frontiers | Frontiers in Water

ORIGINAL RESEARCH
published: 08 July 2022
doi: 10.3389/frwa.2022.930481

Can the Right Crop Mix Reduce the Water Rebound Effect Following Improvements in Irrigation Efficiency?

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Water rebound has been recognized as a significant issue that reduces the effectiveness of irrigation efficiency improvement policies aimed at water conservation. However, there is an absence of quantitative analysis of the impact of crop mixes on the water rebound effect, and studies focusing on the heterogeneous effects of various climatic regions are scarce. Thus, this study aims to explore the effects of water rebound on irrigation efficiency improvements from the perspectives of crop mix and climatic region. First, we construct a double-layered moderating effect framework to incorporate the two interactive factors of crop mix and climatic region combined with two rebound mechanisms, cost reduction and increased revenue. Second, we conduct empirical analyses to test three hypotheses based on provincial-level data from 2003 to 2017 in China, which provides a unique empirical context wherein changes in the crop mix depend on factors other than the water-use policy. This paper takes advantage of the implementation of Rural Land Contracting Law since 2003 and Water Conservancy Key Counties Construction Program since 2009 to identify the effects of water rebound on irrigation efficiency improvements from the perspectives of crop mix and climatic region. We found that the water rebound effect was about 67.72%. Crop mixes involving higher proportions of non-grain crops were associated with higher levels of water conservation and less water rebound. Furthermore, non-grain crops in humid regions were more likely to experience water rebound than those in non-humid regions. Thus, given China's national strategy of food security, reducing the proportion of non-grain crops in humid regions will help to sustain agricultural water resources and conserve the environment.

Keywords: irrigation efficiency, water rebound, crop mix, double-layered moderating effect, China

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Specialty section:
This article was submitted to Water and Human Systems, a section of the journal Frontiers in Water

Received: *28 April 2022*
Accepted: *15 June 2022*
Published: *08 July 2022*

Citation:
Chai Y, Zhang H, Ma Z, Pan S and Zhou J (2022) Can the Right Crop Mix Reduce the Water Rebound Effect Following Improvements in Irrigation Efficiency? Front. Water 4:930481. doi: 10.3389/frwa.2022.930481

INTRODUCTION

In recent decades, the water rebound effect has become a focal issue in the field of agricultural water resource conservation (Perry and Steduto, 2017; Berbel et al., 2018). The water rebound effect means that improvements in irrigation efficiency as a result of technological innovation do not necessarily generate ideal outcomes in terms of water conservation, and can even result in increased water use when part or all of the saved water is applied elsewhere (Paul et al., 2019). Grafton et al. (2018) defined the water rebound effect as the paradox of irrigation efficiency, similar to Jevons' paradox in the field of resource economics. Although the European Commission (2021) issued a warning regarding the water rebound effect, both developing and developed countries have been unable to avoid it (Pfeiffer and Lin, 2014; Song et al., 2018; Wheeler et al., 2020; Dench and Morgan, 2021; Abd-Elaty et al., 2022). The design of policies aimed at achieving improvements in irrigation efficiency and by conserving water have been criticized because the water rebound effect has reduced the potential water savings (Berbel et al., 2015; Levers et al., 2019; Perez-Blanco et al., 2020). These policies have also been responsible for wasting significant amounts of government money through the water rebound effect (Perry and Steduto, 2017; Wheeler et al., 2020), such as the five billion Australian dollars spent by the Australian government subsidizing farmers in updating their irrigation technology, which failed to achieve its objective (Australian Parliament, 2017). Thus, it is important to identify the mechanisms underlying the water rebound effect, alleviate its occurrence, and increase water conservation as a result of improved irrigation efficiency.

The main object of this study is to identify the right crop mix, grain or non-grain crops, which one can reduce water rebound effect. Prior researchers have found that crop mix change is the significant factor to cause water rebound effect after the improvements in irrigation efficiency (Pfeiffer and Lin, 2014; Grafton et al., 2018; Paul et al., 2019). Crop mixing involves the production of various types of crops in a given area, and affects water demand by regulating water use based on the irrigation requirements of each type of crop. This provides economic value for farmers who decide to update their irrigation technology, and enables them to adapt to environmental changes such as reduced precipitation. However, although previous studies have suggested the potential benefits of an appropriate crop mix in relation to water rebound (Berbel et al., 2015; Zhou et al., 2020), there is an absence of quantitative analysis of the impact of crop mixes on the water rebound effect. One challenge is that farmers are likely to adjust their crop mix after updating their irrigation technology, and thus the crop mix cannot be treated as an exogenous factor affecting water use. The endogeneity issue has caused problems and restricted the progress of research analyzing water rebound mechanisms.

In this study, we conduct a quantitative analysis of the water rebound mechanism in relation to crop mixing, thereby contributing to relevant theoretical research. We investigate a unique empirical context wherein changes in the crop mix depend on factors other than the water-use policy. In China, changes in the crop mix have occurred since 2003, when the Contract Law of Rural Land was enacted, enabling farmers to transfer small-scale farmlands, pursue production maximization, and switch from growing grain crops to growing non-grain crops. In 2003, the sown area of grain and vegetables are 7.68 million ha and 1.79 million ha, respectively. During the more than one decade's development, the average growth rate of vegetables is about 1%, much higher than the growth rate of each of the grain crops; the average growth rate of rice, wheat, and corn are about 0.74, 0.36, and 0.32%, respectively. A policy promoting improved irrigation efficiency was subsequently introduced in 2009, and thus crop mix changes occurred independent of irrigation efficiency improvements. The sample we used from China provided a strong database, allowing independent analysis of the impact of crop mixes on the water rebound effect while enabling us to avoid the endogeneity problem. In addition, some provinces include mixed cropping patterns, which provide a diverse sample range.

Another reason for basing the study on China is that identifying the mechanism responsible for the water rebound effect is important in relation to policy enforcement in China, where a stringent water resource management system has been in place since 2011, including targets for increased irrigation efficiency and control of overall water use. The Chinese government has prioritized improvements in irrigation technology among other measures aimed at achieving these objectives. China has around 69 million ha of irrigated land, of which 54% is subject to water conservation measures such as irrigation system modernization, canal lining for surface irrigation systems, and high-efficiency technology for groundwater irrigation (such as sprinkler and drip systems). By 2030, 75% of the irrigated area will be covered by irrigation systems that enable water conservation. However, the desired water conservation is at risk of being impacted by the water rebound effect (Guo et al., 2021). Each year, the Ministry of Water Resources of the People's Republic of China divides provinces into "excellent attainment," "attainment," or "nonattainment" categories based on whether they have achieved their water conservation objectives. Provinces that are included in the "excellent attainment" category are rewarded, while those that are included in the "nonattainment" category are subject to administrative punishment. Therefore, local governments are keen to identify the factors that cause the water rebound effect, and thus how to mitigate or avoid it.

Furthermore, previous related studies have mainly focused on the heterogeneous effects of crop mixing on the relationship between irrigation efficiency and the water rebound effect, while studies focusing on the heterogeneous effects of various climatic regions are scarce. Under different climatic conditions, such as a humid climate or an arid climate, is the moderating effect of crop mixing the same? Which climatic condition is the main cause of increasing water rebound? At present, the answers to these questions are unknown. Thus, it is important in relation to policy development to investigate which climatic regions either enhance or inhibit the water rebound effect.

The contributions of this study are focused on two gaps in our knowledge. First, we use a sample from China to explore the effects of crop mixing on the water rebound effect. Crop mixing in China can be treated as an external factor given the increasing trend toward non-grain production, which is being driven by market demand and profitability rather than irrigation issues. Second, we investigate the heterogeneous effects of climatic regions to enrich our knowledge of the mechanism underlying

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Abbreviations: W, water; IE, irrigation efficiency; PE, physical efficiency; WRE, water rebound effect; LB, labor; F, fertilizer; LD, land; M, machinery; AR, agricultural production; CMC, cop mix change; CR, climatic region; IAWC, irrigated area of water conservation; LnIE, the change in irrigation efficiency; LnW, the change in agricultural water resource demand; LnCSC, the change in the ratio of non-grain crops to grain crops; LnIAWC, the change in irrigated area of water conservation.

the impact of crop mixing on the water rebound effect. This is also the novelty of our study.

The rest of this paper is organized as follows. Section Literature Review and Theoretical Analysis presents a review and theoretical analysis of previous studies on the water rebound effect and the moderating effects of crop mixing and climatic regions, proposes three hypotheses, and presents the double-layered moderating effect framework. Section Study Design presents the study design including the data, method, and model used. Section Results presents the results of our empirical analysis and the tests of the three hypotheses. Sections Discussion and Conclusion present a discussion of the results and our conclusions, respectively.

LITERATURE REVIEW AND THEORETICAL ANALYSIS

Irrigation Efficiency and Water Rebound

Based on the general theory of resource efficiency, policies designed to achieve improvements in irrigation efficiency aim to conserve agricultural water resources for industry and environmental uses while sustaining agricultural production (Paul et al., 2019). Typical irrigation efficiency improvement innovations are technology-based, including irrigation modernization, physical infrastructure updates, and the adoption of high-efficiency conservation technology (Lecina et al., 2010; Gleick et al., 2011). Technologies such as irrigation modernization and irrigation infrastructure updates are among the main tools used to reduce water use in both developed and developing countries (Ahmad et al., 2007; Gleick et al., 2011). The logic is that improvements in irrigation efficiency enable farmers to conserve water during the water delivery and consumption phases. On one hand, irrigation efficiency improvements in one location can affect water demand by farms in neighboring locations. For example, if surface irrigation systems are updated by canal lining, upstream water users require less water than before, leaving more water for downstream users (Lam and Chiu, 2016). On the other hand, irrigation efficiency improvements such as introducing drip irrigation technology can reduce water losses during consumption by reducing water transpiration (Berbel et al., 2015). Thus, the success of water conservation policies is highly dependent on irrigation efficiency improvements because policy-makers assume that reduced water use at the regional level can alleviate water stress and even provide additional water for other uses.

However, various empirical studies have found that irrigation efficiency improvements cannot achieve both of these objectives. Water conservation technology is often designed with a dual purpose, that is to stabilize (if not increase) agricultural production while conserving water. However, the enhanced local agricultural production and income as a result of water conservation technologies is often at the expense of increased water consumption and reduced water availability for downstream uses (Perez-Blanco et al., 2020). That is to say, the policy is unable to achieve two outcomes that necessitate a trade-off. Since early 2000, it has increasingly been recognized that increased irrigation efficiency is not a Pareto efficient outcome because of the water rebound effect (Molle and Turral, 2004; Perry, 2007). Water conservation technologies often worsen rather than alleviate water scarcity, that is, the saved water at the field scale does not necessarily translate into a reduction in overall water use because of water percolation into the groundwater that is later reused by farmers through pumping and increasing water demand as a result of increased productivity (Ahmad et al., 2007).

There are two types of water rebound effect. A few studies have reported a large rebound effect of between 50 and 100%, with some degree of reduction in water use with the increase in irrigation efficiency, such as those by Song et al. (2018) and Fei et al. (2021) regarding China. Various other studies in countries other than China, such as those by Ahmad et al. (2007) regarding Pakistan, Wheeler et al. (2020) regarding Australia, Lecina et al. (2010) regarding Spain, Pfeiffer and Lin (2014) regarding the US, and Dench and Morgan (2021) regarding New Zealand, have reported "backfire," that is a water rebound effect in excess of 100%, with water use actually increasing despite the increase in irrigation efficiency.

In summary, we propose the following hypothesis.

> **Hypothesis 1:** Increased irrigation efficiency is likely to conserve water in China. However, the water rebound effect is likely to occur, meaning that the percentage water saved is less than that resulting from the increased irrigation efficiency.

Crop Mix as an Important Moderating Factor

Some studies have suggested the existence of an interactive effect between the crop mix and irrigation efficiency on water use, and provided empirical proof of its occurrence in the US, Spain, and China (Lecina et al., 2010; Pfeiffer and Lin, 2014; Berbel et al., 2018). Based on the standard water use quotas set by the Ministry of Water Resources of China, grain crops are the most water-intensive crops, and thus a crop mix with more grain crops requires more water than one with more non-grains crops after the irrigation technology has been updated. With crops being the main application of agricultural water use, changes in the quantity of water used mainly depend on the attributes of various crops in terms of their water intensity. Thus, based on the water rebound classification proposed by Paul et al. (2019), the water rebound effect is mainly applicable to direct producers, by whereby production expansion is derived from increased consumption of irrigation services.

There is no price-related mechanism involved in the interactive relationship between irrigation efficiency and water rebound. As a resource, agricultural water displays the following attributes: it is free, has no substitute, and is administratively pricing of its agricultural products such as grain. Thus, neither resource nor product pricing provides a pathway to influence irrigation efficiency, and thus water use. This differs from the mechanism underlying energy efficiency, which can lead to changes in energy prices and output prices, through the substitution effect and the income effect.

There are two mechanisms underlying the water rebound effect through the interaction of irrigation efficiency improvements and the crop mix: a cost-reduction mechanism and a revenue-increasing mechanism. An improvement in irrigation efficiency triggers these two mechanisms, resulting in a water rebound effect that differs between non-grain and grain crops.

Cost-Reduction Mechanism

The cost-reduction mechanism can lead directly to water rebound, by emphasizing the combination of water-intensive crops and modern irrigation technology. Crop mixing, particularly that featuring a majority of water-intensive crops such as grains, promotes the use of water conservation technology rather than traditional irrigation systems by enabling a higher water conveyance capacity, less labor input, and thus greater net revenues (Lecina et al., 2010; Paul et al., 2019).

First, advanced irrigation technology can reduce the marginal cost of irrigation service, which can incentivize farmers to increase their irrigation intensity and expand their production of water- intensive crops, as increased water consumption can increase agricultural production (Sears et al., 2018; Wu et al., 2018; Paul et al., 2019). Because the agricultural water resource is free to use, improved irrigation efficiency is indirectly associated with reduced costs and the water rebound effect (Maxwell et al., 2011). Particularly in relation to the surface irrigation systems used for grain production in China, after implementing a program under the food-security policy of lining the canals to reduce water seepage and improve conveyance capacity, downstream farms can now access more water than before, and thus the change in irrigation efficiency is coupled with the available water supply (Chai and Schoon, 2016).

Second, the reduction in water-use costs means that farmers have more incentive to increase their production of grain crops. The increasing scale of these crops reduces the average cost of production, which further increases water demand. This generates a cycle of cost reduction and water rebound (García et al., 2015). Such incentives are further enhanced when subsidies are provided for investment in advanced technologies (Grafton et al., 2018). Sanchis-Ibor et al.'s (2019) study based on Spain provided empirical proof from the opposite side, that is, while retaining an unchanged crop mix, the adoption of drip irrigation can reduce water use by 26% on average. Similar results have also been found in regions where crop selection is limited by natural conditions such as soil and weather, for example in northwestern China (Zhang et al., 2020). However, given the difficulty of controlling crop mixes (Li et al., 2019), there is no measuring tool available at the farm scale that can be used to monitor water usage under various crop mixes. Upgraded technologies alone cannot ensure improvements in resource-use efficiency (Levidow et al., 2014). As Perry and Steduto (2017) noted, the introducing of hi-tech irrigation usually makes the situation worse, with water consumption per unit area increasing.

Revenue-Increasing Mechanism

The revenue-increasing mechanism focuses on updating both irrigation efficiency and crop mix selection. Farmers aim to maximize their economic productivity (Knox et al., 2012; Ortega-Reig et al., 2017), and thus they update their irrigation technology with a view to increased profitability rather than water conservation (Perez-Blanco et al., 2020). Carey and Zilberman (2022) noted that under conditions of uncertainty, it is rational for farmers to wait until the expected benefits of investment exceed the costs by a significant amount before investing in water conservation technology, again highlighting the fact that the adoption of water conservation technology is driven by profitability.

Farmers growing water-intensive crops are willing to use more water to meet the plants' requirements because their marginal revenue from increasing irrigation efficiency is higher than that for other types of crops. Improved irrigation efficiency makes more water available for water- intensive crops (Yang and Mu, 2020). For example, grain crops require more water than non-grain crops (Gao and Luo, 2008), and thus farmers growing grain crops will make full use of the savings by updating their irrigation technology (Li et al., 2019). For instance, in Ningxia of China, water-intensive crops such as rice require about 13,500 m^3/ha of water per year compared with 11,100 m^3/ha for vegetable crops (Chen, 2019). Thus, issues related to water over-use, such as groundwater depletion, shallow wells that are dry, and falling water tables, are more prevalent in regions where water-intensive crops are grown (Molle et al., 2018; Chen, 2019).

In Spain, Lecina et al. (2010) found that water-intensive crops benefited more from modern sprinkler systems than from traditional surface irrigation systems, estimating that net land (water) productivity was 29–45% (75–93%) higher in sprinkler-irrigated areas than in surface-irrigated areas. The water accounting framework proposed by Perry (2007) stated that although efficiency improvements can reduce the unconsumed proportion of water (such as return flows), they can also increase the proportion of water consumed (such as through crop transpiration) (Perez-Blanco et al., 2020). Subsequent studies have confirmed that most farmers who have adopted water conservation technologies have increased their income, as there is a positive correlation between income and water consumption, and a negative correlation between income and water conservation (Perez-Blanco et al., 2020).

On the contrary, we can infer that non-grain crops, such as vegetables, are likely to save water through increased irrigation efficiency. Since increased irrigation efficiency is costly because of the need to update infrastructure and equipment [e.g., in Spanish, the costs of updated infrastructure and equipment were found to be 400% higher than those of traditional gravity-fed systems (Rodriguez-Diaz et al., 2011)], farmers of cash crops are best placed to afford the capital costs, and thus have incentives to save water and increase profitability (Alarcon et al., 2016). Similarly, in the US, water conservation technology is more likely to be adopted in those areas that produce higher-value crops such as vegetables (GAO, 2019).

In summary, we propose the following hypothesis.

Hypothesis 2: A crop mix with more non-grain crops has a positive moderating effect on water conservation and a negative moderating effect on water rebound following improvements in irrigation efficiency.

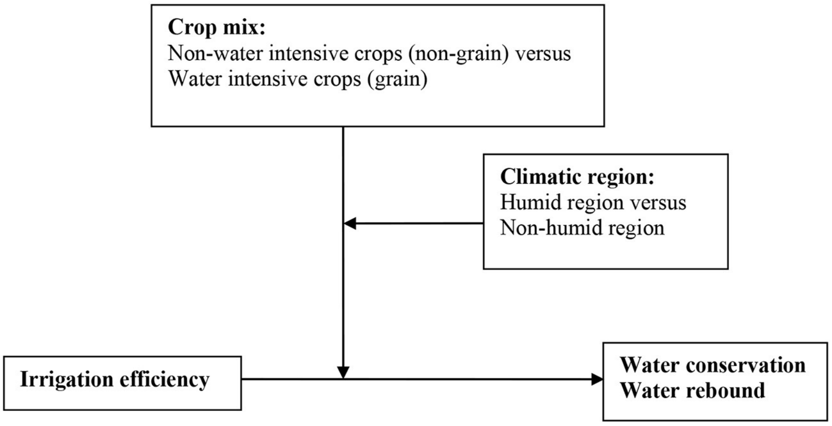

FIGURE 1 | Theoretical model.

TABLE 1 | Variable definitions and summary statistics.

Variables	Definition	Mean	Standard deviation	Min	Max
W: water	Agricultural water resource use, 100 million m^3	122.1456	108.4489	5.1	844.7
IE: irrigation efficiency	Also physically technical efficiency, using DEA-Malmquist method to obtain, from 0 to 1	0.7583	0.2304	0.283	1
CMC: crop mix change	The ratio of non-grain crop area to grain area, % non-grain crop: vegetables, grain crop: rice, wheat and corn	0.3208	0.2187	0.0166	1.1351
CR: climatic region	Humid region or non-humid region, =1 if the province belongs to humid region	0.4839	0.5003	0	1
IAWC: irrigated area	Irrigated area of water conservation, ha	859,252.6	845,484.1	2,540	4,000,000
LB: labor	The population of agricultural labors, 10 thousand people	954.3653	712.9684	37	3,332
F: fertilizer	The consumption of chemical fertilizer, 10 thousand tons	175.3641	141.7978	3.2	716
LD: land	The total sown areas of farm crops, 1000 ha	5,167.206	3,642.977	121	14,767
M: machinery	The total power of agricultural machinery, kw	2,848.406	2,755.505	95.3	13,353
AR: agricultural production	The real gross output value of agriculture at the 1990 price level, 100 million Yuan	781.8387	610.7917	28.0939	3,083.425

Heterogeneous Moderating Effect of Crop Mixes on Water Rebound Following Improvements in Irrigation Efficiency

As mentioned above, water-intensive crops are likely to produce a greater water rebound effect following improved irrigation efficiency. This reflects the assumption that there is a relative abundance of water that can be saved for use on water-intensive crops. However, Berbel et al. (2018) found that water-intensive crops are rarely planted in water-stressed regions, confirming the findings of Batchelor et al. (2014) in relation to India. This shows that the moderating effect of the crop mix on the water rebound effect depends on natural conditions such as the climatic region, for example a humid region or a non-humid region (Gomez and Perez-Blanco, 2014; Li et al., 2019).

Compared with non-humid region (arid, semi-arid, and semi-humid regions), humid regions can see a more negative moderating effect of water-intensive crops on irrigation efficiency and water conservation. In other words, the moderating effect of water-intensive crops on the water rebound effect can be reinforced. Saunders (2000) found that when the demand for a particular resource is not satisfied, improved efficiency is likely to cause a large rebound effect in relation to that resource. In humid regions, water is less scarce than in arid and semi-arid regions, water -intensive crops require more water, and once extra water is available, farmers have more incentive to increase their irrigation intensity and use the additional water that is available after updating their irrigation systems. Based on the economic incentives provided by higher marginal revenue, farmers also face more demands to increase their irrigation efficiency. Thus, we can infer that the water rebound effect in humid regions is likely to increase as a result of the moderating function of water-intensive crops and is likely to decease in arid and semi-arid regions. This leads to the following hypothesis.

> **Hypothesis 3:** The negative moderating effect of water-intensive crops is likely to be greater in humid regions than in non-humid regions.

Based on the three abovementioned hypotheses, we construct the theoretical model shown in **Figure 1**. The three one-direction arrows in **Figure 1** exhibit the relationships that are shown in the three hypotheses. The moderating factor of crop mix embodies exogenous characteristic obtained from our sample and data, which can avoid endogeneity problem that previous studies fail to resolve.

TABLE 2 | Results of the main effect, moderating effect, and double-layered moderating effect.

Variables	(1) LnW Model 1 Main effect	(2) LnW Model 2 Moderating effect	(3) LnW Model 3 Double-layered moderating effect
Independent variable			
LnIE	−0.3228*** (0.0894)	−0.2947** (0.0909)	−0.3268** (0.1181)
Moderating variable			
LnCMC		−0.0203 (0.0457)	−0.1550** (0.0569)
CR			−0.0356 (0.0979)
Moderating effect			
LnIE*LnCMC		−0.5593*** (0.1738)	−0.9186*** (0.2167)
LnIE*CR			−0.4051 (0.1871)
LnCMC*CR			0.9998*** (0.1901)
LnIE*LnCMC*CR			1.7530** (0.4967)
Control variable			
LnIAWC	0.5470*** (0.0288)	0.5313*** (0.0317)	0.4974*** (0.0344)
Year	Control	Control	Control
_cons	−2.7476*** (0.4253)	−2.3655*** (0.4510)	−1.9361*** (0.4797)
R^2	0.4402	0.4508	0.4653
Observations	465	465	465

Huber-White standard errors are reported in parentheses. *, **, *and* *** *indicate statistical significance at the 10, 5, and 1% levels, respectively.*

STUDY DESIGN

Data and Sample

We conducted an empirical analysis of 496 samples from 31 Chinese provinces or autonomous regions from 2004 to 2017. The data are from the China Rural Statistics Yearbooks, the China Water Resources Bulletin, and the China Environment Statistics Yearbooks.

Variable Descriptions

Dependent Variable

The dependant variable is water demand (W), denoted as LnW. Water demand can be measured by the amount of agricultural water used. In the field of resource economics, scholars use the elasticity of water demand with respect to irrigation efficiency (IE) as a proxy for the water rebound effect (Song et al., 2018). Thus, dLnW/dLnIE represents the relationship between irrigation efficiency and the water rebound effect.

The water rebound effect (WRE) in the agricultural sector describes the size of the impact of improved irrigation efficiency on water use in relation to its theoretical water saving potential, referring to the definition put forward by Sorrell and Dimitropoulos (2008) and Lange et al. (2021), and its application by Fei et al. (2021). WRE can be represented as follows:

$$WRE = 1 + \alpha \tag{1}$$

where α denotes the irrigation efficiency elasticity of agricultural water use, which is the coefficient of LnIE in the empirical analysis models. The ideal state is where α is $<$-1, which means that a 1% increase in irrigation efficiency would lead to no less than a 1% reduction in water demand, that is, no water rebound effect. If α is in the range $(-1, 0)$, a 1% increase in irrigation efficiency would lead to a $<1\%$ reduction in water demand, that is, a water rebound effect. If α is positive, a 1% increase in irrigation efficiency would increase water demand, that is, backfire would occur.

Specifically, if the water rebound effect is small (e.g., $0\% < WRE < 10\%$), irrigation efficiency policies will be largely unaffected by rebound, and will have the potential to translate into effective water conservation. However, if the water rebound effect is large (e.g., $WRE > 50\%$), failure to account for rebound effects will result in a significant overestimate of the effectiveness of irrigation efficiency policies, with serious implications for the ability to achieve water conservation targets.

Additionally, in this study, the rebound effect is caused by the exogenous factor of increased irrigation efficiency. The improvement in irrigation technology is mainly attributable to investment by the government, typically the Water Conservancy Key Counties Construction Program since 2009. Thus, for farmers, increasing irrigation efficiency is almost without cost. Following the definition by Gillingham et al. (2016), the resulting farmer responses are a pure rebound effect, as they capture direct responses induced by the improvement in irrigation efficiency.

Another possible explanation is that the prices of both agricultural water resources and agricultural products are not included in the causes of the water rebound effect. This differs from the common analysis of the rebound of energy efficiency, which considers energy prices and output prices as causes of the rebound effect. Since agricultural water resources are free and the price of agricultural products in China is set by the government rather than depending on market adjustments such as cost reductions, prices cannot affect the response of farmers in terms of water use. Thus, the endogenous impact of prices is impossible to estimate in relation to the water rebound effect.

Explanatory Variable

The explanatory variable is irrigation efficiency (IE), which results from improvements in physical efficiency or technology and can be obtained using the DEA-Malmquist method, which was used in this study to estimate the contribution of improved technology (PE) to irrigation efficiency. This method was selected because of its comprehensive nature and, more importantly, its ability to provide a continuous measure of irrigation efficiency in a given region using panel data. In addition, in relation to agricultural practices, irrigation efficiency, which is a performance-based indicator measured by the ratio of outputs to inputs, is mainly determined by management capability rather than a specific irrigation technology under a standard level of management efficiency. The DEA-Malmquist method, which compares multiple inputs with multiple outputs to generate a relative efficiency score that accounts for the ratio between unique virtual outputs and inputs, has been highly recommended and is the method most frequently used to measure irrigation efficiency, as noted by Pereira and Marques (2017).

To calculate irrigation efficiency using the DEA-Malmquist method, we adopted the input and output variables used by Pereira and Marques (2017) and Song et al. (2018). The agricultural inputs included agricultural water use (W), labor (LB), fertilizer (F), land (LD), and machinery (M). The gross agricultural output value at 1990 price level, that is agricultural production (AR), was used to represent output. The gap between agricultural water use efficiency and water productivity narrowed with increasing spatial scale (Zhou et al., 2021).

PE was used as a proxy for IE, as improved irrigation efficiency in China is mainly the result of updated physical technology, and thus PE is the technical component of the DEA score.

Moderating Variables

As **Figure 1** shows, the first level of moderating variables includes crop mix change (CMC), which plays a role in inducing the water rebound effect following improvements in irrigation efficiency. We use the ratio of non-grain crop area to grain crop area to represent the changes in the crop mix.

In China, CMC can be treated as an external variable influencing irrigation efficiency because there is a time gap between the emergence of CMC and changes in irrigation efficiency that has not been considered in previous studies. The cropping pattern has shifted from grain crops being dominant until 2003 to non-grain crops such as vegetables gradually increasing since then. In 2003, China enacted the Rural Land Contracting Law, which enabled farmers to transfer small-scale farmlands to form large-scale farmlands, which are used for non-grain production. Since grain crops provide relatively low earnings (Zhao et al., 2017), more and more farmland has been used to grow cash crops in preference to grain crops. Thus, the ratio of non-grain crops to grain crops has been changing in each region. While the obvious improvement in irrigation efficiency is mainly attributed to the introduction of the Water Conservancy Key Counties Construction Program in 2009, this occurred after the crop mix had started to change. Thus, CMC is an appropriate moderating variable, and avoids the endogeneity issue.

The second level of moderating variable is the climatic region (CR). Similar to the field of environmental economics, in which scholars often use humidity/aridity to classify the climatic regions, we use humid and non-humid regions to classify the climatic regions. The statistical data indicate that humid regions include 15 provinces, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, and Yunnan, while the remaining 16 provinces, Beijing, Tianjin, Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Xizang, Shanaxi, Shandong, Henan, Xijiang, Ningxia, Qinghai, Gansu, and Inner Mongolia, are classified as non-humid regions (i.e., semi-humid, arid and semi-arid regions). We allocated humid regions a value of 1 and non-humid regions a value of 0.

Control Variable

To effectively exclude other factors that might interfere with the results of this study, we chose one control variable. Farmers reuse saved water by extending the irrigated area, which might induce the water rebound effect (Pfeiffer and Lin, 2014; Perry and Steduto, 2017). Thus, we used irrigated area (IAWC) to represent a control variable.

Model Selection

In this study, we used balanced panel data for empirical testing. Regarding the panel data, there are two types of evaluation methods, the fixed effects model and the random effects model. Following Wooldridge (2006), we conducted a Hausman test to determine which model best fit the data used in this study. The results of the Hausman test did not support the null hypothesis, and thus the fixed effects model was chosen. To test our hypotheses, we constructed the following equations:

$$LnW_{it} = \alpha_0 + \alpha_1 LnIE_{it} + \alpha_2 LnIAWC_{it} + u_{it} \tag{2}$$

$$\begin{aligned} LnW_{it} &= \beta_0 + \beta_1 LnIE_{it} + \beta_2 LnCMC_{it} \\ &\quad + \beta_3 LnIE_{it} * LnCMC_{it} + \beta_4 LnIAWC_{it} + u_{it} \end{aligned} \tag{3}$$

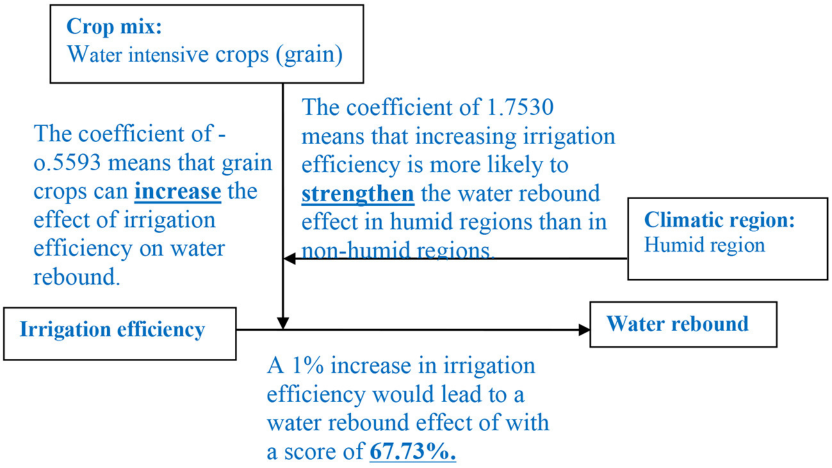

FIGURE 2 | Results of the double moderating effect.

TABLE 3 | Robustness checks.

	(1) LnW CMC ≤ median	(2) LnW CMC > median	(3) LnW CR = 0	(4) LnW CR = 1	(5) LnW CR = 0	(6) LnW CR = 1
LnIE	−0.0992 (0.1087)	−0.6970*** (0.1726)	0.0931 (0.1208)	−0.4706*** (0.1358)	0.0938 (0.1213)	−0.3949*** (0.1395)
LnIAWC	0.5312*** (0.0514)	0.5548*** (0.0402)	0.7349*** (0.0442)	0.4974*** (0.0327)	0.6878*** (0.0607)	0.4714*** (0.0360)
LnCMC					−0.4344* (0.2318)	−0.0075 (0.0504)
LnIE*LnCMC					−1.5524*** (0.4523)	−0.6619*** (0.2325)
Year	Control	Control	Control	Control	Control	Control
_cons	−2.5261*** (0.7030)	−2.7379*** (0.6524)	−4.9171*** (0.5237)	−2.1527*** (0.4837)	−4.2712*** (0.7437)	−1.5921*** (0.5117)
R^2	0.3762	0.4233	0.8646	0.3614	0.8881	0.3749
Observations	233	232	75	390	75	390

*Huber-White standard errors are reported in parentheses. *, **, and *** indicate statistical significance at the 10, 5, and 1% levels, respectively.*

$$\begin{aligned} LnW_{it} &= \gamma_0 + \gamma_1 LnIE_{it} + \gamma_2 LnCMC_{it} + \gamma_3 CR_{it} \\ &\quad + \gamma_4 LnIE_{it} * LnCMC_{it} + \gamma_5 LnIE_{it} * CR_{it} \\ &\quad + \gamma_6 LnCMC_{it} * CR_{it} + \gamma_7 LnIE_{it} * LnCMC_{it} * CR_{it} \\ &\quad + \gamma_8 LnIAWC_{it} + u_{it} \end{aligned} \tag{4}$$

where the subscript *i* represents each region and the subscript t represents the year. LnW, LnIE, and LnCMC represent the change in agricultural water resource demand, irrigation efficiency, and the ratio of non-grain crops to grain crops, respectively. CR represents the climatic region, LnIAWC represents the change in irrigated area of water conservation, and u is the error term. α_1 refers to the elasticity of IE on W, that is, the percentage change in W, when IE increases by 1%. Based on hypothesis 1, we infer that α_1 is negative, in other words, a 1% increase in irrigation efficiency would yield a -α_1% decrease in water use. Based on hypothesis 2, we infer that β_3 is negative, which means that CMC strengthens the water rebound effect by increasing irrigation efficiency. That is, increased non-grain (grain) production reduces (increases) the water rebound effect. Similarly, hypothesis 3 infers that γ_7 is positive, which means that humid regions increases the water rebound effect through increased production of non-grain crops.

Our study has several limitations that can inform future research. Due to the limitation of data availability, it is difficult for us to conduct more robustness checks and identify the mechanisms. Improvements in irrigation efficiency may reorganize existing resource. Distinguishing between water conservation and reorganization for the reduced form regressions on the effects of the irrigation efficiency improvement seems an obvious direction for further research.

RESULTS

Descriptive Statistical Analysis

Table 1 presents definitions and descriptive statistics for the selected variables. For the period 2004–2017, the mean agricultural water resource use was about 12,215 million m^3, ranging from a minimum of 510 million m^3 to a maximum of 84,470 million m^3 in various regions in China. The average IE was 0.758, reflecting a high level of water use efficiency, and the mean ratio of non-grain crop area to grain crop area was about 0.32, indicating that non-grain crops had been increasing and accounted for almost one-third of the irrigated area. Sixteen provinces featured non-humid climatic conditions, and thus had the potential to save water. The mean irrigated water conservation area has increased to about 859, 252 ha, and will continue to increase in the future.

Hypothesis Tests

Irrigation Efficiency and Water Conservation

Model 1 in **Table 2** was used to test the main effect. The dependent variable is LnW, the independent variable is LnIE, and the control variable is LnIAWC. A dummy variable representing the year is also used as a control. **Table 2** shows that the coefficient of LnIE is negative ($\alpha_1 = -0.3228$; $p < 0.01$), indicating that increasing irrigation efficiency is likely to reduce agricultural water use. In this study, the water rebound effect is 67.72%, or 0.6772 (WRE = 1–0.3228), which shows that China experienced a large agricultural water rebound effect. Thus, model 1 supports hypothesis 1.

In 2014, Chairman Xi stated that water conservation should be given priority in relation to water security. Updating irrigation technology to increase irrigation efficiency has been the first step toward saving water. However, as is evident from our results, increased irrigation efficiency does not necessarily enhance water conservation.

The Moderating Effect of the Crop Mix on the Relationship Between Irrigation Efficiency and Water Conservation

Model 2 in **Table 2** was used to evaluate the moderating effect of the crop mix on the relationship between irrigation efficiency and water conservation. Compared with model 1, model 2 has two additional variables, namely the moderating crop mix variable (LnCMC) and the variable representing the interaction between irrigation efficiency and the crop mix (LnIE*LnCMC). Hypothesis 2 states that non-grain crops are likely to reduce the water rebound effect, or increase the conservation effect, by increasing irrigation efficiency. The coefficient of LnIE*LnCMC is negative ($\beta_3 = -0.5593$; $p < 0.01$), which means that non-grain crops can increase the effect of irrigation efficiency on water conservation. The higher the ratio of non-grain crops to grain crops, the less the water rebound effect, and the less conserved water is reused on non-grain crops. In other words, if the crop mix includes more grain crops, increasing irrigation efficiency is likely to reduce water conservation and increase the water rebound effect. This supports hypothesis 2.

Higher water rebound effects for grain crops than non-grain crops suggests that grain crops are more rebound-prone as a result of the reduced marginal cost of water application. In China, the policy of updating irrigation technology, which targets both food security (water supply) and water conservation, has favored the former over the latter. The Water Conservancy Key Counties Construction Program, which was introduced in 2009, involved two tasks, lining canal irrigation systems and promoting high-efficiency water conservation technology. Obviously, this program has made more water available for grain-growing farmlands that previously had insufficient irrigation as a result of higher input costs in terms of the time and labor required. The program has been operating for more than a decade and is the main driver of improved irrigation efficiency. However, by inducing increased demand for water, it has exacerbated the water rebound effect and has failed to decouple grain production from water use.

Another possible reason for the difference in water conservation between grain crops and non-grain crops, that is less water being saved in relation to grain crops, is that grain crops generally use standard irrigation technology, while non-grain crops use high-efficiency irrigation technology. For example, the Standard of Water Conservation Irrigation Engineering Technology of China notes that the irrigation infrastructure used for rice crops features lined canals based on the gravity system, whose water utilization coefficient of irrigation at the tertiary level is about 0.7, while non-grain crops tend to use sprinkler or drip systems whose water utilization coefficient of irrigation is 0.8 and 0.85, respectively. Comparing the irrigation technology used, non-grain crops require less water than grain crops, and thus the water rebound effect is smaller.

Humid Regions vs. Arid and Semi-arid Regions

Hypothesis 3 states that the increased effect of non-grain crops on water rebound through improved irrigation efficiency is likely to be stronger in humid regions than in arid and semi-arid regions. Hypothesis 3 involves two moderating variables, and thus we developed a double-layered moderating effect model, including a three-way interaction term, as shown in Equation (4) above.

Model 3 in **Table 2** reports the results of Equation (4), and includes four variables, CR, LnIE*CR, LnCMC*CR, and LnIE*LnCMC*CR, in addition to those used in model 2. **Table 2** shows that the coefficient of LnIE*LnCMC*CR is positive ($\gamma_7 = 1.7530$; $p < 0.05$). The negative impact of non-grain crops on the relationship between irrigation efficiency and water use is greater in humid regions than in arid and semi-arid regions. That is, for a crop mix involving more non-grain crops, increasing irrigation efficiency is more likely to strengthen the water rebound effect in humid regions than in non-humid regions. This supports hypothesis 3.

Figure 2 summarizes the magnitude of water rebound effect and the quantitative means of coefficients, which are presented in the theoretical model. This figure also shows the response of the empirical analysis to the theoretical hypotheses.

Robustness Checks

We repeated the regressions using split samples to check the robustness of the results. First, we split the sample into two groups based on the median CMC score, with one group consisting of those with a CMC score below the median and the other group consisting of those with a CMC score above the median, as shown in columns (1) and (2), respectively, in **Table 3**. The coefficient of lnIE in column (2) is significantly negative (−0.6970), while the coefficient of lnIE in column (1) is negative but not significant (−0.0992). Thus, a crop mix with more non-grains is more likely to save water through increasing irrigation efficiency than a crop mix with more grain crops. The regression analysis of the split sample produced the same results as that including the two interactive terms, confirming the robustness of the first moderating effect.

Next, we split the sample into two groups based on CR, with one group consisting of those with CR equal to 0 (non-humid regions) and the other group consisting of those with CR equal to 1 (humid regions), as shown in columns (3), (4), (5), and (6) in **Table 3**. The coefficients of LnIE*LnCMC in columns (5) and (6) are significantly negative, at −1.5524 and −0.6619, respectively. However, the coefficient of LnIE*LnCMC in column (6) is larger than that in column (5), showing that compared with the non-humid regions, the humid regions are more likely to reduce the water conservation effect of increasing irrigation efficiency because of crop mixes including more non-grain crops (LnIE*LnCMC). The regression analysis of the split sample produced the same results as the double-layered moderating effect analysis using three interactive terms, confirming the robustness of our results.

DISCUSSION

Through constructing a double-layered moderating effect model including a three-way interaction term, we tested three types of relationships: the relationship between irrigation efficiency and water use, the moderating-effect of the crop mix on the relationship between irrigation efficiency and water use, and the difference in the moderating effect between humid regions and non-humid regions. The first relationship also includes the water rebound effect as a result of improved irrigation efficiency. The empirical results provide support for hypotheses 1, 2, and 3.

The results of this study provide three theoretical contributions to the literature. First, previous researches exploring the relationship between irrigation efficiency and water use, or the water rebound effect following improved irrigation efficiency at the regional scale, have focused on overall efficiency rather than efficiency related to irrigation technology. Since improved irrigation efficiency mainly arises from updating physical irrigation technology, we used technology improvements assess changes in irrigation efficiency. This allowed us to reflect changes in irrigation efficiency over time, unlike Song et al. (2018), who treated irrigation efficiency as a constant. We found that improved irrigation efficiency is less likely to reduce water use because of the water rebound effect, which was estimated at 67.72% in this study, similar to the figures of 61.49% and 66% obtained by Song et al. (2018) and Fei et al. (2021), respectively. Failure to consider the rebound effect in policy appraisals will lead to a significant overestimate of water savings.

Second, previous studies have pointed out the importance of the crop mix in relation to the water rebound effect following irrigation efficiency improvements (Pfeiffer and Lin, 2014; Grafton et al., 2018). However, empirical evidence is scarce. Additionally, researches on the impact of irrigation efficiency improvements on the relationship between the crop mix and water use are rare. The results of this study quantitatively prove the interactive effect of the crop mix and irrigation efficiency on water use. The results of this study also extend our understanding of the importance of the crop mix, showing that a higher ratio of grain crops is more likely to increase the water rebound effect, while a higher ratio of non-grain crops is more likely to save water and decrease the water rebound effect. Although the work of Lecina et al.'s (2010) Spanish study mentioned that modern sprinkler systems in combination with water-intensive crops increase water use, our findings further identify that grain crops, rice in particular, are associated with the large water rebound effect and thus the depletion of water resources.

Third, this study is the first to examine the differences in the moderating effect of the crop mix on the relationship between irrigation efficiency and water use between humid regions and non-humid regions. The moderating effect of the crop mix in humid regions is smaller than that in non-humid regions, indicating that the water rebound effect of non-grain crops in humid regions is greater than that in non-humid regions, where water conservation technologies enable an increase in water consumption, thereby reducing water availability for other users. This finding confirms the importance of the climatic region and that non-grain crops have a greater water rebound effect under specific conditions such as those found in humid regions. Thus, the results of this study provide new insights into the heterogeneity of the water rebound effect.

CONCLUSIONS

Main Conclusion

The results of this study enrich our understanding of the theory of resource efficiency and Jevons paradox in relation to the mechanism underlying the water rebound effect. The aim of increasing irrigation efficiency is mitigation of the water rebound effect. The results of this study confirm that the crop mix is a significant factor in improved irrigation efficiency aimed at conserving water. The greater the ratio of non-grain crops in a region, the lower the water rebound effect that is likely to occur, because water-intensive crops, such as grain crops, use more of the water saved through improved irrigation efficiency than non-grain crops.

Grain production in China provides a specific example of a crop mix that can be used to explain the paradox of irrigation efficiency. Over the last two decades, although irrigation efficiency has been increasing and will continue to increase in the future, the expected agricultural water resource conservation has not been achieved because the crop mix involving a majority of grain crops has proved challenging. Grain production is driven by China's food security strategy, however the increased production of grain crops offsets the water conservation achieved by updating irrigation technology. Given that grain-growing to achieve food security is set to increase in the future, the water rebound effect is unlikely to be avoided.

Climate is another factor that impacts the water rebound effect, especially in relation to non-grain crops. Even though non-grain crops offer more water conservation opportunities than grain crops, the water rebound effect in relation to non-grain crops remains heterogonous. Non-grain crops consume more water that is saved through increased irrigation efficiency in a humid climate than in a non-humid climate. Thus, non-water-intensive crops are also subject to the water rebound effect, confirming the importance of the crop mix.

Policy Implications of Increased Irrigation Efficiency

To optimize the effect of improved irrigation efficiency, policymakers should consider the crop mix and the climatic region, both of which can produce heterogeneous rebound effects.

First, policies aimed at increasing irrigation efficiency, such as irrigation infrastructure modernization and updating of irrigation technology, should continue to be promoted in regions with non-water-intensive crops. Particularly in humid regions with a higher ratio of non-grain crops, increasing irrigation efficiency is more likely to conserve agricultural water resources. Improved irrigation efficiency generates a trade-off between grain production and water conservation, as well as a coupling relationship between grain production and the water rebound effect. Since food security is a key strategy in China, it is not appropriate to pursue policies that sacrifice grain production to conserve water. Rather, policies aimed at sustaining agricultural water resources should focus on non-grain production.

Second, an alternative way to reduce the water rebound effect involves consideration of the climatic region. In humid regions, reducing the proportion of non-grain crops is likely to improve water conservation by enabling improved irrigation efficiency. The development of high-value water-conserving crops in humid regions is a potential solution that can contribute to decoupling the relationship between water use and agricultural production.

Third, another means of increasing the water conservation effect of improved irrigation efficiency lies in innovations regarding grain crops. To achieve the simultaneous objectives of increasing water conservation while maintaining agricultural production, it is necessary to develop water-conserving grain crops. From the perspective of water use comparisons, reducing the cost gap between water-conserving gain crops and water-intensive grain crops will encourage farmers to grow more of the former, thereby reducing their tendency to use more water after updating their irrigation technology.

In summary, this study provides quantitative supports for policies aimed at promoting water-conserving crop mixes. Shifting the cropping pattern to a higher proportion of non-grain crops in non-humid regions can mitigate the water rebound effect and increase water conservation. The findings of our study provide guidance for the government in developing policies designed to achieve Sustainable Development Goal 6 put forward by the United Nations.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

YC is a researcher and lead author. YC, HZ, and ZM contributed to project design, conceptual framework development, and manuscript preparation. ZM, SP, and JZ reviewed different versions of the manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

This research was funded by Foundation for Innovation Team in Guangdong Higher Education, grant no. 2021WCXTD010 and Natural Science Foundation of Guangdong, grant nos. 2021A1515011880 and 2018A030313453.

ACKNOWLEDGMENTS

We are grateful for the audience of World Development Conference 2022 and the 10th ASAE International Conference: Gearing Asian Agriculture under the Fourth Industrial Revolution: Opportunities and Challenges for their constructive comments and suggestions.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.