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Impacts of Irrigation Time and Well Depths on Farmers' Costs and Benefits in Maize Production

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Abstract: In the North China Plain, drought usually occurs during the interval between wheat harvest and maize sowing in normal and dry years. The first irrigation for maize plays a critical role in guaranteeing seed germination and grain yields. Using experimental data from Xinxiang in 2019 and survey data of 641 farmers from the North China Plain in 2020, this study adopts a cost-benefit analysis method to investigate the impacts of irrigation time and well depths on farmers' costs and benefits in maize production. The results showed that farms with well depth > 120 m accounted for 49% of total farms, especially in Hebei Province, and 38% wells had low water yield < 2.7 m^3 kW^{-1} h^{-1}. Delaying the time of the first irrigation made maize yields decline by up to 307 kg ha^{-1} day^{-1}. Well depths increased irrigation costs and total maize production cost in an exponential manner, causing farmers' benefits to decrease exponentially with well depths. With well depth > 180 m, the proportion of irrigation cost to total cost rose to 14%, whereas well depth > 230 m directly caused the farmers' profits negative. A critical well depth of 230 m was put forward as the upper limit for farmers adopting maize planting in the NCP. The concept of 'rotational irrigation strategy' and suggestions of adopting drip irrigation, sprinkler irrigation, or hose-reel sprinkler irrigation were recommended to advance 6–8 days for the first irrigation period, compared with traditional flood irrigation.

Keywords: North China Plain; social survey; irrigation strategy; agricultural output; *Zea mays* L.

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1. Introduction

The North China Plain (NCP) is one of China's major granary, producing 61% wheat (*Triticum aestivum* L.) and 31% maize (*Zea mays* L.) of the domestic food production [1]. So far, the agricultural sector has been the major consumer of water resources in China, accounting for 70% of total groundwater use [2]. With the increasing demand for food and water resources, irrigated farmland has substantially increased in the NCP [3]. Consequently, several areas in the NCP have become the severest groundwater depression zone in the world. To maximize the land-use efficiency and profits, irrigated areas in the NCP are dominated by a winter wheat-summer maize rotation [4]. The shortage of surface water resources and uneven distribution of precipitation have made agricultural planting principally dependent upon compensatory irrigation. In general, soil water storage left for summer maize after wheat harvest was often insufficient, and the topsoil (0–30 cm) moisture content was only 10–13%, not adequately guaranteeing the germination of maize seeds [5]. Therefore, we should pay close attention to soil moisture status prior to maize sowing. If the weather before maize sowing continued to be dry, and the soil moisture content was lower than 14% (or 55% of field capacity), it was necessary to apply the first irrigation after maize sowing in time [6]. In practice, it was essential for local farmers to apply supplementary irrigation immediately after sowing due to an extremely poor soil moisture condition induced by the previous crops in the NCP.

In recent years, rapid decline in groundwater level has made the irrigation coverage area per well shrink from 10 ha to 5 ha, and the water level has deepened to a maximum depth of 350 m in the NCP [7]. This has caused a recession of vegetation, intensification of salinization, and an increasing water crisis for local residents [8]. Moreover, water yield per well has also been declining year by year [9]. In China, as public interest for agricultural development, the construction of water conservancy projects was mainly invested in by local governments and was then transferred to farmers after the project was completed [10]. However, neither side paid much attention to the maintenance of the projects, accelerating the aging of canal systems, wells, and irrigation equipment [11].

In a winter wheat-summer maize cropping rotation, the first irrigation is key to maize seed germination due to over-depletion of soil moisture by wheat plants [5]. However, the first irrigation can usually not be guaranteed immediately after maize sowing due to increasing sizes of farmland, and rising costs of labor input [11]. With the development of agricultural mechanization, it took a shorter time for wheat harvest and maize sowing than before, saving more time for field preparation and early sowing of maize. However, the deterioration of the water yield of wells prolonged the irrigation period, wasting valuable time for rapid completion of the first irrigation [12]. Our previous surveys have shown that, compared with traditional technologies, advances in agricultural mechanization significantly improved the efficiency in crop harvest and seeds sowing, saving 10 more days for the application of the first irrigation than before. However, it was the low irrigation efficiency that made crops not irrigated in time. As a result, a longer irrigation duration delayed the germination of seeds. That was also unfavorable to the formation of reasonable plant groups [13]. Therefore, advancing the time of the first irrigation and shortening the irrigation duration are extremely critical for maize production in the NCP.

However, farmland scale has been substantially expanding in recent years due to land transfer policy in China, imposing a challenge on in-time application of the first irrigation to crops [14,15]. In this study, we tried to find a solution to the immediate application of the first irrigation and to figure out strategies that shortened the irrigation duration. A social survey combined with an on-farm experiment was carried out to investigate impacts of irrigation time and well depths on farmers' costs and benefits in maize production in the NCP. Besides, several meaningful suggestions were put forward for local farmers. The scientific objectives of this study are (1) to quantify the effect of delaying the first irrigation after sowing on maize yield components, and (2) to identify the critical well depth that makes a trade-off between farmers' costs and benefits in maize production. We hope that the findings may provide scientific references for the efficient use of groundwater resources in the NCP.

2. Materials and Methods

2.1. Experiment Site Description

A field experiment was carried out from June to September 2019, at the Qiliying Experimental Station, Xinxiang, Henan Province, China (35°08′ N, 113°45′ E, a.s.l. 81 m) to investigate the effects of the first irrigation time on yield components of maize (Figure 1). The experimental plots were irrigated with groundwater from wells with a depth of 50 m. The cropping system is a winter wheat-summer maize cropping rotation. The place has a continent temperate monsoon climate. The mean annual precipitation (1951–2018) is 578 mm, of which 68% (393 mm) occurs during the summer maize growing season, and the mean annual temperature is 14.1 °C. In 2019, precipitation was 224 mm during the growing season of summer maize, which was 169 mm less than the average value, indicating a normal-dry year for maize growing. The annual evaporation is 1909 mm, annual sunshine hours are 2408 h, and the annual frost-free period is 201 days. The soil is a sandy loam (4.52% clay, 40.3% silt, and 55.2% sand) with a bulk density of 1.42 g cm^{-3}. The available soil N, P, K, and soil organic matter content were 43.1 mg kg^{-1}, 15.2 mg kg^{-1}, 126 mg kg^{-1}, and 13.1 g kg^{-1}, respectively.

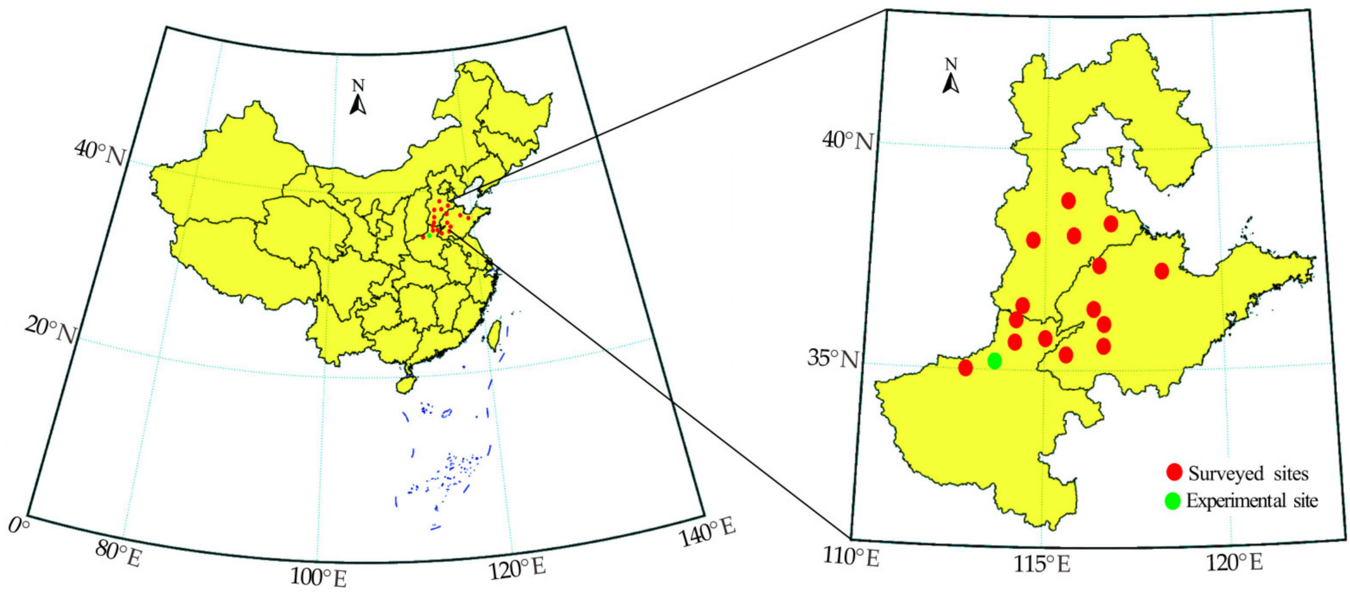

Figure 1. Location of surveyed sites and experimental site in the study.

2.2. Experiment Design and Measurements

A completely randomized design was adopted with three replicates. Six treatments (time of the first irrigation) were set up, namely, the first was irrigation applied 1, 6, 11, 16, 21, and 26 days after sowing (corresponding to 5 June, 10 June, 15 June, 20 June, 25 June, and 30 June, respectively) with a fixed amount of 30 mm for each plot (Figure 2). The plot area was 10 m long and 5 m wide. A popular-used maize hybrid (cv. DH 605) was selected. The seedbed was prepared by a tractor-drawn rotary cultivator up to a depth of 30 cm to form a smoothed seedbed. Maize seeds were sown on 4 June 2019 while harvest dates varied from 15 September to 5 October 2019, according to different irrigation time. The plant spacing of maize was 30 cm, and the row spacing was 50 cm, giving a planting density of 6.75×10^4 plants ha^{-1}. A drip fertigation system was adopted in the experiment to complete the process of irrigation and fertilization simultaneously. The spacing between drip lines was 60 cm so that one row of drip tape could irrigate two rows of maize plants. Based on soil tests in the 0–100 cm soil profile, base fertilizers including ammonium nitrate (120 kg ha^{-1} N), calcium super-phosphate (90 kg ha^{-1} P_2O_5), and potassium sulfate (30 kg ha^{-1} K_2O) were applied prior to sowing. To ensure a non-limited supply of water and nutrients for crops, additional urea (300 kg ha^{-1} N) was applied as a top dressing at the V8 and R1 stages for maize plants at a ratio of 6:4, along with supplementary irrigation events of 30 mm. All treatment plots received the same amounts of total water and fertilizer, whereas the only difference of irrigation treatments was the time of the first irrigation. A precision flow meter (Shanghai Water Meter Manufacturing Co., Ltd., Shanghai, China) was installed at the pump outlet to measure the irrigation volume. Weeds and pests were managed according to the local governments' recommendations.

Soil water content (SWC, % v/v) was measured at 10 cm increment to a depth of 100 cm using Insentek sensors (Zhejiang Oriental Insentek Technology Co., Ltd., Hangzhou, China). Antecedent soil volumetric moisture prior to maize sowing in 2019 was measured 13.5%, 17.3%, and 18.4% in the 0–30 cm, 30–60 cm, and 60–100 cm soil layers, respectively. Our previous study indicated that the Insentek sensor was a reliable tool to represent real SWC values in the field with a root mean square error (RMSE) of 0.927% v/v between the Insentek sensor and oven-dry method [5]. By checking the year-round data, the data of Insentek sensors also had good continuity and stability. Crops around the sensors were not missed and uniform, and were representative of the experimental conditions with similar sizes and vigor.

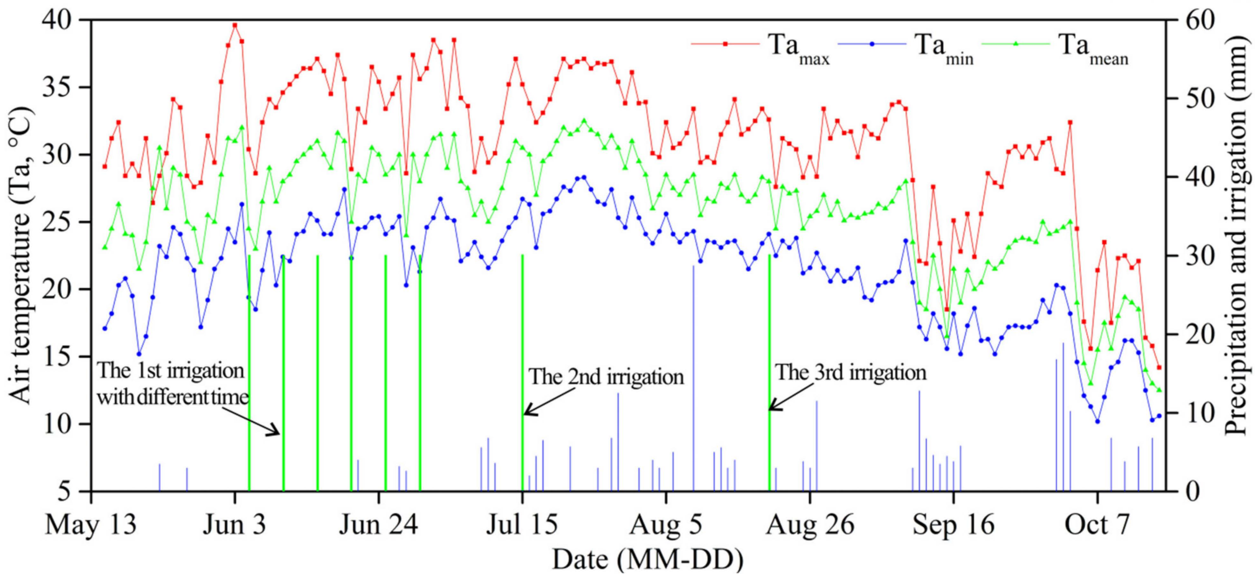

Figure 2. Maximum, mean, and minimum air temperature, irrigation time and amount, and precipitation at the experimental site in 2019 growing season of maize.

A randomly selected 1 m^2 of plants was sampled for all experimental plots before harvest for yield estimation. The grain was winnowed, solar-dried to a 14% moisture content, and weighed using a precise digital balance (Ohaus, AX224 Adventurer, Parsippany, NJ, USA). Weather data were collected from an automatic weather station installed near the experimental field.

2.3. Surveyed Sites Description

A questionnaire survey was conducted in Henan, Hebei, and Shandong Provinces, North China Plain (NCP) from April to September 2020. The surveyed areas contained major parts of the NCP, representing the typical winter wheat-summer maize cropping regions (112°44′−118°19′ E, 34°03′−38°89′ N; 36−158 m a.s.l.). The areas have a continent temperate monsoon climate with the weather being cold and dry in winter, hot and rainy in summer. The mean annual precipitation is 410−650 mm. The rainfall is distributed unevenly seasonally, mainly falling in summer seasons. The three provinces are typical water shortage areas of China. The regional water resources account for about 1.6% of the total water resources in China, and water resources per capita are 335 m^3 $year^{-1}$, less than 1/7 of the national average level [16]. Because there are few surface water resources in the areas, groundwater has become the major water source for irrigation. Due to long-term over-exploitation of groundwater, the areas have become the most serious zones of groundwater depression on the planet [17].

2.4. Survey Data Collection

Primary survey data were collected from farmers at the surveyed sites through formal surveys. In total, 15 counties in Henan, Hebei, and Shandong provinces were selected as surveyed objects. The selection of the survey area mainly considered two factors. First, the surveyed counties are important irrigated agricultural counties in the North China Plain (NCP), and the scale and distribution of household farmlands are representative of the NCP. Second, the surveyed counties are the major well-irrigated areas with well depths ranging from 30 to 300 m in the provinces, and effects of irrigation costs on farmers' total benefit in agricultural production are evident. Based on the above-mentioned factors, five counties were separately chosen from each province, and a representative township was selected from each county. Stratified and random sampling methods were adopted in the survey. According to the size of irrigated farmland (ha), which was previously collected by local village committees and cadres, three strati were finally defined, including small-scale (1–40 ha), moderate-scale (40–170 ha), and large-scale (170–240) households. In each town, 20 households were randomly selected from the three strati of representative villages. In total, 720 questionnaires were finally dealt out. Excluding unqualified samples, the number of valid questionnaires was 641, with an effective rate of 89%, an average sampling error of 2.8%, and a confidence degree of 95%. The questionnaire mainly adopted a 'one-to-one' interview to investigate the family members who run their own farms.

The questionnaire included necessary information regarding the size of farmland, well depths, the number of wells, water yield per well, irrigation coverage area per well, duration of wheat harvest, maize sowing, and time of the first irrigation, costs in seeds, fertilizers, pesticides, irrigation and mechanized operations (i.e., sowing, tillage, and harvest, etc.), and benefits of the incorporation of advanced irrigation systems and strategies into winter wheat-summer maize rotation (the questionnaire was attached as Supplementary Materials). In those factors, well depths exerted major effects on the cost of irrigated maize production. Farms with different well depths (10–300 m) were investigated. In the surveyed areas, soil water content (SWC, % w/w) in the 0–30 cm soil depth before maize sowing (% w/w) was obtained through oven-drying method during the survey period. Relative soil water content (RSWC, %) was calculated by dividing the measured SWC by field capacity (FC). The degree of drought stress was determined by a range of RSWC, namely, no drought stress means RSWC > 85% FC; light drought stress refers to RSWC within 75–85% FC; mild drought stress refers to RSWC within 65–75% FC; heavy drought stress refers to RSWC within 55–65% FC; extreme drought stress refers to RSWC within 45–55% FC [18]. Precipitation between wheat harvest and maize sowing in the surveyed areas was obtained from local meteorological stations. In all the surveyed areas, farmers take groundwater as their major source for irrigation. In addition to the questionnaire survey, the research team also interviewed the experts from the comprehensive experiment stations of the China Agriculture Research System to collect relevant information.

2.5. Assessment of Costs and Benefits

In the calculation of irrigation costs, the power of pumps was estimated to meet the lowest water yield of 40 m^3 h^{-1}. The annual fee in the use of wells was calculated according to the service life for a 20-year lifetime. During the growth period of maize, the total irrigation amount was 1200 to 1800 m^3 ha^{-1}. Irrigation cost (USD ha^{-1} $year^{-1}$) was calculated as follows:

$$\text{Irrigation cos t} = \frac{\text{Pump power} \times \text{Irrigation duration} \times \text{Electricity charge}}{\text{Irrigation efficiency}} \quad (1)$$

where pump power varied from 11 to 55 kW with different well depths. Irrigation duration varied from 1 to 20 days. In well-irrigated areas of the NCP, water price (≈0.01584 USD m^{-3}) was included in the electricity charge during the process of irrigation because water use quantity was proportional to electricity use [19]. Electricity charge (≈0.1014 USD kW^{-1} h^{-1}) was a sum of costs that included the costs of electricity and water use. Irrigation efficiency varied from 0.75 to 0.95 based on different irrigation methods. The efficiency values were empirical values relative to the local farms in the NCP.

Total cost was defined as a series of costs in the process of seeds, fertilizers, irrigation, labor input, and so on. All costs in the base year (base year = year 0) were regarded as establishment costs. Thereafter, costs were taken as annual maintenance costs. Empirical evidence revealed that most of the irrigation equipment had a lifetime of 10 years, whereas PE pipes had a lifetime of 3 years, and drip tapes were used for only one year and were replaced every year.

According to our survey, seed cost was 114 USD ha^{-1} $year^{-1}$, fertilizer cost was 295 USD ha^{-1} $year^{-1}$, irrigation cost varied from 17.8 to 976 USD ha^{-1} $year^{-1}$ with different well depths, pesticide cost was 66.5 USD ha^{-1} $year^{-1}$, mechanical operation cost was 309 USD ha^{-1} $year^{-1}$, labor cost was 440 USD ha^{-1} $year^{-1}$ and land tenancy fee was

589 USD ha^{-1} year^{-1} after land subsidy by governments. The costs only included the inputs in the maize growing seasons.

A cost-benefit analysis was carried out to compare the irrigation project efficacy with irrigation time and well depths at different farm scales. Using the method, a critical well depth achieving a trade-off between irrigation costs and benefits was determined. In this study, benefit in maize production included all gains caused by implementing irrigation measures.

The major benefit considered was increased grain yield due to the adoption of the different irrigation techniques. Benefits were converted into monetary values by multiplying by the market price and then summed to obtain the total benefit. Annual benefit (USD ha^{-1} year^{-1}) was the net benefit obtained in the maize growing season. It showed the current year's value of the net benefit generated by each irrigation equipment compared over their lifetime period and was calculated as follows:

$$Annual\ benefit = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+r)^t} \tag{2}$$

where B_t was benefits at time t, C_t was investment cost at time t, t was time horizon, and r was discount rate. A nominal discount rate of 6% was applied [20]. An investment was economically feasible when the annual benefit was positive.

2.6. Relationships between Costs-Benefits and Well Depths

The relationship between annual cost (y) in maize production and well depth (x) was fitted to a positive exponential function, whereas a negative exponential function was adopted to describe the relationship between annual benefit (y) and well depth (x) as follows:

$$y = a + be^{kx} \tag{3}$$

where y was annual cost or benefit (USD ha^{-1} year^{-1}) generated during the process of maize production; x was well depth; a, b, k were parameters to be fitted; a was a constant representing an interception; b determined whether cost/benefit had a positive or negative correlation with well depth.

2.7. Statistical Analysis

Analysis of variance (ANOVA) was performed to test the differences in yield components and grain yields among treatments. Correlation analysis was conducted with SPSS 18.0 software (SPSS 19.0, SPSS Institute Inc., Chicago, IL, USA) to determine the relationships between the time of the first irrigation and yield components, as well as the relationship between well depth and cost-benefit in maize production. Means were compared using Fisher's least significant difference tests at $p < 0.05$. Graphs presented were plotted using Sigmaplot 12.0 (Systat Software, San Jose, CA, USA).

3. Results and Discussion

3.1. Basic Survey Information Related to Irrigation Practices

To make the results representative, the surveyed farm sizes covered a range from smallholders to large scale households, with sizes > 80 ha accounting for 47% of total farmers (Figure 3). Most of the rural households (79%) in charge of their farmland were male, and the average age of the households was about 49 years old (Table 1). More than 50% of the households held at least a middle school diploma. Their annual income per capita was 4670 USD year^{-1} person^{-1}. Mild to heavy drought (mean soil water content of 11.8%) usually occurred during the interval between wheat harvest and maize sowing. Therefore, the first irrigation was key to maize production, which was consistent with the previous results in the NCP [21]. The surveyed well depths were from 10 to 300 m, while approximately half (49%) of the well depths exceeded 120 m, imposing great pressure on farmers' burden in groundwater withdrawal. It should be noticed that the groundwater level was 120–300 m deep in most survey areas of Hebei Province, which was 2–3 times deeper than that in Shandong and Henan Provinces, indicating the severest groundwater depression zone in Hebei Province. This finding was in agreement with a number of previous studies [22–26]. Water yields with different well depths varied from 2.4 to 8 m^3 kW^{-1} h^{-1}. More than 1/3 (38%) wells had low water yield (<2.7 m^3 kW^{-1} h^{-1}) in the NCP due to over-exploitation. Generally, the irrigation coverage area per well was associated with well depth and pump power. On average, the coverage area was 6.2 ha $well^{-1}$. Among them, 24% wells had coverage areas of < 6.2 ha $well^{-1}$, resulting in an increase in density of wells per farm, undoubtedly increasing the farmers' costs in well drilling. In the NCP, the occurrence probability of drought before sowing was nearly 100% without effective precipitation [27–29]. In this study, the probability of precipitation > 10 mm between wheat harvest and maize sowing was only 27% averaged across 2017–2020, according to the weather data collected from the local meteorological stations. Due to different farm sizes, the wheat harvest period was about 1–7 days, the maize sowing period was 1–10 days, and the first irrigation duration was 3–15 days. Basically, a larger farm scale was associated with longer duration of harvest, sowing, and irrigation [30].

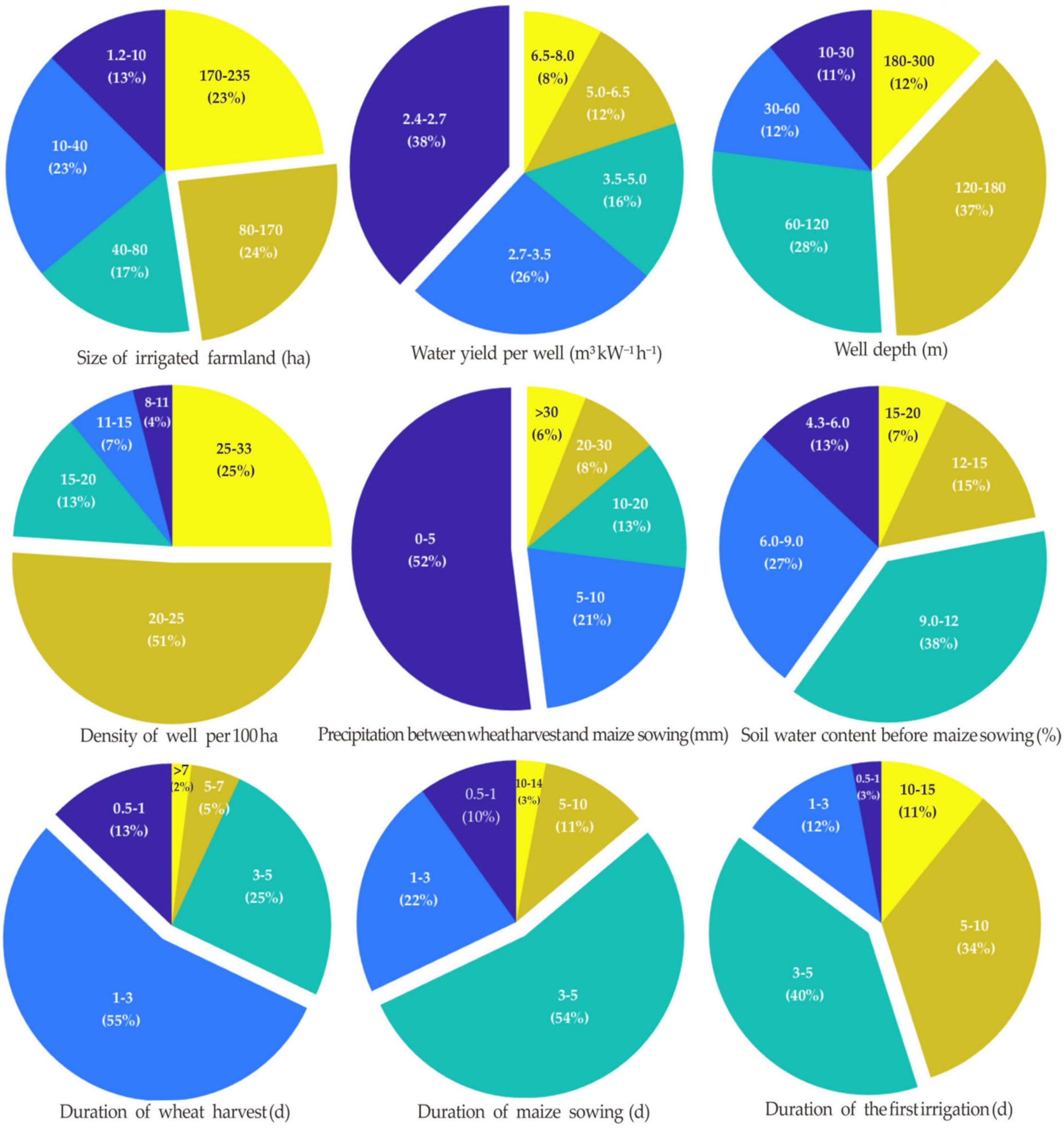

Figure 3. Proportional pie chart of surveyed indicators.

Table 1. Summary statistics.

Items	Min.	Max.	Mean	Std. Dev.
Gender (female = 0; male = 1)	0	1	0.79	-
Age	27	63	49.4	3.65
Education (years)	6	16	8.9	0.58
Annual income per capita of the family (10^3 USD year^{-1} person^{-1}) *	1.91	10.1	4.67	0.55
Well depth (m)	10	300	117	42.5
Size of irrigated farmland (ha)	1.2	235	96.8	37.5
Number of wells per farm	1	30	12.6	11.6
Irrigation coverage area per well (ha)	3.5	9.8	6.2	1.25
Water yield per well (m^3 kW^{-1} h^{-1})	2.4	8	3.3	3.0
Density of wells per 100 ha	8	33	19	2.5
Soil water content before maize sowing (% *w/w*)	5.3	19.4	10.8	2.6
Degree of drought stress at sowing (none = 1; light = 2; mild = 3; heavy = 4; extreme = 5)	1	5	3.5	1.1
Precipitation during the interval between wheat harvest and maize sowing (mm)	0	42	5.2	14.3
Period of wheat harvest (day)	0.5	8	3.1	3.8
Period of maize sowing (day)	0.5	15	4.3	7.5
Duration of the first irrigation (day)	0.5	15	6.3	7.3

Note: * Annual income per capita was expressed using USD as the currency unit. RMB was converted to USD based on an exchange rate of 1 RMB ≈ 0.1584 USD released on 25 February 2022. The same below.

3.2. Time of the First Irrigation Affects Yield Components of Maize

The time of the first irrigation had significant effects on yield components of maize (cv. DH 605), including available ear number per ha, kernel number per ear, and 100-kernel weight (Figure 4). When the first irrigation was implemented from days after sowing (DAS) 1 to 16, both available ear number per ha and kernel number per ear reduced significantly, at a decreasing rate of 581 ears ha^{-1} day^{-1} and 5 kernels ear^{-1} day^{-1}, respectively. When the first irrigation was applied after DAS 16, they dropped at a faster rate than previously. This indicated that the reduction of yield components would accelerate if the first irrigation time was delayed more than 16 days. A similar study conducted in the NCP also showed that summer maize planted after June 23 had a grain yield around 30% less than those planted on the normal sowing date (cv. XY 335) [31]. In this study, a maximum yield reduction of 32% was observed after the first irrigation was delayed > 16 days. In other words, the late irrigation time exerted equivalent yield reduction impacts as the late sowing date did especially in normal and dry years [32]. Though 100-kernel weight showed non-significant differences within DAS 1 to 6, it displayed a significant decreasing trend when the irrigation was applied after DAS 6. Within DAS 1 to 16, maize yields declined at a rate of 99 kg ha^{-1} day^{-1}. When the first irrigation was postponed > 16 days, yields greatly reduced at a rapid rate of 307 kg ha^{-1} day^{-1}. Our study confirmed that compared to the irrigation time on June 5, both the 100-kernel weight and grain yields showed a decreasing trend when irrigation time was postponed for 6–26 days. A similar study also reported that, when maize was sown in early July, maize plants would not be fully mature with a growth period of <90 days, probably resulting in yield failure at maize maturity [33]. Although DH 605 was a medium late maturing hybrid sensitive to reduction of effective accumulated temperature due to delayed emergence, similar results of yield reduction effect (by 21–29%) was also observed on medium early maturing hybrids of DH 518, JNK 728 [34], and XD 29 [35] when the sowing date was delayed by 10–20 days, indicating that delay of the first irrigation may exert similar yield reduction effects despite of maize varieties.

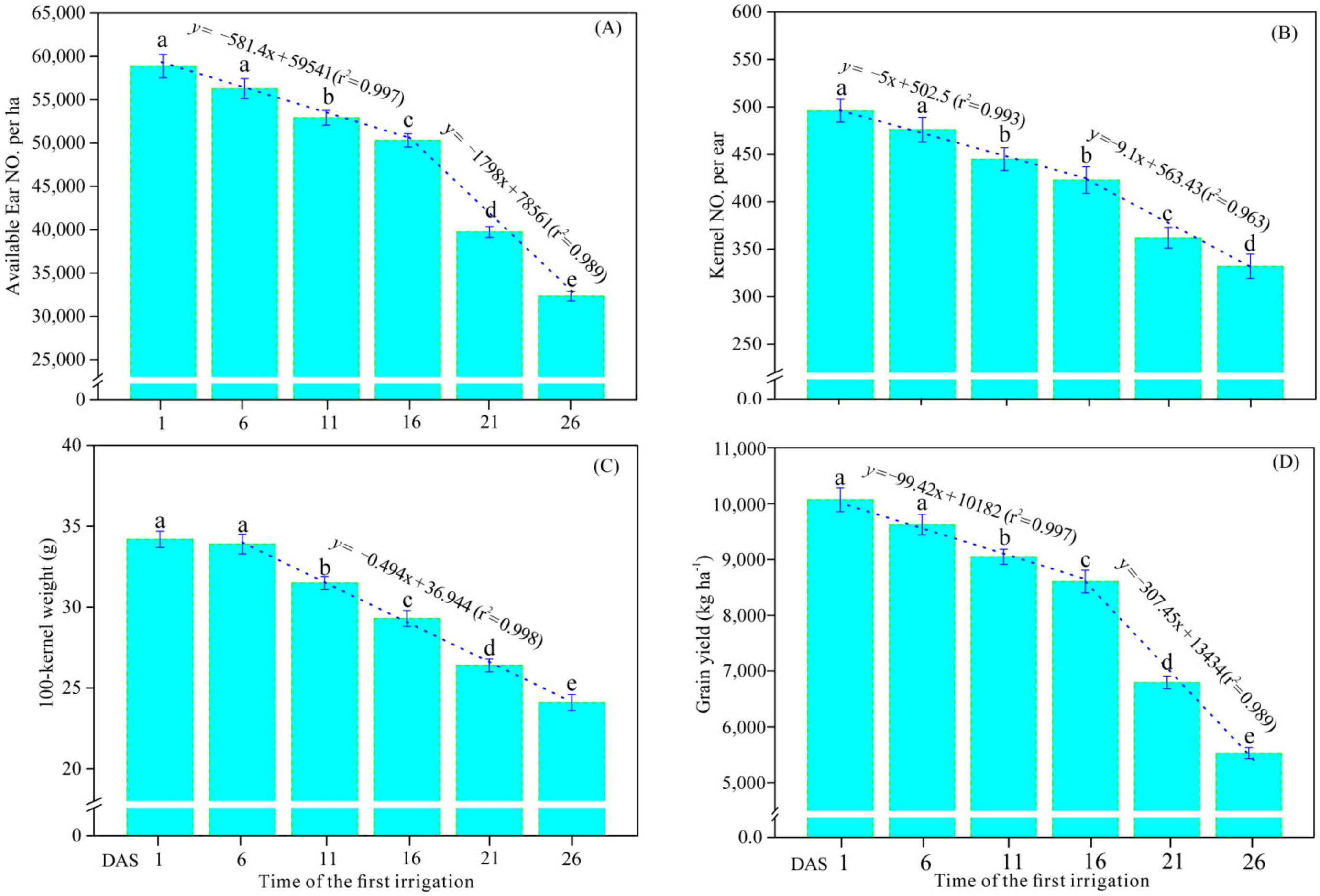

Figure 4. Effects of time of the first irrigation (DAS: days after sowing) on yield components ((**A**): available ear number per ha; (**B**): kernel number per ha; (**C**): 100-kernel weight) and grain yields (**D**) of summer maize under a plant density of 6.75 × 10^4 plants ha^{-1} in the North China Plain. Different letters indicate significant differences at $p < 0.05$.

3.3. Cost-Benefit Analysis for Maize Production with Different Well Depths

Deep well depth significantly increased the power consumption of irrigation equipment [36]. In this study, the cost of well construction, cost of depreciation and maintenance of wells, and irrigation cost increased with well depth in a positive exponential manner (Figure 5). In detail, irrigation cost increased from 38 (well depth 30 m) to 673 USD ha^{-1} $year^{-1}$ (well depth 300 m). Similarly, total cost in maize production also displayed a positive exponential relationship with well depth, generating a total cost varying from 1840 to 2795 USD ha^{-1} $year^{-1}$. Irrigation cost accounted for 1.5% to 35.2% of the total cost, indicating that labor cost and land transfer cost were still the major cost for farmers, contributing at least 56.7% to the total cost. The result was similar to the findings in a previous study [37]. In contrast, there existed a negative exponential function between benefit in maize production and well depth. When the well depth exceeded 180 m, the proportion of irrigation cost rose to 14%, making annual profit less than 266 USD ha^{-1} $year^{-1}$. When the well depth exceeded 230 m, the profit became negative. Due to the increase in maize production cost and the decline in domestic maize sale price in recent years, the profit of maize production has been declining since 2017 [38]. Some farmers adopting traditional flood irrigation even had negative profits in 2018 and 2019 because of soaring labor costs [39]. In 2020, affected by the COVID-19 epidemic, the import of maize markedly decreased, the domestic sale price of maize gradually warmed up, and the average profit in maize production increased to 473 USD ha^{-1} in 2020 in the NCP [40].

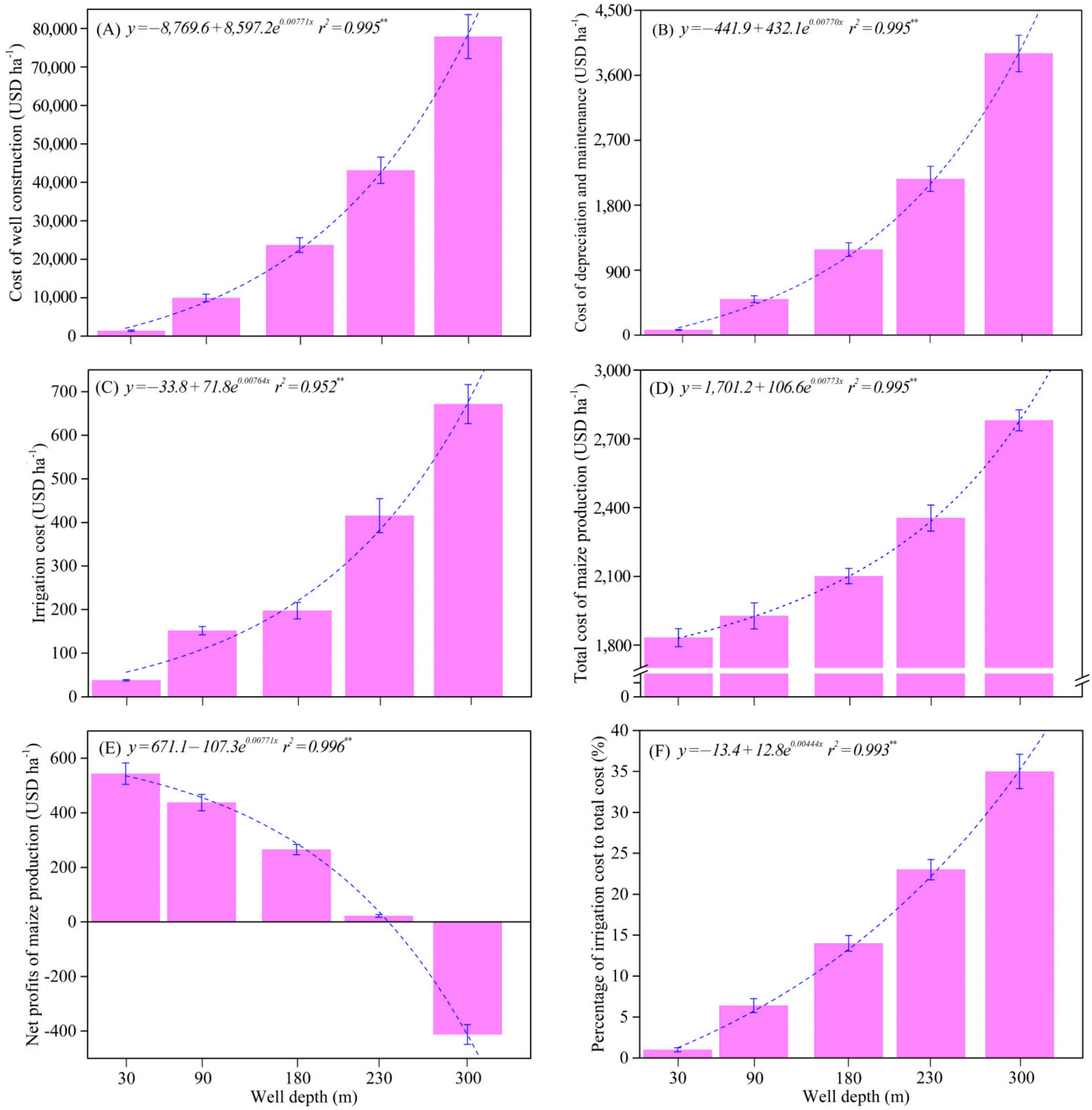

Figure 5. Costs and benefits in maize production and their relationships with well depth according to the survey data collected in the North China Plain. (**A**) cost of well construction; (**B**): cost of depreciation and maintenance; (**C**): irrigation cost; (**D**): total cost of maize production; (**E**): net profits of maize production; (**F**): percentage of irrigation cost to total cost. ** indicates extremely significant correlation at $p < 0.01$.

3.4. Cost-Benefit Analysis for Different Irrigation Methods

In practice, sprinkler irrigation technology includes hose-reel sprinkler irrigation, semi-fixed or fixed sprinkler irrigation, buried telescopic sprinkler irrigation, lateral movable sprinkler irrigation, center pivot irrigation, etc. [41,42]. Among them, the hose-reel irrigation machine, semi-fixed sprinkler, and movable sprinkler irrigation machine were able to move their positions to different farmlands, while fixed sprinkler, telescopic sprinkler irrigation, and drip irrigation system were fixed at a certain position [43,44]. In this study, the cost of irrigation projects was calculated on a basis of 100 ha farmland, and then the cost was divided by 100 to obtain a hectare basis cost (Table S1). On average, the total investment into hose-reel sprinkler irrigation machines was the lowest, which is 1215 USD ha^{-1}, followed by semi-fixed sprinkler irrigation (Table 2). The investment into telescopic sprinkler irrigation system was the highest, which is 6355 USD ha^{-1}. Since the service life of the equipment was 10 years, the annual investment of hose-reel sprinkler irrigation was only 121 USD ha^{-1}. The investment of drip irrigation equipment per single time was extremely low, but drip tapes needed replacing every year, making the annual cost of drip tapes (285 USD ha^{-1}) the largest proportion (68%) of the total cost. This was consistent with previous findings that the annual replacement of drip tapes was a major contributor to the total cost of drip irrigation [45,46]. The total investment into center pivot irrigation machine and telescopic sprinkler irrigation system was high, which was 4954 and 6355 USD ha^{-1}, respectively. However, those irrigation techniques were suitable for the mechanized harvest and sowing of winter wheat and summer maize, and the labor cost during the irrigation period was relatively low [5]. The drip irrigation system was characterized by its lower single input but higher continuous inputs every year. In terms of annual cost, we recommended using hose-reel sprinkler irrigation machines or the semi-fixed sprinkler irrigation method. In terms of labor saving, the drip irrigation system and telescopic sprinkler irrigation systems were recommended. A possible alternative that could reduce the annual input of drip tapes would be the use of subsurface drip lines with longer service lives. However, their installation cost was higher. In practice, local farmers found that the use of subsurface drip lines did affect the application of rotary tillage during the intervals between harvest and sowing. Generally, the buried depth of subsurface drip lines was up to 30 cm, whereas the tillage depth was at least 30 cm in many places of the NCP [19]. Consequently, the application of subsurface drip lines in the NCP is rare.

Table 2. Investment of irrigation equipment per ha for maize production in the North China Plain.

Irrigation Method	Irrigation Coverage Area	Total Investment (USD ha^{-1}) *	Annual Investment (USD ha^{-1} $year^{-1}$)
Hose-reel sprinkler irrigation	230 m × 300 m	1215 e	122 e
Semi-fixed sprinkler irrigation	340 m × 200 m	1431 d	143 d
Drip irrigation	340 m × 200 m	4196 c	420 c
Center pivot irrigation	260 m × 260 m	4954 b	495 b
Buried telescopic sprinkler irrigation	340 m × 200 m	6355 a	636 a

Note: * Service life was 10 years for pump, back-washing sand filter, sprinkler head, disc filter, fertilizer applicator, center pivot irrigation machine, hose-reel sprinkler irrigation machine, head connector, solenoid valve, while the lifetime was 3 years for PE pipes, and 1 year for drip-tapes. Investment cost was calculated as a 10-year cumulative input for all equipment and materials. Annual investment was defined as total investment divided by 10 years. Different letters in each column stand for significant differences at $p < 0.05$.

3.5. General Discussion

We found that the duration of the first irrigation was generally longer than 8 days for most large-scale households, with a farm size > 80 ha. Up to now, there have been still more than 50% of households adopting surface flood irrigation, and the irrigation efficiency was low. This traditional method usually needed a large number of laborers employed for irrigation, resulting in a labor cost of 285 USD ha^{-1} $person^{-1}$, 10 times the labor cost for drip irrigating maize plants [47]. With the middle east of Hebei Province being the groundwater over-exploitation area, the groundwater level was generally 100–300 m [39]. Pump power > 22 kW was essential to ensure water output (40 m^3 h^{-1}) in that case, which increased farmers' electricity charge [48]. Our results showed that when the well depth was greater than 180 m, the irrigation cost accounted for about 14% of the total cost, making profits greatly shrink to 249 USD ha^{-1} $year^{-1}$. When the well depth reached 230 m, farmers' benefits would become negative. We considered a critical well depth of 230 m as the upper limit for farmers in the NCP. Since most irrigation and well equipment was powered by electricity other than fossil fuels in the well-irrigated areas of the NCP, the consumption of electricity accounted for almost 100% of the energy costs [2]. The electricity price was stable for the recent decade in the NCP. Therefore, the fluctuation of a variation of this price, which would affect the determination of the critical depth in the areas of NCP, did not exist.

Although smallholders usually chose flood irrigation to water crops due to its low investment in equipment, a few farmers preferred using sprinkler irrigation combined with flood irrigation to lower labor cost according to our survey. During flood irrigation, the irrigation water needed to infiltrate into the field capacity at first before soil saturation, resulting in deep percolation loss in flood irrigation [49]. Furthermore, the irrigation coverage area of flood irrigation was about 5 ha per well. While our study showed that adopting high-efficient irrigation techniques significantly extended the coverage area up to 9.8 ha per well.

Generally, the amount for the first irrigation was 60 mm per time in the NCP [12,43]. Guaranteeing a water output of 40 m^3 h^{-1} per well, it would take 22.5 h to irrigate a hectare of farmland. Taking an irrigation coverage area of 7 ha per well and an irrigation efficiency of 80% for example, flood irrigation would take 7.8 days to irrigate the entire 7 ha farmland, which meant a delay of 7.8 days for maize seeds emergence. To shorten the irrigation duration, drip irrigation or sprinkler irrigation technology was recommended. More importantly, the concept of 'rotational irrigation strategy' was put forward by the study. That is, dividing the one irrigation time into twice with half irrigation amount. Namely, an irrigation amount of 30 mm (half amount) is suggested to give first priority to the emergence of maize seeds. The next 30 mm of water can be irrigated immediately after the first round of irrigation. The irrigation strategy is expected to shorten irrigation duration by 4 days, which would increase grain yield by 8% [34,35].

In this study, hose-reel sprinkler irrigation was also recommended to replace traditional flood irrigation due to its flexible mobility on farmland [50]. The hose-reel sprinkler irrigation machine drives the water turbine through high-pressure water flow, making the hose-reel move back automatically on the farm [51]. Generally, the water output of hose-reel spray gun was 30–50 m^3 h^{-1}, the spraying radius was 30 m, and the moving speed was 15 m h^{-1}, giving rise to an irrigation efficacy around 1.6 ha day^{-1}. In this way, the irrigation duration for 10 ha of farmland can be shortened to 6 days, saving 6–8 days compared with traditional flood irrigation.

It was essential to comprehensively calculate the cost and benefit of maize production. When the benefit was greater than the total cost in maize production, we suggested adopting the winter wheat-summer maize cropping system. When the yield increase benefit was not able to cover the total cost, we suggested changing to plant high-value cash crops or legumes with less water consumption.

4. Conclusions

The first irrigation is key to maize production. During the period from DAS 1 to 16, advancing the time of the first irrigation increased maize yields by 99 kg ha^{-1} day^{-1}, whereas the yield boosting effect was 307 kg ha^{-1} day^{-1} during DAS 16 to 26 days. However, the irrigation duration was generally longer than 8 days for farm sizes larger than 80 ha since more than 50% of households were still adopting surface flood irrigation. The concept of a 'rotational irrigation strategy' was put forward to shorten the irrigation duration, which was expected to shorten the duration by 50% while realizing an early and uniform emergence of maize seedlings. Besides, drip irrigation, sprinkler irrigation, or hose-reel sprinkler irrigation was recommended to optimize the current irrigation strategy, which can save 6–8 days compared with traditional flood irrigation. Increment of well depth increased total costs of maize production in a positive exponential manner and decreased the farmers' benefits exponentially. A critical well depth of 230 m was put forward as the upper limit for local farmers in the NCP. We conclude that the results of the study provide scientific reference for farmers to optimize their irrigation and planting strategies in the NCP.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12040456/s1. Table S1: Detailed information for costs of irrigation equipment for maize production on a 100 ha basis. Questionnaire on irrigation costs and maize production benefits.

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