



## Article

# The Thresholds and Management of Irrigation and Fertilization Earning Yields and Water Use Efficiency in Maize, Wheat, and Rice in China: A Meta-Analysis (1990–2020)

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**Abstract:** The increases in crop yield in China are linked to massive increases in fertilizer and water input, which have also accelerated the degradation of soil and environmental pollution. Nevertheless, the long-term changes in crop yield and water use efficiency (WUE) of three major cereals (maize, wheat and rice) in response to field management practices are rarely reported. This meta-analysis evaluated the effect of field management (nitrogen input (N), irrigation, fertilizer type, fertilization frequency, and irrigation method) on crop yield and WUE between 1990 and 2020 based on 3152 observations. We found that the N thresholds for maize, wheat, and rice were 150–200 kg ha<sup>-1</sup>, 140–210 kg ha<sup>-1</sup>, and 90–135 kg ha<sup>-1</sup>, respectively. N fertilization within the threshold levels increased the crop yield and WUE of maize (84% and 74%), wheat (47% and 41%), and rice (55% and 30%). The irrigation (mm) thresholds for maize and wheat were 180–240 mm and 300–400 mm and crop yield and WUE were increased by 37% and 13% for maize and by 84% and 41% for wheat. Agricultural management increased yield and WUE (% and %) through drip irrigation (23 and 13 maize; 31 and 14 wheat), alternate wetting and drying (AWD) (26 and 30 rice), split fertilization (31 and 21 maize; 64 and 40 wheat; 33 and 25 rice) and organic–inorganic fertilizer (43 and 39 maize; 68 and 66 wheat; 38 and 34 rice). With the increase in HI (humidity index) from 10 to 30, the contribution of irrigation to WUE decreased, but that of fertilization increased. This study concludes that N fertilizer and irrigation applications between threshold levels along with suitable field management is a win–win strategy to achieve climate-smart agricultural production with minimum damages to soil and environment and at lower dependence on fertilizer and irrigation.

**Keywords:** fertilization; irrigation; field management; yield; water use efficiency; meta-analysis



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## 1. Introduction

Being the world's most populous country (1.4 billion people), China has an enormous demand for food [1]. With the rapid development of China's economy, the demand for water resources is increasing [2]. China feeds 21% of the world's population with only 6% of the world's total water resources [3]. Currently, China's per capita water resources only make up 2100 m<sup>3</sup>, which is less than one-third of the world's per capita water resources, ranking 127th worldwide [4]. Water shortages have threatened China's food security [5,6]. Population growth, ongoing global warming and accelerating climate change have exacerbated the decline in water levels [7]. Therefore, to achieve food security, the emphasis should be on producing more food with less water, which is only possible

with the adoption of better field and nutrient management practices [8]. Synthetic nitrogen fertilizers have played an integral role in increasing crop yields and meeting the needs of a growing population [9]. Every ton of N fertilizer manufactured and used in China emits 13.5 tons of CO<sub>2</sub>-equivalent (eq) (t CO<sub>2</sub>-eq), compared with 9.7 t CO<sub>2</sub>-eq in Europe, based on the carbon footprint of China's N fertilizer production and consumption chain. Fertilizer-related emissions accounted for 7% of greenhouse gas emissions from the entire Chinese economy, which exceeds the soil carbon gains by several-fold, resulting from N fertilizer use [10]. Meanwhile, inefficient water utilization severely affects crops yield and nutrient losses which altogether impairs soil health and environmental sustainability [11–13].

Water use efficiency (WUE) (crop productivity per unit of water) is a key factor for determining the efficiency of water use by crops [14,15]. The plant WUE is a complex trait controlled by several factors, from genetic-level to field management [16,17]. Over recent decades, numerous studies have reported the effects of field management practices on WUE in various cereals [18–20], which has improved our understanding of the underlying mechanisms. Liu et al. (2004) studied the relationship between fertilizer type, soil nutrition and maize yield in the North Plain, and reported that maize yield and soil nutrients with organic–inorganic mixed fertilizer were the highest among all the fertilizer treatments [21].

Fertilization and irrigation are two vital factors of agronomic production for most crop species [22–24]. Studies on irrigation covered a variety of topics, such as: irrigation method [25,26], irrigation regimes [27,28], and irrigation amount [29–31]. Under limited water supply conditions, fertilization play a very important role in enhancing WUE. Just like irrigation, fertilization includes many topics such as: fertilizer type [32,33], fertilization frequency [34,35], and fertilizer amount [36]. In China, the effects of fertilization or irrigation for crop yield and WUE on maize, wheat, and rice have been well documented. For example, manure application increased yield by 7.6% (8.5–14.2 kg ha<sup>-1</sup>) compared to mineral fertilizer based on 153 field experiments in China [32]. The previous studies on the interaction of WUE and field management practices were usually conducted on a small scale and showed contradictory results. Di Paolo and Rinaldi (2008) reported that supplementary irrigation increased maize WUE by 45–56% compared to non-irrigation [37]. Hernández et al. (2015) reported that, under low N input, maize WUE with irrigation was 3–23% lower than non-irrigation [38]. Fan et al. (2005) reported that wheat yield with fertilizer and manure input declined by 77–81 kg ha<sup>-1</sup>, and WUE declined 0.1–0.3 kg ha<sup>-1</sup>mm<sup>-1</sup> more than the control [39]. Cao et al. (2021) reported that N input increased crop yield by 105–118% more than non-fertilization [40]. Fertilization or irrigation can decrease or increase crop yield and WUE, which are further affected by several other factors: (i) environment (climate and soil) and (ii) management practices (N input (kg ha<sup>-1</sup>), fertilizer type, fertilization frequency, irrigation (mm), and irrigation method).

Numerous studies have reported the effects of field management on crop yield and WUE for individual crops or for various crops in a particular region [41–44]. There is lack of large and complete datasets to quantify crop yield and WUE for three main cereal crops (maize, wheat, and rice) and their responses to various management practices at the country scale in China. We integrated the available data from different sources to evaluate the yield and WUE of main crops from 1999 to 2020.

In our study, a meta-analysis was used to assess the effects of field management (N input (kg ha<sup>-1</sup>), irrigation (mm), fertilizer type, fertilization frequency, and irrigation method) on crop yield and WUE for maize, wheat and rice in China. We hypothesize that, (1) with regard to crop yield, WUE is greatly affected by field management (fertilizer type, fertilization frequency, and irrigation method); (2) environmental conditions can dramatically affect the intensity of the above factors; and (3) some important thresholds and indices of irrigation and N input amount will be identified, which could be used by producers as guidelines for managing field crop production in the future.

## 2. Materials and Methods

### 2.1. Data Compilation

In this meta-analysis, peer-reviewed publications were identified from ISI Web of Science and China Knowledge Resource Integrated Database between 1990 and 2020. Nine keywords and different combinations of these words, “maize, wheat, rice, nitrogen, fertilization, water input, irrigation, yield, and water use efficiency”, were used to search the databases mentioned above. The following criteria were used to select appropriate papers: (1) field studies of fertilization or irrigation experiments performed in China (pot experiments or model simulations were excluded); (2) the field studies consisted of a control treatment, without irrigation or fertilization; (3) WUE ( $\text{kg ha}^{-1} \text{mm}^{-1}$ ) was calculated as a ratio of crop yield ( $\text{kg ha}^{-1}$ ) to water consumed, including the amount of water lost as evapotranspiration (mm) in the growing season [45–47]; (4) the field experiment had at least two sample sizes and the experiment was carried out for more than two years; and (5) the mean value and sample size of crop yield or WUE were available in the paper or can be calculated. Based on above criteria, finally, 191 publications including 3152 observations were selected for this meta-analysis.

To evaluate how field management influences the crop yield and WUE, we classified it into three categories: (i) fertilizer, which was sub-categorized into N input amount ( $\text{kg ha}^{-1}$ ), fertilization type, and fertilization frequency; (ii) irrigation, which includes irrigation amount (mm) and irrigation method; and (iii) humidity index ( $\text{HI} = \text{MAP}/(\text{MAT} + 10)$ ). HI was used as a climatic factor [48] and was divided into four groups: (a)  $\text{HI} < 10$ , (b)  $10 \leq \text{HI} < 20$ , (c)  $20 \leq \text{HI} < 30$ , and (d)  $\text{HI} \geq 30$ , which represent arid, semi-arid, semi-humid, and humid air conditions, respectively [49]. In addition to this, climatic conditions, such as the mean annual temperature (MAT), mean annual precipitation (MAP) and geographical location were also extracted from these original studies. We digitized graphs with the Get Data Graph Digitizer to extract data from publication. Lacked meteorological data were extracted from the National Centers for Environmental Information database based on the reported location.

### 2.2. Meta-Analysis

The response ratio (R) was adopted to evaluate the impact of field management on crop yield and WUE. R was calculated as a ratio of the treatment value ( $X_t$ ) to the corresponding control value ( $X_c$ ). The effect size was the natural logarithm-transformed value of R, which can improve statistical behavior for the meta-analysis [50].

$$R = \frac{X_t}{X_c} \quad (1)$$

$$\ln R = \ln \left( \frac{X_t}{X_c} \right) = \ln X_t - \ln X_c \quad (2)$$

where  $X_t$  is the mean crop yield or WUE of the field management treatment, and  $X_c$  is the mean value from the corresponding control.

The results are expressed as percentage change by using a conversion equation.

The conversion equation is [48]:

$$\% \text{ change} = \left( e^{\ln R} - 1 \right) \times 100 \quad (3)$$

More than 70% studies in our database did not report standard deviation, but all had replications. Therefore, replication-based weighting was used. This was widely used in recent meta-analyses and can avoid extreme weightings [51,52].

$$W = \frac{n_t n_c}{n_t + n_c} \quad (4)$$

where  $n_t$ ,  $n_c$  are the number of replicates for the treatment and control, respectively.

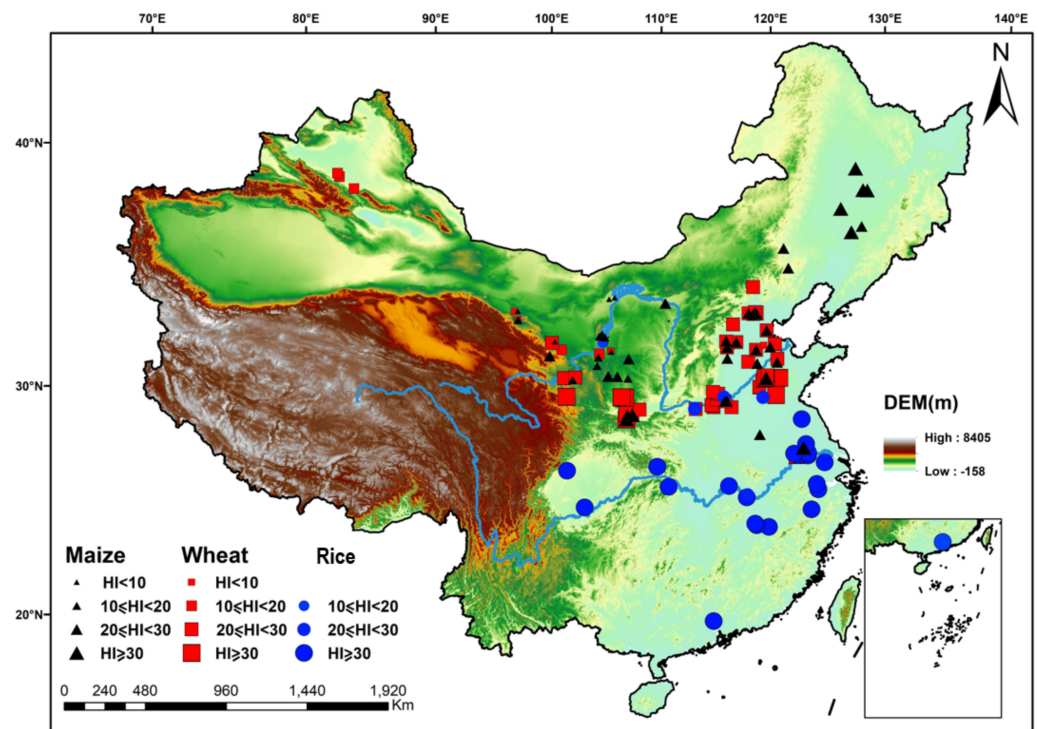
A categorical random-effect model was used to calculate the mean effect size (d++) for each group and 95% confidence intervals (CIs) of effect size were generated by a bootstrapping procedure with 4999 iterations. All the relevant calculations were performed in Metawin 2.1. The crop yield and WUE of field management were considered significantly different when 95% CIs did not overlap with zero. Further, a positive percentage change presented that the field management treatment increased crop yield and WUE compared to control, whereas a negative change indicates a decreased crop yield and WUE.

### 2.3. Statistical Analysis

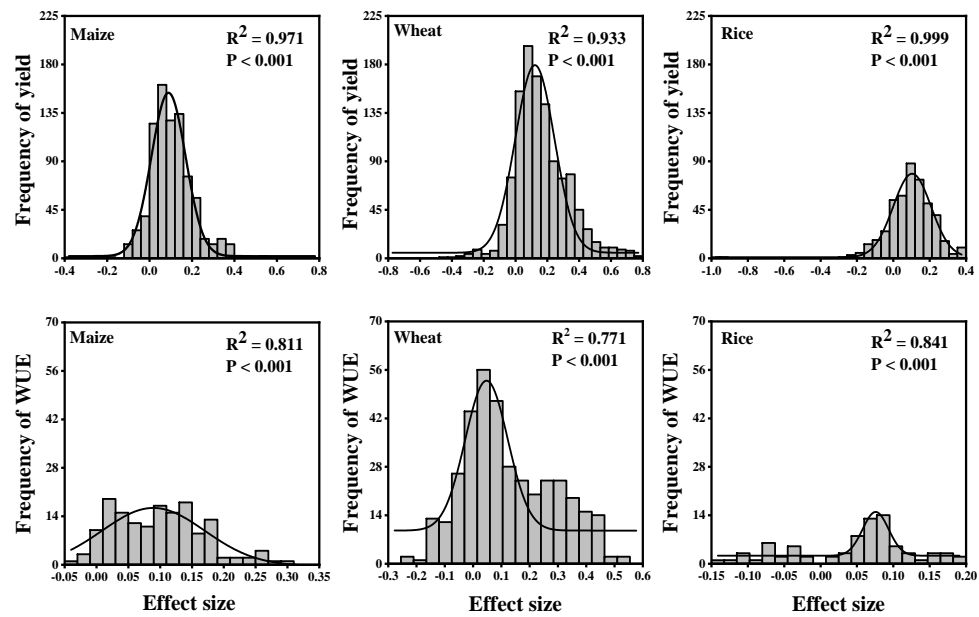
The frequency distribution of the effect sizes of crop yield and WUE met the requirement of Gaussian normal distribution for maize, wheat, and rice. Non-linear curve fitting (Gaussian normal distribution) was used to visualize the relationship between the frequency distributions of crop yield, WUE (maize, wheat, and rice) and effect size. Meanwhile, non-linear curve fitting was applied to evaluate the relationship of fertilization ( $\text{kg ha}^{-1}$ ) or irrigation (mm) to crop yield and WUE (maize, wheat, and rice). A combination of “gbm”, “dismo”, “survival”, “lattice”, “splines”, “parallel”, “raster” and “sp” packages were used in the R programming environment (Team, 2018) to calculate the contribution of fertilization ( $\text{kg ha}^{-1}$ ), irrigation (mm), and HI to crop yield and WUE. All graphs were prepared in Origin (version 9.0).

### 2.4. Meta-Data Overview

The data collected for this study represent different climatic zones and crop systems (maize, wheat, and rice) with variable changes in HI (Figure 1). Our dataset contained 191 studies, including 2466 observations for crop yield and 686 observations for WUE. The frequency distributions of effect sizes among all studies met the criteria for Gaussian normal distribution, indicating that the datasets were homogeneous (Figure 2).



**Figure 1.** Fertilization or irrigation distribution of field experiment locations for maize, wheat, and rice in this meta-analysis in 1990–2020 ( $n = 151$ ). Note: HI, humidity index =  $\text{MAP}/(\text{MAT} + 10)$ . The digital Elevation Model (DEM) is a digital simulation of the terrain by using limited terrain elevation data. The symbols represent HI and differ in size.

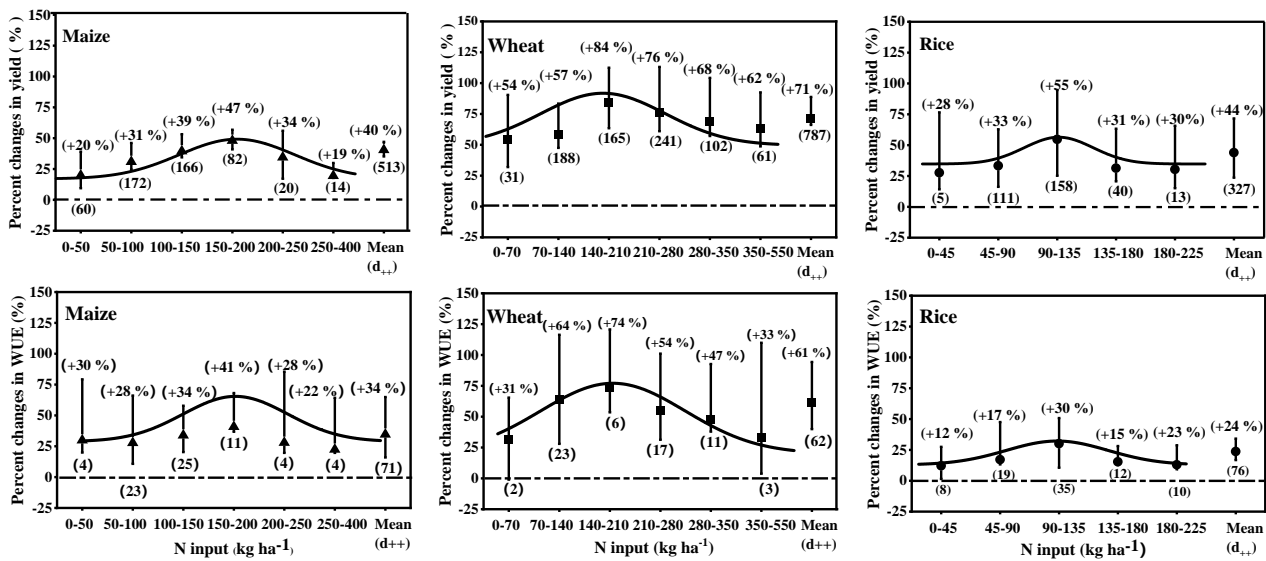


**Figure 2.** Frequency size distribution of effect sizes for crop yield and WUE of maize, wheat, and rice. The solid lines are normal (Gaussian) distributions fitted to frequency datasets.

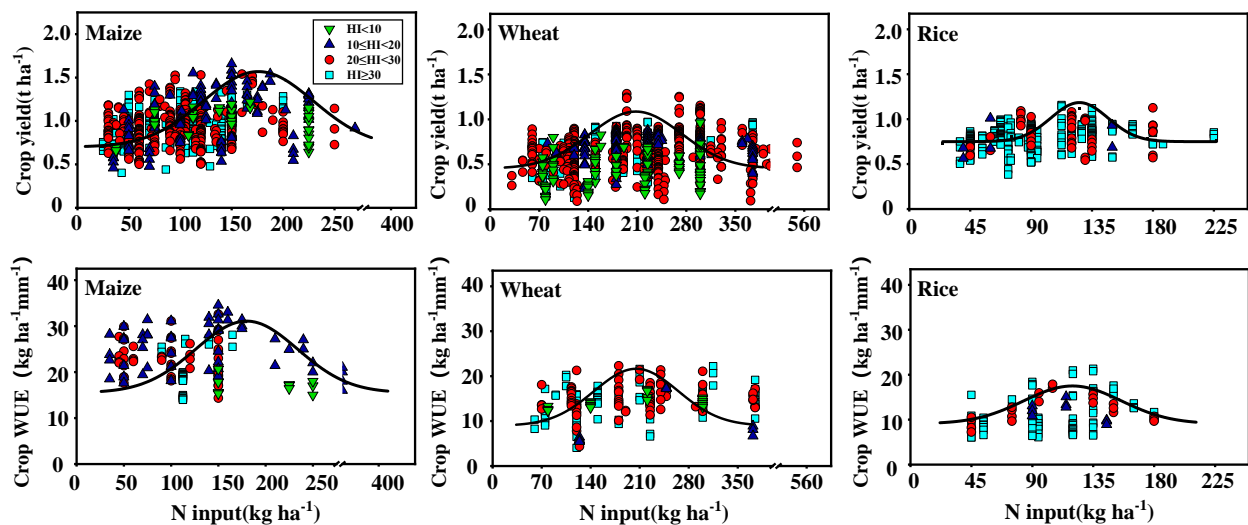
### 3. Results

#### 3.1. Response of Crop Yield and Water Use Efficiency to Fertilization

The application of N fertilization strongly influenced crop yield and WUE, which followed a similar pattern of gradually increasing with increases in N input, reaching the peak and then gradually decreasing (Figure 3). The optimal amount of N for maize was between 150 and 200 kg ha<sup>-1</sup>, with the potential of significantly increasing yield by 47%, and enhancing WUE by 41%. The increases in yield and WUE were the highest at 10 ≤ HI < 20, with the maximum yield of 16,578 kg ha<sup>-1</sup> (+5621 kg ha<sup>-1</sup>) and WUE of 35 kg ha<sup>-1</sup>mm<sup>-1</sup> (+13.2 kg ha<sup>-1</sup>mm<sup>-1</sup>). The optimal N amount for wheat was between 140 and 210 kg ha<sup>-1</sup>, increasing the yield by 84%, and enhancing WUE by 74%. The increases in yield and WUE were the highest at 20 ≤ HI < 30, with the maximum yield of 13,309 kg ha<sup>-1</sup> (+4270 kg ha<sup>-1</sup>) and WUE of 22 kg ha<sup>-1</sup>mm<sup>-1</sup> (+6.5 kg ha<sup>-1</sup>mm<sup>-1</sup>). The optimal N amount for rice was between 90 and 135 kg ha<sup>-1</sup>, increasing the yield by 55%, and enhancing WUE by 30%. The increases in yield and WUE were the highest at HI > 30, with the maximum yield of 11,971 kg ha<sup>-1</sup> (+3434 kg ha<sup>-1</sup>) and WUE of 22 and (+2.8 kg ha<sup>-1</sup>mm<sup>-1</sup>) (Figures 3 and 4).



**Figure 3.** Percent changes in crop yield and WUE according to N input (kg ha<sup>-1</sup>), expressed as the mean value with bias-corrected 95% confidence intervals. Percentage change and observation numbers for each group are given in parentheses. The solid lines are fitted by non-linear regression model to percent changes datasets. Triangles represent field experiment of maize, squares represent field experiment of wheat, and circles represent field experiment of rice.

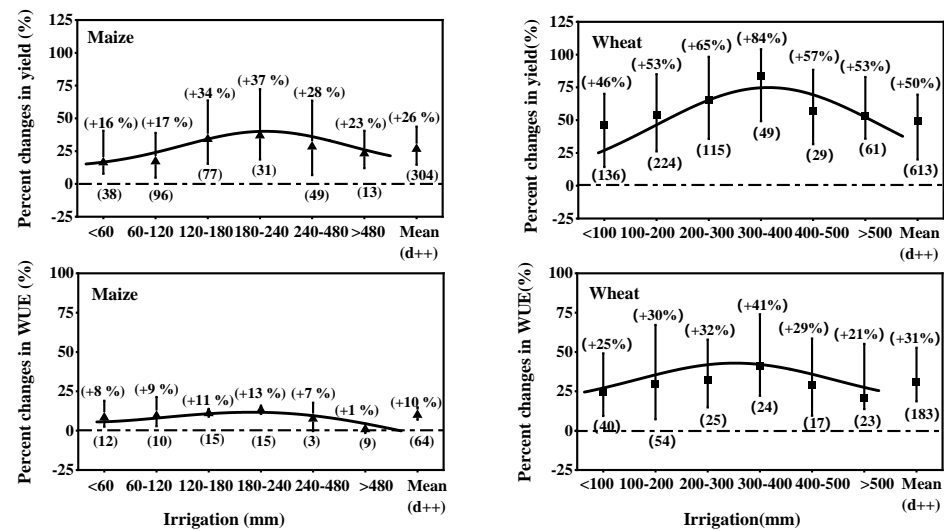


**Figure 4.** The crop yield and WUE according to N input (kg ha<sup>-1</sup>). The solid lines are fitted by non-linear regression model to yield and WUE datasets of maize, wheat, and rice. Triangles represent field experiment of maize, squares represent field experiment of wheat, and circles represent field experiment of rice. The color of symbol represents HI.

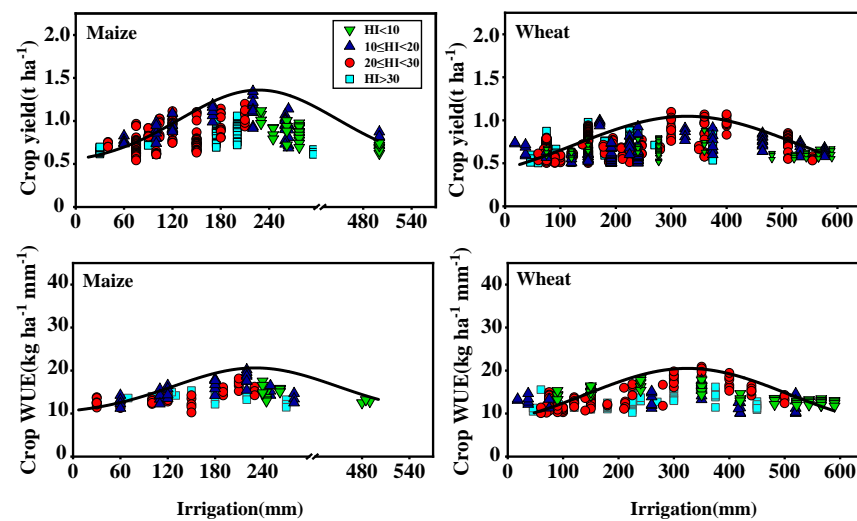
### 3.2. Response of Crop Yield and Water Use Efficiency to Irrigation

Irrigation increased maize and wheat yield on average by 26%, and 50% and WUE by 10% and 31% (Figure 5). Similar to the N input, irrigation followed the same pattern; crop yield and WUE increased with increases in the amount of irrigation, reaching a peak, and then decreased. The optimal amount of irrigation for maize was between 180 and 240 mm, where yield and WUE were increased by 37% and 13%, respectively. The yield and WUE reached a maximum at 10 ≤ HI < 20, with the maximum yield of 13,486 kg ha<sup>-1</sup> (+4842 kg ha<sup>-1</sup>) and WUE of 20 kg ha<sup>-1</sup>mm<sup>-1</sup> (+5.9 kg ha<sup>-1</sup>mm<sup>-1</sup>). The optimal irrigation amount for wheat was 300–400 mm, with the potential of significantly increasing the yield by 84% and enhancing WUE by 41%. The increases in yield and WUE were the

highest at  $20 \leq HI < 30$ , with the maximum yield of  $10,697$  ( $+3452 \text{ kg ha}^{-1}$ ) and WUE of  $21 \text{ kg ha}^{-1}\text{mm}^{-1}$  ( $+8.8 \text{ kg ha}^{-1}\text{mm}^{-1}$ ) (Figures 5 and 6).



**Figure 5.** Percent changes in crop yields and WUE according to irrigation (mm), expressed as the mean value with bias-corrected 95% confidence intervals. Percentage change and observation numbers for each group are given in parentheses. The solid lines are fitted by non-linear regression model to percent changes datasets. Triangles represent field experiment of maize and squares represent field experiment of wheat.

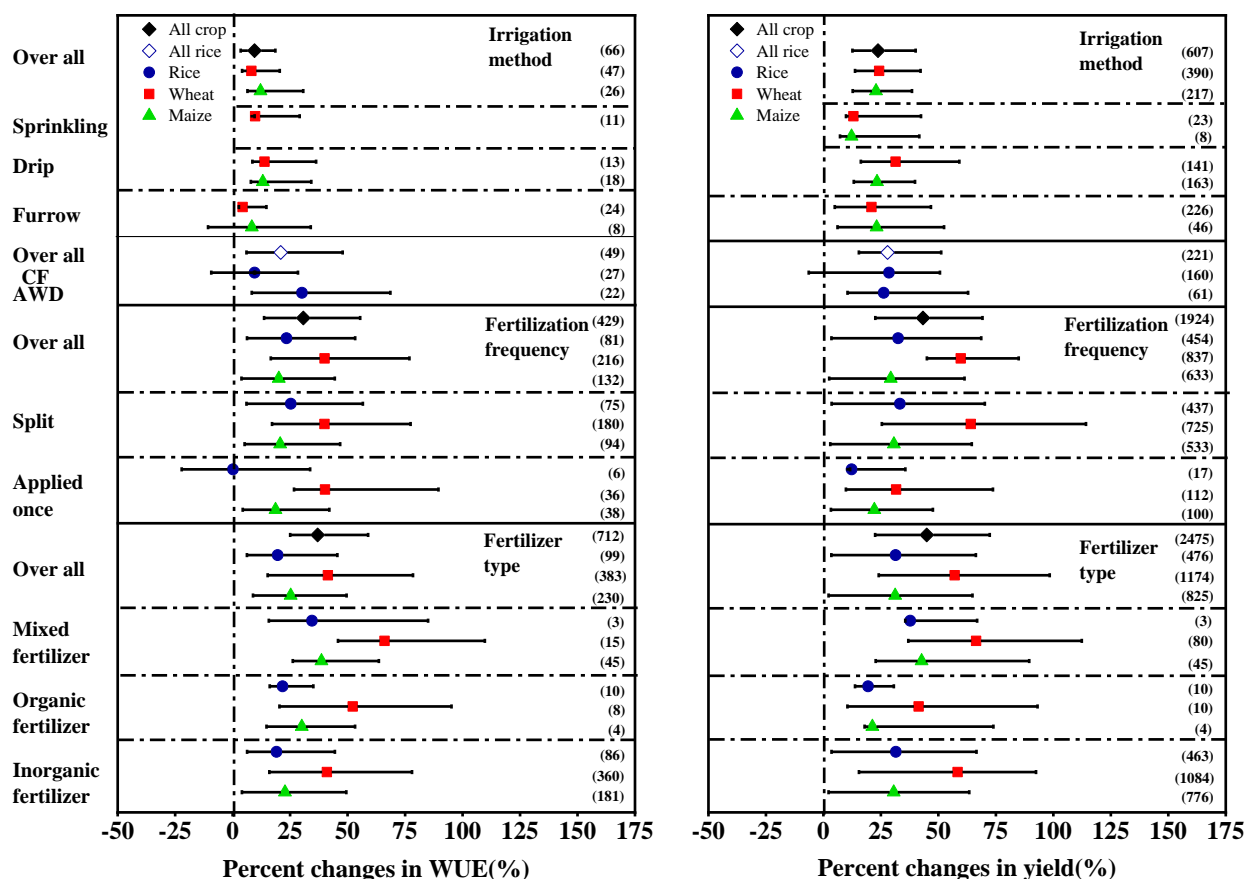


**Figure 6.** The crop yield and WUE according to irrigation (mm). The solid lines are fitted by non-linear regression model to yield and WUE datasets of maize and wheat. Triangles represent field experiment of maize and squares represent field experiment of wheat. The color of symbol represents HI.

### 3.3. Response of Crop Yield and Water Use Efficiency to Agricultural Practices

Crop yield and WUE were also greatly affected by management practices, such as the irrigation method, fertilization frequency and fertilizer type. Our results showed that irrigation increased crop yield and WUE under furrow, drip and sprinkling irrigation methods for maize and wheat, and under CF and AWD irrigation methods for rice (Figure 7). The drip irrigation system was the most effective in increasing yield and WUE, showing increases in maize by 23% and 13%, and by 31% and 14% in wheat. Alternate wetting and drying (AWD) decreased the rice yield by 5% compared to the continuously flooded (CF) condition, but it increased WUE by 216% (Figure 7). Fertilizer application all-at-once and in splits increased crop yield and WUE for maize, wheat and rice. Maize, wheat,

and rice yields were on average increased by 29%, 60%, and 32% under two fertilization methods, and they also increased WUE by 20%, 40%, and 23%, respectively, compared with no fertilization (Figure 7). The crop yields and WUE of maize (31% and 21%), wheat (64% and 40%), and rice (33% and 25%) were higher with split fertilizer applications than that of one-time sole application (Figure 7). All fertilization sources (organic, inorganic, and organic–inorganic mixed) on average increased the yields of maize, wheat, and rice by 31%, 57%, and 32%, respectively, and increased WUE by 25%, 41%, and 20%, respectively (Figure 7). Organic–inorganic mixed fertilizer was the most effective as it increased the crop yields of maize, wheat, and rice by 43%, 68%, and 38%, respectively, and WUE by 39%, 66%, and 34%, respectively.



**Figure 7.** Percent changes in crop yield and WUE according to agronomy practices (fertilizer type, fertilization frequency, and irrigation methods) of maize, wheat, and rice, expressed as the mean value with bias-corrected 95% confidence intervals. Observation numbers for each group are given in parentheses. Triangles represent field experiment of maize, squares represent field experiment of wheat, circles represent field experiment of rice, hollow diamonds represent average of rice field experiment, and black diamonds represent average of three crop field experiment of maize, wheat, and rice.

### 3.4. The Factors' Influence on the Crop Yield and Water Use Efficiency

Crop yield and WUE increased with field management practices under all levels of HI. The yields of maize, wheat, and rice were on average increased by 30%, 36%, and 29%, and WUE increased by 25%, 29%, and 13%, respectively, under four HI levels (Figure 8). Crop yields were at the minimum at lower HI (<10) and increased strongly with increases in HI, more notably in wheat and rice, while the increases in maize yield remained relatively constant, between 25 and 30%. At a higher HI level, the yields of wheat and maize decreased and were comparable to the yields observed at a lower HI (<10). A similar trend was observed for WUE. HI-derived increases in yield resulted in a higher WUE. Among



crops, WUE was higher in wheat and maize, and comparatively lower in rice. The HI levels of  $10 \leq HI < 30$  were suitable for maize and wheat in terms of a better yield and higher WUE. Because of the poor WUE in rice, it might require water even more than  $HI > 30$  to achieve maximum yield potential.

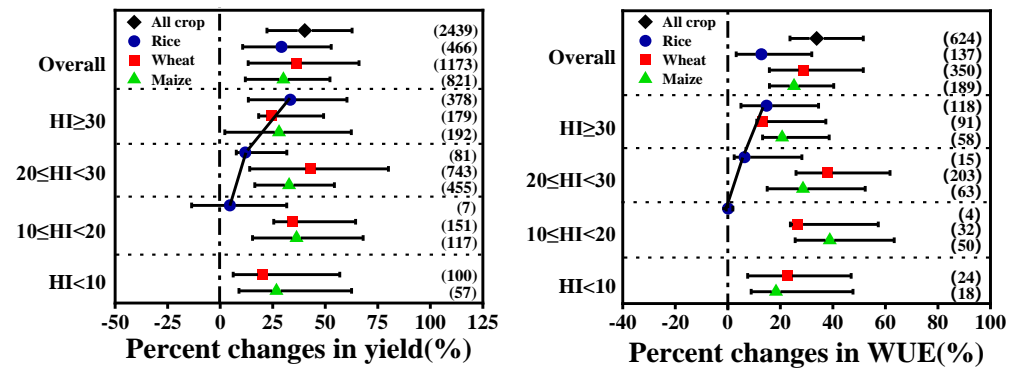


Figure 8. Percent changes in crop yield and WUE with field management practices under four levels of HI for maize, wheat, and rice, expressed as the mean value with bias-corrected 95% confidence intervals. Observation numbers for each group are given in parentheses.

The boosted regression tree analysis (BRT) showed that HI had the biggest effect on the effect size of crop yield and WUE compared to irrigation and fertilization (Figure 9). Overall, 97%–98% of the variations in the response ratio of crop yield and WUE could be explained by three factors (HI, irrigation amount, and fertilization amount). The magnitude order of the influence of these factors on yield and WUE was: HI (68%, 65%) > irrigation (21%, 22%) > fertilization (9%, 9%) (Figure 9). With increases in HI from 10 to 30, the contribution of irrigation (%) to WUE decreased (70–54 maize, 73–56 wheat, and 91–65 rice), while the contribution of fertilization (%) increased (29–44 maize, 24–42 wheat, and 7–33 rice). Irrigation contributions to yield (%) were higher when  $HI < 10$  (80–95) and it was the limiting factor for rice cultivation (75–96).

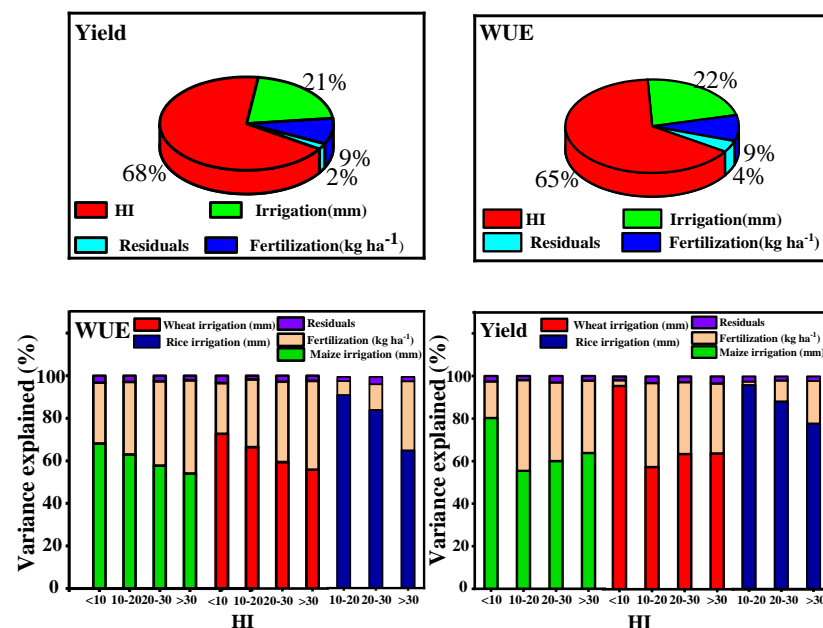


Figure 9. Significance of explanatory variables for the response of crop yield and WUE of maize, wheat and rice according to BRT (boosted regression tree) analysis.

## 4. Discussion

### 4.1. N Input Threshold for Higher Crop Yield and Water Use Efficiency

Crop yield and WUE increased with N input and then decreased with excessive N input. These responses might be due to several factors: (i) the optimum N input ensures the nutrient supply and the growth of the lateral roots and increases root quality, which promotes the absorption of water and other essential nutrients in the root zone [53], thereby increasing crop yield. (ii) An excessive input of N fertilizer reduces microbial activity, induces acidification, and impairs biochemical characteristics in the rhizosphere, which decrease the nutrient absorption and utilization capacities [54,55], eventually leading to lower crop yield. Moreover, high N input increases nitrate accumulation [56], which is one of the main reasons for the secondary salinization of soils. Higher secondary salinization impairs root growth and reduces nitrogen use efficiency and crop yield [57].

China is the world's greatest consumer of nitrogen fertilizer, and its overuse is generally common among the farming community [58]. The recovery rate of nitrogen fertilizer in crop production decreased from 30% to 35% in the 1980s to <20% in the 2000s [59], lower than the global value (33–37%) [60,61]. Except for crop yield, N input also affected crop WUE. We found that N application did not consistently increase WUE, which could partly be because a high N input increases root hypoxia and the acidification of the rhizosphere, which decrease root growth and subsequent water absorption [62]. N input also affected greenhouse gas emissions. The amount of N used is the main factor influencing N<sub>2</sub>O and CO<sub>2</sub> emissions; generally, these emissions increase exponentially with N inputs in excess [63]. Cumulative CO<sub>2</sub> emissions for the high N input increased by 19.3% in comparison with the medium and low N input levels [64].

### 4.2. Irrigation Threshold for Higher Crop Yield and Water Use Efficiency

Water is a major limiting factor for most crop cereals, more prominently in rainfed areas where supplementary irrigation is necessary to sustain better crop growth when the rainfall fails to supply sufficient moisture [65]. This meta-analysis showed that optimum irrigation strongly increased crop yield. Irrigation increased maize and wheat yields by 26% and 50%, and WUE increased by 10% and 31% compared to non-irrigation systems (Figure 5). The maximum maize yield and WUE were at 180–240 mm irrigation and at 300–400 mm irrigation for wheat (Figure 5). Appropriate irrigation promotes the coordinated growth of root crowns and shapes a reasonable canopy structure, which is conducive to the accumulation of above-ground biomass and lays a foundation for high yields [66,67]. Simultaneously, appropriate irrigation or intermittent water deficits resulted in root adaptations that enabled plants to maximize their water use in these critical stages, which ultimately resulted in a better WUE [68,69]. For example, Du et al. (2010) found that a mild water deficit during early growth was beneficial for improving WUE for crops [70]. Li et al. (2019) reported that maize yield and WUE decreased by 26% and 27% when the irrigation amount was above the optimal water input level. Likewise, maize yield and WUE decreased by 25%, and 25% when the irrigation amount was below the optimal input. Thus, the crop requires optimum moisture for its growth [71].

### 4.3. Agricultural Field Management for Higher Crop Yield and Water Use Efficiency under Different Humidity Index

The intensive or imbalanced use of fertilizer negatively affects plant growth, soil health and environment, by causing problems such as soil acidification, greenhouse gas emissions, nitrate leaching and eutrophication [72]. The application of organic fertilizer mainly in the form of manure could alleviate these problems. Wei et al., (2020), based on 133 studies, reported that organic–inorganic mixed fertilizer increased maize yield by 4.22% worldwide compared to a mineral fertilizer application [73]. Similarly, Han et al. (2019) reported that an organic–inorganic mixed fertilizer increased rice yield by 11.7% compared to a mineral fertilizer application in China (1988–2017) [74]. Du et al. (2020) reported that additional manure application increased crop yield by 7.6% compared to a mineral

fertilizer in China [32]. The results of our study are consistent with previous ones, as the organic–inorganic mixed fertilizer increased maize, wheat, and rice yields by 43%, 68%, and 38%, respectively (Figure 7). Increases in the nutrient pool and decomposition capacity of the soil may explain the positive effects of manure application on yield. Manure increased the nutrient supply with increases in soil organic carbon content (17.7%), total nitrogen (15.5%), available potassium (19.1%), and available phosphorus (66.2%) and decreased bulk density (3.9%) and soil water-stable aggregation (28.8%), which are beneficial for crop growth, and thus resulted in a higher crop yield [32]. The appropriate amount of organic fertilizer is beneficial for crops; a 25% to 75% mixture of organic and inorganic nitrogen led to the highest yield and N use efficiency under equivalent N input for rice [75]. The application of organic fertilization led to higher soil organic carbon concentrations, stocks and carbon management index, which improved nutrient cycling services and led to a higher soil quality [76,77].

The N uptake of maize at the post-silking stage was positively related to yield ( $+577 \text{ kg ha}^{-1}$ ) [34]. The sole application of N one time did not meet the crop nutrient requirements in the middle and later stages of growth, and therefore split fertilization can maintain a better nutrient supply throughout the crop season [34,78,79]. Split N treatment, a simple practice, matches the N supply to crop nitrogen requirements and reduces environmental losses [80]. In our study, crop yields with split application were higher, 1023, 855, and  $2132 \text{ kg ha}^{-1}$ , than when applied once for maize, wheat, and rice, respectively. A global meta-analysis based on 129 studies reported that 3–4 split N applications improved wheat yield by 7.0% and crop protein by 5.2%. Splitting N fertilization can increase the annual production of winter wheat by 12.9 t cereals and 1.3 t protein globally [81].

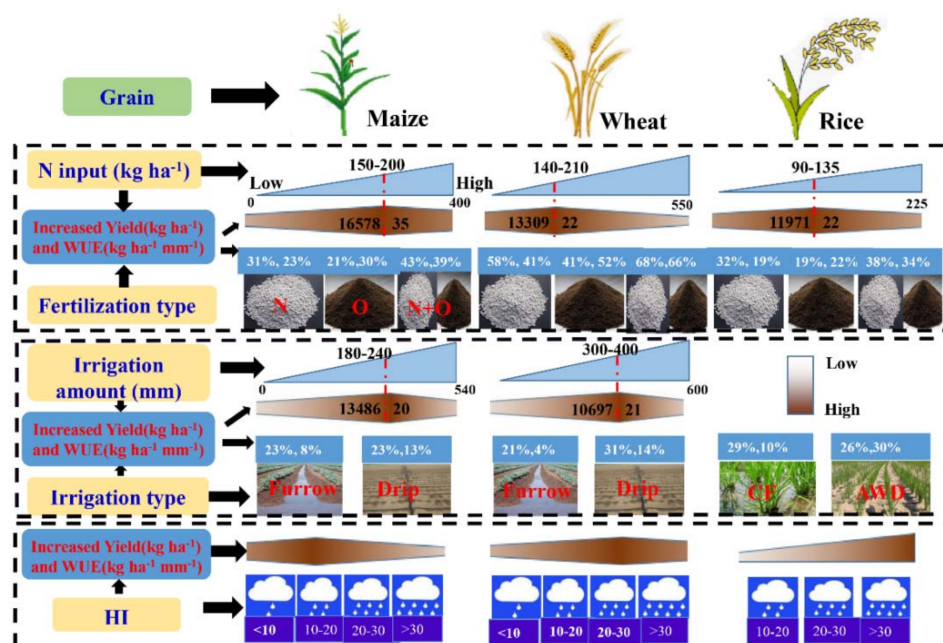
The irrigation method strongly influences crop yield and WUE. Choosing a suitable irrigation method for different crops can have a significant impact on ensuring better food production, the rational use of resources and protecting the ecological environment. In our study, drip irrigation increased maize and wheat yields by 23% and 31%, and WUE by 13% and 14%, respectively (Figure 4). Li et al. (2021) reported that drip irrigation increased crop yield by 12.0% and WUE by 26.4% compared to furrow in China (1990–2019) [82]. Drip irrigation delivers a water and fertilizer solution to the vicinity of the plant root with plastic tubing [83]. Drip irrigation facilitates better nutrient uptake and reduces the evaporation losses in the conveyance, seepage and percolation [82,84]. AWD is an irrigation method which can reduce water use in rice irrigation systems [85,86]. AWD can save 27.5% more water than continuous flooding but reduces the yield by 5.4% for rice, which is consistent with the results of our study (−5%) [87]. Bouman et al. (2001) found that rice yield did not reduce when reflooding with a field water level below 15 cm of the soil surface [88]. The time for AWD did not have a great effect for crop yield at the condition of mild AWD [87]. The irrigation method had a significant influence on CO<sub>2</sub> emissions. Under drip irrigation, soil CO<sub>2</sub> flux after irrigation was 9% and 29% lower than that under sprinkler irrigation and furrow, respectively [89]. Irrigation affects CO<sub>2</sub> emissions by affecting soil temperature, soil moisture, soil nutrients, soil structure and soil microorganisms [90].

Identifying the relevant factors and quantifying their effects on yield and WUE variation is the key to improving crop water stress management. Therefore, it is important to understand which interfering factors in the cereals can be manipulated for better crop performance within the given environmental constraints. Our results revealed that HI is the most important factor affecting crop yield and WUE, followed by irrigation (Figure 9). Because the variations of precipitation had small impacts on the maize and wheat yields, and a high mean annual temperature can cause physiological stresses which lead to stomatal closure, leaf curling, shrinkage of the length of the growing cycle, and a reduction in the carbon dioxide assimilation rate, maize and wheat yields reduced to a low HI level [91]. During the rice growth process, a lot of water and sunlight are needed, so with the increase in HI from HI < 10 to HI > 30, rice yield and WUE increased.

#### 4.4. Implications, Perspectives, and Uncertainties

The well-managed fertilization and irrigation practices are beneficial to ensure higher crop yield and WUE, with minimum disturbance to soil resources and the environment. Given the existing environmental costs, an effective solution for irrigation and N input should be designed to reconcile the concern of resource consumption and food security. Although soil conditions and climate factors vary greatly by region, achieving a higher WUE with fewer environmental costs is always our goal.

Our research could give field management suggestions for areas with similar climate conditions. Firstly, all observations in this meta-analysis were focused on China. China's vast territory means there are big differences between climate and soil of different areas, and our results could guide regional and even global agricultural development. Secondly, most previous studies carried out either fertilization or irrigation individually. The simultaneous optimization of fertilization or irrigation occurred in a few studies. Additionally, simultaneous optimization is complex and challenging, with many factors interacting, mainly those related to environmental and management conditions. Third, our study focused on the effect sizes of maize, wheat, and rice in field management. These are main crops in China and distributed widely. HI had the biggest effect on crop yield and WUE compared to irrigation and fertilization (Figures 9 and 10). According to the different HI values, the possible fertilization and irrigation amounts were provided (150–200 kg ha<sup>-1</sup> N at 10 ≤ HI < 20 for maize; 140–210 kg ha<sup>-1</sup> N for wheat at 20 ≤ HI < 30; 90–135 kg ha<sup>-1</sup> N at HI > 30 for rice; 180–240mm irrigation at 10 ≤ HI < 20 for maize, 300–400 mm irrigation at 20 ≤ HI < 30) (Figure 10), which could give the field management suggestions for similar areas. Agricultural management increased yield and WUE (23–68% and 13–66%) through drip irrigation (23–31% and 13–14%), alternate wetting and drying (AWD) (26% and 30%), split fertilization (31–64% and 21–40%) and organic–inorganic fertilizer (38–68% and 34–66%) (Figures 7 and 10). Climate change, affecting precipitation and temperature, has profound impacts on water and N requirements for crops. In the actual management process, it is recommended to combine the results of our study with regional field management to determine the precise amount of irrigation, fertilizer application and appropriate field management methods.



**Figure 10.** The effect of different agricultural management methods on crop yield and WUE of maize, wheat and rice. Abbreviations: N, nitrogen fertilizer; O, organic fertilizer; N+O, organic-inorganic mixed fertilizer; CF, continuously flooded; AWD, alternate wetting and drying.

## 5. Conclusions

Our research quantitatively evaluated the responses of three main cereals (maize, wheat and rice), their yields and WUE to agronomic practices under field conditions. The results indicated that crop yield and WUE improved significantly in response to better management practices (water conservation and organic–inorganic fertilization mixed applications). N input and irrigation obtained the highest yield and WUE of maize, wheat and rice. The N ( $\text{kg ha}^{-1}$ ) input threshold values for maize, wheat and rice were 150–200, 140–210, and 90–135, respectively. The irrigation (mm) threshold values for maize and wheat were 180–240 and 300–400. Variable fertilizer types (organic–inorganic fertilizer), fertilization frequencies (split fertilization), and irrigation methods (drip irrigation and alternate wetting and drying) significantly modulated the effects on crop yield (23%–68%) and WUE (13%–66%). HI (humidity index) had the biggest effect on crop yield and WUE based on the BRT analysis, followed by irrigation and fertilization. Our research offers a greater understanding of the effects of N or irrigation supply on crop yield, and WUE under variable management practices (HI, fertilizer type and irrigation method) to produce better crops with limited usage of valuable inputs.

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