Agricultural and Forest Meteorology 256–257 (2018) 283–291

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Original Article

Identifying key meteorological factors to yield variation of potato and the optimal planting date in the agro-pastoral ecotone in North China

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ARTICLE INFO

Keywords:
Dryland agriculture
Effective precipitation
Potential evapotranspiration
Optimal planting date

ABSTRACT

Precipitation is the key yield–determining factor for rainfed agricultural production such as the agro-pastoral ecotone in North China with high variation in precipitation. However, the yield–precipitation relationship depends on the distribution and amount of precipitation over the crop growth period. Understanding crop yield responses to precipitation can help develop appropriate measures to ensure stable crop production in the agro-pastoral ecotone. In this study, an experiment was conducted consisting of five planting dates each year across four years and three planting dates in one year, to investigate the potato yield response to precipitation at a representative site (Wuchuan) in the ecotone. The optimal planting date, with the highest potato yield, varied substantially in different years during the experimental period. It was found that potato yield had the highest correlation with the ratio of precipitation to potential evapotranspiration during the tuberization stage (P_T/ET_{pT}) ($R^2 = 0.51$, $P < 0.01$), followed by the effective precipitation during the post-tuber bulking period (EP_{poTB}) ($R^2 = 0.43$, $P < 0.01$) and during the entire growth period (EP_{gp}) ($R^2 = 0.28$, $P < 0.05$). The potato yield was positively related to total solar radiation during the growth period (S_{gp}) ($R^2 = 0.37$, $P < 0.01$), especially during the pre-tuber bulking period (S_{prTB}) ($R^2 = 0.44$, $P < 0.01$), while growth-period maximum temperature (T_{maxgp}) had a negative effect on potato yield ($R^2 = 0.27$, $P < 0.05$). The multiple linear regression equation of potato yield and meteorological factors during the potato growth period showed that the variation in P_T/ET_{pT}, EP_{poTB} and S_{prTB} could explain 71% of the variation in potato yield. The optimal planting dates, based on the 80 t h percentile of the highest yield related to P_T/ET_{pT}, EP_{poTB} and S_{prTB} within the potential planting window from 1961 to 2010, were found to be May 27–June 12 for a wet year, May 3–May 26 for a normal year, and April 4–May 2 for a dry year, if sufficient soil moisture could ensure emergence of potato.

1. Introduction

Water shortage, characterized by low and highly variable amounts of precipitation, is a major limiting factor for crop production in dryland agriculture (Potgieter et al., 2002; Boyer and Westgate, 2004; Cabello et al., 2012). Unsurprisingly, in many dryland regions there is a good correlation between growing-season total precipitation and crop yield (Epstein and Grant, 1973; Benoit and Grant, 1985; Rockström and Falkenmark, 2000; Condon et al., 2004; Martone et al., 2007). However, this may not be the case in dryland regions where the crop yield is determined by the effectiveness and distribution of precipitation during the growing season, rather than the total amount (Hane and Pumphrey, 1984; Keating and McCown, 2001; Rockström et al., 2009; Saue and Kadaja, 2009; Stewart and Peterson, 2015). In such regions, frequent smaller precipitation events are less efficient for crops because water can evaporate from the soil or crop surface before infiltrating into soil (Wang et al., 2005). In addition, the precipitation distribution can have a greater impact on crop yield than the amount of precipitation when water shortage occurred during critical growth stages (Deblonde and Ledent, 2001; Qin et al., 2013).

Crop yields are sensitive to the variation in precipitation in the agro-pastoral ecotone (APE) of North China, where the annual average precipitation amount is low (less than 400 mm), but highly variable (Wang et al., 1999; Xia et al., 2010; Tang et al., 2016). Potato (*Solanum tuberosum* L.) is one of the region's staple crops, accounting for 46.8% of total crop dry matter yield in this area and its sown area has been

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https://doi.org/10.1016/j.agrformet.2018.03.022
Received 5 September 2017; Received in revised form 18 March 2018; Accepted 25 March 2018
0168-1923/

increasing in recent years due to suitable temperature conditions for potato growth (Hijmans, 2003; Xia et al., 2010; Rykaczewska, 2015). However, water shortages frequently threaten potato production because annual and growing-season precipitation often does not meet the water requirements (450–500 mm) for potato growth (Wu et al., 2009; Yang et al., 2010; Xie et al., 2012). Song and Hou (2003) revealed that potato yield increased with the increase in total growing season precipitation, however contrasting results found by Yuan et al. (2013) suggested the importance of effective precipitation on potato yield. More efficient use of precipitation and higher potato yields could be achieved by matching the precipitation distribution with the water requirements for potato growth. However, this requires an understanding of the relationship between potato yield and precipitation in terms of the amount and distribution, which has rarely been investigated in the APE. Serial planting experiments are used widely to analyze the impact of meteorological factors on crop growth and development and to determine optimal planting dates (d'Orgeval et al., 2010; Sadras et al., 2015; Wang et al., 2015a). However, no previous study analyzing systematically the relationship between meteorological factors and potato yield has been carried out in our study region.

The objectives of the present study were to: 1) test the hypothesis that growing-season precipitation determines potato yield; 2) identify the determining factor(s) for the variation in potato yield, based on serial planting experiments; and 3) recommend optimal planting dates for potato in different year types (in terms of precipitation, i.e., wet, dry, normal) in the APE of North China.

2. Materials and methods

2.1. Study site, climate and soil data

Field experiments were conducted at the Scientific and Observation Experimental Station of Agro-environment in Wuchuan County (41°06′N, 111°28′E, altitude 1756 m), located at the center of the APE in North China during 2009–2012, and 2014. Wuchuan is characterized by a typical continental climate with abundant solar radiation, warm summers and cold winters. The annual total solar radiation and average temperature were 5923 MJ m^{-2} and 3.47 °C (1961–2010), respectively. Annual average precipitation and crop growing-season precipitation (April–September) were 344 mm and 302 mm, with coefficients of variation (CVs) of 23% and 25%, respectively. The soil type is kastanozems with a loam texture and detailed soil information is shown in Table 1.

Climate data, including daily maximum temperature (°C), minimum temperature (°C), precipitation (mm) and sunshine hours (h), from 1961 to 2015, were obtained from the China Meteorological Administration. Daily solar radiation was estimated from the daily sunshine hours, based on the Ångström equation (Black et al., 1954; Wang et al., 2015b).

2.2. Experimental design

To investigate the impact of meteorological factors on the growth and development of potato, serial planting experiments were conducted

Table 1
Vertical distribution of the physical and chemical properties of soil in the study site.

Soil depth (cm)	pH	Bulk density (g $\cdot$cm $^{-3}$)	Available P (mg$\cdot$kg $^{-1}$)	Available K (mg$\cdot$kg $^{-1}$)	OM (%)
0–10	8.24	1.58	13.37	159.84	2.08
10–30	8.27	1.56	3.54	130.31	5.06
30–50	8.41	1.69	2.57	70.78	1.41
50–80	8.60	1.66	1.58	66.90	0.67
80–100	8.45	1.83	1.86	98.50	0.48

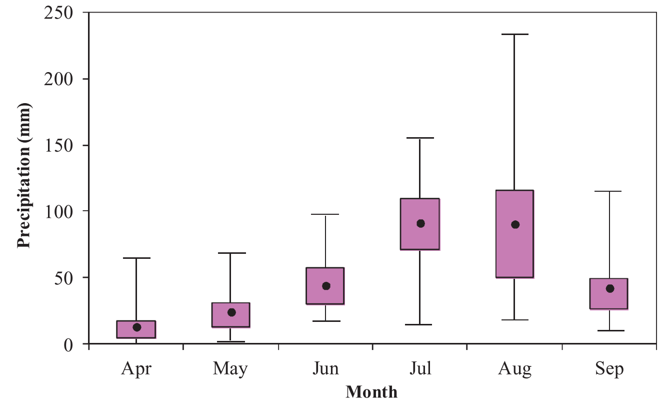

Fig. 1. Distribution of growing-season precipitation for potato at Wuchuan during 1961–2010. The horizontal lines show the maximum and minimum values; the "●" shows the average value; the upper and lower edges of boxes show 75% and 25%.

for four years from 2009 to 2012, with five planting dates each year (April 26, May 6, May 16, May 26 and May 31), and in 2014 with three planting dates (April 26, May 6, May 16). These planting dates covered the normal planting dates used by local farmers from early May to late May. A randomized experimental design was used with planting date as the treatment, each with four replicates. The potato was planted in $5 \times 5\ m^2$ plots and the cultivar Kexin_1 was used in all the treatments. The planting density was 40,000 plants per ha, with the same row and plant spacing (0.5 m). Base fertilizer was applied before planting, with 75 kg ha^{-1} of ammonium diammonium phosphate, 37.5 kg ha^{-1} of urea, and 37.5 kg ha^{-1} of potassium chloride. To guarantee the emergence of potato, 30 mm of irrigation was applied before planting for each treatment. The phenological stages, including planting, emergence, tuberization, tuber bulking and maturity, were recorded. The fresh tuber yield was measured through harvesting potato in four 5 m rows in the center of the block, with a harvesting area of 10 m^2.

2.3. Relationship between yield and meteorological factors during different growth stages of potato

We tested the correlation of potato yield and meteorological factors (solar radiation, temperature and precipitation) during different growth stages of potato, including the pre-tuber bulking stage (planting–tuber bulking), post-tuber bulking stage (tuber bulking–maturity), and the whole growth period (planting–maturity). The division of the growth stage was based on the allocation of carbohydrate to different organs of potato. Carbohydrate is mainly allocated to the leaves and stems before tuber bulking, and then to the subterranean tuber after tuber bulking (van Heemst, 1986; Kooman and Rabbinge, 1996). Because the tuberization stage of potato is most sensitive to water stress, we therefore additionally selected different days prior to and after the tuberization date to test which period around the tuberization stage led to the highest correlation between meteorological variables and potato yield. To account for the effectiveness of precipitation, we calculated the effective precipitation, defined as daily precipitation being more than 10 mm (Huang et al., 2015) and the ratio of precipitation to potential evapotranspiration (P/ET_P) (Ali and Talukder, 2008). The calculation of ET_p is shown as follows:

$$ETp = ET_0 \times K_c \tag{1}$$

where K_c is the crop coefficient at different development stages, taking the value of 0.45, 0.80, 1.10 and 0.80 at the initial stage, development stage, middle stage and late stage (Tang et al., 2016). ET_0 was calculated by the FAO Penman-Monteith equation (Allen et al., 1998):

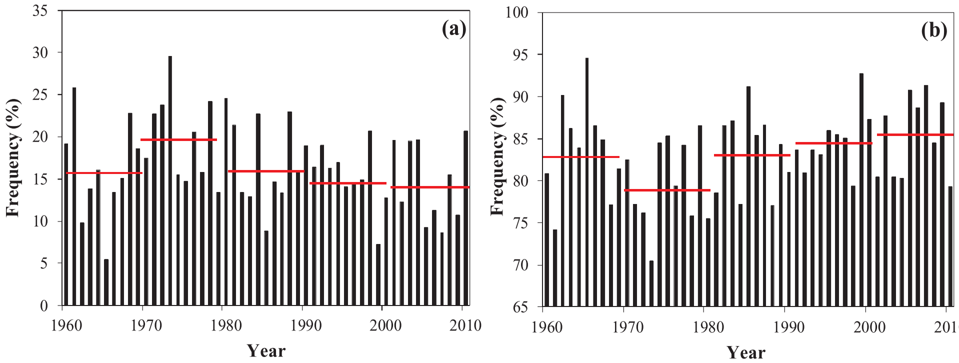

Fig. 2. Change in frequency of daily precipitation more than 10 mm (a) and less than 10 mm (b) during the potato growing season from 1961 to 2010. The frequency of daily precipitation more than 10 mm or less 10 mm means the ratio of the day number of daily precipitation events (≥10 mm or < 10 mm) to the total day number of daily precipitation events during the potato growing season. The red line represents the decadal average frequency from 1961 to 2010 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

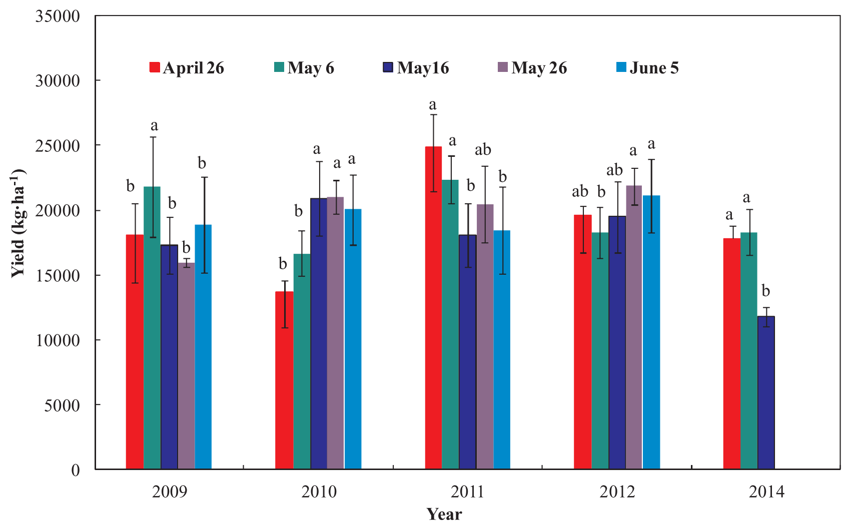

Fig. 3. Potato yield under different planting dates during the experimental period in 2009–2012 and 2014 (the same letters above the error bars indicate no significant difference at $P = 0.05$; error bars show ± one standard deviation of potato yield under different planting dates).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{t + 273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (2)$$

where ET_0 is the daily reference crop evapotranspiration (mm day^{-1}), R_n is the net radiation (MJ m^{-2} day^{-1}), G is the soil heat flux (MJ m^{-2} day^{-1}), t is the daily average temperature at 2m height (°C), U_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturated vapor pressure (kPa), e_a is the actual water vapor pressure (kPa), Δ is the slope of the saturation vapor pressure versus temperature relationship (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}). ET_0 is calculated in daily steps, and G is negligible in this study.

Linear regression analysis was performed to analyze the individual correlations between potato yield and meteorological factors using the slope and coefficient of determination (R^2) of the regression lines. Subsequently, those meteorological factors with a significant correlation with potato yield were used to develop a yield-determining equation via a multiple linear regression. The significance was tested using the Student's t-test at the 95% and 99% confidence levels.

2.4. Planting window and optimal planting date

The planting window was defined as the period (in days) from the earliest potential planting date to the latest potential planting date at the study site. The earliest potential planting date of potato was set as the day when the five-day moving average of daily average air temperature was over 8 °C, which is the base temperature for potato growth (Manrique and Hodges, 1989; Tang et al., 2016). The latest potential planting date of potato was set as the day on which planted potato could mature before the first frost day, i.e. the five-day moving average of daily average temperature was below 0 °C. Based on the above yield-determining equation developed by a multiple linear regression between key meteorological factors and potato yield, the optimal planting period was selected as the dates with above the 80 t h percentile of the highest yield within the potential planting window from 1961 to 2010.

2.5. Classification of year types based on annual precipitation

Based on the exceedance probability of annual precipitation, the year types were classified as wet, normal and dry from 1961 to 2010 (Liu et al., 2002; Zhang et al., 2007). Wet, normal and dry years were defined as the exceedance probability of annual precipitation being less than 25%, 26%–75% and 76%–100% respectively. The total annual precipitation ranged from 414 to 553 mm for wet years, from 307 mm to 413 mm for normal years and less than 307 mm for dry years.

3. Results

3.1. Distribution and decadal change in precipitation during the potato growing season

Growing–season precipitation (April–September) was highly variable, with a maximum of 525 mm, minimum of 161 mm and coefficient of variation (CV) of 25% from 1961 to 2010. The precipitation in July and August accounted for 58% of the growing-season precipitation (Fig. 1). Monthly precipitation was also highly variable, with the highest CV (99%) occurring in April and the lowest (30%) in July. The precipitation intensity changed from year to year during 1961–2010 (Fig. 2), with a decrease in the frequency of larger daily precipitation

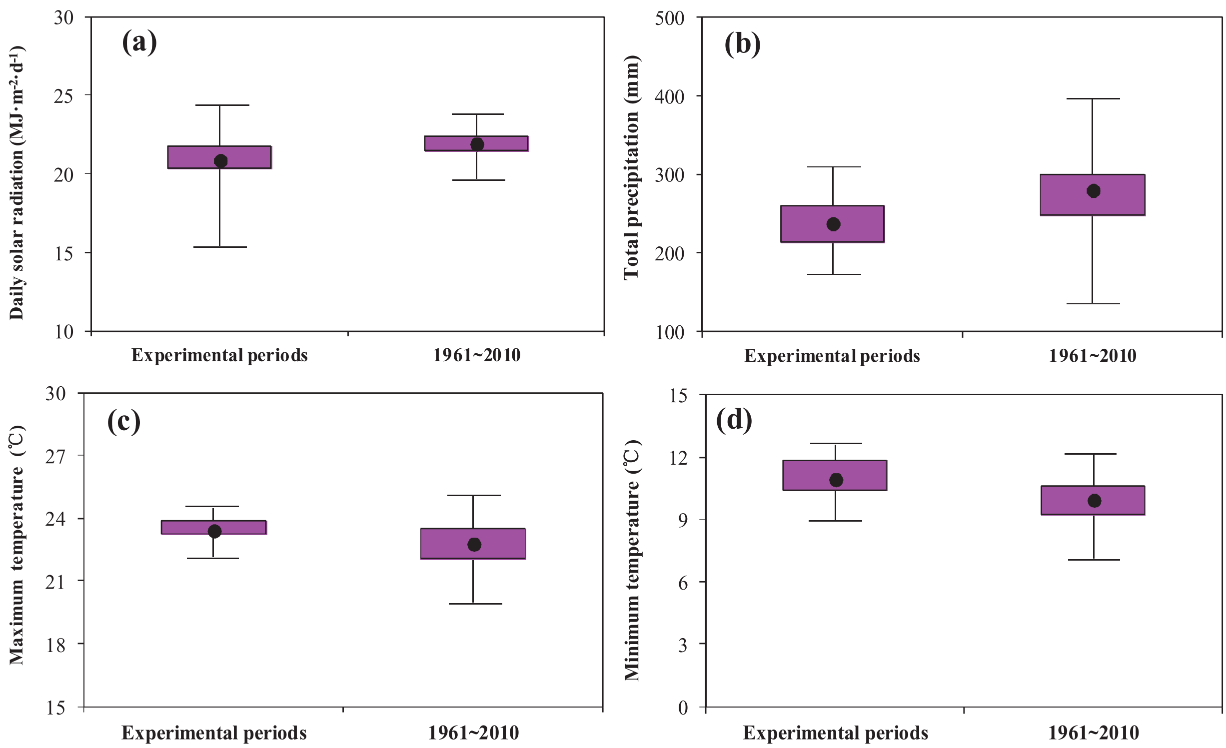

Fig. 4. Comparisons of growing-season average solar radiation (a), total precipitation (b), maximum temperature (c) and minimum temperature (d) under different planting dates during the experimental period and under the normal date of May 10 during 1961–2010. The horizontal lines show the maximum and minimum values; the "●" shows the average value; the upper and lower edges of boxes show 75% and 25%.

events (> 10 mm) and an increase in the frequency of smaller precipitation events (< 10 mm) since the 1970s ($P < 0.01$).

3.2. Potato yield under different planting dates

Potato fresh yield ranged from 11,000 kg ha^{-1} to 25,000 kg ha^{-1} under different planting dates with similar dry matter concentrations of ~20% during the experimental period (Fig. 3). The optimal planting date varied considerably between different years, with higher potato fresh yields under the treatments of early planting in 2011 and 2014, late planting in 2010 and 2012, and intermediate planting in 2009. Comparisons of growing-season average solar radiation, total precipitation, maximum and minimum temperatures under different planting dates during the experimental period and with a normal planting date of May 10 during 1961 to 2010, were made to see if the serial planting date experiments covered the historical climatic variability during the past 50 year s (Fig. 4). Growing-season average solar radiation ranged from 15.4 to 24.3 MJ m^{-2} d^{-1} under different planting dates during the experimental period, while it ranged from 19.1 to 23.8 MJ m^{-2} d^{-1} during 1961–2010. Growing-season total precipitation ranged from 173 to 308 mm under different planting dates during the experimental period and covered 76% of the variation in precipitation under the condition of a normal planting date during 1961–2010. However, growing-season maximum and minimum temperatures under different planting dates during the experimental period were higher than those during 1961–2010, reflecting the warming climate over the past 50 years.

3.3. Determining factors of variation in potato yield

Fig. 5 shows the relationships between variation in potato yield and meteorological factors during the potato growth period. Variation in potato yield had a higher correlation with variation in the ratio of precipitation to potential evapotranspiration during the tuberization stage (P_T/ET_{pT}) from 10 days before to 15 days after the tuberization date ($R^2 = 0.51$, $P < 0.01$) than the effective precipitation during the post-tuber bulking period (EP_{poTB}) ($R^2 = 0.43$, $P < 0.01$) and the effective precipitation during the growth period of potato (EP_{gp}) ($R^2 = 0.28$, $P < 0.05$). There was no significant correlation between variation in potato yield and growth-period total precipitation (P_{gp}) ($R^2 = 0.15$, $P > 0.05$). In addition, growth-period total solar radiation (S_{gp}) had a significantly positive effect on potato yield ($R^2 = 0.37$, $P < 0.01$), especially total solar radiation during the pre-tuber bulking period of potato (S_{prTB}) ($R^2 = 0.44$, $P < 0.01$). Variation in potato yield appeared to be negatively correlated with variation in average (T_{agp}), minimum (T_{mingp}) and maximum (T_{maxgp}) temperatures during the growth period; however, the correlation was only significant with maximum temperature ($R^2 = 0.27$, $P < 0.05$). A multiple linear regression analysis was used to relate potato yield (Y) to meteorological factors, enabling the development of a yield-determining equation ($Y = 7964 + 3965\ P_T/ET_{pT} + 35\ EP_{poTB} + 2.78\ S_{prTB}$). This equation explained 71% of the variation in potato yield across planting dates treatments and years.

3.4. Planting window and optimal planting date in years with different levels of precipitation from 1961 to 2010

The planting window ranged from April 1 to July 1 during 1961–2010, with the widest planting window being in 2007 (Fig. 6). The planting window lengthened by 3.5 days per decade from 1961 to 2010 ($P < 0.01$) due to the increase in temperature. The optimal planting date within the planting window almost occurred in May, accounting for 81.2% of all optimal planting dates, including 33.3% and 47.9% during May 1–May 15 and May 16–May 31, respectively. Fig. 7 shows the optimal planting date in different year types based on the exceedance probability of annual precipitation. When total annual precipitation ranged from 414 to 553 mm, with the exceedance probability of annual precipitation being less than 25%, the optimal planting date was between May 27 and June 12; when the total annual precipitation ranged from 307 mm to 413 mm, with the exceedance

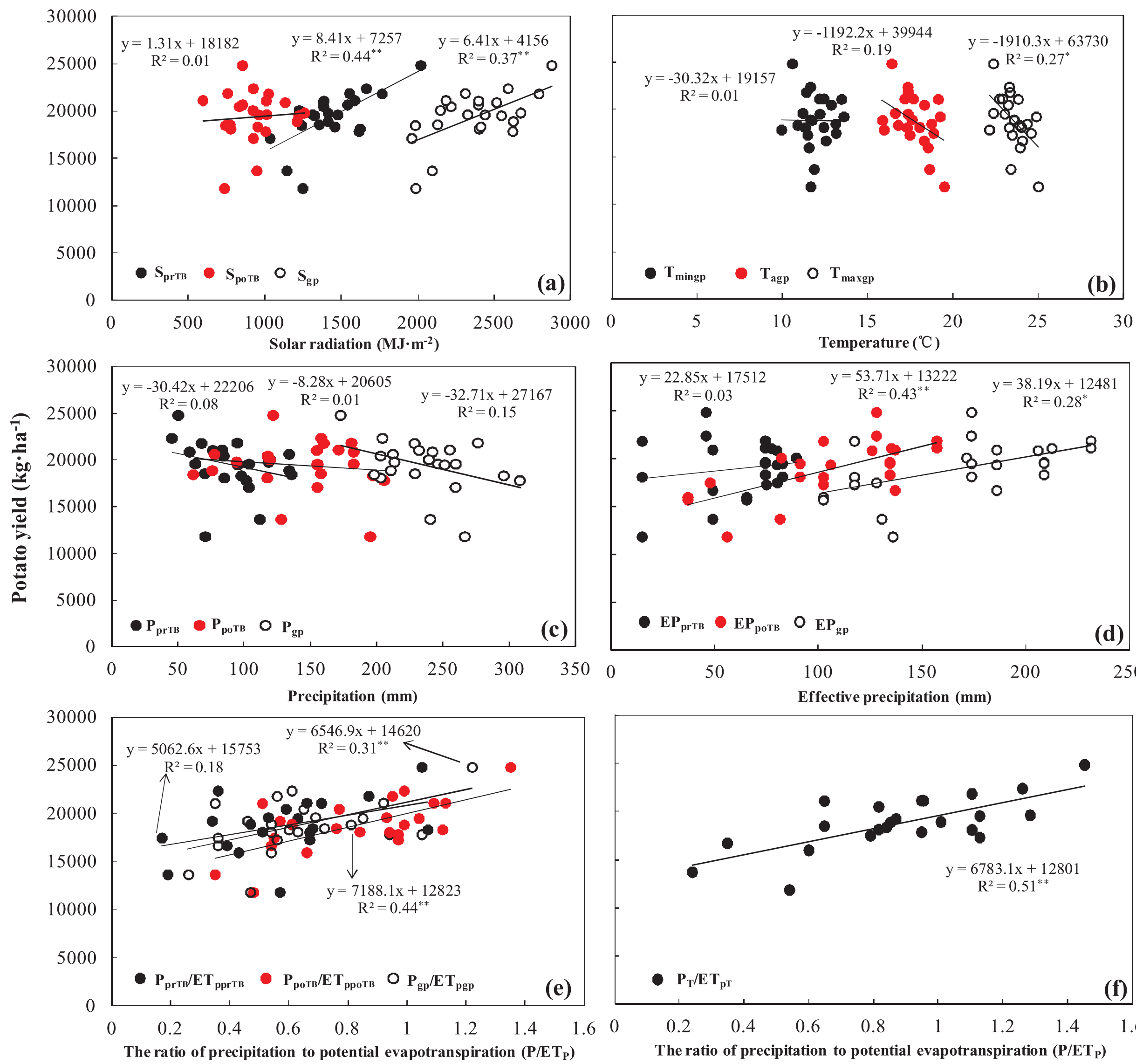

Fig. 5. Relationships between potato yield and (a) pre-tuber bulking, post-tuber bulking and growing-season total solar radiation (S_{prTB}, S_{poTB} and S_{gp}); (b) growing-season minimum, average and maximum temperatures (T_{mingp}, T_{agp} and T_{maxgp}); (c) pre-tuber bulking, post-tuber bulking and growing-season total precipitation (P_{prTB}, P_{poTB} and P_{gp}); (d) pre-tuber bulking, post-tuber bulking and growing-season total effective precipitation (EP_{prTB}, EP_{poTB} and EP_{gp}); (e) pre-tuber bulking, post-tuber bulking and growing-season ratio of precipitation to potential evapotranspiration (P_{prTB}/ET_{pprTB}, P_{poTB}/ET_{ppoTB} and P_{gp}/ET_{pgp}); and (f) ratio of precipitation to potential evapotranspiration during the tuberization stage (P_T/ET_{pT}). The solid line represents the linear trend for each variable; single and double asterisks indicate statistical significance at the 0.05 level and 0.01 level, respectively.

probability of annual precipitation being between 26% and 75%, the optimal planting date was between May 3 and May 26. The optimal planting date in dry years was between April 4 and May 2, in which the total annual precipitation amount was less than 307 mm, and the exceedance probability of annual precipitation was 76%–100%.

4. Discussion

4.1. Factors determining the variation in potato yield in the APE of North China

Precipitation plays a key role in determining crop yield in dryland agriculture, with many previous studies having found that crop yield increases with growing-season precipitation in such regions (Rockström and Falkenmark, 2000; Condon et al., 2004; Martone et al., 2007; Harms and Konscheuh, 2010). However, several studies have shown that the relationship between precipitation and crop yield depends on the effectiveness and distribution of precipitation (Rockström et al., 2010; Yu et al., 2014). Our study found that variation in potato yield correlated significantly with variation in growing-season effective precipitation, as well as variation in the ratio of precipitation to potential evapotranspiration during the tuberization stage, but not with variation in growing-season total precipitation. This is because potato yield is most sensitive to water stress during the tuberization stage, i.e., the tuber formation stage (van Loon, 1981; MacKerron and Jefferies, 1986; Haverkort et al., 1990; Lynch et al., 1995; Ren et al., 2015). Moreover, potential evapotranspiration is very high due to high levels of solar radiation and wind speed during the potato growth period in the APE of North China; thus, if the precipitation amount of a single precipitation event is low, this can mean that the moisture will evaporate before it can infiltrate into the soil and become available for crop transpiration. The criterion for effective precipitation depends on the soil moisture and potential atmospheric evaporation demand (Ebrahimpour et al., 2015), mostly taking the values of 5 mm and 10 mm. Huang et al. (2015) found that daily precipitation below 10 mm would evaporate from the soil surface directly in the APE. We also found no significant

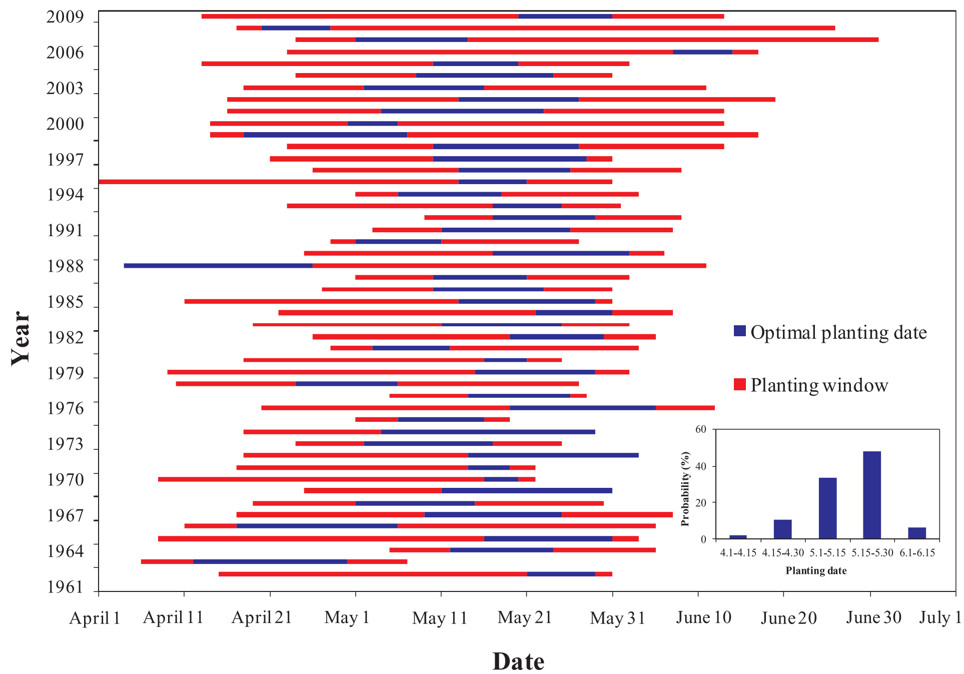

Fig. 6. Planting window and optimal planting date at Wuchuan during 1961–2010. The inset figure shows the probability of the optimal planting date falling within different dates.

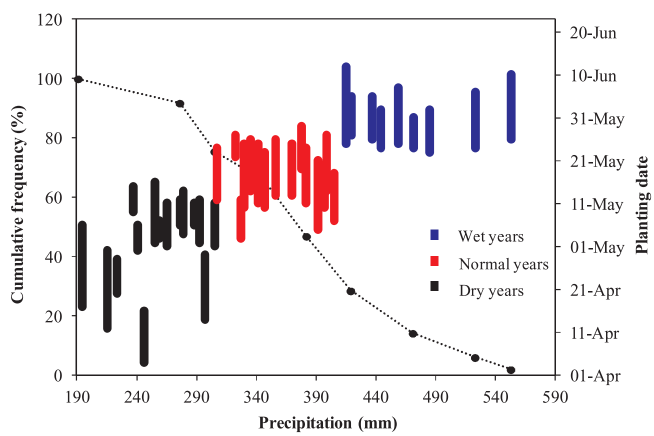

Fig. 7. Optimal planting date in different year types during 1961–2010. The dotted line represents the exceedance probability of annual precipitation. The bar chart represents the optimal planting date of potato.

correlation between variation in potato yield and growing effective precipitation being more than 5 mm ($R^2 = 0.08$, $P > 0.05$). Therefore the effective precipitation was defined as daily precipitation being more than 10 mm in this study. A previous study also showed that heavier precipitation events have a higher use-efficiency for crops than lighter precipitation events, even with the same total amount of precipitation falling during the crop growth period (Wang et al., 2009). The frequency of heavy precipitation (> 10 mm) has decreased significantly since the 1970s at the study site, which could be detrimental to potato yield. The above-mentioned results also implied the relationship between crop yield and crop water consumption. In general, crop yield increases with the increase in ET (water consumption) when crop transpiration increases correspondingly (Onder et al., 2005; Harms and Konscheuh, 2010; Steyn et al., 2016). However, high ET could not produce high crop yield if soil moisture is used more by soil evaporation than by crop transpiration (Yuan et al., 2013; Paredes et al., 2018). Under such conditions, plastic mulch or residue mulch can be used as useful measures to reduce soil evaporation and increase the effectiveness of the precipitation (Hu et al., 2014; Li et al., 2016).

In addition, an increase in the frequency of light precipitation events leads to lower solar radiation (Fig. 8), which has a negative impact on potato yield. Our study showed that potato yield is more related to solar radiation before tuber bulking ($R^2 = 0.44$, $P < 0.01$) than after tuber bulking ($R^2 = 0.01$, $P > 0.05$). Previous studies also showed that more pre-tuber bulking solar radiation could enhance dry matter accumulation (Manrique et al., 1991;Kooman and Rabbinge, 1996; Sainio et al., 2010) and more post-tuber bulking precipitation is required for tuber bulking (Onder et al., 2005).

4.2. Relationship between potato yield and meteorological factors in the APE of North China

Variations in crop planting date modify the irradiative, thermal and precipitation conditions during crop growth periods (Stalham and Allen, 2001; Wang et al., 2015a), therefore, serial planting experiments can provide a method to explore the relationships between crop yield and meteorological factors within a relatively shorter period than multiyear experiments. The serial planting experiments in our study, consisting of five planting dates each year across four years and three planting dates in one year, covered most of the variation in solar radiation and precipitation during the past 50 years, which are the two most important factors impacting the variation in potato yield in the study area. Growing-season maximum and minimum temperatures during the experimental period were higher than their historical average values because of significant warming in the APE of North China (Tang et al., 2016; Dong et al., 2018). Increased growing-season maximum temperature had a negative effect on potato yield ($R^2 = 0.27$, $P < 0.05$) because potato grows best in cool but frost-free seasons (Hijmans, 2003). For potato, haulm growth is fastest under temperatures of 20–25 °C, whereas the optimal range for tuberization and tuber growth is 15–20 °C (Rykaczewska, 2015). Intercepted solar radiation had higher correlation with potato yield than incident solar radiation (Fig. 9). However, incident solar radiation is easier to be estimated than intercepted solar radiation which needs detailed leaf area index (LAI) dynamics. In order to develop the relationship between yield and meteorological factors and extrapolate our conclusions to

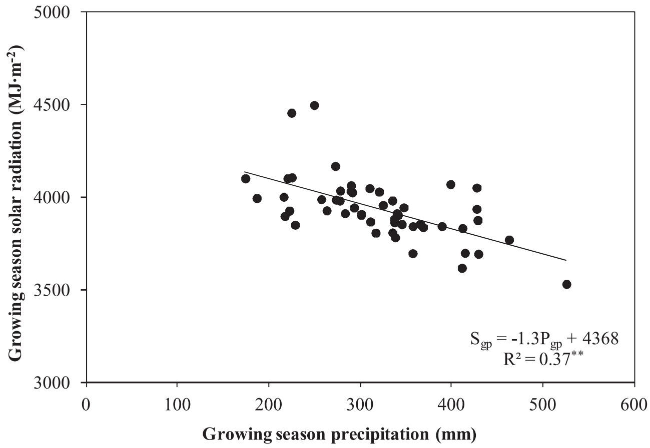

Fig. 8. Relationship between growing season precipitation (P_{gp}) and growing season solar radiation (S_{gp}) at Wuchuan from 1961 to 2010. ** indicates statistical significant at 0.01 level.

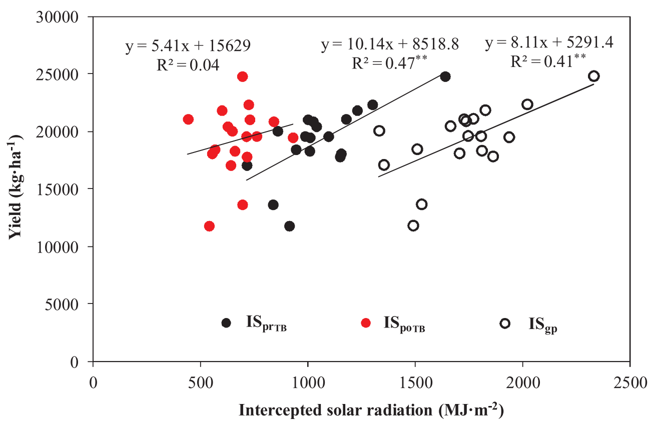

Fig. 9. Relationships between potato yield and pre-tuber bulking, post-tuber bulking and growing-season intercepted total solar radiation (IS_{prTB}, IS_{poTB} and IS_{gp}) during the experimental period at Wuchuan.

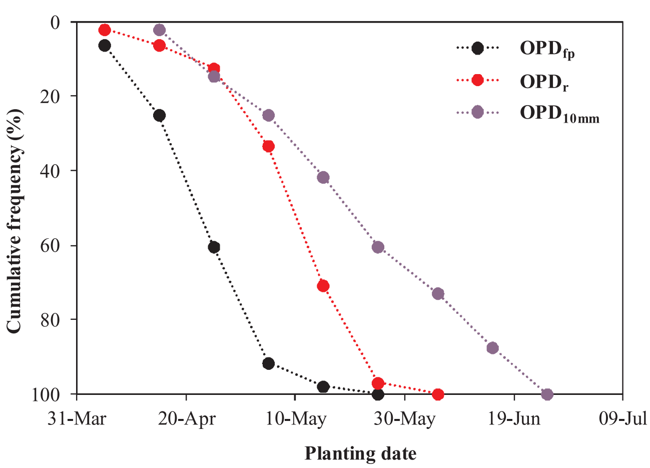

Fig. 10. Optimal planting date recommended by our study (OPD_r), the onset of first precipitation event (OPD_{fp}), and the amount of precipitation reaching 10 mm within continuous 5 days (OPD_{10mm}).

other sites for farmers to reference, we used incident solar radiation instead of intercepted solar radiation although the latter had higher correlation with potato yield. In addition to meteorological factors, the plant available water content (PAWC) at planting is an important factor impacting the variation in crop yield and water use efficiency in dryland agriculture (van Duivenbooden et al., 2000). However, PAWC had no significant correlation with potato yield at our study site due to its low variation across years (data not shown) caused by low precipitations before planting potato.

4.3. Optimal planting date for potato in the APE of North China

Irrigation is the most effective agronomic measure to improve crop yield in arid and semi-arid regions. However, there is little room for applying irrigation in the APE of North China due to the low availability of surface and ground water (Xia et al., 2010). Therefore, adjusting the planting date is the next most effective way to enhance potato yield and precipitation use efficiency in this region (Hu et al., 2017). Studies of dryland agriculture have reported that early planting can increase yields, while delayed planting can decrease yields because it shortens the crop growth period (Khan et al., 2011). However, in our study in the APE of North China, we found that the optimal planting date fell in May mostly, based on the match between the water and solar radiation requirements of potato and the patterns of precipitation during the stages of tuberization and post-tuber bulking and solar radiation during the pre-tuber bulking stage, although potential planting dates in April were also found. We estimated a larger potential planting window ranging from April 1 to July 1 during 1961–2010 in the APE in comparison with optimal planting window. The earliest potential planting date was estimated when the five-day moving daily average temperature was over 8 °C (Manrique and Hodges, 1989; Tang et al., 2016). Although some studies used 7 °C and even lower daily average temperature as the base temperature for potato (Francl, 1989; Streck et al., 2007), the base temperature was only used to calculate the earliest potential planting date and had little effects on our study results.

Based on our findings, we recommend an optimal planting date based on a high ratio of precipitation to potential evapotranspiration during the tuberization stage, post-tuber bulking effective precipitation and pre-tuber bulking solar radiation. However, this approach should be taken with caution. Firstly, we did not consider factors other than climatic conditions, including disease, insects, pests, soil conditions, quality of potato seed and agronomic management practices (Sparks et al., 2014; Chandel et al., 2015; Kadaja and Saue, 2016; Woli et al., 2016). Secondly, we used water supplementation to ensure the emergence of potato during the experimental period. However, the planting date must be selected around the day with the first precipitation event when farmers have insufficient water supplements for ensuring the emergence of potato. In Africa and Australia, optimal sowing dates have been recommended based on the onset of the rainy season (Mugalavai et al., 2008; Marteau et al., 2011; Cammarano et al., 2012). When there was insufficient water to ensure the emergence of potato, the planting date should be determined based on the onset of the first precipitation event or the amount of precipitation reaching 10 mm when temperature conditions could meet the requirement of potato emergence. The optimal planting date based on the onset of the first precipitation event (OPD_{fp}) was generally earlier than the optimal planting date recommended by our study (OPD_r); however, the optimal planting date based on the amount of precipitation reaching 10 mm within five continuous days (OPD_{10mm}) was later than OPD_r in 60% of the study period (Fig. 10).

We also recommend different planting dates depending on the year type in terms of the level of precipitation (i.e., wet, dry, normal). Therefore, farmers can adjust their planting dates based on the results of our study and climate forecasting information. This highlights the importance of improving climate forecasting because current climate forecasting efforts are unable to meet the requirements of agricultural production (Meinke et al., 2007; Nidumolu et al., 2016).

5. Conclusions

Low amount and high variability of annual and growing season precipitation limited crop yield in the agro-pastoral ecotone in North China. Our study found that higher precipitation during the tuberization stage and the post-tuber bulking stage together with higher solar radiation during the pre-tuber bulking stage resulted in higher potato yield. This reflects that the effectiveness and distribution of precipitation is the yield-determining factor of potato in the agro-pastoral ecotone. Adjusting planting date is an effective means in increasing potato yield and reducing the variability of potato yield by matching the precipitation distribution with water requirement of potato growth and tuber formation. Potato should be planted earlier in dry years to increase growing season precipitation, whereas earlier planting is less beneficial to potato production in normal and wet years in the agro-pastoral ecotone in North China.

Acknowledgements

The work was supported by the National Science Foundation of China (41475104) and National Agricultural Introducing Intelligence Platform (2015Z007). We would like to thank China Meteorological Administration for providing the historical climate data. The authors acknowledge the anonymous referees for their valuable comments.

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