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Adaptability of Maize Farmers to Drought and the Selection of Irrigation Period—A Survey of Irrigation Behavior of Farmers in the Three Provinces of Huang-Huai-Hai, China

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Abstract: The summer maize area of Huang-Huai-Hai is the main summer maize production area in China, droughts occur frequently during the growth period of summer maize and irrigation water resources are scarce in this region. This paper studied the adaptability of maize farmers to drought and the selection of irrigation period in the three provinces of Huang-Huai-Hai. The adaptability index of irrigation at different growth stages was analyzed by establishing an extended C-D production function model, while the marginal income of irrigation in each growth period was calculated based on the estimation results of adaptability index model. The results showed that: (1) The growth period with the largest adaptability index in the three provinces of Huang-Huai-Hai was milk ripening stage. The adaptability index in milk ripening stage in Hebei, Henan, and Shandong was 1.063, 1.081, and 1.053, respectively. (2) The maize key growth periods of water sensitivity in the three provinces of Huang-Huai-Hai were tasseling period and milk ripening period, and in most cases, the irrigation period of farmers was consistent with the key growth period of water sensitivity. (3) In Hebei, Henan, and Shandong provinces, the marginal benefits of irrigation were greater than the marginal costs in each growth period. The marginal income of irrigation during tasseling period in the three provinces was relatively large, and tasseling period was the preferred irrigation period of most farmers. To optimize future irrigation water allocation, farmers should prioritize ensuring sufficient water supply during tasseling stage and milk ripening stage in Hebei and Shandong, and during big bell mouth stage and tasseling stage in Henan.

Keywords: maize; drought; irrigation behavior; adaptability index; selection of irrigation period

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1. Introduction

IPCC (Intergovernmental Panel on Climate Change) research defines adaptability as the capacity of human systems to adjust to reduce losses or seek profits in response to actual or expected climate change and its impact [1]. There have been many discussions on the concept and connotation of adaptability in the academic community, both domestically and internationally. At the end of the 20th century, scholars defined adaptation in the field of climate change, linking adaptation with concepts such as “response”, “mitigation”, and “adjustment”. At the beginning of the 21st century, the concept of adaptability was widely applied in the field of sustainable science [2]. Adaptability from the sociological or economic perspective emphasizes the adjustment of individual and collective behavior in human system [3]. Smit (1994) defined adaptation to climate change as the adjustment of socio-economic activities to reduce vulnerability to climate change [4].

Adaptability research is an important research topic in the economics of climate change, and the analytical framework for adaptation research includes five main aspects [5]. Firstly, adaptation object refers to what to adapt to, which in numerous studies is meteorological disaster. Secondly, adaptation subject, that is who will adapt, has both macro level adaptation subject (such as government department) and micro level adaptation subject (such as farmer). Different levels of adaptation subjects adopt different adaptive behaviors. Thirdly, adaptation process, that is how adaptation occurs, refers to the decision-making process of adaptation subject adopting adaptive measures. Fourthly, adaptive strategy refers to the manifestation of adaptive behavior adopted by adaptation subject. Adaptive behavior, also known as adaptive measure, represents the response measure taken by humans to mitigate the adverse effect of meteorological disaster [6]. Fifthly, adaptation effect, which represents the effectiveness of adaptive measure, can be evaluated based on costs, benefits, efficiency, and other aspects [5]. The current research literature on drought adaptation can be divided into two categories. The first category is focused on the influencing factors of adaptive behavior selection. Some scholars use empirical models to study adaptive behavior selection by farmers. Chen Xue (2022) conducted empirical analysis on the factors influencing farmers' adaptive behavior in Zhalute Banner using binary logistic regression model [7]. Peng Junjie (2018) conducted empirical analysis on the factors influencing farmers' adaptive behavior in Henan province using binary logistic regression model [8]. The research results indicated that family characteristics, regional economic characteristics, and policy factor are important factors affecting adaptive behavior selection [9]. The second category is the research on adaptability index, which focuses on the impact of adaptive behavior on agricultural production and the evaluation of effectiveness of adaptive behavior. Chen Jiafei (2012) constructed an agricultural drought adaptability evaluation index system based on eight indicators: labor quality, labor proportion, irrigation index, per capita grain production, multiple crop index, grain sowing yield per unit area, per capita productive net income of rural residents, and irrigation power. The expert scoring method was used to assign weight to each index, and the research results showed that the adaptability levels of agricultural drought in all types of areas in Xingtai County were as follows: plain area > hilly area > mountain area [10].

Cognition of climate change and adaptive strategies adopted by farmers may vary to some extent under different environments and economic development levels [8]. A survey by Liu Hui and Martin Chou (2020) revealed that most farmers adopt behavior types that they can control and benefit from when dealing with climate change [11]. Balboa G. R. et al. (2019) observed that farmers respond to changes in temperature or precipitation by constructing irrigation facilities or covering with plastic films [12]. Previous studies have shown that adaptive behaviors of farmers in response to drought disaster include adopting irrigation measure, adjusting sowing or harvesting period, changing agricultural production input, introducing drought-tolerant crop varieties, adjusting crop types, etc. [13–17]. Kang Xiyan et al. (2012) demonstrated that the main adaptive measure to prevent and mitigate the effect of drought in crops is irrigation of dry land [18].

In an analysis of the frequency of drought during growth period of maize in China from 1991 to 2009, Zhang et al. (2014) found that the frequency of drought during the reproductive growth period of maize was higher than that during the nutritional growth period [19]. The summer maize area of Huang-Huai-Hai is the frequent and severe drought disaster area. Irrigation measure implemented by farmers in the dry period could reduce yield loss caused by drought and ensure the sustainable development of maize industry. Irrigation is the predominant adaptive behavior of farmers to drought disaster in the survey, and there are differences in adaptability of irrigation during different growth stages. Thus, the adaptive behavior studied in this paper is the irrigation behavior of farmers in each growth period. Farmers who adopt irrigation measures have different choices of irrigation period. In recent years, Huang-Huai-Hai region has become one of the regions with the most severe water resource shortage in China [20]. As the decline of groundwater level in the three provinces of Huang-Huai-Hai has limited agricultural water use, optimizing the allocation of irrigation water resources in agricultural production is of great importance at this stage. The adaptive behavior of most farmers to drought is to use underground well water for flood irrigation, which is characterized by relatively low water use efficiency of irrigation. The government departments of the three provinces of Huang-Huai-Hai have issued documents to clarify the irrigation water quota for various crops, the irrigation water quota is for the irrigation water during the whole growth period. Under the premise of limited water resources in the three provinces of Huang-Huai-Hai, local governments and farmers need to know how to choose the irrigation period to improve water use efficiency of irrigation. There are differences in maize sensitivity to drought during different growth periods, and the growth period with higher sensitivity is the key growth period of water sensitivity. For the selection of irrigation period, whether farmers irrigate in maize key growth period of water sensitivity is an urgent issue that must be studied. Therefore, this paper studied the adaptability of maize farmers to drought and the selection of irrigation period in the three provinces of Huang-Huai-Hai.

The main research contents of this paper are as follows: (1) The adaptability index of irrigation at different maize growth stages in the three provinces of Huang-Huai-Hai was analyzed using random effect model, and the yield increase value of irrigation at different growth stages in Hebei, Henan, and Shandong was calculated based on the adaptability index. (2) We compared maize key growth period of water sensitivity with irrigation period of farmers in the three provinces of Huang-Huai-Hai, and studied whether farmers irrigate in key growth period of water sensitivity. (3) The marginal income of irrigation in each growth period was calculated using the estimation results of adaptability index model. According to the theory of farmers' behavior selection, the selection of irrigation period for farmers was analyzed by comparing the marginal cost and marginal income of irrigation during different growth periods in the three provinces of Huang-Huai-Hai.

2. Materials and Methods

2.1. Data Source

The data in this paper included macro data and micro data. The macro data were maize yield and price over the years (2012–2020) in Hebei Rural Statistical Yearbook [21], Henan Statistical Yearbook [22] and Shandong Statistical Yearbook [23]. The statistical data in the three provinces of Huang-Huai-Hai were all from the National Bureau of Statistics.

The micro data were the survey data of maize farmers in the three provinces of Huang-Huai-Hai. The survey data included maize yield per unit area, sowing area of maize, maize price, irrigation amount at different growth stages, and various input costs of each farmer. Through consulting relevant experts and conducting interviews with farmers, this study designed and developed a questionnaire on farmers' basic characteristics and maize production. The questions in the questionnaire mainly included the household characteristics and members profile of farmers, crop production and management status, etc. This study relied on the Industrial Economy Research Office of National Modern Agricultural Industrial Technology System, which organized agricultural production personnel from various demonstration counties to conduct questionnaire surveys on local farmers.

This paper investigated the farmers in 14 prefecture-level cities in the three provinces of Huang-Huai-Hai (2012–2016), including five in Hebei, three in Henan, and six in Shandong, respectively. From the questionnaire of farmers, the prefecture-level cities with drought and farmers irrigation in the three provinces were selected. Data from 10 prefecture-level cities, including three (Hengshui, Tangshan, and Qinhuangdao) in Hebei, one (Kaifeng) in Henan, and six (Weihai, Yantai, Weifang, Linyi, Qingdao, and Rizhao) in Shandong were used to calculate adaptability index.

The descriptive statistics of variables of adaptability index model are shown in Table 1. The explained variable was maize yield per unit area. The explanatory variables were irrigation amount at different growth stages, including jointing stage, big bell mouth stage, tasseling stage, and milk ripening stage. The control variables included labor input, fertilizer input, land lease cost, other material input, and sowing area of maize, among which, other material input included seed cost, agricultural film cost, pesticide cost, and mechanical operation cost. It could be seen from the table that there were obvious differences in the irrigation amount of farmers at different growth stages. Among them, the irrigation amount at jointing stage was the smallest, while the irrigation amounts at tasseling stage and milk ripening stage were greater.

Table 1. Descriptive statistics of variables.

Variable	Observed Value	Mean Value	Standard Deviation	Minimum Value	Maximum Value
Maize yield per unit area	370	7.02	0.182	5.521	7.378
Irrigation amount at jointing stage	370	0.165	0.694	0	3.258
Irrigation amount at big bell mouth stage	370	0.196	0.781	0	4.087
Irrigation amount at tasseling stage	370	1.041	1.638	0	4.498
Irrigation amount at milk ripening stage	370	0.904	1.592	0	4.476
Labor input	370	1.857	0.448	0	3.664
Fertilizer input	370	5.007	0.295	4.094	5.704
Land lease cost	370	4.969	0.394	3.401	5.501
Other material input	370	0.987	2.211	0	6.909
Sowing area of maize	370	1.583	1.089	−0.223	6.908

Note: The explanatory variable and the explained variable were all processed with logarithm. For variables with high values of 0, the logarithmic treatment is taken by adding 1.

2.2. Evaluation Method

2.2.1. Evaluation Method of Adaptability Index

Water resource is the most crucial factor in mitigating the impact of drought. This study focused on irrigation behavior of farmers. Considering differences in the effect of irrigation at different growth stages on maize yield, the adaptability index of irrigation at different growth stages was evaluated.

The adaptability index of irrigation at different growth stages refers to the effect of irrigation measures taken by farmers at different growth stages on maize yield. This study used the yield improvement rate of farmers' irrigation as the adaptability index of irrigation. The formula for calculating the adaptability index of irrigation at different growth stages is as follows:

$$GPAI = \frac{\sum WY_i \times WA_i + \sum IFY_i \times IA_i}{\sum WY_i \times WA_i + \sum IWY_i \times IA_i} \quad (1)$$

In the formula, i is farmer, farmers in the three provinces were classified as farmers without irrigation and farmers with irrigation. *GPAI* (adaptability index in each growth period) is the adaptability index of irrigation at different growth periods. WY_i is the actual yield of farmers without irrigation, IFY_i is the predicted yield of irrigation in different growth periods of farmers with irrigation, and IWY_i is the predicted yield of non-irrigation of farmers with irrigation, with the unit of kg/mu. WA_i is the planting area of farmers without irrigation, and IA_i is the planting area of farmers with irrigation, with the unit of mu.

Based on key growth period of water sensitivity and irrigation situation of farmers in the three provinces of Huang-Huai-Hai, this paper mainly analyzed the adaptability index in jointing stage, big bell mouth stage, tasseling stage, and milk ripening stage. Both the predicted yield of irrigation in different growth periods of farmers with irrigation (IFY_i) and the predicted yield of non-irrigation of farmers with irrigation (IWY_i) could be calculated by establishing the adaptability index model.

2.2.2. Construction of Adaptability Index Model

C-D production function (Cobb-Douglas Production Function) is mainly used to describe the relationship between yield and production factors. There are many factors that affect maize yield, and water is one of the important constraining factors. According to agricultural production theory, this paper extended C-D production function by introducing the irrigation water volume in each growth period. Using the expanded production function, this paper constructed the adaptability index model to analyze the adaptability of irrigation at different growth stages.

The explained variable of adaptability index model was maize yield per unit area. The explanatory variables included the irrigation water volume at jointing stage, big bell mouth stage, tasseling stage, and milk ripening stage of maize. The control variables included labor input, fertilizer input, land lease cost, other material input, and sowing area, among which, other material input specifically included seed cost, agricultural film cost, pesticide cost, and mechanical operation cost. Mixed regression model, fixed effect model, and random effect model of panel model were used to calculate the coefficients of each variable, and the model results were tested, finally adaptability index model in this paper was obtained. The specific form of the model is as follows:

$$lny_{it} = \alpha_0 + \beta_1 lnLF_{it} + \beta_2 lnF_{it} + \beta_3 lnLL_{it} + \beta_4 lnOM_{it} + \beta_5 lnSA_{it} + \eta_1 IW1_{it} + \eta_2 IW2_{it} + \eta_3 IW3_{it} + \eta_4 IW4_{it} + \mu_{it} \quad (2)$$

In the formula, i is farmer, and t is year. Y represents the explained variable, and y is maize yield per unit area, the unit is jin/mu. LF, F, LL, OM, and SA represent the control variables, LF is labor input per unit area, the unit is day; F is fertilizer input per unit area, the unit is yuan/mu; LL is land lease cost per unit area, the unit is yuan/mu; OM is other material input per unit area, the unit is yuan/mu; SA is sowing area of maize, the unit is mu. IW represents the explanatory variable, and IW is irrigation amount at different growth stages of maize. $IW1$, $IW2$, $IW3$, and $IW4$ represent irrigation amount at jointing stage, big bell mouth stage, tasseling stage, and milk ripening stage, respectively.

2.2.3. Evaluation Method of Marginal Cost and Marginal Benefit of Irrigation

Marginal cost of irrigation refers to the additional cost incurred for adding one cubic meter of irrigation water. That is, the water and electricity charges required to add one cubic meter of irrigation water. Marginal income refers to the additional income obtained by adding one unit of production factor, and marginal income of irrigation refers to the increase of output value brought by adding one cubic meter of irrigation water. Therefore, marginal income is equal to marginal yield multiplied by maize price.

Calculation of marginal yield of irrigation. Before calculating marginal income of irrigation, marginal yield of irrigation needs to be calculated. Marginal yield refers to the increase of unit output obtained by adding one unit of production factor. The general form of the model is as follows:

$$lny = \alpha + \beta lnx + \delta lnz + \mu \quad (3)$$

In adaptability index model of this paper, y is maize yield of per unit area, x is irrigation amount at different growth stages of maize, z represents the control variable.

$$\beta = \frac{\partial(lny)}{\partial(lnx)} = \frac{x}{y}\frac{\partial y}{\partial x} \quad (4)$$

β is model estimated coefficient, β represents the elasticity of yield to irrigation water; that is, with other conditions unchanged, the average yield per mu would increase by β% for every 1% increase in irrigation water.

The formula for calculating marginal yield of irrigation is as follows:

$$\frac{\partial y}{\partial x} = \beta\frac{y}{x} \quad (5)$$

It can be seen from the formula that the marginal yield of irrigation depends on maize yield per unit area, irrigation water volume in each growth period, and estimated coefficient of irrigation in each growth period.

Therefore, the marginal cost of irrigation is the additional cost incurred by increasing one cubic meter of irrigation water, and the marginal income of irrigation is estimated as the increase in output value due to the increase in irrigation water by one cubic meter.

3. Results

3.1. Adaptability Index of Irrigation at Different Growth Stages in the Three Provinces of Huang-Huai-Hai

3.1.1. Benchmark Results

The estimated results of mixed regression model and random effect model based on robust standard error are shown in Table 2. LM test (Lagrange multiplier test) was first used to determine the best model between mixed regression model and random effect model. LM test results in Table 2 showed that it was more appropriate to reject the original hypothesis that "there was no individual random effect", that is, to use random effect model. In addition, Hausman test results also showed that random effect model should be selected compared with fixed effect model.

Table 2. Estimation results of adaptability index model.

Variable	Mixed Regression Model	Random Effect Model
Irrigation amount at jointing stage	0.0206 **	0.0146 *
	(0.0096)	(0.0079)
Irrigation amount at big bell mouth stage	0.0211 *	0.0174 **
	(0.0117)	(0.0083)
Irrigation amount at tasseling stage	0.0285 ***	0.0215 ***
	(0.0043)	(0.0044)
Irrigation amount at milk ripening stage	0.0259 ***	0.0231 ***
	(0.0049)	(0.0048)
Labor input	0.0476 **	0.0288
	(0.0196)	(0.0183)
Fertilizer input	0.0652 *	0.0670 **
	(0.0348)	(0.0288)
Other material input	0.0148	0.0350
	(0.0255)	(0.0251)
Land lease cost	0.0073 **	0.0037
	(0.0033)	(0.0033)
Sowing area of maize	0.00330	0.0099
	(0.0105)	(0.0115)
Constants	6.4870 ***	6.3852 ***
	(0.1652)	(0.1628)
The number of samples	370	370
R^2	0.3704	0.1912
F-statistics	16.46 ***	
Wald statistics		67.69 ***
LM test		35.66 ***
Hausman test (*p* value)		0.3658

Note: All values in brackets represent robust standard errors; ***, **, and * denote significance at 1%, 5%, and 10% levels, respectively.

It could be seen from Table 2 that irrigation amount at different growth stages had a significant positive impact on maize yield per unit area. The estimated results of random effect model showed that, with other variables constant, maize yield could increase by 0.0146%, 0.0174%, 0.0215%, and 0.0231% for each 1% increase in irrigation volume at jointing stage, big bell mouth stage, tasseling stage, and milk ripening stage, respectively. The effect of irrigation amount at different growth stages on maize yield ranged from small to large in the order of jointing stage, big bell mouth stage, tasseling stage, and milk ripening stage. In terms of control variables, fertilizer input also significantly affected maize yield. Specifically, labor input, fertilizer input, and other material input had large positive impacts on maize yield. With other variables unchanged, maize yield could increase by 0.0288%, 0.0670%, and 0.0350% for each 1% increase in labor input, fertilizer input, and other material input, respectively.

3.1.2. Robustness Test

In this paper, the tail reduction process was used to test the robustness of the estimated results of random effect model (Table 3). Column (1) listed the results of narrowing irrigation volume of four growth periods; Column (2) listed the results of narrowing maize yield per unit area and irrigation amount of four growth periods. By comparison with the estimated results of random effect model in Table 2, the estimated coefficients of core explanatory variables of the tail reduction treatment were basically consistent with the estimated results of random effect model in terms of significance and sign (impact direction). Therefore, it could be demonstrated that the model estimation results in this paper were relatively robust.

Table 3. Robustness test of adaptability index model.

Variable	Winsorize	
	(1)	**(2)**
Irrigation amount at jointing stage	0.0140 *	0.0131 *
	(0.0073)	(0.0069)
Irrigation amount at big bell mouth stage	0.0175 **	0.0177 **
	(0.0083)	(0.0082)
Irrigation amount at tasseling stage	0.0216 ***	0.0214 ***
	(0.0044)	(0.0043)
Irrigation amount at milk ripening stage	0.0233 ***	0.0228 ***
	(0.0048)	(0.0048)
Labor input	0.0290	0.0286
	(0.0183)	(0.0183)
Fertilizer input	0.0672 **	0.0671 **
	(0.0287)	(0.0284)
Other material input	0.0348	0.0339
	(0.0251)	(0.0249)
Land lease cost	0.0037	0.0038
	(0.0033)	(0.0032)
Sowing area of maize	0.0099	0.0104
	(0.0115)	(0.0115)
Constants	6.3851 ***	6.3904 ***
	(0.1627)	(0.1623)
The number of samples	370	370
R^2	0.1920	0.1897
Wald statistics	67.77 ***	67.64 ***

Note: All values in brackets represent robust standard errors; ***, **, and * denote significance at 1%, 5%, and 10% levels, respectively.

3.1.3. Adaptability Index of Irrigation at Different Growth Stages in the Three Provinces of Huang-Huai-Hai

The adaptability index of irrigation at different growth stages is defined as the effect of irrigation at different growth stages on maize yield. Based on the estimated results of adaptability index model, using the evaluation method of adaptability index in this paper, the adaptability index of irrigation at different growth stages in the three provinces of Huang-Huai-Hai could be calculated.

As shown in Table 4, there were regional differences in adaptability index in each growth period in the three provinces of Huang-Huai-Hai. The adaptability index in jointing stage and big bell mouth stage in Hebei was relatively small, the farmers surveyed in Henan did not irrigate during jointing stage, the adaptability index in jointing stage in Shandong was relatively small, while the adaptability index in big bell mouth stage in Shandong was the maximum of the adaptability index in big bell mouth stage in the three provinces. The growth period with the largest adaptability index in the three provinces was milk ripening period. The adaptability index in milk ripening stage in Hebei, Henan, and Shandong was 1.063, 1.081, and 1.053, respectively. The adaptability index in milk ripening stage in Henan was the maximum of the adaptability index in milk ripening stage in the three provinces. The larger adaptability index in milk ripening stage indicated that the effect of irrigation on yield would be more significant if farmers increased irrigation water in milk ripening stage.

Table 4. Adaptability index of irrigation at different growth stages in the three provinces of Huang-Huai-Hai.

GPAI	Jointing Stage	Big Bell Mouth Stage	Tasseling Stage	Milk Ripening Stage
Hebei	1.027	1.024	1.041	1.063
Henan	-	1.029	1.051	1.081
Shandong	1.027	1.044	1.052	1.053

3.2. Increase in Yield Value of Irrigation at Different Growth Stages in the Three Provinces of Huang-Huai-Hai

Based on the adaptability index of irrigation at different growth stages, maize yield, and price of each year, the increase in yield and yield value of irrigation in different growth periods in the three provinces of Huang-Huai-Hai could be calculated.

3.2.1. Increase in Yield Value of Irrigation at Different Growth Stages in Hebei Province

The increase in yield value of irrigation at different growth stages in Hebei province were from high to low in the order of milk ripening stage, tasseling stage, jointing stage, and big bell mouth stage (Table 5). The yield increase effect of irrigation during milk ripening stage and tasseling stage was significant. In Hebei province, adding one irrigation at jointing stage, big bell mouth stage, tasseling stage, and milk ripening stage, the yield per mu could increase by 26 jin, 23 jin, 40 jin, and 60 jin, respectively, and the yield value per mu could increase by 25.8 yuan, 22.8 yuan, 39.9 yuan, and 60.2 yuan, respectively. From a time perspective, the increase in yield value of irrigation at different growth periods in Hebei province from 2012 to 2014 and 2020 was relatively large.

Table 5. The increase in yield value of irrigation at different growth stages in Hebei province.

Increase in Yield Value	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average Value
Jointing stage	29.047	29.207	29.559	24.053	20.52	22.16	22.796	25.131	29.862	25.815
Big bell mouth stage	25.66	25.801	26.113	21.248	18.127	19.576	20.138	22.2	26.38	22.805
Tasseling stage	44.842	45.089	45.633	37.132	31.677	34.21	35.192	38.796	46.1	39.852
Milk ripening stage	67.7	68.072	68.893	56.059	47.824	51.649	53.131	58.571	69.599	60.166

3.2.2. Increase in Yield Value of Irrigation at Different Growth Stages in Henan Province

The increases in yield value of irrigation at different growth stages in Henan province are shown in Table 6. The main irrigation periods in Henan province were big bell mouth stage, tasseling stage, and milk ripening stage. The increase in yield value of irrigation at different growth stages in Henan province were from high to low in the order of milk ripening stage, tasseling stage, and big bell mouth stage. In Henan province, adding one irrigation at big bell mouth stage, tasseling stage, and milk ripening stage, the yield per mu could increase by 28 jin, 49 jin, and 78 jin, respectively, and the yield value per mu could increase by 26.3 yuan, 45.8 yuan, and 72.6 yuan, respectively. The increase in yield value at different growth periods in Henan province from 2012 to 2015 and 2020 was relatively large, which indicated that the yield increase effect of irrigation on farmers in these years was relatively significant.

Table 6. The increase in yield value of irrigation at different growth stages in Henan province.

Increase in Yield Value	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average Value
Big bell mouth stage	29.995	27.786	31.999	26.273	21.093	22.384	23.067	20.833	33.148	26.287
Tasseling stage	52.269	48.42	55.76	45.782	36.756	39.006	40.196	36.303	57.763	45.806
Milk ripening stage	82.811	76.713	88.342	72.535	58.234	61.799	63.684	57.516	91.517	72.572

3.2.3. Increase in Yield Value of Irrigation at Different Growth Stages in Shandong Province

The increase in yield value of irrigation at different growth stages in Shandong province were from high to low in the order of milk ripening stage, tasseling stage, big bell mouth stage, and jointing stage (Table 7). The yield increase effect of irrigation on farmers during milk ripening stage and tasseling stage was significant. In Shandong province, adding one irrigation at jointing stage, big bell mouth stage, tasseling stage, and milk ripening stage, the yield per mu could increase by 27 jin, 44 jin, 53 jin, and 53 jin, respectively, and the yield value per mu could increase by 26.1 yuan, 42.7 yuan, 51.0 yuan, and 51.4 yuan, respectively. From a time perspective, the increase in yield value of irrigation at different growth periods in Shandong province from 2012 to 2014 and 2020 was relatively large.

Table 7. The increase in yield value of irrigation at different growth stages in Shandong province.

Increase in Yield Value	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average Value
Jointing stage	28.937	27.617	32.139	23.997	21.294	22.832	23.604	21.081	33.737	26.137
Big bell mouth stage	47.224	45.069	52.45	39.162	34.751	37.261	38.52	34.402	55.057	42.655
Tasseling stage	56.413	53.839	62.655	46.782	41.512	44.511	46.015	41.096	65.769	50.955
Milk ripening stage	56.883	54.287	63.177	47.172	41.858	44.882	46.399	41.439	66.318	51.379

3.3. Comparison between Irrigation Period of Farmers and Maize Key Growth Period of Water Sensitivity in the Three Provinces of Huang-Huai-Hai

The maize key growth period of water sensitivity was greatly affected by drought, resulting in a significant yield reduction. The maize key growth periods of water sensitivity in the three provinces of Huang-Huai-Hai were tasseling period and milk ripening period. In order to alleviate the negative impact of drought on maize, farmers generally took irrigation measures. By comparing irrigation period of farmers with maize key growth period of water sensitivity, we could find out whether farmers in the three provinces of Huang-Huai-Hai irrigate in key growth period of water sensitivity.

The irrigation periods of farmers in various cities in Hebei Province are shown in Table 8. The irrigation times of farmers in Hebei Province were 1–4 times, and most farmers chose to irrigate during tasseling stage. The irrigation times of farmers in Hengshui were 1–3 times. The irrigation times of farmers in Tangshan were 1–2 times, and irrigation twice was more common. The irrigation times of farmers in Qinhuangdao were once, twice, and four times, and most farmers chose to irrigate in milk ripening stage.

The irrigation periods of farmers in Henan province are shown in Table 9. Due to there were more occurrences of severe droughts in multiple periods in Henan province, there were more cases of irrigation twice and three times in Kaifeng. Whether it was irrigation once, twice, or three times, farmers would irrigate in tasseling stage. The irrigation twice in Kaifeng were carried out in big bell mouth stage and tasseling stage, and the irrigation three times in Kaifeng were carried out in big bell mouth stage, tasseling stage, and milk ripening stage.

Table 8. Irrigation period of farmers in various cities in Hebei province.

Year	District	Irrigation Times	Irrigation Period	Year	District	Irrigation Times	Irrigation Period
2012	Hengshui	1	Tasseling	2015	Tangshan Zunhua	1	Tasseling
2013	Tangshan	2	Jointing, tasseling	2015	Tangshan Luanxian	2	Big bell mouth, tasseling
2013	Qinhuangdao	2	Jointing, tasseling	2015	Qinhuangdao	1	Milk ripening
2014	Hengshui	2	Tasseling, milk ripening	2016	Hengshui	3	Big bell mouth, tasseling, milk ripening
2014	Tangshan	2	Jointing, milk ripening	2016	Tangshan Zunhua	1	Tasseling
2014	Qinhuangdao	4	Jointing, big bell mouth, tasseling, milk ripening	2016	Tangshan Luanxian	2	Tasseling, milk ripening
-	-	-	-	2016	Qinhuangdao	2	Big bell mouth, milk ripening

Table 9. Irrigation period of farmers in Henan province.

Year	District	Irrigation Times	Irrigation Period
2012	Kaifeng	2	Big bell mouth, tasseling
2013	Kaifeng	3	Big bell mouth, tasseling, milk ripening
2014	Kaifeng	1	Tasseling
2015	Kaifeng	2	Big bell mouth, tasseling
2016	Kaifeng	3	Big bell mouth, tasseling, milk ripening

Due to the low occurrence of severe drought during big bell mouth stage, tasseling stage, and milk ripening stage in Shandong province, the irrigation times of farmers were mainly once and twice. The irrigation periods of farmers in various cities in Shandong province are shown in Table 10, and most farmers conducted irrigation during tasseling stage and milk ripening stage. Most farmers in Yantai, Weihai, and Weifang irrigated once, whether it was irrigation once or twice, most farmers in Yantai, Weihai, and Weifang chose to irrigate in milk ripening stage. Most farmers in Linyi, Qingdao, and Rizhao chose to irrigate in tasseling stage, whether they irrigated once or twice.

Table 10. Irrigation period of farmers in various cities in Shandong province.

Year	District	Irrigation Times	Irrigation Period	Year	District	Irrigation Times	Irrigation Period
2012	Yantai Laizhou	1	Milk ripening	2014	Linyi	2	Jointing, tasseling
2012	Yantai Yuyang	2	Big bell mouth, milk ripening	2014	Qingdao	1	Tasseling
2012	Yantai Laiyang	1	Milk ripening	2015	Weihai	1	Milk ripening
2012	Weifang	1	Milk ripening	2015	Yantai Muping	1	Tasseling
2012	Linyi	1	Big bell mouth	2015	Yantai Laizhou	2	Jointing, milk ripening
2012	Qingdao	2	Tasseling, milk ripening	2015	Weifang	1	Milk ripening
2013	Yantai Laiyang	2	Tasseling, milk ripening	2016	Yantai Muping	1	Tasseling
2013	Weifang	2	Tasseling, milk ripening	2016	Weifang	2	Big bell mouth, milk ripening
2013	Qingdao	1	Tasseling	2016	Linyi	1	Tasseling
2014	Weifang	1	Big bell mouth	2016	Rizhao	2	Tasseling, milk ripening

3.4. Analysis of Marginal Cost and Marginal Benefit of Irrigation in Different Growth Stages in the Three Provinces of Huang-Huai-Hai

The choice of irrigation period by farmers often depended on the marginal income of irrigation in each growth period, and farmers tended to irrigate in the growth period with large marginal income. According to the calculation method of marginal cost and marginal income, this paper analyzed the marginal cost and marginal income of irrigation in jointing stage—milk ripening in the three provinces of Huang-Huai-Hai.

3.4.1. Analysis of Marginal Cost and Marginal Benefit of Irrigation in Different Growth Periods in Hebei Province

The marginal cost and marginal benefit of irrigation in each growth period in Hebei province are shown in Table 11. The marginal cost of irrigation in Hebei province was 0.34–0.55 yuan/m^3. The marginal cost increased with time, with the largest marginal cost of irrigation in Hebei province being observed in 2016. In the same year, the marginal cost of irrigation in Hengshui was smaller than that in Tangshan and Qinhuangdao. The periods of greater marginal benefits of irrigation in Hebei province were tasseling stage and milk ripening stage. The marginal income of irrigation in tasseling stage and milk ripening stage was 0.79 yuan/m^3 and 0.83 yuan/m^3, respectively. Most farmers chose to irrigate in these two growth periods. Farmers in Hebei province had the most irrigation in tasseling stage. Except for Tangshan in 2014, Qinhuangdao in 2015, and Qinhuangdao in 2016, farmers in the three cities in Hebei province conducted irrigation in tasseling stage from 2012 to 2016.

Table 11. Marginal cost and marginal income of irrigation in different growth periods in Hebei province (Unit: yuan).

Hebei	Marginal Cost	Marginal Benefit			
		Jointing Stage	Big Bell Mouth Stage	Tasseling Stage	Milk Ripening Stage
2012	0.349	-	-	1.215	-
2013	0.402	0.477	-	0.746	-
2014	0.406	0.577	0.629	0.781	1.018
2015	0.468	-	0.637	0.882	0.614
2016	0.541	-	0.652	0.607	0.675
Average value	0.459	0.527	0.643	0.791	0.832

Comparing the marginal cost and marginal benefit of irrigation in Hebei province, the marginal benefit was greater than the marginal cost in each growth stage. The marginal income of irrigation in tasseling stage and milk ripening stage in Hebei province was far greater than the marginal cost, and the gap between the marginal income and the marginal cost in milk ripening stage was the largest.

3.4.2. Analysis of Marginal Cost and Marginal Benefit of Irrigation in Different Growth Periods in Henan Province

The marginal cost and marginal benefit of irrigation in different growth periods in Henan province are shown in Table 12. The marginal cost of irrigation in Henan province was 0.32–0.51 yuan/m^3, and the marginal cost of irrigation in the first three years in Henan province was relatively large. The year with the largest marginal cost of irrigation was 2014, and the marginal cost was 0.5 yuan/m^3. Most farmers in Henan province chose to irrigate in big bell mouth stage and tasseling stage. The marginal income of irrigation in big bell mouth stage and tasseling stage in Henan province was relatively large, with 0.65 yuan/m^3 and 0.73 yuan/m ^{3}, respectively. The marginal income of irrigation in milk ripening stage in Henan province was the smallest, and the situation of irrigation in milk ripening stage was the least.

Table 12. Marginal cost and marginal income of irrigation in different growth periods in Henan province (Unit: yuan).

Henan	Marginal Cost	Marginal Benefit			
		Jointing Stage	Big Bell Mouth Stage	Tasseling Stage	Milk Ripening Stage
2012	0.485	-	0.927	0.955	-
2013	0.41	-	0.615	0.779	0.621
2014	0.503	-	-	0.704	-
2015	0.391	-	0.696	0.832	-
2016	0.329	-	0.412	0.398	0.455
Average value	0.421	-	0.654	0.726	0.534

Comparing the marginal cost and marginal benefit of irrigation in Henan province, the marginal benefit was greater than the marginal cost in each growth stage. The marginal income of irrigation in big bell mouth stage and tasseling stage in Henan province was far greater than the marginal cost, and the gap between the marginal income and the marginal cost in tasseling stage in Henan province was the largest. The change trend of the marginal income of irrigation during big bell mouth stage and tasseling stage was the same. In 2012, the marginal income of irrigation during big bell mouth stage and tasseling stage was far greater than the marginal cost. In 2016, the gap between the marginal income and the marginal cost of irrigation during big bell mouth stage and tasseling stage was small.

3.4.3. Analysis of Marginal Cost and Marginal Benefit of Irrigation in Different Growth Periods in Shandong Province

The marginal cost and marginal benefit of irrigation in different growth periods in Shandong province are shown in Table 13. The marginal cost of irrigation in Shandong province was 0.43–0.57 yuan/m^3. The marginal cost increased with time, and the largest marginal cost of irrigation in Shandong province was observed in 2015 (0.57 yuan/m^3). In Shandong province, there was less irrigation in jointing stage and big bell mouth stage, and the marginal income of irrigation in jointing stage and big bell mouth stage was small. There were many times of irrigation in tasseling stage and milk ripening stage, the marginal income of irrigation in tasseling stage and milk ripening stage was relatively large, and the marginal income of irrigation in tasseling stage was the largest (0.69 yuan/m^3).

Table 13. Marginal cost and marginal income of irrigation in different growth periods in Shandong province (Unit: yuan).

Shandong	Marginal Cost	Marginal Benefit			
		Jointing Stage	Big Bell Mouth Stage	Tasseling Stage	Milk Ripening Stage
2012	0.432	-	0.6	1.383	0.68
2013	0.473	-	-	0.605	0.545
2014	0.473	0.526	0.564	0.659	-
2015	0.567	0.636	-	0.682	0.699
2016	0.468	-	0.521	0.492	0.531
Average value	0.474	0.57	0.565	0.688	0.636

Comparing the marginal cost and marginal benefit of irrigation in Shandong province, the marginal benefit was greater than the marginal cost in each growth stage. The gap between the marginal income and the marginal cost of irrigation in jointing stage and big bell mouth stage in Shandong province was small. The growth period with a large gap between the marginal income and the marginal cost of irrigation in Shandong province was tasseling stage and milk ripening stage, and the gap between the marginal income and the marginal cost of irrigation in tasseling stage was the largest (0.21 yuan/m^3).

Comparing with the marginal cost of irrigation in the three provinces of Huang-Huai-Hai, the marginal cost of irrigation in Shandong province was the largest, followed by the marginal cost of irrigation in Hebei province, and the marginal cost of irrigation in Henan province was the smallest. Comparing with the marginal income of irrigation in the three provinces of Huang-Huai-Hai, the periods of greater marginal benefits of irrigation were tasseling stage and milk ripening stage in Hebei province, big bell mouth stage and tasseling stage in Henan province, tasseling stage and milk ripening stage in Shandong province. The marginal income of irrigation in tasseling stage in the three provinces of Huang-Huai-Hai was relatively large, most farmers in the three provinces chose to irrigate in tasseling stage, which indicated the choice of irrigation period of farmers had a strong relationship with the marginal income of irrigation, and farmers tended to irrigate in the growth period with large marginal income.

4. Discussion

Currently, there is a lack of representative methods for adaptability research, which mainly relies on vulnerability and resilience assessment methods and indicator systems, and most adaptability research focuses on adaptability index throughout the whole growth period [24]. Due to the singularity of research theories and methods, as well as the reliance on other disciplinary fields, the development of adaptability research is faced with severe challenges [2]. For research on irrigation amount at different stages, previous studies have mostly simulated the impact of irrigation amount at different stages on crop yield [25,26], with less attention paid to the selection of irrigation period for farmers.

The innovation of this paper mainly had two points. One was to propose the evaluation method of adaptability index of irrigation in different growth periods. Unlike previous studies, this study focused on the adaptability index of irrigation in different growth stages of maize in the three provinces of Huang-Huai-Hai. The evaluation method of adaptability index of irrigation in different growth periods in this paper was used to calculate the adaptability index and the increase in yield value of irrigation in different growth periods. The adaptability index of irrigation in different growth stages in this paper was applicable not only to flood irrigation but also to water-economical systems, like drip irrigation and sprinkler irrigation, etc. The evaluation method of adaptability index of irrigation in different growth periods in this paper is also applicable to other regions. The other was to analyze the selection of irrigation period by comparing the marginal benefit and marginal cost of irrigation in different growth periods. Whether farmers irrigate in maize key growth period of water sensitivity is an urgent issue that must be studied, thus this paper compared maize key growth period of water sensitivity with irrigation period of farmers in the three provinces of Huang-Huai-Hai. Some scholars have conducted research on the maize key growth period of water sensitivity in Hebei, Henan, and Shandong using field experimental data. The research results of Mei Ruyu et al. (2022) indicated that the key growth periods of water sensitivity in Hebei were tasseling period and milk ripening period [27]. Liu Xiaoxue's research results (2014) indicated that seedling emergence stage to jointing stage in western Henan were the key climatic periods for precipitation to affect maize yield [28]. The research results of Ma Yuping et al. (2015) indicated that the period from tasseling to milk ripening were the key water periods for maize growth in Henan and Shandong [29]. Therefore, the maize key growth periods of water sensitivity in the three provinces of Huang-Huai-Hai were tasseling period and milk ripening period. The choice of irrigation period by farmers often depended on the marginal income of irrigation in each growth period, and farmers tended to irrigate in the growth period with large marginal income. Therefore, the marginal cost and marginal income of irrigation in different growth periods were compared to analyze the selection of irrigation period for farmers in the three provinces of Huang-Huai-Hai. The limitation of this paper is that, due to the time constraints of household survey data, it is mainly based on the five-year household survey data from 2013 to 2017 for research.

According to the results in this paper, the yield increase effect of irrigation in jointing stage—milk ripening stage was considerable. The growth period with the largest adaptability index in the three provinces of Huang-Huai-Hai was milk ripening stage, which indicated that if farmers increased irrigation water in milk ripening stage, the yield increase effect of irrigation would be more obvious. In addition, the marginal incomes of irrigation in jointing stage—milk ripening stage were greater than the marginal costs. The marginal income of irrigation during tasseling period in the three provinces of Huang-Huai-Hai was relatively large, and most farmers in the three provinces chose to irrigate during tasseling period. Specifically, the periods of greater marginal benefits of irrigation in Hebei and Shandong were tasseling stage and milk ripening stage, and the marginal incomes of irrigation in big bell mouth stage and tasseling stage in Henan were relatively large. Therefore, for the allocation of irrigation water resources for farmers, priority should be given to ensuring the water supply during tasseling stage and milk ripening stage in Hebei and Shandong, as well as during big bell mouth stage and tasseling stage in Henan. Under the premise of ensuring water supply in key growth period of water sensitivity, farmers who irrigate more than three times in the three provinces of Huang-Huai-Hai could adjust the irrigation times to two times.

5. Conclusions

This paper studied the adaptability of maize farmers to drought and the selection of irrigation period in the three provinces of Huang-Huai-Hai. The following conclusions are drawn:

The growth period with the largest adaptability index in the three provinces of Huang-Huai-Hai was milk ripening stage. The adaptability index in milk ripening stage in Hebei, Henan, and Shandong was 1.063, 1.081, and 1.053, respectively. The increase in yield value of irrigation at different growth stages varied in the three provinces. In Hebei province, adding one irrigation at jointing stage, big bell mouth stage, tasseling stage, and milk ripening stage, the yield value per mu could increase by 25.8 yuan, 22.8 yuan, 39.9 yuan, and 60.2 yuan, respectively. In Henan province, adding one irrigation at big bell mouth stage, tasseling stage, and milk ripening stage, the yield value per mu could increase by 26.3 yuan, 45.8 yuan, and 72.6 yuan, respectively. In Shandong province, adding one irrigation at jointing stage, big bell mouth stage, tasseling stage, and milk ripening stage, the yield value per mu could increase by 26.1 yuan, 42.7 yuan, 51.0 yuan, and 51.4 yuan, respectively.

The maize key growth periods of water sensitivity in the three provinces of Huang-Huai-Hai were tasseling period and milk ripening period, and in most cases, the irrigation period of farmers was consistent with the key growth period of water sensitivity. Farmers in Hebei province had the most irrigation in tasseling stage. In Henan province, the irrigation twice in Kaifeng were carried out in big bell mouth stage and tasseling stage, and the irrigation three times in Kaifeng were carried out in big bell mouth stage, tasseling stage, and milk ripening stage. Most farmers in various cities in Shandong province conducted irrigation during tasseling stage and milk ripening stage. Most farmers in Yantai, Weihai, and Weifang chose to irrigate in milk ripening stage, and most farmers in Linyi, Qingdao, and Rizhao chose to irrigate in tasseling stage.

Comparing with the marginal cost of irrigation in the three provinces of Huang-Huai-Hai, the marginal cost of irrigation in Shandong was the largest (0.43–0.57 yuan/m^3), followed by the marginal cost of irrigation in Hebei province (0.34–0.55 yuan/m^3), and the marginal cost of irrigation in Henan province was the smallest (0.32–0.51 yuan/m^3). Comparing with the marginal income of irrigation in the three provinces, the marginal income of irrigation in tasseling stage (0.79 yuan/m^3) and milk ripening stage (0.83 yuan/m^3) was relatively large in Hebei province. The marginal income of irrigation in big bell mouth stage (0.65 yuan/m^3) and tasseling stage (0.73 yuan/m^3) was relatively large in Henan province. The marginal income of irrigation in tasseling stage (0.69 yuan/m^3) and milk ripening stage (0.64 yuan/m^3) was relatively large in Shandong province.

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