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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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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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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 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 × 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.

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

Soil depth (cm)	pH	Bulk density (g cm^{-3})	Available P (mg·kg^{-1})	Available K (mg·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

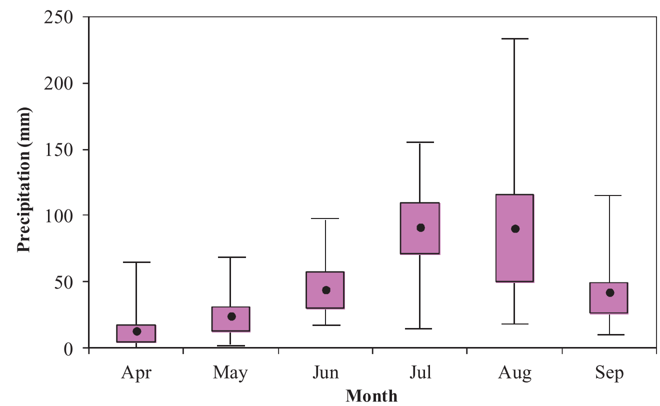

Fig. 1. Distribution of growing-season precipitation for potato at Wuchuan during 1961–2010. The horizontal lines show the maximum and minimum values; the "●" shows the average value; the upper and lower edges of boxes show 75% and 25%.

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:

$$ETp = ET_0 \times K_c \quad (1)$$

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):