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Optimizing the Optimal Planting Period for Potato Based on Different Water-Temperature Year Types in the Agro-Pastoral Ecotone of North China

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Abstract: Potato is the fourth staple crop in China after wheat, maize and rice. The agro-pastoral ecotone (APE) in North China is a main region for potato production. However, potato yield has been seriously constrained by water shortages because of low precipitation and highly variable precipitation patterns during the growing season in this area. In this study, the Agricultural Production Systems Simulator (APSIM) model was used to simulate potato water-limited yield and historical years were divided into different water-temperature year types to optimize the optimal planting period (OPP) and cultivar of potato. The results showed that the potato yield varied in different water-temperature year types. Fast-developing cultivar Favorita could obtain the highest yield in most places and water-temperature year types due to its relatively short length of tuber formation stage. In this study, we suggest changing the planting date according to the water-temperature year type, which offers a new way to adapt to a highly variable climate. However, our method should be adopted carefully because we only considered climate factors; other agronomic management practices (adjusting planting density, plastic film mulch, conservation tillage etc.) also have a great effect on planting date and cultivar selection, which should be further investigated in the future.

Keywords: potato management; tuber formation stage; precipitation patterns

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1. Introduction

With the implementation of the "potato as the staple food" strategy, potato has gradually become the fourth staple crop after wheat, corn and rice in China [1]. The APE in North China, characterized by suitable temperature and soil conditions [2–4], is a main region for potato production in China [5]. Rainfed potato is one of the most common crops in this region, accounting for 46.8% of the total crop yield [4]. Therefore, studies on increasing potato production to ensure local food security are meaningful. However, the APE is a sensitive zone to climate change, and highly variable precipitation distributions and amounts, both temporally and spatially, result in large fluctuations in potato yield [4,6]. Thus, to cope with the local highly variable climate and enhance potato production, adaptation strategies must be adopted according to different seasonal precipitation patterns [5,7].

Among many agronomic adaptations, adjusting the planting date and selecting suitable cultivars are two effective way to adapt to local and annual climate variations. Tang et al. [5] conducted several planting experiments and found that the ratio of precipitation to potential evapotranspiration around the potato tuber formation stage accounts for 71% of the potato yield variation in Wuchuan County, a typical site in the middle APE of North China. Li et al. [7] showed that precipitation from the tuber formation stage to maturity could explain 87% of potato yield variation. Yu and Wang [8] showed that rapidly developing cultivars should be planted in a drier place, the eastern APE, according to water consumption of different cultivars and precipitation distribution in critical growth stage. In addition, different maturing cultivars can generate a series of growing season lengths to help the potato's critical growing period better match the local rainy season [9]. Therefore, adjusting the planting date and selecting suitable cultivars to meet the period of the precipitation peak during the potato's critical water stage is a useful method for increasing potato yield [7,10,11]. Li et al. [12] optimized planting date and cultivar of potato in North China using APSIM-potato and suggested late planting should be considered in most locations of North China. Tang et al. [5] divided historical years into wet, dry and normal years according to precipitation and found that the OPP of potato had delayed trends from dry years to wet years in the middle APE. Li et al. [7] also conducted a two-year field experiment to identify the optimal planting date in the middle APE, and his result showed that planting date and cultivar should be selected according to different year types.

Although there have been many studies on optimizing OPP and cultivar of potato in the APE of North China, these studies were constrained in specific site and years. In addition, the effect of different water-temperature year types on optimized planting date and cultivar was not investigated. An integrated study on the development of management strategies (principally planting date and cultivar choice) in different water-temperature year types is particularly essential for improving potato yield and ensuring local food security. Long-term field experiments can help explore the relationship between meteorological factors and the yield of different planting dates; however, experiments such as this are time consuming and relatively expensive [13]. Agricultural system models provide a powerful tool to capture interactions between crop growth and development, agronomic management practices and environmental factors (e.g., planting date × cultivar × location) across multiple seasons [14]. Studies investigating adaptation strategies (e.g., optimizing planting date) to improve crop production using simulation models such as the APSIM have been reported previously [10,11,15–17]. However, no study has focused on optimizing the planting date and selecting suitable cultivars according to different water-temperature year types across the APE in North China. Thus, in this study, we aimed to (1) optimize planting dates and recommend the most suitable cultivar according to different water-temperature year types in the APE of North China; and (2) investigate factors that affect OPP in different water-temperature year types.

2. Materials and Methods

2.1. Study Region, Climate and Soil Data

Twelve agrometeorology experimental sites (AESs) spanning the APE of North China were selected to explore the OPP and suitable cultivar in different water-temperature year types (Figure 1). Climate data including sunshine hours (h), precipitation (mm), daily maximum and minimum daily air temperature (°C) from 1979 to 2019 were obtained from the China Meteorological Administration (http://data.cma.cn, 1 March 2021). Sunshine duration was converted to daily solar radiation using the Angstrom equation with parameters 0.5 for a and 0.25 for b [18,19]. Soil parameters (e.g., soil bulk density, soil organic carbon, soil water pH, drained upper limit, etc.) of each layer were obtained from Han et al. [20], a 10 km resolution global soil profile dataset for crop modeling.

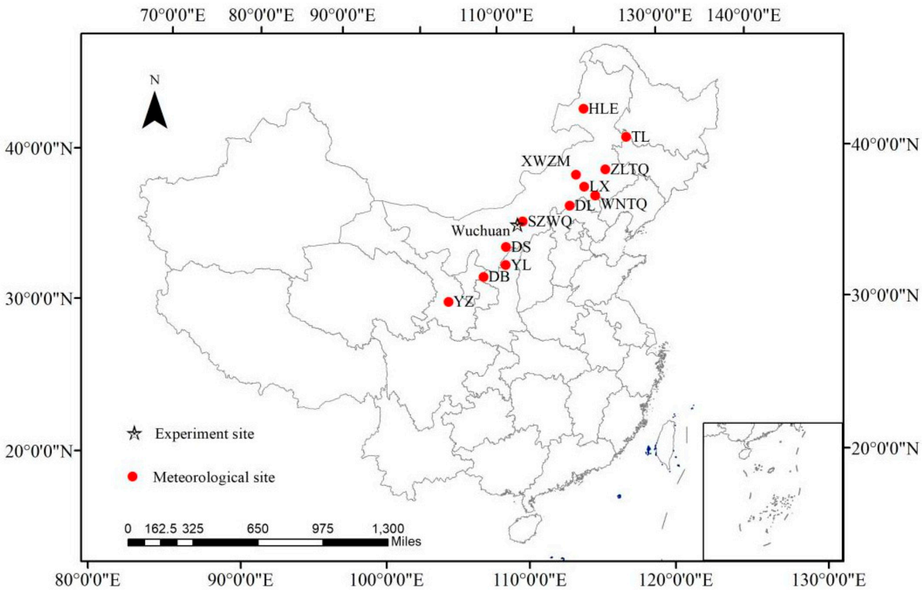

Figure 1. Distribution of experimental site and meteorological sites across the APE in North China. The full name of each meteorological site can be found in Table 1.

Table 1. Study meteorological sites and experiment site.

Site	Latitude (°)	Longitude (°)	Altitude (m)
Dingbian (DB)	37.35	107.35	1360.3
Yulin (YL)	38.16	109.47	1157
Yuzhong (YZ)	35.52	104.09	1874.4
Dongsheng (DS)	39.50	109.59	1461.9
Siziwangqi (SZWQ)	41.32	111.41	1490.1
Duolun (DL)	42.11	116.28	1245.4
Linxi (LX)	43.36	118.04	799.5
Xiwuzhumuqinqi (XWZM)	44.34	117.38	995.9
Wengniuteqi (WNTQ)	42.56	119.01	634.3
Zhaluteqi (ZLTQ)	44.34	120.54	265
Tailai (TL)	46.40	123.45	149.5
Hailaer (HLE)	49.13	119.45	610.2

2.2. Serial Planting Experiments

A series of planting experiments were carried out in 2017 and 2018 in Wuchuan County (111.41° E, 40.49° N, alt. 1756 m), located at the center of the APE in North China (Figure 1). Three different maturing cultivars (fast-developing cultivar Favorita, mid-developing cultivar Connibeck and slow-developing cultivar Kexin_1) were selected to investigate the OPP and most suitable cultivar in different water-temperature year types. The three cultivars have been proven suitable for planting in the APE of North China [11,12]. Potato was planted in 4 × 7 m plots with three replicates on three planting dates (27 April, 15 May, and 2 June in 2017 and 28 April, 16 May, and 3 June in 2018). The row spacing was 50 cm and the planting density was 5 plants m^{-2}. Urea (46% N), 37.5 kg/hm^2 of potassium chloride and 75 kg/hm^2 of ammonium-diammonium phosphate (18% N) were applied at planting as base fertilizers. Thirty millimeters of irrigation was applied at planting to ensure potato emergence. After that, irrigation was not carried out during the whole potato growing season. All experimental information was obtained from published literature [12].

2.3. APSIM-Potato Model

APSIM-potato is a process-based crop model that has been tested and applied in variable climates across the APE in North China [5,21,22]. It can mimic potato water dynamics, phenology and yield [23]. The key APSIM modules used in our study were potato (simulating potato crop growth and development) and manager (specifying planting, harvest, irrigation and fertilizer rules). Daily weather data (maximum and minimum air temperatures, solar radiation and precipitation), soil properties (e.g., organic carbon content, clay content field saturation capacity, soil lower wilting, etc.) and management information (e.g., planting dates, planting depth, fertilizer, etc.) are needed as inputs to the model. APSIM-potato simulates daily potato growth and development in response to environmental conditions and crop management, including phenological stages, leaf area index, soil water, biomass and tuber yield at a daily time step. The potato phenological phase was divided into six phases from planting to maturity in APSIM potato, i.e., planting-germination, germination-emergence, emergence-early tuber, early tuber-senescing, senescing-senesced and senesced-maturity. Potato requires a certain cumulative thermal time to complete each development stage. The daily dry matter accumulation rate is calculated by radiation interception and radiation-use efficiency and multiplied by water and nitrogen stresses. Potato yield is simulated daily based on partitioning and reallocation of total dry matter to plant organs [24]. Potato genetic parameters of photoperiod for emergence (x_pp_emergence, °Cd), thermal time of planting to emergence (y_tt_emergence, °Cd), emergence to early tuber (tt_earlytuber, °Cd), early tuber to senescing phase (tt_senscing, °Cd) and other parameters were received from published documents [12] (Table 2), which have been well tested in the simulation of potato phenology and yield of different planting dates [12]. To better simulate soil water and thus potato yield, parameters of upper limit of stage 1 evaporation (U) and stage 2 evaporation coefficient which related to soil evaporation were increased to 10 and 4.5 versus default values of 6 and 3.5 due to high evaporation in the APE of China [11].

Table 2. Main potato phenology parameters of APSIM-potato.

Parameter	Favorita	Connibeck	Kexin_1
Degree days from planting to emergence (y-tt-emergence, °C d)	265	320	335
Degree days from emergence to early tuber formation (tt-earlytuber, °C d)	185	205	210
Degree days from early tuber formation to senescing (tt-senescing, °C d)	510	590	660
Photoperiod after emergence (x_pp_emergence, h)		12	
Maximum specific leaf area for delta LAI (y_sla_max, $mm^2\ g^{-1}$)		35,000–40,000	

2.4. APSIM Simulation Set up

APSIM 7.10 was used to mimic water-limited potato yield using 41 years (1979–2019) of climate data, and simulations were conducted at 12 locations roughly uniformly distributed across the APE in North China. Planting was simulated at a three-day interval in a potential planting window for three cultivars at each location and each year. The first date of the potential planting window was defined as a five-day running average of daily average temperature higher than 8 °C [4], and the last date was defined when the five-day running average of daily average temperature was lower than 0 °C [11,12]. APSIM was set to harvest when potato matured or when the daily minimum temperature was lower than 0 °C to prevent potato frost events due to the higher risk of frost events in the APE of North China. The OPP of potato was defined by corresponding planting dates exceeding 95% of the peak 15-day running mean water-limited yield in different water-temperature year types at each site.

The crop received 30 mm of irrigation at planting to ensure that it would emerge shortly after it was sown. After that, no irrigation was applied throughout the growth period. APSIM-potato was simulated continuously from 1979 to 2019 with the soil parameters (soil water, soil nitrogen and organic matter, etc.) at the end of last year not resetting, which is more realistic. To avoid nitrogen stress, nitrogen was applied as NO_3^- using a separate fertilizer rule, which was maintained above 300 kg/hm^2 in the top three layers of the soil throughout the whole potato growing season [24].

2.5. Data Processing

2.5.1. Divide Historical Years into Different Water-Temperature Year Types

Forty-one years were divided into different water-temperature year types (dry-cool, dry-hot, wet-cool and wet-hot years) according to the average temperature and the amount of precipitation during the potato growth period in each location. Different water-temperature year types were divided by the following rules (1):

$$\begin{array}{c}\text{Wet-Hot year: Pre\_s} > \text{Pre\_a \& Tav\_s} > \text{Tav\_a}\\ \text{Wet-Cool year: Pre\_s} > \text{Pre\_a \& Tav\_s} < \text{Tav\_a}\\ \text{Dry-Hot year: Pre\_s} < \text{Pre\_a \& Tav\_s} > \text{Tav\_a}\\ \text{Dry-Cool year: Pre\_s} < \text{Pre\_a \& Tav\_s} < \text{Tav\_a}\end{array} \quad (1)$$

where Pre_s is the total precipitation during the potato growing season in a specific year, Pre_a is the average value of Pre_s from historical years, Tav_s is the mean temperature during the potato growth season in a specific year and Tav_a is the average value of Tav_s from historical years.

2.5.2. Statistical Analysis

Linear regression was conducted to test the relationship of potato yield and water and temperature stresses. All statistical analyses and data processing were carried out using the R programming language [25].

The coefficient of variance (CV) was used to represent the year-to-year variation in precipitation in each month:

$$CV = S/X \quad (2)$$

where S is the standard variation for precipitation and X is the mean value of precipitation.

3. Results

3.1. Precipitation Distribution in the APE of North China

The annual precipitation of different months in the potato growing season varied significantly. DL had the lowest CV of 0.43 in June, and LX had the highest CV of 1.29 in October (Table S1). Figure 2 shows an example of the precipitation distribution in different water-temperature year types. The distribution and amount of precipitation varied in water-temperature year types. The variation in precipitation distribution in dry-cool and dry-hot years was relatively lower than that in wet-cool and wet-hot years. The other sites of APE also showed similar features (data not shown).

3.2. Water and Temperature Stresses

The linear regression results showed that water stress in the tuber formation stage explained the most variation in potato yield (Table S2); however, temperature only had a minor effect on potato yield (Table S2, Figure 3). The average water stress in the potato tuber formation stage of different planting dates was lower than 0.2 in dry-hot years and dry-cool years; in contrast, the water stress was lower than 0.3 for most planting dates in wet-hot years and wet-cool years (Figure 3). The average yields in dry-cool and dry-hot years were less than those in cold-wet and warm-wet years. Generally, potato yield increased or decreased with increased or decreased water stress in the tuber formation stage. However, in dry-cool years, potato yield decreased with decreasing water stress when potato was planted after 15 June.

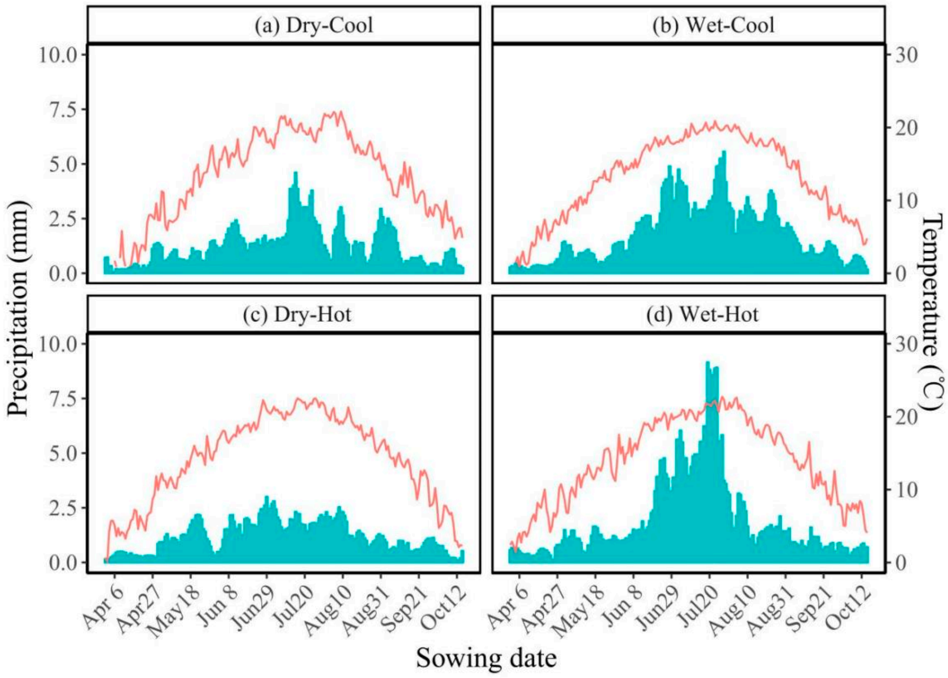

Figure 2. An example of precipitation and temperature distribution during the potato growing season in different water-temperature year types at XWZM of the APE in North China. (**a**–**d**) represent the dry-cool year, wet-cool year, dry-hot year and wet-hot year, respectively.

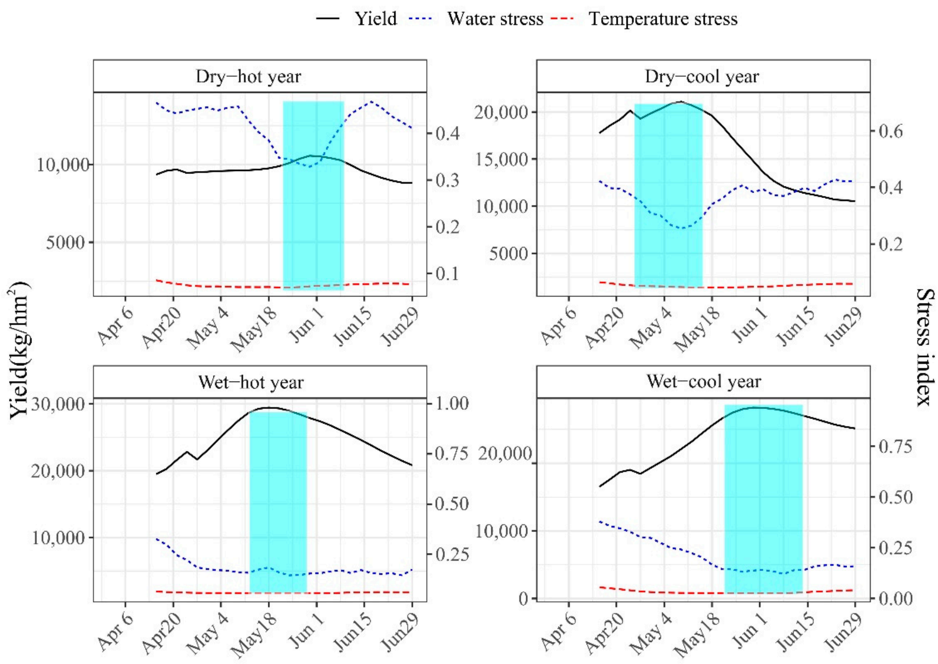

Figure 3. Example of the relationship between average simulated water-limited yield and planting dates for a rapidly developing cultivar (Favorita) in different water-temperature year types at ZLTQ. The blue dashed line indicates the average water stress during the early tuber phase, the red dashed line shows the average temperature stress in the potato growing season, and the cyan rectangle zone represents the optimal planting period at which yield >95% of the running peak mean yield in different water-temperature year types.

3.3. Potato Yield Variation

Potato yield varied in four water-temperature year types across the APE of North China (Figures 4 and S1–S3). The highest yield was achieved by Favorita at TL in the wet-hot year, with an average yield of 31,196 kg/hm^2. The lowest yield was obtained by Favorita at SZWQ in the dry-hot year, with an average yield of 1882 kg/hm^2 (Tables S3–S5). Favorita could obtain the highest yield in most locations across the APE in North China in different water-temperature year types. In the dry-cool year, the greatest yield was obtained by the mid-developing cultivar Favorita at DS for planting on 27 June, with an average yield of 21,293 kg/hm^2. In the dry-hot year, the highest yield was obtained by the rapidly developing cultivar Favorita at TL for planting on 2 May, with an average yield of 17,903 kg/hm^2 (Figures 4 and S1). In the wet-hot year, the highest yield was obtained by Favorita at TL for planting on May 17, with an average yield of 31,196 kg/hm^2. In the wet-cool year, the greatest yield was received by Favorita at TL for planting on 29 May, with an average yield of 31,145 kg/hm^2 (Figures S2 and S3). Potato yield varied across the APE of North China in each type of water-temperature year; however, the trend of potato yields of different cultivars was highly similar. Adjusting the planting date can increase potato yield in each type of water-temperature year; however, in low-yield environments such as SZWQ, potato yield is still very low after the planting date is optimized.

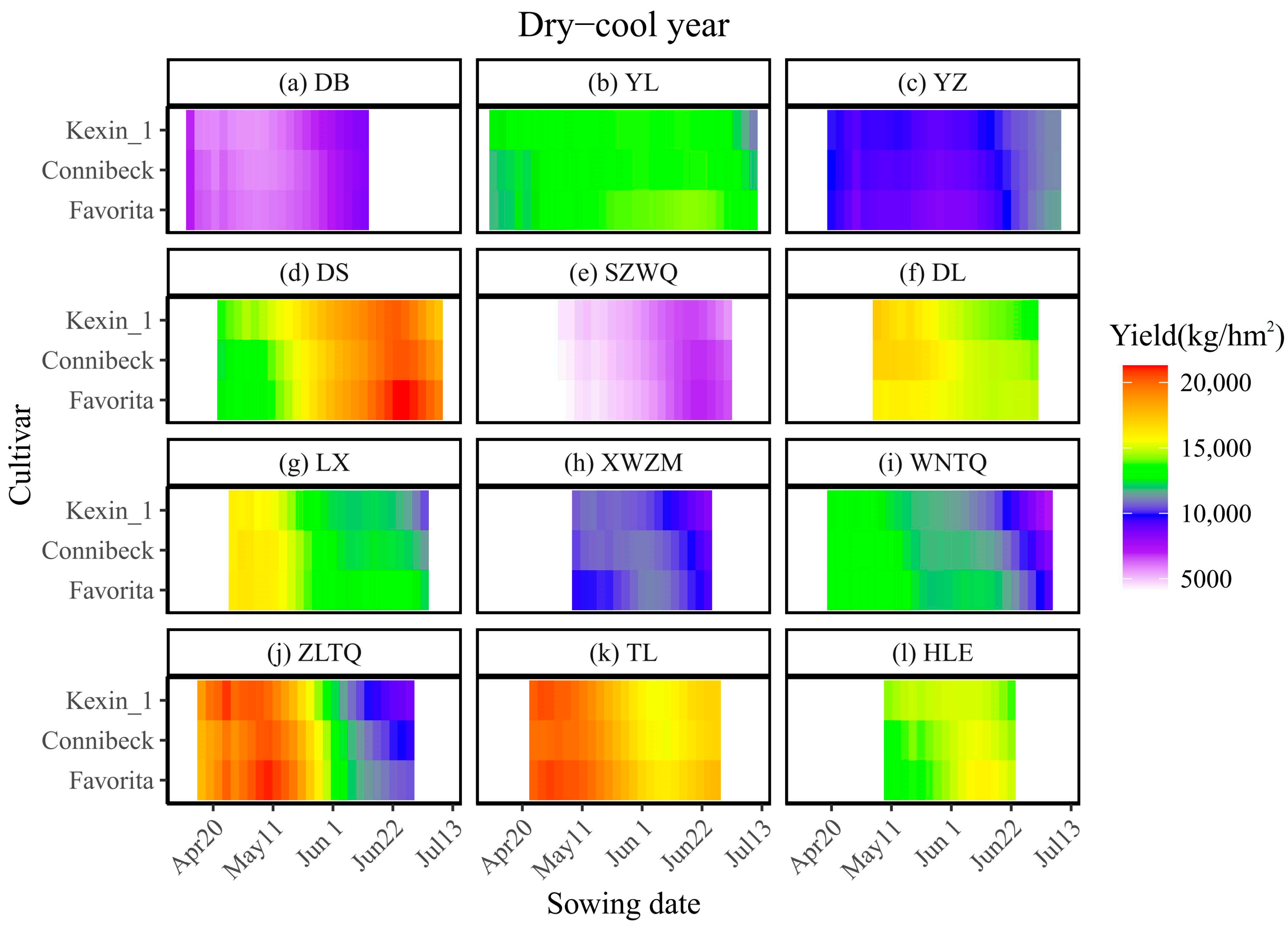

Figure 4. Yield variations across the APE of North China with regard to cultivars and planting dates in dry-cool years. Different horizontal bands represent different cultivars. (**a**–**l**) refers to different meteorological stations in the APE of North China.

3.4. OPP Variation

The start date of OPP of potato and its duration varied across different water-temperature year types and APE in North China (Figure 5). However, the OPP of different maturing cultivars at each site of APE were similar. The earliest start date of OPP was 9 April, and the latest start date of OPP was 11 July. Both were achieved by Kexin_1 at YL in a dry-cool year (Table S4). The longest duration of OPP was 61 days achieved by the mid-developing cultivar Connibeck at YL in a dry-cool year. The shortest duration of OPP was 4 days, achieved by Favorita and Connibeck at YZ, DB and YL in dry-hot, dry-cool and wet-hot years, respectively (Tables S5 and S6). The average duration of OPP in APE for cultivar Favorita, Connibeck and Kexin_1 are 20.25, 22.25, 21.5 days, respectively, in dry-cool years, 22.25, 21.25, 22.25 days, respectively, in dry-hot years, 23, 25, 26 days, respectively, in wet-hot years and 19, 20, 22 days, respectively, in wet-cool years. Compared to wet-hot and wet-cool years, the distribution of the start date and duration of OPP are more variable in dry-hot and dry-cool years (Figure 5).

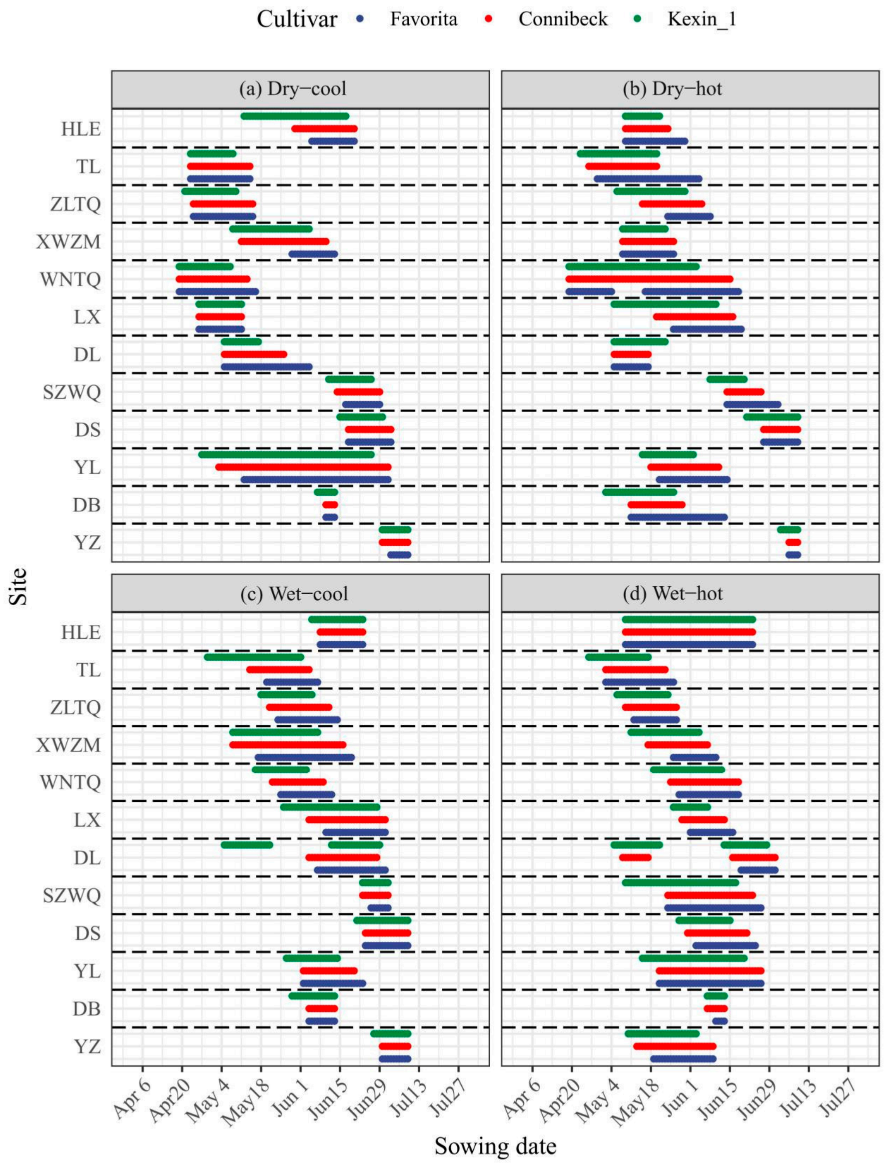

Figure 5. OPP of three mature cultivars in different water-temperature year types across the APE of North China. Different horizontal bands represent different meteorological stations of the APE in North China. (**a**–**d**) refers to four different year types. Different colors represent different cultivars: blue line for cultivar Favorita, red line for cultivar Connibeck and green line for cultivar Kexin_1.

4. Discussion

4.1. Significance of Dividing Water-Temperature Year Type

The variance in annual precipitation during the potato growth period is very high in the APE of North China. The highest precipitation was 525 mm, while the lowest rainfall was 161 mm, and the coefficient of variation (CV) was 25% [4]. The CV of annual precipitation of different months in the potato growing season also varied significantly (Table S1). To adapt to the highly local variability of precipitation and increase potato yield, Li et al. [12] suggested stabilizing yield by selecting a late planting coupled with mid- and slow-developing cultivars, which is a simple and effective method. The difference with his research is that we advocate changing agricultural management measures to cope with variable climate according to annual precipitation patterns. Therefore, we simulated the potato yield of three different maturing cultivars by using the APSIM-potato model, and divided the historical years (1979–2019) into different water-temperature year types (dry-hot, dry-cool, wet-hot and wet-cool years) across the APE in North China, which is a new attempt to adapt the variability of precipitation distribution in the APE of North China. The results showed that the potato yield and OPP varied in different water-temperature year types across the APE (Figure 2).

The difference in OPP in different seasons indicated the necessity of year-type division. The linear regression results indicated that water stress during the tuber formation stage of potatoes played a dominant role in determining potato yield, while temperature had little effect on yield (Table S2). However, we also found that different water-temperature year types had different precipitation patterns, which means that adding temperature in years dividing provides a method to classify the distribution of precipitation in detail. In actual production and field management, farmers should be told the water-temperature year type in that season by their local Agrometeorological Service, and plant potato at OPP as far as possible and select the most suitable cultivar. This calls for more accurate prediction of future climate [26]. The accuracy of current short-term climate prediction is approximately 70% [27,28], which still cannot fully meet the requirements of agricultural production [29]. Therefore, the identification of OPP will play a more important guiding role in future agricultural production with the improvement of the accuracy of short period and mid-long period climate prediction [7].

4.2. Potato Yield Variation across APE

The APE of North China is a typical arid agricultural area. Many studies have shown that there is a strong correlation between crop yield and precipitation during the growth period under dry land farming [30–33]. However, recent studies have shown that precipitation distribution during crop growth periods has a greater effect on yield [34,35]. The potato tuber formation stage is a critical stage for potato yield and is highly sensitive to water stress [36,37]. A previous study had already shown that there is a good correlation between water conditions in the tuber formation stage and yield in the APE of North China [5]. Our results also showed that the variation in potato yield in different water-temperature year types across the APE in North China is mainly determined by the difference in water stress in the tuber formation stage due to the varied amount and distribution of precipitation. Thus, adjusting the planting date and selecting a suitable cultivar to improve the water condition in the potato tuber formation stage can significantly increase potato yields in the APE of North China (Figures 4 and S1–S3).

Irrigation could significantly increase potato yield in arid and semiarid environments. In recent years, however, the groundwater level in this region has decreased by approximately 0.5–1 m per year to meet the irrigation demand of crops in the APE of North China [38,39] and has induced serious problems of soil salinization and groundwater depletion [40]. In addition to irrigation, plastic film mulching can effectively improve potato yield by reducing soil moisture emissions [41] and increasing soil water storage [42–44]. However, excessive application of plastic film mulching aggravates environmental pollution [45–47]. Adjusting planting dates and selecting suitable cultivars are the simplest and most efficient measures that farmers can choose [48] and impose little pressure on water resources, which is of great significance for ensuring regional food security and sustainable agricultural development. Potato yield can be significantly improved by using an adjusted planting period in different year types. However, other management measures, such as tillage, were not considered in our study, which can also improve potato water productivity and yield [49]. Moreover, in dry-hot and dry-cool years, such as SZWQ, potato yield was still lower than that in wet-hot and wet-cool years after adjusting the planting date and cultivar due to low precipitation (Figures 4 and 5). Tang et al. [10] proposed an effective management strategy to collect rainfall and carry out supplementary irrigation at an appropriate time. Further research should be carried out to study the OPP of potato in combination with supplementary irrigation and cultivar.

4.3. Variation in OPP

Potato yield is closely related to precipitation in the APE of North China, and the starting time of the OPP depends on the starting time of the rainy season [10]. Adjusting the planting date can match the critical water demand stage of potato with the rainy season, thus obtaining sufficient rainfall and minimizing water stress [9]. Our study found that the amount and distribution of precipitation varied in different water-temperature year types (Figure 2), which led to different water conditions in the tuber formation stage corresponding to planting dates and thus resulted in the variance of OPP of potato (Figures 3 and 5). The OPP of different maturing cultivars were very similar; however, the OPP in different water-temperature year types were highly different. Thus, we suggest selecting planting dates according to the water-temperature year type to adapt to various distributions of precipitation.

The duration of OPP represented the variation of the water condition in the tuber formation period of different planting dates. The longer duration of OPP indicates that the variation in rainfall was lower, which resulted in similar water conditions in the tuber formation stages of different planting dates, e.g., YL in dry-cool year and WNTQ in dry-hot year. The shorter OPP indicates that rainfall was concentrated at a certain period, which means that the water stress of the tuber formation stage varies greatly with different planting dates. We further analyzed factors influencing OPP and yield in different water-temperature year types (Figure 3). The OPP of different water-temperature year types varied greatly from April to June, mainly affected by the water stress of the tuber formation stage of different planting dates. However, the yield would be reduced due to the shortening of the growth period when the potato sown too late, especially when a cultivar with a long growth cycle was sown too late (Figure 3). This also explained why the yield of Favorita was slightly higher than that of the other cultivars with a longer growing period.

Li et al. [12] suggested that late planting coupled with fast developing cultivar Favorita was recommended along an 'N-S' transect in North China, while late planting coupled with slow developing cultivar Kexin_1 was recommended along a 'W-E' transect in North China. However, our study found that Favorita can obtain the highest yield in most places of the APE in North China. This is because Favorita can reduce the risk of encountering frost events when planting late due to the relatively short growing period compared to the other two cultivars. Moreover, the duration of the tuber formation stage of Favorita was lower than that of the other two cultivars, which means that Favorita can easily find suitable planting dates with lower water stress in the tuber formation stage (Table 2).

4.4. Uncertainties and Limitations

In this study, we suggest selecting OPP and cultivars according to the water-temperature year type, which responds to the variable distribution of precipitation with changing management practices. However, it is difficult to predict the distribution of precipitation even when the approximate precipitation is known. Therefore, those places in the water-temperature year type with a shorter duration OPP indicate that the distribution of precipitation is relatively similar with historical years, while those places with a longer duration OPP mean that the distribution of precipitation in historical years is more variable, and planting date should be selected carefully in this case. Additionally, readers should note the following limitations in our study. We only considered the impacts of climate factors on potato yield; however, other environmental factors, such as disease, insects and pests, can also impact potato yield and planting date [50,51]. In addition, adjusting planting density, conservation tillage and other agronomic management practices were not considered [12,52], which also have a great impact on planting date and cultivar selection. These influencing factors need to be further investigated in the future. Additionally, to calibrate crop model and further validate our result, more field experiments should be carried out at other sites of the APE in North China in the future.

5. Conclusions

Potato yield and OPP varied in different water-temperature year types; however, the OPP showed little difference between different maturing cultivars. Generally, Favorita obtained the highest yield in different water-temperature year types at most places in the APE of North China. The yield and OPP of potato in different water-temperature year types were mainly affected by water stress in the tuber formation stage due to the varied distribution and amount of precipitation in different water-temperature year types. Compared with unaltered management, increasing yield is recommended by selecting OPP and suitable cultivars according to the water-temperature year type. This study offered a new method to cope with the highly variable climate in the APE of North China, which can help farmers make decisions when climate prediction precision is improved in the future. However, we only considered the impact of climate factors on OPP of potato, but other factors (disease and pests, planting density, conservation tillage, etc.) also have a great effect on OPP and cultivar selection of potato. These factors need to be further explored and more field experiments need to be performed at other sites of the APE in North China in the future.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agriculture11111061/s1, Table S1: Coefficient variation (CV) of year-to-year precipitation in different months of the potato growing season. Table S2: Linear regression between the stress index in the tuber formation stage and potato yield. Table S3: An example of OSP for cultivar Favorita in different water-temperature year types across APE of North China. DOSP represent the duration of OSP. Table S4: An example of OSP for cultivar Connibeck in different water-temperature year types across APE of North China. DOSP represent the duration of OSP. Table S5: An example of OSP for cultivar Kexin_1 in different water-temperature year types across APE of North China. DOSP represent the duration of OSP. Figure S1: Yield variations across APE of North China with regard to cultivars and sowing dates in dry-hot years. Figure S2: Yield variations across APE of North China with regard to cultivars and sowing dates in wet-hot years. Figure S3: Yield variations across APE of North China with regard to cultivars and sowing dates in wet-cool year.

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References

1. Lu, X.P. Strategy of potato staple food: Significance, bottlenecks and policy suggestions. *J. Huazhong Agric. Univ.* **2015**, *103*, 1–7.
2. Hijmans, R.J. The effect of climate change on global potato production. *Am. Potato J.* **2003**, *80*, 271–279. [CrossRef]
3. Rykaczewska, K. The Effect of High Temperature Occurring in Subsequent Stages of Plant Development on Potato Yield and Tuber Physiological Defects. *Am. Potato J.* **2015**, *92*, 339–349. [CrossRef]
4. Tang, J.Z.; Wang, J.; He, D.; Huang, M.X.; Pan, Z.H.; Pan, X.B. Comparison of the impacts of climate change on potential productivity of different staple crops in the agro-pastoral ecotone of North China. *J. Meteorol. Res.* **2016**, *30*, 983–997. [CrossRef]
5. Tang, J.Z.; Wang, J.; Fang, Q.X.; Wang, E.L.; Yin, H.; Pan, X.B. Optimizing planting date and supplemental irrigation for potato across the agro-pastoral ecotone in North China. *Eur. J. Agron.* **2018**, *98*, 82–94. [CrossRef]
6. Xia, Z.C.; Pan, Z.H.; Zhang, L.Y.; Zhou, M.M.; Pan, X.B.; Tuo, D.B.; Zhao, P.Y. Examining Mechanisms of Vegetation Ecosystems Degradation Based on Water in Northern Farming-pastoral Zone. *Res. Sci.* **2010**, *32*, 317–322.
7. Li, Y.; Wang, J.; Tang, J.Z.; Ma, X.Q.; Pan, X.B. Selecting planting date and cultivar for high yield and water use efficiency of potato across the agro-pastoral ecotone in North China. *Trans. CSAE* **2020**, *36*, 118–126.
8. Yu, T.T.; Wang, F.X. Planting of different potato cultivars adapted to water availability in Inner Mongolia. *Chin. Agric. Sci. Bull.* **2015**, *31*, 70–77.
9. Liu, K.; Harrison, M.T.; Hunt, J.; Angessa, T.T.; Meinke, H.; Li, C.D.; Tian, X.H.; Zhou, M.X. Identifying optimal planting and flowering periods for barley in Australia: A modelling approach. *Agric. For. Meteorol.* **2019**, *282*, 107871.
10. Hu, Q.; Yang, N.; Pan, F.F.; Pan, X.B.; Wang, X.X.; Yang, P.Y. Adjusting planting Dates Improved Potato Adaptation to Climate Change in Semiarid Region, China. *Sustainability* **2017**, *9*, 615. [CrossRef]
11. Tang, J.Z.; Wang, J.; Wang, E.L.; Yu, Q.; Yin, H.; He, D.; Pan, X.B. Identifying key meteorological factors to yield variation of potato and the optimal planting date in the agro-pastoral ecotone in North China. *Agric. For. Meteorol.* **2018**, *256–257*, 283–291. [CrossRef]
12. Li, Y.; Wang, J.; Tang, J.Z.; Wang, E.L.; Pan, Z.H.; Pan, X.B.; Hu, Q. Optimum planting date and cultivar maturity to optimize potato yield and yield stability in North China. *Field Crop. Res.* **2021**, *269*, 108179. [CrossRef]
13. Singh, R.; Kroes, J.G.; Van Dam, J.C.; Feddes, R.A. Distributed ecohydrological modelling to evaluate the performance of irrigation system in Sirsa district, India: I. Current water management and its productivity. *J. Hydrol.* **2006**, *329*, 692–713. [CrossRef]
14. Padovan, G.; Martre, P.; Semenov, M.A.; Masoni, A.; Bregaglio, S.; Ventrella, D.; Lorite, I.J.; Santos, C.; Bindi, M.; Ferrise, R.; et al. Understanding effects of genotype × environment × planting window interactions for durum wheat in the Mediterranean basin. *Field Crop. Res.* **2020**, 259.
15. Flohr, B.M.; Hunt, J.R.; Kirkegaard, J.A.; Evans, J.R. Water and temperature stress define the optimal flowering period for wheat in southern-eastern Australia. *Field Crop. Res.* **2017**, *209*, 108–119. [CrossRef]
16. Lilley, J.M.; Flohr, B.M.; Whish, J.P.; Farre, I.; Kirkegaard, J.A. Defining optimal planting and flowering periods for canola in Australia. *Field Crop. Res.* **2019**, *235*, 118–128. [CrossRef]
17. Chen, C.; Fletcher, A.L.; Ota, N.; Flohr, B.M.; Lilley, J.M.; Lawes, R.A. Spatial patterns of estimated optimal flowering period of wheat across the southwest of Western Australia. *Field Crop. Res.* **2020**, *247*, 107710. [CrossRef]
18. Black, J.N.; Bonython, C.W.; Prescott, J.A. Solar radiation and the duration of sunshine. *Q. J. R. Meteorol. Soc.* **1954**, *80*, 231–235. [CrossRef]
19. Jones, H.G. *Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology*, 2nd ed.; Cambridge University Press: Cambridge, UK, 1992.
20. Han, E.J.; Ines, A.V.; Koo, J. Development of a 10-km resolution global soil profile dataset for crop modeling applications. *Environ. Model. Softw.* **2019**, *119*, 70–83. [CrossRef]
21. Shen, J.J. *Study on Optimalization of Planting Date and Climate Suitability of Main Crops in Agro-Pastoral Ecotone*; China Agricultural University: Pekin, China, 2011.
22. Tang, J.Z. *A Study on Planting Pattern of Potato to Narrow Yield Gap and Increase Precipitation Use Efficiency in the Agro-Pastoral Ecotone*; Agriculture University: Beijing, China, 2019.
23. Chen, R.Y.; Meng, M.L.; Liang, H.Q.; Zhang, J.; Wang, Y.H.; Wang, Z.X. Effects of different treatments of irrigation and fertilization on the yield and nitrogen utilization characteristic of potato. *Chin. Agric. Sci. Bull.* **2012**, *28*, 196–201.
24. Brown, H.E.; Huth, N.; Holzworth, D. A potato model built using the APSIM plant. NET Framework. In Proceedings of the 19th International Congress on Modeling and Simulation, Perth, WA, Australia, 12–16 December 2011; pp. 961–967.
25. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2016. Available online: https://www.R-project.org/ (accessed on 1 April 2021).
26. Hansen, J.W.; Challinor, A.; Ines, A.; Wheeler, T.; Moron, V. Translating climate forecasts into agricultural terms: Advances and challenges. *Clim. Res.* **2006**, *33*, 27–41. [CrossRef]
27. Jones, J.W.; Hansen, J.W.; Royce, F.S.; Messina, C.D. Potential benefits of climate forecasting to agriculture. *Agric. Ecosyst. Environ.* **2000**, *82*, 169–184. [CrossRef]

28. Zhao, J.H.; Yang, J.; Gong, Z.Q.; Feng, G.L. Analysis of and discussion about dynamic-statistical climate prediction for summer rainfall of 2013 in China. *Adv. Meteorol. Sci. Technol.* **2015**, *5*, 24–28.
29. Fraisse, C.W.; Breuer, N.E.; Zierden, D.; Bellow, J.G.; Paz, J.; Cabrera, V.E.; Garcia, A.G.Y.; Ingram, K.T.; Hatch, U.; Hoogenboom, G. AgClimate: A climate forecast information system for agricultural risk management in the southeastern USA. *Comput. Electron. Agr.* **2006**, *53*, 13–27. [CrossRef]
30. Rockström, J.; Falkenmark, M. Semiarid crop production from a hydrological perspective: Gap between potential and actual yields. *Crit. Rev. Plant. Sci.* **2000**, *19*, 319–346. [CrossRef]
31. Condon, A.G.; Richards, R.A.; Rebetzke, G.J. Breeding for high water-use efficiency. *J. Exp. Bot.* **2004**, *55*, 2447–2460. [CrossRef] [PubMed]
32. Martone, L.; Pilar, P.M.; Grewal, M.S. Long term studies of crop yields with changing rainfall and fertilization. *Agric. Eng. Res.* **2007**, *13*, 37–47.
33. Harms, T.E.; Konscheuh, M.N. Water savings in irrigated potato production by varying hill-furrow or bed-furrow configuration. *Agric. Water Manag.* **2010**, *97*, 1399–1404. [CrossRef]
34. Rockström, J.; Karlberg, L.; Wani, S.P.; Barron, J.; Hatibu, N.; Oweis, T.; Bruggeman, A.; Farahani, J.; Qiang, Z. Managing water in rainfed agriculture: The need for a paradigm shift. *Agric. Water Manag.* **2010**, *97*, 543–550. [CrossRef]
35. Yu, Q.; Li, L.H.; Luo, Q.Y.; Eamus, D.; Xu, S.H.; Chen, C.; Wang, E.L.; Liu, J.D.; Nielsen, D.C. Year patterns of climate impact on wheat yields. *Int. J. Climatol.* **2014**, *34*, 518–528. [CrossRef]
36. Lynch, D.R.; Foroud, N.; Kozub, G.C.; Fames, B.C. The effect of moisture stress at three growth stages on the yield, components of yield and processing quality of eight potato varieties. *Am. Potato J.* **1995**, *72*, 375–386. [CrossRef]
37. Ren, W.J.; Ren, L.; Liu, S.X. Moisture dynamics and supply and demand on potato fields inarid areas of southern Loess Plateau. *Chin. Potato J.* **2015**, *29*, 355–361.
38. Li, D.; Qian, L.H. The estimation of variation of groundwater table in the Inner Mongolia in 2015. *Inn. Mong. Water Res.* **2016**, *5*, 3–5.
39. Zhu, J.L.; Liang, X.J.; Wang, Y.N. Research on the evaluation of groundwater resources in the districts of saving water and increasing grain yield in Jalaid Banner of Inner Mongolia. *China Water Res.* **2014**, *11*, 28–30.
40. Zhang, J.; Zhao, P.Y.; Pan, Z.H.; Duan, Y.; Li, H.C.; Wang, B.; Jing, Y.P.; Dong, Z.Q. Determination of input threshold of nitrogen, fertilizer based on environment-friendly agriculture and maize yield. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 136–143.
41. Gao, S.M.; Zhang, X.C.; Wang, Y.H. Influence of Different Mulching and Furrow-Ridge Planting Motheds on Soil Moisture and Yield of Potato on Dryland. *J. Soil Water Conserv.* **2010**, *24*, 249–251.
42. Hou, X.Q.; Tang, J.; Yu, L.L.; Zhao, F.P.; Wang, Q.W.; Hu, E.J.; Wei, K.R. Effect of autumn mulching tillage on growth and water use efficiency of potato. *J. Drain. Irrig. Mach. Eng.* **2016**, *34*, 165–172.
43. Li, R.; Wang, Y.L.; Wu, P.N.; Sun, R.P.; Qiu, J.X.; Su, M.; Hou, X.Q. Ridge and furrow mulching improving soil water-temperature condition and increasing potato yield in dry-farming areas of south Ningxia. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 168–175.
44. Fan, S.J.; Wang, D.; Zhang, J.L.; Bai, J.P.; Liu, W.X.; Ma, Z.X.; Peng, H.Y. Effects of different cultivation techniques on soil temperature, moisture and potato yield. *Trans. CSAE* **2011**, *27*, 216–221.
45. Liu, E.K.; He, W.Q.; Yan, C.R. 'White revolution' to 'white pollution'—Agricultural plastic film mulch in China. *Environ. Res. Lett.* **2014**, *9*, 091001. [CrossRef]
46. Zhang, D.; Liu, H.B.; Hu, W.L.; Qin, X.H.; Ma, X.W.; Yan, C.R.; Wang, H.Y. The status and distribution characteristics of residual mulching film in Xinjiang. *China J. Integr. Agric.* **2016**, *15*, 2639–2646. [CrossRef]
47. Jiang, R.; Guo, S.; Ma, D.D. Plastic film mulching system and the impact on soil ecological environment in rain-fed drylands of China. *Chin. J. Eco Agric.* **2018**, *26*, 317–328.
48. Zhang, Y.; Zhang, L.Z.; Yang, N.; Huth, N.; Wang, E.L.; Werf, W.V.D.; Evers, J.B.; Wang, Q.; Zhang, D.S.; Wang, R.N.; et al. Optimized planting time windows mitigate climate risks for oats production under cool semi-arid growing conditions. *Agric. For. Meteorol.* **2019**, *266–267*, 184–197. [CrossRef]
49. Hou, X.Q.; Li, R. Effects of mulching with no-tillage on soil physical properties and potato yield in mountain area of southern Ningxia. *Trans. CSAE* **2015**, *31*, 112–119.
50. Sparks, A.H.; Forbes, G.A.; Hijmans, R.J.; Garrett, K.A. Climate change may have limited effect on global risk of potato late blight. *Glob. Chang. Biol.* **2014**, *20*, 3621–3631. [CrossRef] [PubMed]
51. Chandel, R.S.; Pathania, M.; Verma, K.S.; Bhatacharyya, B.; Vashisth, S.; Kumar, V. The ecology and control of potato whitegrubs of India. *Potato Res.* **2015**, *58*, 147–164. [CrossRef]
52. Carter, M.R.; Sanderson, J.B. Influence of conservation tillage and rotation length on potato productivity, tuber disease and soil quality parameters on a fine sandy loam in eastern Canada. *Soil. Tillage Res.* **2001**, *63*, 1–13. [CrossRef]