agronomy

MDPI

Article

Current State and Limiting Factors of Wheat Yield at the Farm Level in Hubei Province

Rui Yang [1], Matthew Tom Harrison [2] and Xiaoyan Wang [1,*]

[1] Hubei Key Laboratory of Waterlogging Disaster and Agricultural Use of Wetland, Engineering Research Center of Ecology and Agricultural Use of Wetland, Ministry of Education, MARA Key Laboratory of Sustainable Crop Production in the Middle Reaches of the Yangtze River, School of Agriculture, Yangtze University, Jingzhou 434025, China; 202073049@yangtzeu.edu.cn

[2] Tasmanian Institute of Agriculture, University of Tasmania, Newnham Drive, Launceston, TAS 7248, Australia; matthew.harrison@utas.edu.au

* Correspondence: wangxiaoyann@yangtzeu.edu.cn; Tel.: +86-716-8066314

Abstract: Longitudinal wheat yields in China have declined in recent times due to climate change, more frequent natural disasters, and suboptimal agronomic management. To date, it has been unclear which factors have predominated yield penalties realised hitherto in Hubei Province. This study aimed to identify key factors limiting wheat production across systems and agroecological regions, and provide a basis for increasing crop production while engendering food security. Survey data from 791 households in Hubei Province were analyzed using descriptive statistics and logistic regression. Significant spatial heterogeneity in average wheat yields was observed, with the Jianghan Plain region having significantly lower yields compared with the northwest region (yield gap: 1125 kg·hm^{-2}). Dryland wheat had higher average yields than rice-rotation wheat (yield gap: 134 to 575 kg·hm^{-2}). Socioeconomic factors, cultivation management measures, and environmental factors contributed differently to yield differences. Input costs and economic benefits were key social factors influencing wheat production. Variation in management were mainly attributed to planting methods, while soil fertility and climatic factors limited yields in some regions. In the northwest, low soil fertility and susceptibility to drought and high temperatures had greater influence on yields. In the Jianghan Plain, soil waterlogging and erosion were key challenges. Waterlogging increased the probability of low yields by 8.6 times, while severe soil erosion increased probability of yield loss by a factor of almost five. Low-yield farms in the Jianghan Plain were 21% higher than those in the northwest. Extreme weather events also contributed to low yields in the Jianghan Plain. We note significant potential for increasing farm-level wheat production in Hubei Province, with large existing differences across agro-ecological regions and planting modes. Differences in cultivation practices was a major driving factor of yield gaps between planting modes, while soil fertility and meteorological disasters drive regional yield differences. These results have implications for those aspiring to narrow the yield gap across regions and increase production of cereal crops.

Keywords: Hubei Province; wheat; farmer level; yield gap; influencing factors

Citation: Yang, R.; Harrison, M.T.; Wang, X. Current State and Limiting Factors of Wheat Yield at the Farm Level in Hubei Province. *Agronomy* **2023**, *13*, 2043. https://doi.org/10.3390/agronomy13082043

Academic Editor: Masoud Hashemi

Received: 17 May 2023
Revised: 9 July 2023
Accepted: 13 July 2023
Published: 31 July 2023

1. Introduction

"Grain self-sufficiency and absolute food security" has been the basic strategic bottom line for national food security since the 18th National Congress of the Communist Party of China. The total amount of grain security and the supply demand balance between the two major food crops of rice and wheat are closely related to the national strategy and people's livelihood security. Wheat is the third-largest main grain crop in China, accounting for 20% of the total grain production in 2021 [1,2]. It is estimated that by 2030, the demand for wheat will be about 150 million tons [3]. As one of China's important wheat producing areas, improving the level of wheat production in Hubei Province is crucial to ensuring national food security. However, the terrain in different regions of

Hubei Province is complex and diverse, and the ecological conditions vary greatly. The average wheat yield is only 3796 kg·hm^{-2} [4], lower than the national average level. But this also indirectly reflects that the wheat production in Hubei Province has great potential for increase. Therefore, understanding the main limiting factors for increasing wheat production in Hubei Province is of great significance for increasing the total wheat production and achieving national food security. Yield gap analysis is an effective way to evaluate the current state and potential for increasing crop yields in a region, and explore yield limiting factors and solutions [5,6]. Yield-limiting factors for crop production mainly include socioeconomic, cultivation management, and environmental factors. Given the complexity of yield gaps, the analysis methods are also diverse, including using crop growth models, remote sensing data, experimental data, and farmer surveys to analyze the factors and potential for increasing yields [7,8]. Han et al. [9] found that only 64.34% of winter wheat farmers in Shandong Province achieved the highest record yield, and the yield gap could be reduced by 23.46% by optimizing cultivation management measures. Wang et al. [10] found, through the AEZ model, that the spatial yield difference of wheat in Henan Province is mainly the north–south difference dominated by climate and the east–west difference dominated by geology and landforms. Liu et al. [11] found, through a survey of farmers, that they attributed more limiting factors of crop yield to objective natural conditions such as climate and soil (about 40.5%), while fertilization level was the most important factor affecting the yield gap of winter wheat in cultivation factors. Yield gap research has been extensively reported in China's major wheat-producing areas, but there are few reports on yield gap research for wheat in Hubei Province.

The objectives of this study are to: (1) systematically analyze the yield gap of wheat in Hubei Province, considering multiple perspectives such as socioeconomics, cultivation management, and environmental factors; (2) comprehensively analyze the existing yield gap and planting characteristics of wheat in Hubei Province based on the results of 791 farmer surveys conducted in the main wheat planting areas, and (3) explore the main limiting factors for wheat production in Hubei Province, taking into account socioeconomic factors, cultivation management practices, and environmental factors. These results could provide a theoretical basis for the comprehensive improvement of regional wheat production in Hubei Province.

2. Data Sources and Research Methods

2.1. Study Area Overview

Hubei Province is an important province in the wheat-growing area of the middle and lower reaches of the Yangtze River. The study area covers the main wheat-planting areas in Hubei Province, such as Xiangyang City, Suizhou City, and Yichang City in the northwestern part of Hubei, as well as Jingzhou City, Jingmen City, and Xiaogan City in the Jianghan Plain region (Figure 1). The northwestern region of Hubei is dominated by hilly terrain, and is affected by seasonal and regional droughts and the difficulty of water storage due to the characteristics of the terrain and geology, resulting in relatively limited water resources [12]. It is the main area for rain-fed agriculture development, such as intercropping of beans and wheat or oats. The Jianghan Plain is located in the central and southern parts of Hubei Province, and is dominated by flat terrain with numerous lakes in the region. Abundant seasonal rainfall provides sufficient water resources for agricultural production [13]. The system of rice–wheat rotation is a common land use pattern in the region. Therefore, the investigation area of this study covers various soil and environmental characteristics in Hubei Province, and can effectively reflect the wheat yield production and planting situation under different natural attributes such as soil and climate, which has certain practical significance for studying the limiting factors of yield differences in wheat production in Hubei Province and even nationwide.

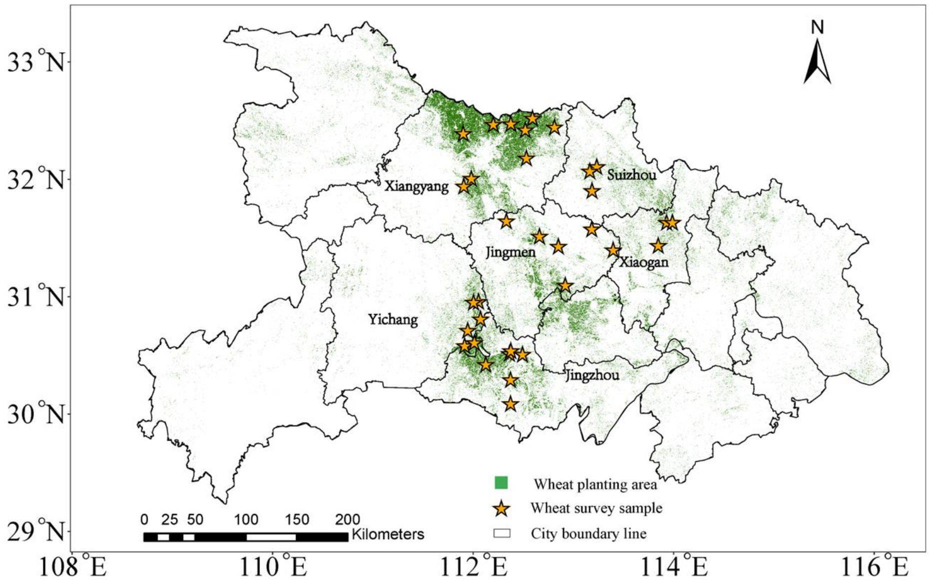

Figure 1. Wheat planting areas in Hubei Province and selected townships for investigation (n = 33). Note: The data of wheat planting distribution in Hubei Province were from the Chinese Academy of Science Discipline Data Center for Ecosystem (http://www.nesdc.org.cn/, accessed 12 July 2023).

2.2. Data Sources

Our research team conducted a large-scale farmer survey in Hubei Province from 2016 to 2018. The survey was conducted through a combination of stratified and random sampling methods (Figure 2). We selected 1–3 sample counties from six pre-selected sample prefecture-level cities, and then selected 2–4 townships from each sample county, totaling 33 townships (Figure 1). We randomly selected 2–4 villages from each sample township and interviewed 10 households in each sample village in person with surveyors. To ensure the quality of the survey, all surveyors participated in pre-survey training. A total of 840 questionnaires were distributed in this survey, and 49 samples were excluded due to missing or false information. We obtained 791 valid samples, with an effective rate of 94.2% according to the research needs.

2.3. Variable Selection and Description

The questionnaire mainly included information on household characteristics, planting features, the state of wheat yield, and the main factors affecting wheat yield as perceived by farmers. For the collection of wheat yield and planting feature data, if a farmer had multiple plots of land, the one with the largest wheat harvest area was selected as a representative.

Household characteristics: The survey mainly investigated the education level of the respondents, as this reflects to some extent the degree of mastery of information and skills by the respondents. Farmers with higher education levels may have more accurate perceptions and feedback on the main factors affecting yield.

Planting features: Two aspects, planting system and soil texture, which may directly or indirectly affect wheat production for farmers, were selected. Under the rotation planting system, wheat production is easily affected by the previous crop. In Hubei Province, the water–dry rotation and dryland rotation are typical large field rotation modes for wheat production in the Jianghan Plain. Soil texture can comprehensively reflect soil structural characteristics and the conservation capacity of fertility and water.

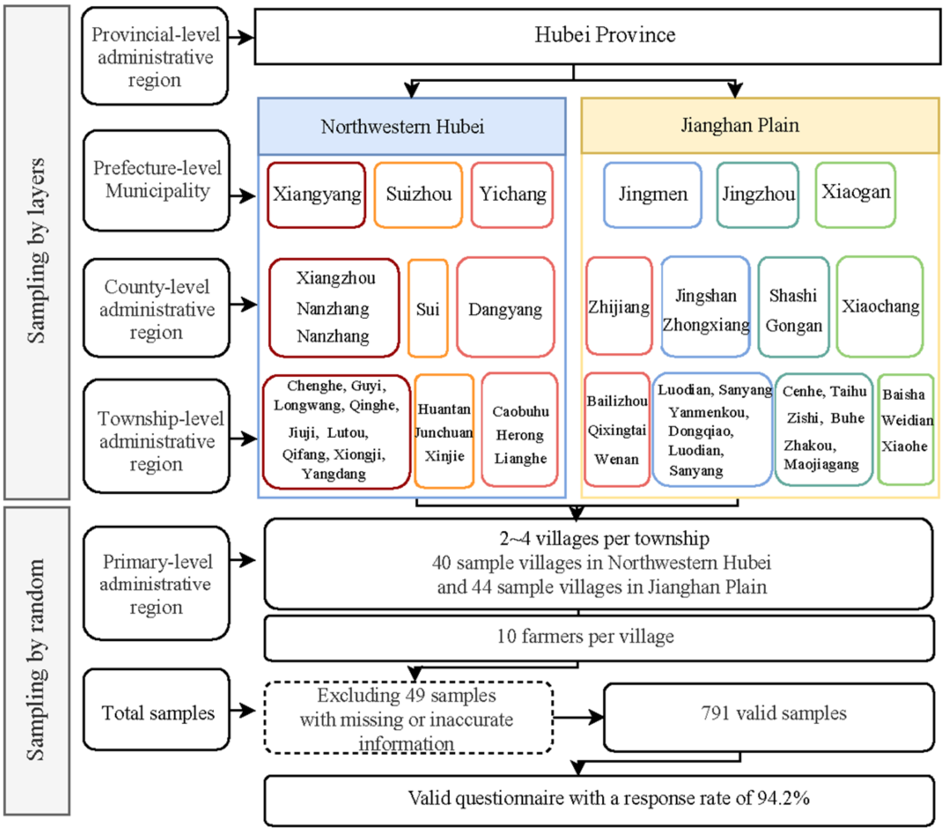

Figure 2. The flow chart of sampling survey in Hubei Province.

Yield level: The yield level was divided into "low yield (<4500 kg·hm^{-2})", "medium yield (4500–6000 kg·hm^{-2})", and "high yield (>6000 kg·hm^{-2})". According to the wheat yield distribution obtained from the survey, which ranged from 1950–9000 kg·hm^{-2}, the 25th percentile (4500 kg·hm^{-2}) and 75th percentile (6000 kg·hm^{-2}) of all yields were used as the basis for division.

Factors affecting wheat yield: The study analyzes the factors that contribute to differences in wheat yield from social, economic, cultivation management techniques, and environmental factors. The specific indicators selected are shown in Table 1. Agricultural policies and investments in agricultural production can encourage farmers' planting enthusiasm, while also indirectly affecting the choice of cultivation management techniques, thereby indirectly increasing yield. However, compared to social and economic factors, differences in yield between regions are more often caused by environmental factors such as climate and soil. Artificial cultivation management factors can adjust the impact of environmental factors on yield formation [6]. Therefore, the formation of yield differences is the result of the interaction of various factors, and the limiting factors of yield differences need to be analyzed from multiple aspects such as social and economic factors, cultivation management techniques, and environmental factors.

2.4. Statistical Analysis

Multivariate logistic regression is suitable for studying the relationship between the dependent variable and the influencing factors. Therefore, this study adopted multivariate logistic regression analysis to investigate the main factors influencing the wheat yield level of farmers. SPSS 22.0 is used for statistical analysis and calculations.

Table 1. Classification and statistics of main factors affecting wheat yield, as considered by farmers.

Influencing Factors	Observable Indicator	Farmers' Selection Rate (%)
Socioeconomic factors	Low market price and poor efficiency	94
	Large investment and high cost	85
	High and unstable prices of agricultural materials	62
	Impact of national food policy	55
	Difficulty in selling food	13
	Seed market instability	6
	Fake fertilizer pesticide	3
Cultivation management factors	Poor sowing quality, low seedling quality	72
	Unreasonable selection of varieties	58
	Water and fertilizer input is not appropriate	55
	Application of chemical control technology	32
	Seed quality issues	29
	Agricultural machinery agronomic not matching	24
	Agricultural technology promotion is not in place	4
Soil factors	Soil water and fertilizer holding is poor	66
	The soil is not fertile enough	63
	Shallow soil layer	54
	Poor soil texture	51
	Serious soil and water loss	23
	Soil salination	7
Climatic factors	Drought	70
	Waterlogging	66
	Heat injury	51
	Chill damage	32
	Light deficiency	16
	Gale hail	11
	Insufficient effective accumulated temperature	9

Logistic regression can be used to predict the probability of the dependent variable Y, and to explain the role and strength of the independent variable Xn in it. In this study, farmer wheat yield was taken as the dependent variable, and the three yield levels "low yield, medium yield, high yield" were assigned values of [1,3], respectively, i.e., yi (i = 1, 2, 3), with $y3$ (high yield level) as the reference level of the model. The main factors affecting farmer's perception of wheat yield were taken as explanatory variables, i.e., xk (k = 1, 2, . . . , k), where k is the number of influencing factors.

The probability of the occurrence of the event y can be expressed as Equation (1):

$$P(y = i|x_{ki}) = \frac{\sum_{i=1}^{3} \exp(y_i)}{1 + \sum_{i=1}^{3} \exp(yi)} \tag{1}$$

The odds ratio (OR), defined as the ratio of the probability of the event occurring (Pi) to the probability of the event not occurring ($1 - Pi$), is used to explain the effect of each independent variable on the probability of the event. The corresponding logistic regression model is Equation (2):

$$\ln[\frac{P}{1-P}] = \alpha + \sum_{k=1}^{k} \beta_k x_{ki} \tag{2}$$

where α is the intercept, and β is the regression coefficient. A positive (negative) value of β indicates that the independent variable can increase (decrease) the probability of the event's occurrence. The larger the value of β, the greater the influence of the independent variable on the event occurrence rate.

3. Results and Analysis

3.1. State of Wheat Yield of Hubei Province Farmers

Analysis of 791 Hubei province farmer survey questionnaires (Figure 3a) revealed an average wheat yield of 5262 kg·hm^{-2} in the region, with average yields of 5867 and 4729 kg·hm^{-2} in the northwestern Hubei and Jianghan Plain regions, respectively, resulting in an average yield difference of 1138 kg·hm^{-2} between the regions. The fluctuation in yield of the Jianghan Plain region (CV = 21.3%) was greater than that of the northwestern Hubei region (CV = 13.9%). In addition, there was also a significant yield difference between the different wheat cultivation patterns in Hubei province (Figure 3b), with the average yield of dryland wheat in the northwestern Hubei and Jianghan Plain regions being higher than that of rice straw wheat by 575 kg·hm^{-2} and 134 kg·hm^{-2}, respectively. Overall, there are significant regional and cultivation pattern differences in wheat yield among Hubei province farmers, with regional yield differences being greater than pattern differences.

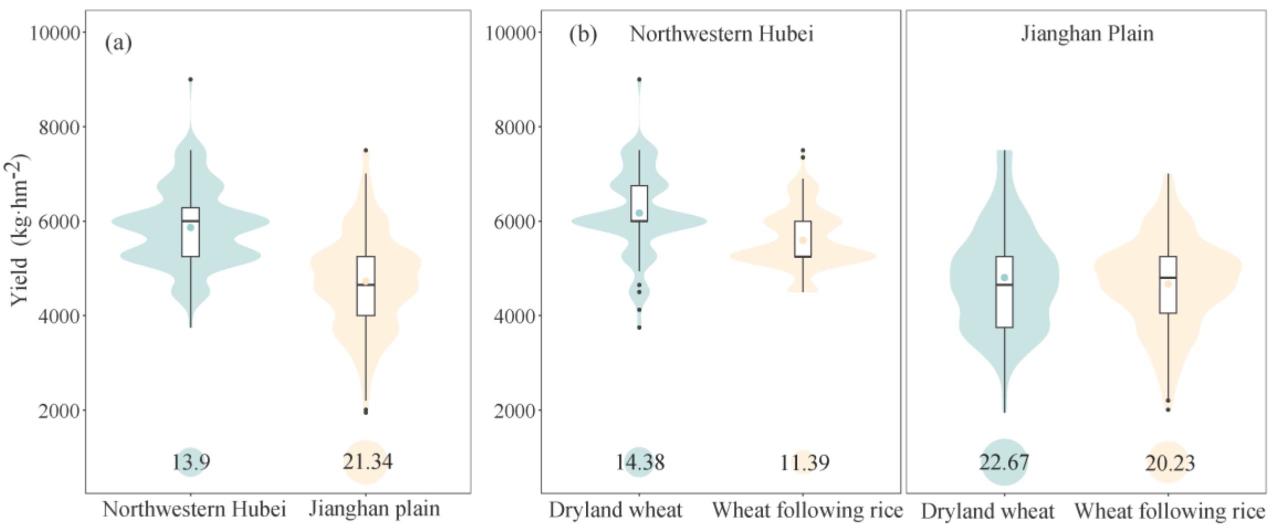

Figure 3. Actual farmers' wheat yield gap in Hubei Province (n = 791). Note: The circle size refers to coefficient of variation.

3.2. Analysis of Sample Farmer Characteristics

The survey found that most of the interviewed farmers had a junior high school education, accounting for 59.5–63.9% (Figure 4a). According to the three yield levels defined for evaluating farmers' production levels, middle-income farmers accounted for 62.6–73.0% of the surveyed farmers. The proportion of farmers in each yield level varied between regions, with high-yield farmers accounting for 26.2% in the northwestern Euxine region and only 0.8% of low-yield farmers, while in the Jianghan Plain region, high-yield farmers accounted for only 5.9%, and low-yield farmers accounted for 31.5%. Therefore, there is still significant room for improvement in farmers' production levels, especially in the Jianghan Plain region, where most farmers have low and middle yields.

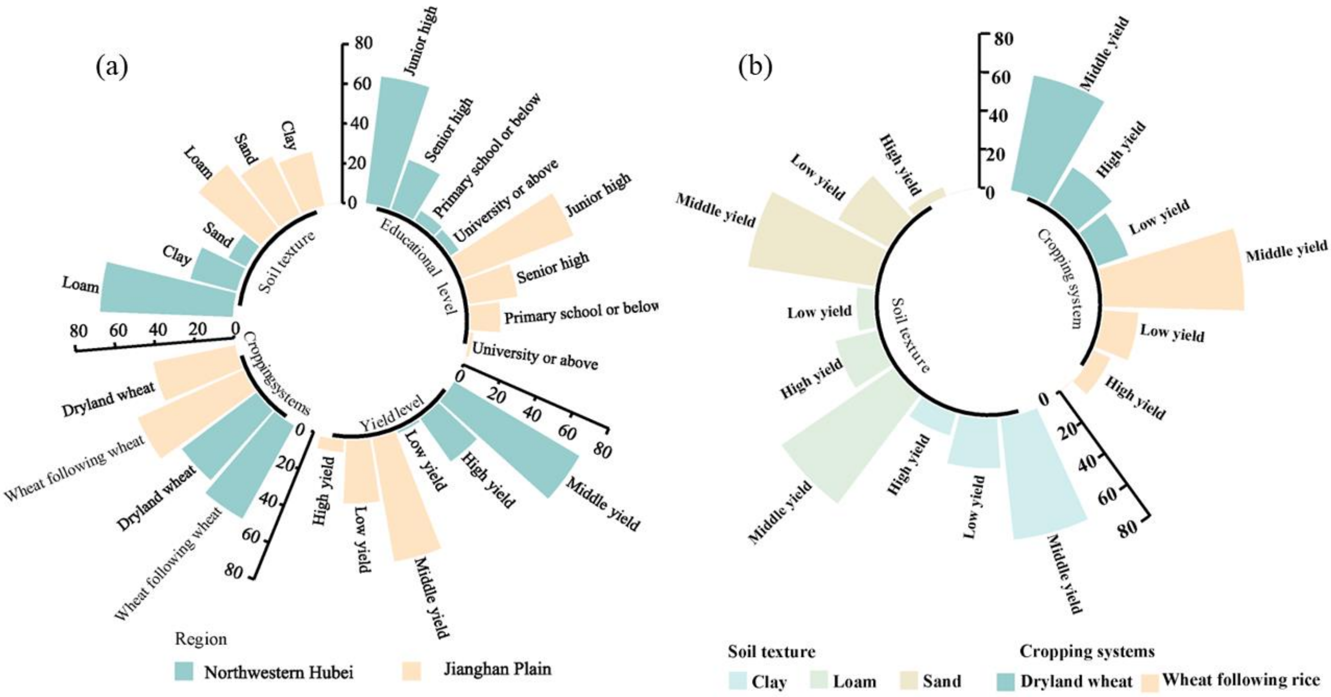

Figure 4. Differences in regional planting characteristics (**a**) and distribution of farmers' yield levels across cropping system and soil texture (**b**).

The proportion of dryland wheat and stubble wheat was roughly the same in both regions, with stubble wheat slightly higher than dryland wheat. Soil texture directly affects crop production, and the survey classified the soil texture of the survey areas into three categories: loam, sandy soil, and clay. Loam was the dominant soil type in Hubei Province's wheat fields, accounting for 40.5–66.6%. In the northwestern Euxine region, farmers with clay soil accounted for 23.8% of the surveyed farmers, and sandy soil accounted for only 9.6%. In contrast, the soil in the Jianghan Plain hinterland was mostly alluvial sandy soil, and farmers with sandy soil accounted for 32% of the surveyed farmers, while those with clay soil accounted for 27.5%.

Further analysis of the proportion of yield levels under different planting characteristics of the surveyed farmers (Figure 4b) showed that the proportions of low-yield farmers planting dryland wheat and stubble wheat was roughly the same. The main difference was in the proportion of high-yield farmers and middle-income farmers, with the proportion of high-yield dryland wheat farmers being 13.6% higher than that of stubble wheat farmers, and the proportion of middle-income stubble wheat farmers being as high as 72.8%. Therefore, the goal of increasing stubble wheat production is mainly to raise the level of middle-income farmers to that of high-yield farmers. There were also significant differences in yield levels among farmers with different soil textures, with high-yield and middle-income farmers with loam soil accounting for a significantly higher proportion than those with clay and sandy soil. In loam soil, the proportion of high-yield and middle-income farmers was 21.6% and 70%, respectively, and the proportion of low-yield farmers was only 8.4%. In contrast, the proportion of low-yield farmers in sandy and clay soils was 29.2% and 25.5%, respectively, and the overall yield level of sandy and clay soils was lower than that of loam soil.

3.3. Analysis of the Influencing Factors of Regional Yield Differences and Planting Pattern Yield Differences

From the Sankey diagram (Figure 5), it can be seen that the observation indicators with the highest proportion in the social and economic factors are mostly directly related to the economy. These are low market grain prices, poor efficiency, high input costs, high and unstable prices of agricultural materials such as fertilizers, etc. Their average proportion among all observation indicators is 8.5%, 7.6%, and 5.6%, respectively, indicating that compared to social policies and markets, farmers are more concerned about the input costs and economic benefits obtained after wheat production. Among the cultivation management factors, the indicators with the highest proportion among all observation indicators are poor sowing quality and low emergence quality (average proportion of 6.5%), followed by unreasonable variety selection (5.2%) and improper water and fertilizer input (5%). This shows that farmers believe that there are still deficiencies in cultivation management techniques such as tillage, varieties, and nitrogen fertilizers. The indicators related to soil fertility are among the top in the soil factors. Among them, poor soil water and fertility retention capacity and low soil fertility account for 6.0% and 5.7% of the total observation indicators, respectively. Shallow soil depth and poor soil texture account for 4.8% and 4.6%, respectively. Temperature and precipitation are the main influencing factors of yield variability. In this study, drought and waterlogging are the most significant yield-limiting factors among climatic factors, accounting for 6.3% and 5.9% of all observation indicators, respectively, followed by heat damage and cold damage, with average proportions of 4.6% and 2.9%, respectively. It can be seen that compared with temperature, wheat production in Hubei Province requires more attention to water stress.

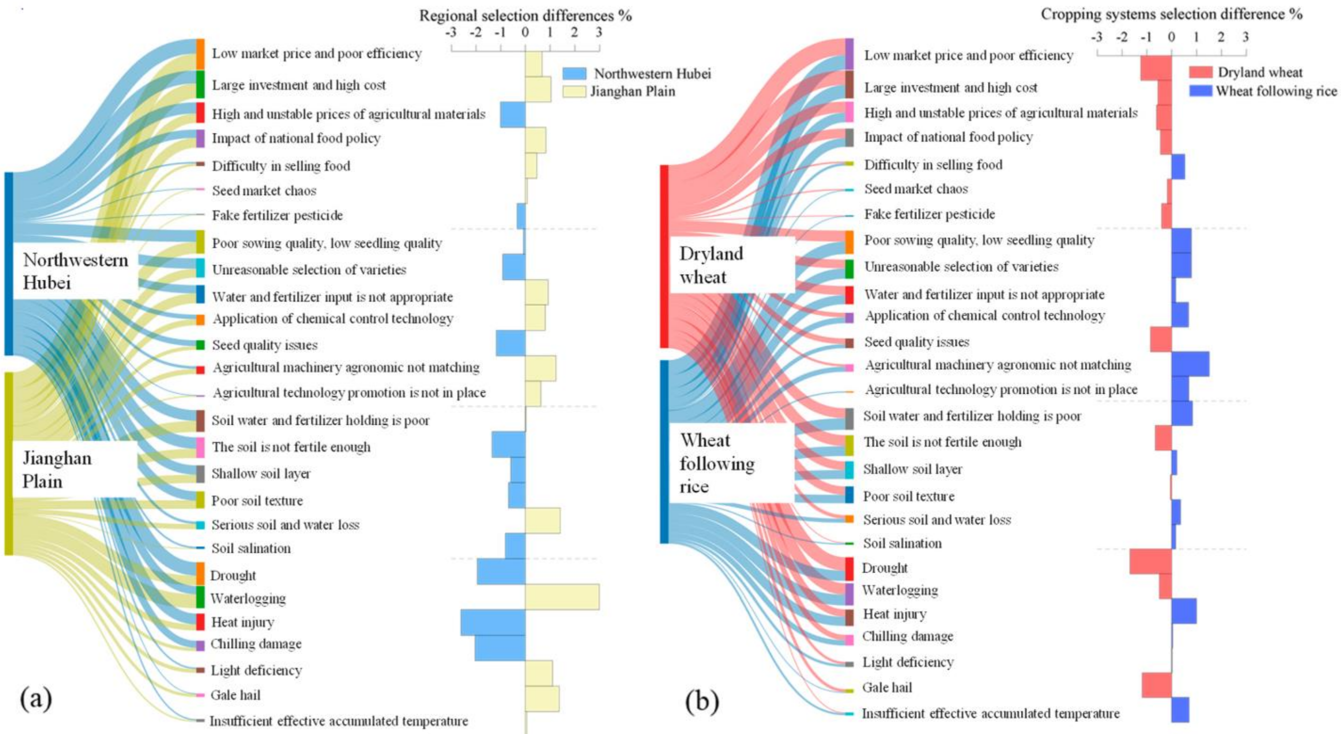

Figure 5. Differences in selection of yield-limiting factors. Note: yield-limiting factors are considered as nodes in the Sankey diagram. The height of each node represents the proportion of each limiting factor accounted for all factors. The connection line between nodes reflects the selection of each limiting factor by farmers in regions (**a**) or cropping systems (**b**). The width of the line represents the proportion of the yield limiting factors accounted for all factors. The two-way bar chart shows the differences in farmers' choices of yield-limiting factors among regions or cropping systems (i.e., selection difference in region or cropping system (%) was calculated as the proportion of the factor accounted for all factors in Jianghan Plain (wheat following rice)—proportion of this factor accounted for all factors in northwestern Hubei (dryland wheat).

The spatial heterogeneity of environmental factors such as soil and climate is the main cause of regional yield differences, and the differences in farmers' choice of yield limiting factors also prove this. Compared with social and cultivation management factors, the selection of yield limiting factors between regions is more different in soil and climatic factors (Figure 5a). Specifically, in social factors, although the factors with the highest selection difference in the western Hubei and Jianghan plain regions have exceeded 1%, they are all considered to have higher input costs (high input, high cost, and high and unstable prices of agricultural materials such as fertilizers). For cultivation factors, the factors with more than 1% difference are poor seed quality (in the western Hubei region) and mismatch between agricultural machinery and techniques (in the Jianghan plain region), with selection differences of 1.18% and 1.23%, respectively. Regarding soil factors, the selection differences between the two regions are the greatest in the lack of fertile soil and serious soil erosion, with selection differences of 1.35% and 1.41%, respectively. More farmers in the western Hubei region believed that the soil is not fertile enough, while more in the Jianghan plain region chose serious soil erosion. The largest difference in the choice of yield-limiting factors between the two regions was in regard to climatic factors, with waterlogging accounting for 7.4% of all yield-limiting factors in the Jianghan plain region, which is 3% higher than that in the western Hubei region, while farmers in the western Hubei region chose drought, heat damage, and cold damage more, with selection differences of 1.94%, 2.61%, and 2.04%, respectively.

The differences in the selection of yield-limiting factors between planting modes are much smaller than those between regions (Figure 5b). Wheat farmers in dryland areas tended to choose socioeconomic factors as yield-limiting factors, while those in rice–wheat areas tended to choose cultivation management factors, with the largest selection difference being the mismatch between agricultural machinery and agronomy (1.5%), followed by poor seed quality and low seedling quality (0.8%). This indicates that further research is needed on the existing cultivation management techniques for rice–wheat rotation in Hubei Province, especially the need to strengthen the deep integration of agricultural machinery and agronomy and improve seedling quality. Soil, water, and nutrient retention capacities and drought are the factors with the largest selection differences in soil and climatic factors for rice–wheat rotation and dryland wheat, with selection differences of 0.8% and −1.7%, respectively.

3.4. Main Limiting Factors of Household Production Level

In order to further understand the main factors limiting the increase of household production, the observation indicators of "whether affecting wheat yield" in the questionnaire (Table 1) were assigned binary values (Yes = 0, No = 1). Multiple logistic regression analysis was used to analyze the specific factors influencing the probability of "middle-income households" and "low-income households" occurring, with each observation indicator acting as an independent variable, introduced into the multiple logistic regression model, with "No" as the reference variable and "high-income households" as the reference level, predicting the probability (OR) of the occurrence of "middle-income households" and "low-income households", and selecting the factors that significantly ($p < 0.05$) affected the production level. The log-likelihood value of the model was 893.239, the chi-squared test value was 361.048, and the significance level (Sig.) was 0.000, indicating that the model was significant.

The management decisions of households with regard to wheat production were largely related to economic factors. The regression analysis showed that when farmers perceived high inputs and costs, the probability of yield at the level of 4500–6000 kg·hm^{-2} would be 3.227 times that of high-income farmers (>6000 kg·hm^{-2}) (Table 2). In daily production, farmers paid more attention to economic yield, and when input costs were too high, farmers may choose to control the input of costs, thereby affecting crop yields. Compared with high-income farmers, more middle-income and low-income farmers chose the difficulty of selling grain as the main influencing factor, and this choice increased the probability of low profit and median profit by 5.987 times and 3.227 times, respectively. The problem of difficulty in selling grain mainly occurs after wheat production, so the results of the model indicate that middle-income and low-income farmers have more problems with difficulty in selling grain than high-income farmers.

Table 2. Logistic model regression results of factors affecting farmers' production levels.

Influencing Factors	Observable Indicator	Low-Yield Farmers			Middle-Yield Farmers		
		Regression Coefficient	Significance Level	Odds Ratio	Regression Coefficient	Significance Level	Odds Ratio
Socioeconomic factors	Low market price and poor efficiency	−1.489	0.04	0.226	-	-	-
	Large investment and high cost	-	-	-	1.112	0.005	3.039
	Difficulty in selling food	1.790	0.003	5.987	1.171	0.020	3.227
Cultivation management factors	Unreasonable selection of varieties	-	-	-	−1.083	0.001	0.339
	Application of chemical control technology	1.522	0.001	4.582	1.320	0.000	1.844
	Seed quality issues	1.080	0.020	2.946	1.478	0.000	4.385
Soil factors	Soil water and fertilizer-holding is poor	0.919	0.024	2.507	-	-	-
	Serious soil and water loss	1.577	0.001	4.840	0.840	0.046	2.316
Climatic factors	Drought	−1.836	0.000	0.099	−1.870	0.000	0.160
	Waterlogging	2.161	0.000	8.683	-	-	-
	Heat injury	−1.468	0.001	0.230	−0.953	0.001	0.386
	Light deficiency	1.979	0.002	7.238	1.306	0.044	3.692

Improper cultivation management measures often result in a decrease in yield level during crop production. The results of this study show that compared with high-income farmers, seed quality issues and problems in the application of chemical control technologies would significantly ($p < 0.05$) increase the probability of low and median profit (Table 2). When seed quality problems occur, the probability of low and median profit increases by 2.946 times and 4.385 times, respectively, compared to high profit; while problems in the application of chemical control technologies increase the probability of low and median profit by 4.582 times and 1.844 times, respectively. The results show that improper use of chemical control technologies is more likely to cause low yield (<4500 kg·hm^{-2}).

In terms of soil factors, serious soil erosion significantly increases the probability of low and median profit, with regression coefficients of 1.577 and 0.84, and OR values of 4.84 and 2.316, respectively. On the other hand, poor soil water and fertilizer retention capacity also significantly influences the likelihood of low profit at the 0.05 level. The regression model results show that when soil water and fertilizer retention capacity is poor, the probability of low profit increases by 2.507 times. The analysis of influencing factors in Figure 4 and the regression model results both indicate that poor soil water and fertilizer retention capacity is the primary soil factor affecting production in the region.

Among the climatic factors, the impacts of drought, waterlogging, high temperature stress, and insufficient light on yields are all significant, with the regression coefficients of drought and high temperature stress being negative (Table 2). When farmers perceive drought and high temperature stress as the main limiting factors, the probability of a low yield decreases by 90.1% and 77%, respectively, and the probability of a median yield decreases by 84% and 61.4%. When waterlogging is identified as the main factor affecting yield, the probability of a low yield increases by 8.683 times. Waterlogging stress also easily leads to insufficient light stress. When light is insufficient, the probabilities of low and median yields increase by 7.238 times and 3.692 times, respectively. In summary, compared with drought and high temperature stress, waterlogging and insufficient light stress have a greater impact on the production of low and median farming incomes in this region.

4. Discussion

This study has conducted a statistical analysis of the current state and planting characteristics of wheat farmers in Hubei Province based on survey data. The study has found that there are regional (northwestern Hubei and Jianghan plain regions) and planting mode (dryland wheat and wheat following rice) differences in wheat yield among farmers in Hubei Province. Combining farmers' wheat planting characteristics and their perception of yield-limiting factors, this study has used descriptive statistics and multiple regression models to analyze the main reasons for the regional and farmer yield differences from various perspectives such as socioeconomic factors, cultivation management techniques, soil factors, and climatic factors. These results have important practical significance for revealing the actual production characteristics of local wheat farmers and the factors limiting yields.

4.1. Analysis of the Factors Affecting Regional Yield Differences

Hubei Province has complex and diverse terrain and significant ecological differences between regions, resulting in obvious spatial heterogeneity in wheat yields. Farmer surveys have shown that wheat yields in northwestern Hubei are significantly higher than those in the Jianghan plain region. Comparing the yield structure of farmers in the two regions, it was found that there were more farmers with yields below 4500 kg·hm^{-2} in the Jianghan plain region than in northwestern Hubei (Figures 3 and 4). There are multiple reasons for the regional yield differences. Firstly, farmers' decision-making behavior in production is driven by socioeconomic policies. In recent years, the prices of seeds, fertilizers, and other agricultural materials have continued to rise. To save costs, farmers in the Jianghan plain region often reduce seed sowing and fertilizer inputs. Insufficient seeding density and improper fertilizer management can lead to reduced wheat yields and promote the formation of regional yield differences. Therefore, it is recommended at the policy-management level to stabilize agricultural production input factors and crop market prices. Secondly, the terrain and soil conditions in different regions of Hubei Province vary greatly. Northwestern Hubei is mainly hilly and mountainous, while the Jianghan plain is a plain area formed by the impact of the Yangtze River and the Han River, with mainly clay and oil sandy soils in the shallow sediment in the hinterland [14]. Although sandy soils have good ventilation, they have poor nutrient retention and fertilizer supply capacity [15], and the results of this study's survey have also confirmed that poor water retention and fertility of soil are the primary factors affecting production in the region (Figure 5). In terms of climatic factors, drought and waterlogging are the main factors affecting northwestern Hubei and the Jianghan plain. The distribution of rainfall during the wheat-growing season in Hubei Province is uneven. In the early growth period of wheat in northwestern Hubei, rainfall is often insufficient, which can easily lead to drought. In the Jianghan plain region [12], wheat is often subjected to continuous rainfall from the jointing to the filling stage, causing waterlogging in the field [16]. The yield reduction caused by waterlogging during the later stages of growth is the most significant, and even short-term waterlogging during the heading stage can cause a significant decrease in wheat yield [17]. Moreover, persistent heavy rain often accompanies insufficient solar radiation (i.e., low-light stress), and if the critical period of yield formation coincides with multiple environmental stresses for a long time, the wheat yield reduction can reach up to 26% [18], which largely explains why the proportion of low-yield farmers in the Jianghan plain region is higher than that in northwestern Hubei (Figure 4).

Climate, soil, and other environmental factors are uncontrollable factors in agricultural production, but the yield gap of crops can be reduced by optimizing cultivation measures, such as selecting optimal crop varieties, optimizing fertilizer and water management, and adjusting sowing dates [5,19]. Compared to climate change, crop management contributes 65.31–96.84% to crop yield [19], with current farm management practices accounting for the largest share (48.99%) of yield differences [9]. Therefore, agricultural policies should vigorously promote and popularize current high-yield and high-efficiency wheat management technology in Hubei Province, focusing on encouraging farmers to adopt new technologies in combination with local conditions. In agricultural scientific research, research on high-yield wheat cultivation and management technology should be conducted simultaneously to continuously optimize the existing cultivation management methods and further improve the level of cultivation management. In terms of factors affecting crop yield from the farmer's perception of cultivation management, this study has also found that the problem of chemical control technology increases the probability of a low yield by 4.582 times (Table 2). Chemical control technology is an important cultivation technology measure to alleviate damage to crop yield and quality caused by adversity stress in the Jianghan Plain region, where non-biological stress is the main limiting factor for agricultural production. By selecting stress-resistant varieties [20] and using chemical control technology for regulation [21], the resistance of crops to stressors can be effectively enhanced to alleviate the yield loss caused by non-biological stress.

4.2. Analysis of Factors Influencing Yield Differences among Planting Patterns

Through farmer surveys, this study has found that the average yield of dryland wheat in the two regions of northwestern Hubei and Jianghan Plain was 575 kg hm^{-2} and 134 kg hm^{-2} higher than rice–wheat rotation, respectively (Figure 3). The yield difference among planting patterns was significantly smaller than among regions. Zhang et al. [22] studied the current situation of wheat production in Tianmen City, Hubei Province, which is located in the Jianghan Plain, through farmer surveys. The results indicated that the average yield of dryland wheat in this region was 1344 kg hm^{-2} higher than rice–wheat rotation. This conclusion indirectly confirms the research results of this paper that there is still a yield difference among planting patterns. However, unlike previous research results, the survey results of this study showed that the yield differences among planting patterns in the Jianghan Plain were relatively small. The reason for this may be that the survey area of this study is extensive. By observing the distribution of survey data in the Jianghan Plain, it can be observed that the coefficient of variation reflecting the degree of dispersion in this region is 21.3%, and the fluctuation of wheat yield is large. Secondly, there are multiple stressors in the Jianghan Plain, such as waterlogging and weak light, and the yield of both wheat varieties is low after stress, in which case, the impact of stress is greater than planting patterns. Therefore, non-biological stress is considered the primary factor that needs attention in wheat production in the Jianghan Plain.

The yield difference between different cropping systems is mainly caused by differences in the soil environment [23]. In the water and drought rotation system, the soil surface structure formed in the rice season and the compact plow layer formed over the years result in significant differences in soil structure between the wheat planted after rice and the wheat planted in dryland [24]. Therefore, the selection of yield-limiting factors by farmers in different wheat-planting systems shows that compared with farmers who grow dryland wheat, farmers who grow wheat after rice believe that cultivation management factors limit the increase in wheat yield (Figure 5). Firstly, it is difficult to uniformly mix rice straw returned to the field with the sticky rice paddy soil, and compared with dryland wheat, wheat after rice is more likely to face problems such as poor seed quality and low seedling quality [25]. Secondly, influenced by the compact plow layer with poor permeability and air permeability, precipitation cannot penetrate into the deeper layers of the soil in time, thus causing surface runoff during seasons with abundant precipitation, which easily leads to water and soil loss [26]. In addition, compared with dryland rotation, the denitrification in rice–wheat fields is strong, and the content of nitrate nitrogen in the surface soil (0–20 cm) is low [27]. Strong rainfall and compact plow layer also easily cause surface runoff. Fan et al. [28] conducted an investigation of nitrogen loss in the rice–wheat rotation area of the Taihu Lake Basin, and observed that denitrification (25.1%) and runoff (11.49%) account for the largest proportion of nitrogen loss. This also indirectly confirms that compared with dryland wheat, wheat after rice faces the problem of poor water and fertilizer retention capacity of its soil. Studies have shown that suitable tillage methods (deep loosening and deep turning) can break the plow layer and reduce soil bulk density [29]. In dryland fields, no-till management is more effective in water storage and yield increase than deep loosening [30]. Therefore, it can be seen that the cultivation management techniques for dryland wheat and wheat after rice need to be tailored to local conditions to achieve thorough integration of agricultural machinery and technology. At the same time, we believe that the yield difference between cropping systems can be reduced from through proper nitrogen fertilizer management.

The focus of this study on yield-limiting factors is to comprehensively analyze the main factors affecting yield, but a quantitative analysis of the extent of limitation from these factors was not conducted. At the same time, the potential for increasing wheat production in Hubei Province is not clear. In future research, a combination of process-based crop models and data-driven machine learning models can be used to clarify the complex mechanisms of environmental changes on crops, and to simulate crop models statistically with higher computational efficiency. This will fully utilize the advantages of both models, which will help to evaluate the contribution of each limiting factor to yield differences and quantify the potential for yield improvement. In addition, this study has pointed out that drought and waterlogging stress are the main climatic factors affecting the yield difference of wheat in Hubei Province. Therefore, understanding the spatiotemporal evolution of drought, waterlogging, and weak light stress between regions undergoing long-term climate change can provide directions for breeding climate-resilient wheat, strengthen the adaptability of wheat in Hubei Province to climate change, and further reduce the yield difference between regions.

This analysis was based on survey data from 791 households in Hubei Province. While this has provided valuable insights, a larger sample size could enhance the representativeness and generalizability of the findings. In addition to this, the current results relied on self-reported data from farmers, which may be subject to recall bias or inaccuracies. Future studies could consider incorporating objective measurements or data verification methods to improve data quality. The findings of this study are specific to the context of Hubei Province and may not be directly applicable to other regions or provinces. When applying the studied methodology to other areas, it is crucial to consider the unique socioeconomic, environmental, and agricultural characteristics of the specific region.

5. Conclusions

In conclusion, this study has revealed significant differences in wheat yields among farmers in Hubei Province, with smaller variations observed between planting patterns compared to regional disparities. Social factors, such as input costs and economic benefits, were found to be major concerns for farmers and to have influenced their cultivation-management practices. Variation in cultivation-management measures emerged as the primary driver of yield differences between planting patterns, while soil and climatic factors played a crucial role in yield disparities across regions. Low soil fertility, drought susceptibility, and high temperatures in the northwestern part of Hubei Province contributed to lower yields, while soil waterlogging and severe soil erosion in the Jianghan Plain region significantly increased the likelihood of low yields. To effectively reduce yield gaps in Hubei Province, targeted breeding efforts are necessary, considering farmers' preferences, policies, and economic considerations. This includes accelerating the selection of high-yield and stress-tolerant varieties. Furthermore, the promotion and optimization of existing high-yield wheat cultivation management technologies in each region should be prioritized to achieve comprehensive improvements in regional yields. Moving forward, further research should focus on tailoring breeding programs to address specific regional needs, incorporating farmer preferences and economic factors. Additionally, the continuous refinement and dissemination of high-yield wheat-cultivation-management technologies will be crucial. These actions will contribute to reducing the yield gaps in Hubei Province and ultimately lead to enhanced wheat production and food security in the region.

Author Contributions: Conceptualization, R.Y. and X.W.; methodology, R.Y.; software, R.Y.; formal analysis, R.Y.; data curation, R.Y.; writing—original draft preparation, R.Y.; writing—review and editing, M.T.H.; visualization, R.Y.; supervision, X.W.; project administration, X.W.; funding acquisition, X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (2016YFD0300107), the National Natural Science Foundation of China (31871578), and the Engineering Research Center of the Ministry of Education for Wetland Ecology and Agricultural Utilization (KFT202104).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts 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.

References

1. National Bureau of Statistics of the People's Republic of China. *China Statistic Yearbook*; China Statistics Press: Beijing, China, 2021. (In Chinese)
2. Kar, S.; Pramanick, B.; Brahmachari, K.; Saha, G.; Mahapatra, B.; Saha, A.; Kumar, A. Exploring the best tillage option in rice based diversified cropping systems in alluvial soil of eastern India. *Soil Tillage Res.* **2021**, *205*, 104761. [CrossRef]
3. State Council. *National Pollution Growth Plan (2016–2030)*; State Council: Beijing, China, 2016. (In Chinese)
4. Statistical Bureau of Hubei Province. *Hubei Statistical Yearbook*; China Statistics Press: Beijing, China, 2021. (In Chinese)
5. Yao, F.; Li, Q.; Zeng, R.; Shi, S. Effects of different agricultural treatments on narrowing winter wheat yield gap and nitrogen use efficiency in China. *J. Integr. Agric.* **2021**, *20*, 383–394. [CrossRef]
6. Zhang, H.; Tao, F.; Zhou, G. Potential yields, yield gaps, and optimal agronomic management practices for rice production systems in different regions of China. *Agric. Syst.* **2019**, *171*, 100–112. [CrossRef]
7. Gao, Y.; Zhao, H.; Zhao, C.; Hu, G.; Zhang, H.; Liu, X.; Li, N.; Hou, H.; Li, X. Spatial and temporal variations of maize and wheat yield gaps and their relationships with climate in China. *Agric. Water Manag.* **2022**, *270*, 107714. [CrossRef]
8. Wang, H.; Ren, H.; Zhang, L.; Zhao, Y.; Liu, Y.; He, Q.; Li, G.; Han, K.; Zhang, J.; Zhao, B.; et al. sustainable approach to narrowing the summer maize yield gap experienced by smallholders in the North China Plain. *Agric. Syst.* **2023**, *204*, 103541. [CrossRef]
9. Han, S.; Si, J.; Yu, W.; Kong, L.; Zhang, B.; Wang, F.; Zhang, H.; Zhao, X.; Li, H.; Meng, Y. Mechanisms analysis on yield gap and nitrogen use efficiency gap of winter wheat in Shandong Province. *Sci. Agric. Sin.* **2022**, *55*, 3110–3122. (In Chinese)
10. Wang, L.; Lu, Y.; Li, Q.; Hu, Z.; Wu, D.; Zhang, Y.; Wang, T. Spatio-temporal analysis of winter wheat yield gaps in Henan Province using AEZ model. *Chin. J. Eco-Agric.* **2018**, *26*, 547–558. (In Chinese)
11. Liu, J.; Wang, H.; Shi, Q.; Tao, T.; Chen, F.; Chu, Q. Analysis of yield gap and limiting factors for wheat on the farmland. *J. China Agric. Univ.* **2012**, *17*, 42–47. (In Chinese)
12. Zheng, Z.; Liu, K. Analysis on characteristics of drought disasters and their impacts in Hubei province. *Hubei Agric. Sci.* **2020**, *59*, 35–40. (In Chinese)
13. Yan, H.; Harrison, M.T.; Liu, K.; Wang, B.; Feng, P.; Fahad, S.; Meinke, H.; Yang, R.; Liu, D.L.; Archontoulis, S.; et al. Crop traits enabling yield gains under more frequent extreme climatic events. *Sci. Total Environ.* **2022**, *808*, 152170. [CrossRef] [PubMed]
14. Liu, R.; Ma, T.; Qiu, W.; Liu, Y. Distribution characteristics of particle size and organic carbon in clay sediments in Jianghan Plain. *Environ. Sci. Technol.* **2019**, *42*, 194–201. (In Chinese)
15. Li, X.; Wang, Y.; Feng, G.; Xu, Z.; Meng, F.; Gao, Q. Differential fertilizer nitrogen fates in maize cropping system among three soil textures based on N^{15}. *Field Crops Res.* **2023**, *291*, 108780. [CrossRef]
16. Liu, K.; Harrison, M.T.; Yan, H.; Liu, D.L.; Meinke, H.; Hoogenboom, G.; Bin Wang, B.; Bin Peng, B.; Guan, K.; Jaegermeyr, J.; et al. Silver lining to a climate crisis in multiple prospects for alleviating crop waterlogging under future climates. *Nat. Commun.* **2023**, *14*, 765. [CrossRef]
17. Liu, K.; Harrison, M.T.; Ibrahim, A.; Manik, S.M.N.; Johnson, P.; Tian, X.; Meinke, H.; Zhou, M. Genetic factors increasing barley grain yields under soil waterlogging. *Food Energy Secur.* **2020**, *9*, e238. [CrossRef]
18. Cai, J.; Jiang, D. The Effect of Climate Change on Winter Wheat Production in China. *J. Agro-Environ. Sci.* **2011**, *30*, 1726–1733. (In Chinese)
19. Liu, Y.; Zhang, J.; Ge, Q. The optimization of wheat yield through adaptive crop management in a changing climate: Evidence from China. *J. Sci. Food Agric.* **2021**, *101*, 3644–3653. [CrossRef] [PubMed]
20. Li, L.; Li, X.; Wang, X. Effect of shading at filling stage on yield of different wheat varieties. *J. Henan Agric. Sci.* **2020**, *49*, 31–39. (In Chinese)
21. Li, L.; Wei, M.; Li, X. Effects of exogenous 6-BA on the yield of wheat after rice in the Jianghan Plain under different shading treatments. *Chin. J. Appl. Ecol.* **2019**, *30*, 3753–3761. (In Chinese)
22. Zhang, Z.; Fu, P.; Li, X.; Wu, H.; Gao, C.; Zhang, Y.; Wang, Q.; Xiao, S.; Tang, H.; Zou, J. Current situation and analysis of wheat production in Jianghan Plain—A case study of Tianmen, Hubei. *Crops* **2022**, *208*, 39–46. (In Chinese)
23. Yang, R.; Wang, Z.; Fahad, S.; Geng, S.; Zhang, C.; Harrison, M.T.; Adnan, M.; Saud, S.; Zhou, M.; Liu, K.; et al. Rice paddies reduce subsequent yields of wheat due to physical and chemical soil constraints. *Front. Plant Sci.* **2022**, *13*, 959784. [CrossRef]
24. Kayombo, B.; Lal, R. Tillage systems and soil compaction in Africa. *Soil Tillage Res.* **1993**, *27*, 35–72. [CrossRef]
25. Gu, K.; Zhang, S.; Gu, D. Effects of rice straw returning and compaction on grain yield and quality of wheat. *J. Nucl. Agric. Sci.* **2015**, *29*, 2192–2197. (In Chinese)

26. Li, Z.; Shen, Y.; Zhang, W.; Zhang, H.; Liu, L.; Wang, Z.; Gu, J.; Yang, J. Effects of long-term straw returning on rice yield and soil properties and bacterial community in a rice-wheat rotation system. *Field Crops Res.* **2023**, *291*, 108800. [CrossRef]
27. Yang, R.; Liu, K.; Geng, S.; Zhang, C.; Yin, L.; Wang, X. Comparison of early season crop types for wheat production and nitrogen use efficiency in the Jianghan Plain in China. *PeerJ* **2021**, *9*, e11189. [CrossRef]
28. Fan, H.; Xu, L.; Zhao, X.; Hu, Y. Study on nitrogen loss in rice-wheat rotation farmland in Taihu Basin. *Ecol. Environ. Sci.* **2015**, *24*, 255–262. (In Chinese)
29. Topa, D.; Cara, I.G.; Jităreanu, G. Long term impact of different tillage systems on carbon pools and stocks, soil bulk density, aggregation and nutrients: A field meta-analysis. *Catena* **2021**, *199*, 105102. [CrossRef]
30. Guo, X.; Wang, H.; Yu, Q.; Wang, R.; Wang, X.; Li, J. Effects of tillage on soil moisture and yield of wheat-maize rotation field in Weibei upland plateau. *Sci. Agric. Sin.* **2021**, *54*, 2977–2990. (In Chinese)