205 with CI of 180–227 kg kg^{-1}, and 133 with CI of 114–152 kg kg^{-1}, respectively (Figure 9). The results also showed that PFP was varied between groups (Figure 10). The average value PFP-N (222 kg kg^{-1}), PFP-P (382 kg kg$^{-1)}$, and PFP-K (277 kg kg^{-1}) of annual fruit crops were significantly higher than that of perennial fruit crops ($p < 0.01$). The average values of PFP-N, PFP-P, and PFP-K of fruit crops after 2000 were 185, 338, and 208 kg kg^{-1}, respectively, all of them were smaller with less variation than those before 2000. In addition, there was no significant difference between evergreen and deciduous groups, or regions (north vs. south China).

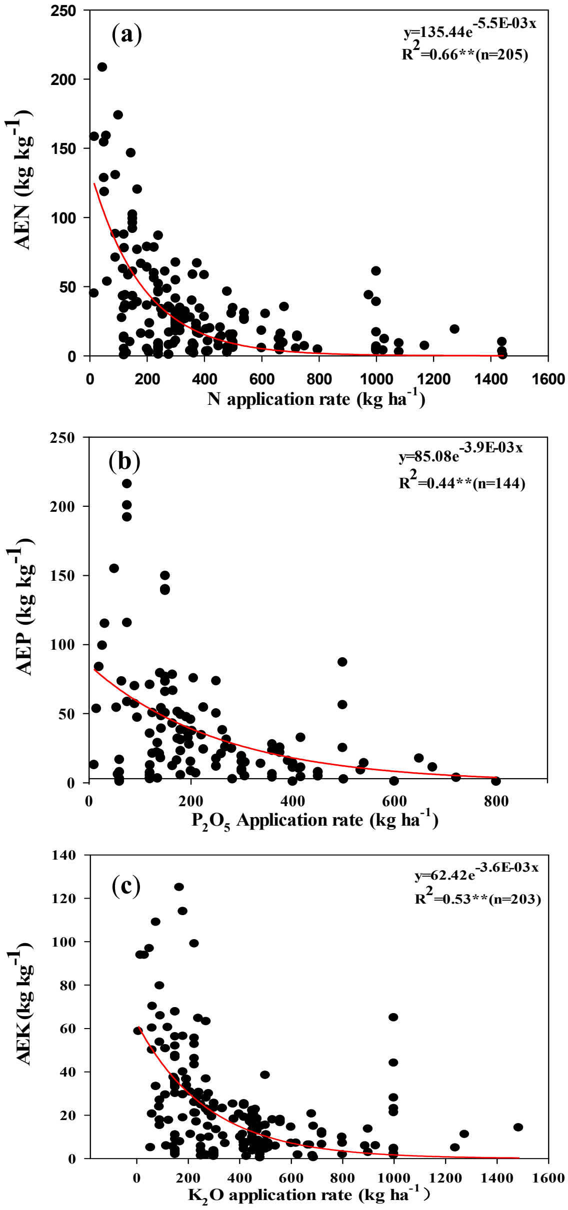

Figure 7. Relationships between fertilizer application rate of nitrogen (N) (**a**), phosphorus (as P_2O_5) (**b**) or potassium (as K_2O) (**c**) and their agronomic efficiency under optimal fertilization conditions collected from 293 research articles. In the regression model, y is the agronomic efficiency, x is the N, P_2O_5, and K_2O application rate, respectively. Significance of regression coefficients and intercepts was determined with a F-test ($p < 0.05$). The number of data points was given in each equation.

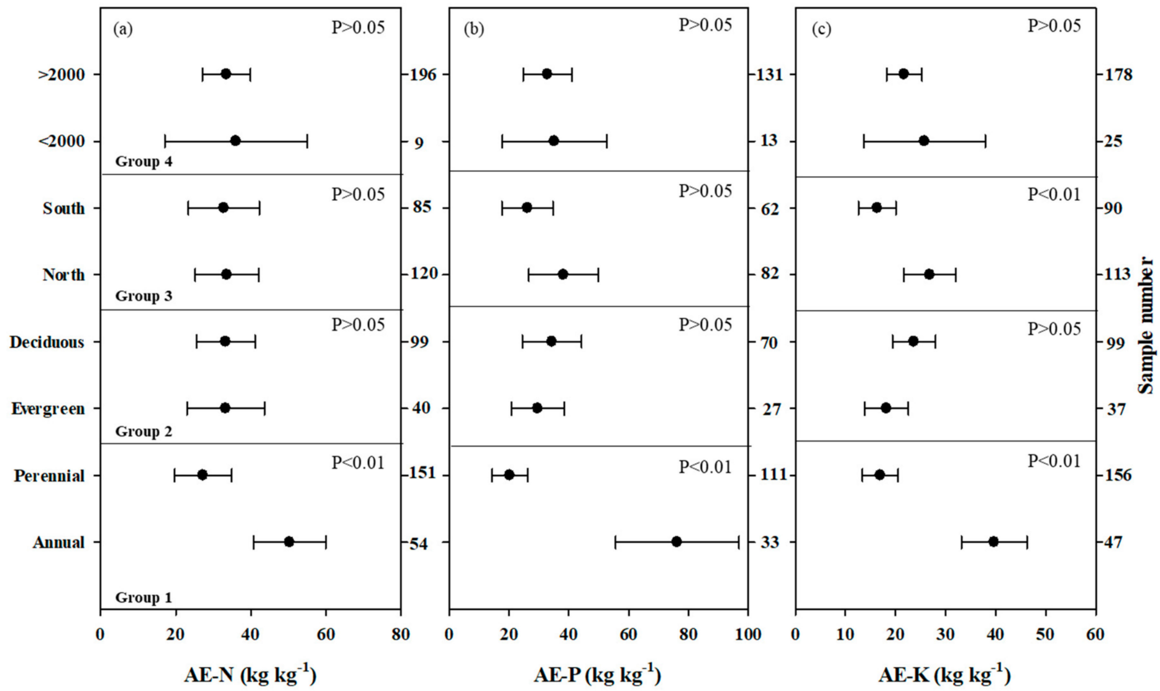

Figure 8. Agronomic efficiency (AE) of nitrogen (N) (**a**), phosphorus (P) (**b**) or potassium (K) (**c**) application rate of China's fruit crops under optimal fertilization conditions collected from 293 research articles. Box circles indicate means, and the horizontal lines on the left and right sides represent the upper and lower limits of the 95% intelligence interval. Each group of data was determined with an F-test ($p < 0.05$).

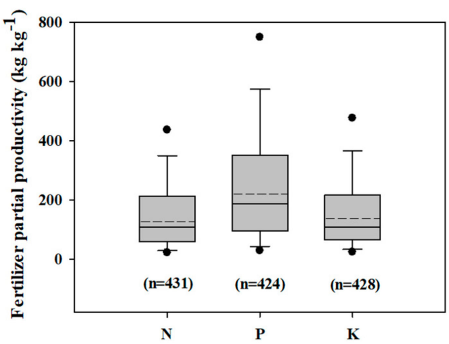

Figure 9. Partial factor productivity of nitrogen (N), phosphorus (P), and potassium (K) fertilizer in China's fruit crops under optimal fertilization conditions collected from 293 research articles. Black solid and dotted lines indicate medians and means, respectively. Box boundaries indicate upper and lower quartiles, whisker caps indicate 95th and 5th percentiles, and circles indicate outliers. The number of data points was given below each box.

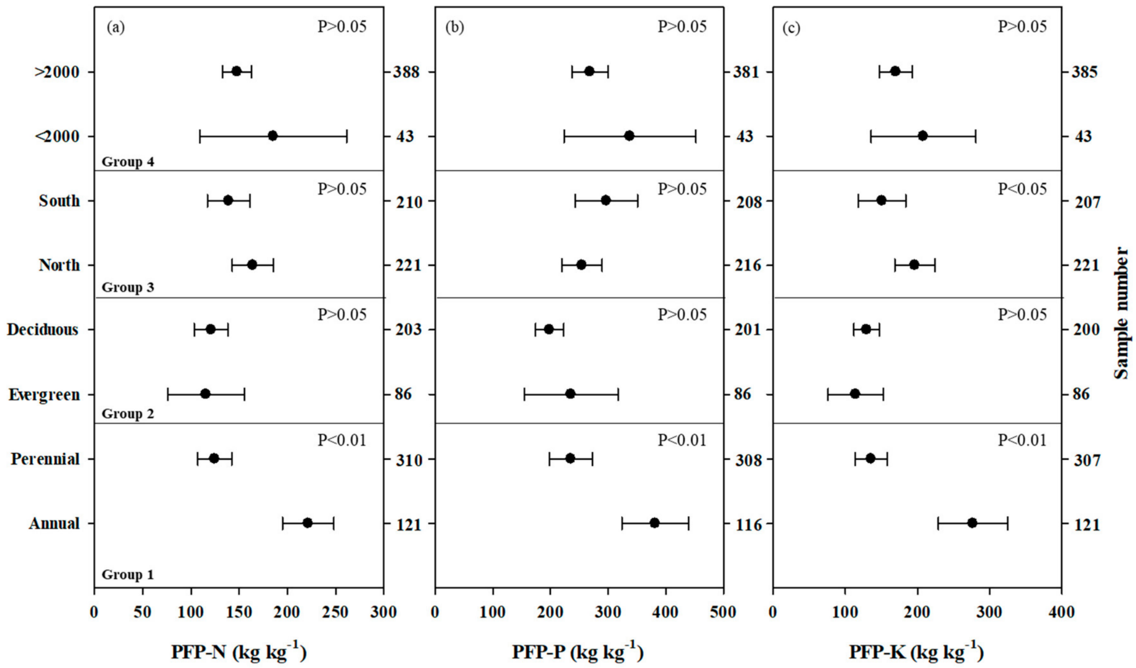

Figure 10. Partial factor productivity (PFP) of nitrogen (N) (**a**), phosphorus (P) (**b**) and potassium (K) (**c**) fertilizer in China's fruit crops under different groups at optimal fertilization conditions collected from 293 research articles. Box circles indicate means, and the horizontal lines on the left and right sides represent the upper and lower limits of the 95% intelligence interval. Each group of data was determined with a F-test ($p < 0.05$).

4. Discussion

4.1. Agronomic Response of Fruit Crops in China to Fertilization

Yield response showed the direct effect of fertilization on yield increase and nutrient limitation on yield. The yield differences in a given fruit crop were related to climatic conditions, soil type, soil texture, fertilization and cultivation management measures [18,19]. The results showed that the average rank of yield response in China's fruit crops were YR-N, followed by YR-K and YR-P (Figure 2a). This indicated that N was the primary nutrient limiting factor for fruit crop production, which was similar for cereal crops such as corn and rice [39]. This study also showed that the RY-N of fruit crops in China was lower than the RY-P and RY-K (Figure 2b), indicating that it could be more challenging to increase soil N supply capacity due to multiple pathways of N loss [9,24]. Different crop types, growing areas, and tested years would also affect the relative yield of crops [40,41]. The RY-N, RY-P, and RY-K of deciduous fruit crops were significantly higher than those of evergreen fruit crops (Figure 3). The major reason for this would be that deciduous fruit crops had a stronger capacity to store and reuse N, P, K and other nutrients than evergreen fruit trees [42]. An additional explanation was that more litter of deciduous fruit crops could be decomposed in the soil, which increased soil nutrients and thus resulted in higher RYs [43,44]. Results showed that perennial fruit crops had RYs similar to that of annual fruit crops (Figure 3), but much higher input of NPK fertilizers (Figure 5). It was agreed with previous studies that perennial fruit crops required more nutrients to maintain the growth and reproduction of the shoot and root parts than the annual fruit crops did [44], although the yield of annual crops (watermelon and melons) were generally higher than that of perennial crops [45,46].

As a result of the different climatic characteristics, natural environment and farming habits, effects of fertilization on yield were different [47,48], which resulted in a difference in RYs of fruit crops between the north and south of China (Figure 3). On the one hand, the soil in the south was mostly brick red soil, red soil, and yellow soil, and most of the brown soil, dark brown soil, black soil, and chernozem soil in the north [49]. Thus, the difference of fertility between the north and the south was due primarily to difference in soil parent materials. On the other hand, there are heavy rainfalls with serious nutrient loss in the southern region, where the soils are becoming less fertile than that in the northern region. In recent years, as the amounts of fertilization in fruit crops were increased [3], there was a gap of fertilization rates between the north and south China (Figure 5), which could contribute to the difference of RYs between these two regions. Furthermore, the RY-N, RY-P, and RY-K of fruit crops after 2000 were higher than those of fruit crops before 2000 (Figure 3), which were similar to the results of rice, corn, and wheat [41,50]. Soil nutrient levels were built up due to continuous overuse of fertilizer over last four decades [51–53], thereby increasing the relative yield of the fruit crops in China. Meanwhile, long-term continuous planting of the same fruit crops was prone to "continuous cropping obstacles", such as abnormal accumulation of soil nutrients and imbalance of microbial population structure, which ultimately affected fruit yield [54]. Taken together, it is necessary to quantify the soil indigenous nutrient supply (as indicated by RY) to follow-up fertilizer management in fruit crops for higher yield and nutrient use efficiency.

4.2. Nutrient use Efficiency of Fruit Crops in China

Nutrient use efficiency had always been one of the focuses in public, government and research communities [55,56]. Studies on fruit crops showed that use efficiency of N, P, and K fertilizers were negatively correlated with the fertilizer rates [57,58]. As stated earlier, the phenomenon of excessive and imbalanced fertilization by farmers was widespread in China, resulted in low fertilizer use efficiency of crops. Imbalanced and excessive fertilization had severe negative impacts on the environment [6,59,60]. Agronomic efficiencies were positively correlated with yield response and negatively correlated with fertilization rate [40]. Partial factor productivity was related to the fertilization amount and yield of fruit crops [61,62]. Over time, the accumulating application of fertilizers in the fruit crops resulted in a decline in agronomic efficiency. The dataset indicated that the average AE-N, AE-P, and AE-K in China's fruit crops were lower than 30 kg kg^{-1} (Figure 6), which was much lower than that of 46.9 kg kg^{-1} in 2003 [2]. In addition, the results also showed that the PFP of N, P, and K fertilizer ranged from 129 to 205 kg kg^{-1} in China's fruit crops (Figure 9), which was lower than in the developed countries, but higher than the developing countries [3,63].

Agronomic efficiency and partial factor productivity were not only related to fertilization rate but also to soil indigenous nutrient supply, crop types, and regions [17]. Lower fertilization rates were applied to deciduous fruit crops, which had higher relative yield than evergreen fruit crops (Figure 5), thus resulting in similar AE and PFP (Figures 8 and 10). These results were consistent with previous studies showing that evergreen fruit crops had higher photosynthesis, and higher carbon recovery rates per unit nutrient input, thus providing a higher nutrient inner utilization than that in deciduous fruit crops [64]. Besides, the nutrient utilization efficiency of perennial and annual crops were also different [65]. In this study, the AE and PFP of perennial fruit crops were significantly lower than those of annual fruit crops (Figures 8 and 10), due to the higher application rate of N, P, and K fertilizer in perennial fruit crops (Figure 5). Moreover, perennial fruit crops generally had a higher nutrient utilization rate compared to annual fruit crops because the former crops have xylem stored nutrients, prolonged growth and development stages, and dense distribution of roots [66,67]. Thus, the projected AE and PFP of perennial fruit crops in China's fruit crops could be doubled through a decrease of fertilizer input and a yield increase in the future. For example, as the world's largest citrus producer, the current average PFP-N in China's citrus orchards was 55 kg kg^{-1}, which could be increased to 133–275 kg kg^{-1} under reduced fertilizer input and a higher yield [63]. Similarly, the N use efficiency of apple orchards in China could be increased from current 3.8% to 14.7–22.3% through fertigation and more effective cultivation practices to reduce production constraints [68].

Previous studies had shown that the total nitrogen and soil organic matter in southern China had increased in recent years, while the northern soil had the opposite trend [49]. Soil organic matter may affect relative yield, leading to differences in agronomic efficiency of fruit crops between the north and south China (Figures 8 and 10). In addition, soil K supply capacity of soil samples across

China was studied by soil available K and slow-released K that determined by national standard methods (available K was determined in the 1.0 mol L^{-1} ammonium acetate (NH_4OAc) extract of the soils in a 1:10 soil-solution ratio. Slow-released K in soil was determined from the difference between the boiling 1.0 mol L^{-1} nitric acid (HNO_3)-extractable K and 1.0 mol L^{-1} NH_4OAc-extractable K. The determination of K in soil samples was performed using a flame photometer); results had shown that soil K supply capacity decreases geographically from north to south in China [47]. This would be the major reason that K application rate in north China is lower than in south China (Figure 5). Thus, the low K application rate is related to the higher AE-K and PFP-K of fruit crops in north China than that in south China (Figures 8 and 10). In addition, studies had shown that a high relative yield would indicate a high soil indigenous nutrient supply [15], thus PFP of fertilizer is projected to increase on croplands with high soil indigenous nutrient supply as indicated by relative yield (Figure 3). However, it was noticeable that the PFP of N, P, and K fertilizer showed declining trend over time (Figure 10). Similar results were also reported in vegetables crops in China [3]. The major reason for this would be the continuously increasing fertilizer input (Figure 5), although most data were obtained from research articles published by agricultural extension experts or researchers who are expected to use less fertilizer than farmers [Table S1]. As mentioned above, soil nutrients were built up due to continuous overuse of fertilizer in soils after 2000 [51–53], resulting a higher soil indigenous nutrient supply than that soils before 2000 [69]. Therefore, it is time to reduce fertilizer input of fruit crops to soils with higher soil fertility, as well as to other crops [3,21,23].

4.3. Uncertainties

This study was based on 552 paired data for agronomic response and 1283 sets for amounts of optimal fertilization from 293 field studies of fruit crops across China. The field experiments included nutrient-limited yield as the control treatments. Other treatments were the yield under optimal management practices. These experiments were used to quantify the agronomic response of Chinese fruit crops, so as to provide a basis for establishing the NE nutrient recommendation method and nutrient management for fruit crops. This study pointed out that agronomic response was affected by crop types, planting areas, or year of trials. However, the yield response and nutrient use efficiency could also be affected by pests, pruning and other measures [70,71], although the variation of these measures was minimized by the same management under different treatments in these studies.

5. Conclusions

This is probably the first whole research article to show the agronomic response of fruit crops to fertilization in China, which is the biggest fruit producer and biggest fertilizer consumer in the world. The findings indicated that N was still the primary limiting factor for fruit production in China as well as in other countries. Average RYs to N, P or K fertilization in studies after 2000 were higher than that before 2000. These results illuminated that soil indigenous nutrient supply, as indicated by relative yield, was enhanced due to continuous fertilization and improving cultivation management (varieties, pest control, irrigation, etc.) over the last four decades in China, and thus contributed more to final fruit yields. The findings also revealed large differences in agronomic responses among grouping studies including fruit types, regions, and year of trials. These results would be helpful for developing nutrient management for given fruit crops at site or regional level. The findings further showed that the average AE of N, P, and K fertilizer were negatively correlated with fertilizer rate in fruit crops and the PFP of N, P, and K fertilizer had a declining trend over time. Thus, it is urgently necessary to reduce fertilizer input of fruit crops to soils with higher soil fertility as well as other crops. Overall, a rational nutrient management is therefore even more crucial for balancing yield and environmental concern in countries like China, India and other countries where fertilizers are generally overused.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/1/15/s1, Figure S1: Distribution of experiment sites in different fruit-producing regions of China; Table S1: Reference Appendix for meta-analysis.

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