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Diverging water-saving potential across China's potato planting regions

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ABSTRACT

China ranks the first in total planting area and production of potato (*Solanum tuberosum* L.) over the world. However, high potato yield depends on a large amount of irrigation that raises a series of environment problems. Assessing the water-saving potential across China's potato planting regions is of importance for maintaining sustainable development of potato production. In this study, we firstly evaluated the potential yields, rainfed yields, and their gaps of potato across different potato planting regions, and then presented optimal agronomic management options (planting date, cultivar maturity, and irrigation schedule) by considering both yield and water use efficiency of potato under the limitation of available water resources with validated APSIM-Potato model. Along the distribution of growth period solar radiation, potential yield of potato was highest in the North Single planting region (NS), followed by the Central Double planting region (CD), Southwest Mixed planting region (SWM), and South Winter planting region (SW). However, rainfed yield of potato was highest in CD followed by NS, SW, and SWM along the distribution of the reproductive growth period precipitation. Under the limitation of available water resources, most potato planting regions should select middle−late maturing cultivars while optimal planting dates varied among regions with earlier planting in north China and later planting in south China compared with normal planting date. Based on the optimization of planting date, cultivar maturity, and irrigation schedule, there is a large water-saving potential in China's potato planting regions. Average irrigation amount could be decreased by 66% in SW, 49% in SWM, 40% in NS, and 29% in CD, respectively, relative to irrigation quota. Our study suggests that optimizing planting date, cultivar maturity, and irrigation management could realize win-win of yield and water use efficiency and provide a scientific support for water-saving irrigation of potato production in China.

1. Introduction

Potato, following maize, wheat, and rice, is the fourth important food crop in terms of human consumption (FAO, 2016). There has been a dramatic increase in potato supply and demand in Asia, Africa, and Latin America during the last 20 years (Devaux et al., 2014). China has been the world's leading potato producer since 1993, and produces 9.6×10^7 tons fresh potato accounting for 25.1% of the world total production with 29.6% of the world total planting area (Wang and Zhang, 2004; FAO, 2016).

In China, potatoes are planted in four agro-ecological zones across China, i.e., North Single planting region (NS), Central Double planting region (CD), South Winter planting region (SW), and Southwest Mixed planting region (SWM) accounting for 49%, 39%, 7%, and 5% of national total potato planting area, respectively (Teng et al., 1989; Wang et al., 2018; Yang et al., 2018). However, due to lack of high quality cultivar and suboptimal agronomic management practices, the fresh potato yield in China (18.7 t ha^{-1}) is much lower than that in the United States (47.1 t ha^{-1}), the Netherlands (45.7 t ha^{-1}), Poland (27.7 t ha^{-1}), and India (22.9 t ha^{-1}) (Jansky et al., 2009; FAO, 2016; Wang et al.,

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2018). In addition, water use efficiency (WUE) of potato in China is also much lower than that of abovementioned countries (Xiao et al., 2013; Haverkort and Struik, 2015). Adjusting planting date, shifting cultivar maturity, and optimizing irrigation schedule have been recognized as effective options to increase yield, yield stability, and water use efficiency of crops (Camargo et al., 2015; Dong et al., 2015; Tang et al., 2018a,b, 2019). In general, combining multiple agronomic management practices performs better in enhancing yield and water use efficiency than any sole management option (Li et al., 2019b, 2020, 2021). However, there are few studies on the interaction of planting date, cultivar maturity, and irrigation schedule on yield and WUE of potato in different potato planting regions in China.

More than 70% of the fresh water resources are used for agricultural production in China (Qu et al., 2005). Recently, with the extension of potato production industry in China, a large amount of irrigation has been applied to increase potato yield and economical profit of farmers (Hou et al., 2010; Wang et al., 2011; Qin et al., 2018). However, increasing use of irrigation has resulted in soil salinization and groundwater depletion (Zhang et al., 2016). Observed groundwater table decreased by 0.5–1.0 m per year mainly due to rising irrigation amounts and planting area of potato in North China (Zhu et al., 2014). Our previous simulation study also showed that applying 240 mm irrigation each year for three decades would decrease groundwater table by 21–42 m across the agro-pastoral ecotone in North China (Tang et al., 2019).

The environmental problems caused by a large amount of irrigation from groundwater have raised great public attention in China and therefore different irrigation strategies, such as deficit irrigation and partial root zone drying irrigation were developed to save water and enhance water use efficiency (Geerts and Raes, 2009; Ahmadi et al., 2010; Davis et al., 2017a). Moreover, local maximum supply amount of irrigation is constrained by available water resources. Therefore, the government had formulated irrigation quota for guiding local irrigation schedule. However, there may be still a large water-saving potential by optimizing planting date, cultivar maturity, and irrigation schedule, which has not been investigated.

Therefore, the objectives of this study are to: (1) investigate the potential yield, rainfed yield, yield gap of potato in different potato planting regions in China, (2) optimize planting date, cultivar maturity, and irrigation schedule for high yield and high WUE for potato across China, (3) and evaluate the water-saving potential in different potato planting regions in China.

2. Materials and methods

2.1. Study area, historical climate, and soil data

China's potato production regions were divided into four planting regions (Fig. 1) based on climate conditions and cropping systems including North Single planting region (NS), Central Double planting region (CD), South Winter planting region (SW), and South Mixed planting region (SWM) (Table S1) (Jansky et al., 2009). 158 agro-meteorological sites with observed climate data were selected to investigate the potential yields, rainfed yields and their gaps, the suitable planting dates, cultivar maturities, and irrigation schedules, and water-saving potential across China's potato planting regions.

Historically observed daily climate data of 158 sites from 1981 to 2015 were available from China Meteorological Administration (http//www.cma.gov.cn/), including daily maximum and minimum temperatures (°C), precipitation (mm), and sunshine hours (h). Daily solar radiation (MJ m^{-2}) was estimated with sunshine hours using the Angström equation because there was a good agreement between observed and calculated solar radiation through sunshine hours in China (Wang et al., 2015; He et al., 2020). Due to the differences in physical and chemical characteristics of soil, 15 types of typical soil were used in this study that represent main soil types across China's potato planting regions (http://www.soil.csdb.cn/, Fig. S1).

2.2. APSIM-Potato model and its parameterization

APSIM-Potato (version 7.6) model was used in this study. Our previous studies showed that the APSIM-Potato model performed well in

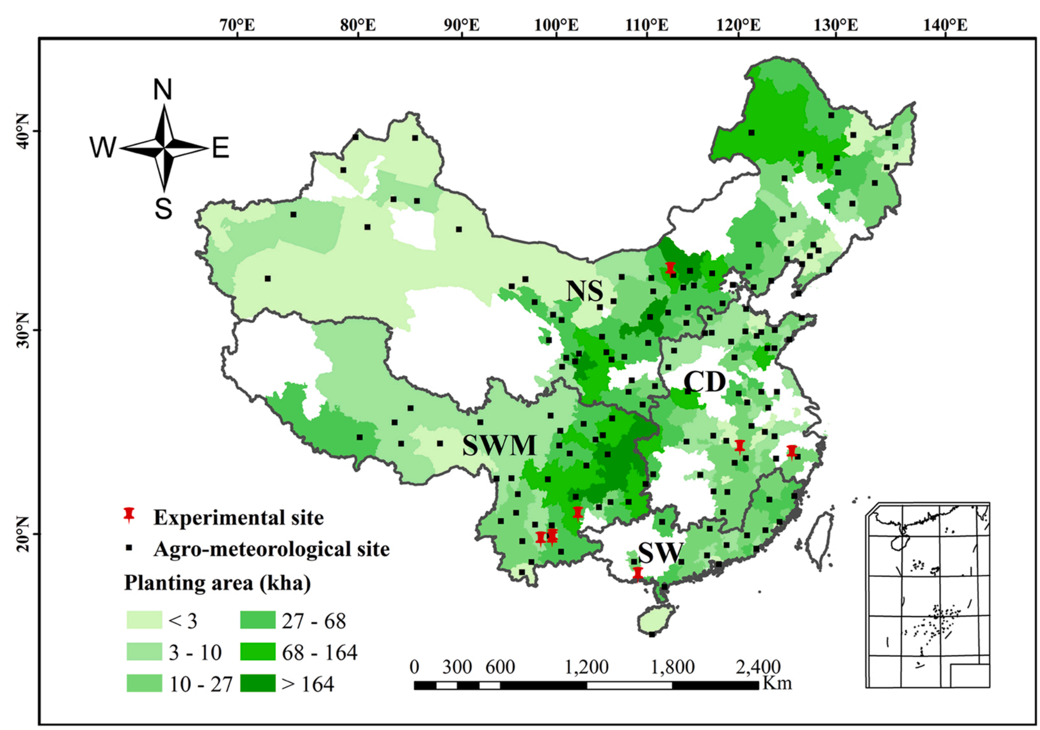

Fig. 1. The planting area (averaged from 1982 to 2011) of four planting regions including North Single planting region (NS), Central Double planting region (CD), South Winter planting region (SW), and Southwest Mixed planting region (SWM), and the distribution of the 158 agro-meteorological sites.

simulating phenology with RMSE < 6.3 days, soil water content in 1 m depth with RRMSE < 15.4%, and potato yields with RRMSE < 8% for different planting dates and cultivar maturities, and the simulated LAI, biomass, and ET of potato could represent the variation in observed ones under different irrigation levels (Tang et al., 2018a, 2019; Li et al., 2019b). Here, we further tested the performance of APSIM-Potato in simulating the response of potato growth to different cultivar maturities under different planting dates based on the published experimental data across China's potato planting regions.

For calibrating and validating the APSIM-Potato model, seven representative cultivars across four planting regions were selected to minimize the possible spatial heterogeneity in local cultivars (Table 1, Ye et al., 2015; Chang et al., 2020; Du and Li, 2021; Li et al., 2021). Potato cultivars used in this study were divided according to their maturities including early-, middle-, and late-maturing because previous studies showed that cultivar maturity resulted in the major difference of yield and water use efficiency of potato (Samanta et al., 2020; Li et al., 2021). Table 1 showed the details on potato cultivars with different maturities, planting regions, calibration and validation periods, experimental sites, and data sources for calibrating and validating the APSIM-Potato model. Experimental data obtained from the literature included the dates of planting, emergence, tuber bulking, maturity, and potato yields with a moisture content of 80%. All of the field experimental data were separated into independent calibration and validation data by regions, planting dates, and years. The statistical metrics for model evaluation were shown in supplementary S1.

In this study, the genetic parameters of each potato cultivar maturity were derived based on field experimental data with a 'trial-and-error' method. The genetic parameters for controlling phenology were adjusted to match observed and simulated emergence, tuber bulking, and maturity. The maximum specific leaf area (y_sla_max, $mm^2\ g^{-1}$) was adjusted slightly to match observed and simulated leaf area index (LAI), biomass, and yield of potato (Brown et al., 2011; Tang et al., 2018a). The canopy extinction coefficient and RUE were 0.8 and 1.44 g MJ^{-1} respectively for each cultivar because previous studies found that they did not change significantly with potato cultivar (Saluzzo et al., 1999; Wang et al., 2005; Brown et al., 2011; Samanta et al., 2020). The model could reproduce the response of potato growth (RMSEs ≤ 5 days) and yield (RRMSEs ≤ 19%) to variations in seven cultivars well. We further validated the APSIM model in simulating potato WUE based on experimental data collected from the literature, which showed that the model could effectively simulate potato WUE under different water conditions (R^2 =0.71, P < 0.01). The performances of the APSIM-Potato model across China's planting regions and cultivar parameters were shown in supplementary S2.

2.3. Irrigation quota in different planting regions

Local government guided agricultural irrigation with a predetermined irrigation quota based on water resources carrying capacity and optimal configuration of water resources (Wang et al., 2017; Shen et al., 2020). Irrigation quota for potato obtained from provincial agricultural water standards (http://www.jsgg.com.cn/) showed a large spatial difference across different potato planting regions (Fig. 2). High irrigation quota was formulated in NS except its northeast part, the north part of CD, the west part of SWM, and the whole SW.

2.4. Long-term simulation settings

2.4.1. Potential yield, actual yield, rainfed yield, and yield gap

Potential yield (Y_p) and rainfed yield (Y_r) of potato were simulated by the APSIM-Potato model to investigate the potential of irrigation in increasing yield and narrowing yield gap. Y_p was defined as the highest yield that the modern potato cultivar for each region could achieve without stresses of water, nutrient, plant diseases and insect pests under optimal planting dates, i.e., crop growth was determined solely by

Table 1
Detailed information on the cultivar, cultivar maturity, region, and calibration and validation data across China's potato planting regions.

Cultivar	Maturity	Region	Calibration and validation information						
			Site	Soil type	Planting dates (year/month/day)	Observed phenology and yield	Irrigation amount and time	Nitrogen application rate and time	Data source
Favorita	E	NS, CD, SW, SWM	Wuchuan	Kastanozems	2017/5/15 2018/5/16	Emergence, tuberization, maturity date, fresh yield	30 mm at planting	37.5 kg ha^{-1} at planting	(Li et al., 2020)
Connibeck	M	NS	Wuchuan	Kastanozems	2017/5/15 2018/5/16	Emergence, tuberization, maturity date, fresh yield	30 mm at planting	37.5 kg ha^{-1} at planting	(Li et al., 2020)
Xingjia_2	M	CD, SW	Qinzhou Jinhua	Latosolic red soil Purple soil	2014/11/20 2018/1/21	Emergence, tuberization, maturity date, fresh yield	Irrigation to 60% of PAWC at planting Rainfed	225 kg ha^{-1} at planting 337.5 kg ha^{-1} at planting	(Ye et al., 2015; Chen et al., 2018)
Lishu_6	M	SWM	Huaning Xinping	Latosolic red soil Latosolic red soil	2016/2/28 2018/1/16	Emergence, tuberization, maturity date, fresh yield	No water stress Rainfed	No nitrogen stress No nitrogen stress	(Dou, 2016; Dao et al., 2019)
Qingshu_9	L	SWM	Liupanshui Tonghai	Yellow soil Latosolic red soil	2016/3/4 2017/12/20	Emergence, tuberization, maturity date, fresh yield	Rainfed No water stress	135 kg ha^{-1} at planting No nitrogen stress	(Wang, 2017; Zhang et al., 2019)
Kexin_1	L	NS	Wuchuan	Kastanozems	2017/5/15 2018/5/16	Emergence, tuberization, maturity date, fresh yield	30 mm at planting	37.5 kg ha^{-1} at planting	(Li et al., 2020)
Daxiyang	L	CD, SW	Qinzhou Jiujiang	Latosolic red soil Red soil	2014/11/20 2017/1/13	Emergence, tuberization, maturity date, fresh yield	Irrigation to 60% of PAWC at planting Rainfed	225 kg ha^{-1} at planting No nitrogen stress	(Ye et al., 2015; Lv et al., 2019)

E, M, L represent early-, middle-, and late maturing cultivars of potato, respectively. NS, CD, SW, and SWM represent North Single planting region, Central Double planting region, South Winter planting region, and Southwest Mixed planting region, respectively. PAWC: Plant-available water content in the 0–100 cm soil profile.

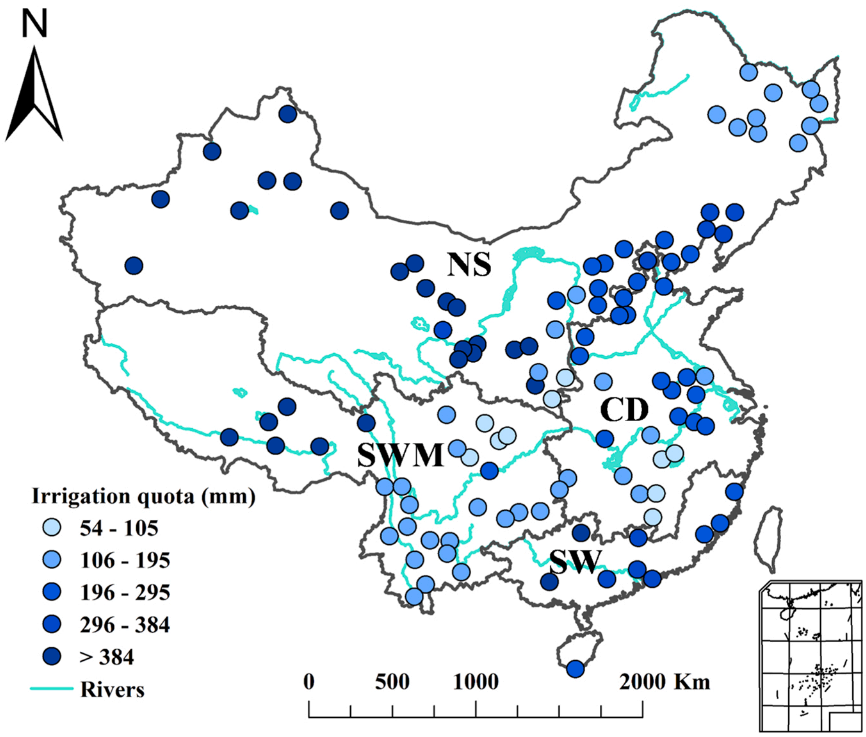

Fig. 2. Irrigation quota used in China's potato planting regions based on available water resource. NS, CD, SW, and SWM represent North Single planting region, Central Double planting region, South Winter planting region, and Southwest Mixed planting region, respectively.

climatic factors (solar radiation and temperature) (Yu et al., 2001; Wang et al., 2018; Tang et al., 2019). Planting density was set as 15 plants m^{-2} under which simulated potato yield would not increase with the increase in planting density. Irrigation was applied automatically if soil water content in the root zone was lower than the field capacity when simulating the Y_p (Li et al., 2022). Y_r was defined as the potential yield under water limitation with optimal planting density, normal cultivar and nitrogen application rate for each region referring to previous studies (Table S4). Yield gap (Y_g) between simulated potential yield and rainfed yield was calculated as:

$$Y_g = Y_p - Y_r \quad (1)$$

Average actual potato yields from 2005 to 2015 recorded by statistical yearbooks were used to compare with potential yields, rainfed yields, and optimized yields to determine the potential in yield enhancing and water saving through optimizing planting date, cultivar maturity, and irrigation schedule. Actual fresh potato yield was highest in CD with the value of 22.5 t ha^{-1} followed by SW, NS, and SWM with the values of 20.5, 19.3, and 18.9 t ha^{-1}, respectively (Fig. 3).

2.4.2. *Optimizing planting date and cultivar maturity based on the predetermined irrigation quota*

For optimizing planting date and cultivar maturity (early-, middle-, and late-planting coupled with early-, middle-, and late-maturing cultivars) based on the predetermined irrigation quota, we set the irrigation for 3–5 times at the key development stages of potato including planting, emergence, earlytuber, senescing, and 10 days after senescing. Generally, supplemental irrigation was applied at planting, earlytuber (tuber initiation), and senescing (tuber bulking) (Tang et al., 2018a; Li et al., 2020). In addition, additional irrigation was used at the emergence and 10 days after senescing for the regions with high predetermined irrigation quota (Shi, 2017). The early- and late-planting dates were set at an interval of 10 days before and after the normal planting date (middle planting) (Table S1). Water use efficiency (WUE) was used to quantify the ratio between yield (Y) and evapotranspiration (ET):

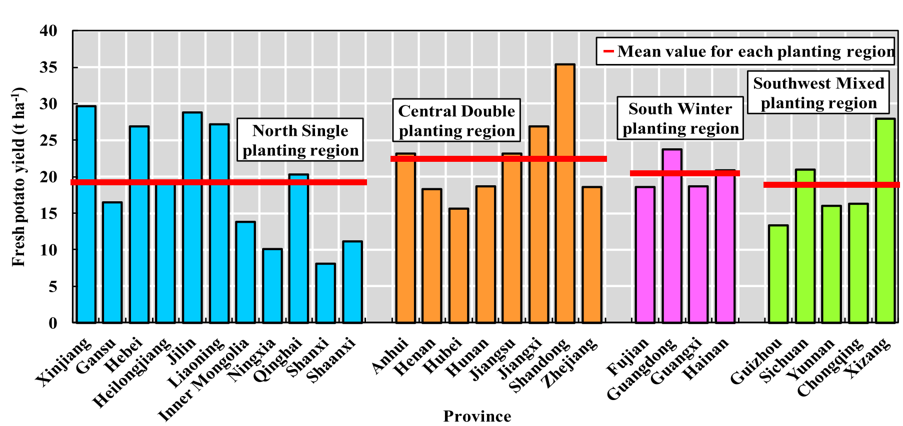

Fig. 3. Actual fresh potato yields averaged from 2005 to 2015 for different provinces in China.

$$WUE = \frac{Y}{\mathrm{ET}} \quad (2)$$

2.4.3. Optimizing irrigation schedule for the synergistic improvement of yield and WUE

For investigating the interaction effects of planting date, cultivar maturity, and irrigation schedule on fresh yield and water use efficiency of potato, four irrigation scenarios were applied with three planting dates and three cultivar maturities: 30 mm for planting (I_1); 30 mm for planting, and 60 mm for emergence (I_2); 30 mm for planting, 60 mm for emergence, and 60 mm for earlytuber (I_3); 30 mm for planting, 60 mm for emergence, 60 mm for earlytuber, and 60 mm for senescing (I_4).

For the synergistic improvement of yield and WUE of potato, a high-yield-WUE (HYW) index was used in this study:

$$HYW = \frac{Y_i}{Y_M} + \frac{WUE_i}{WUE_M} \quad (3)$$

where Y_i and WUE_i were fresh yield (t ha^{-1}) and water use efficiency (kg m^{-3}) of potato respectively under different irrigation scenarios with each combination of planting date and cultivar maturity. Y_M and WUE_M were the maximum fresh yield and water use efficiency of potato, respectively, for all irrigation scenarios with each combination of planting date and cultivar maturity. The irrigation scenario achieving highest HYW was chosen as the optimal irrigation schedule with both high fresh yield and water use efficiency of potato. The water-saving potential across China's potato planting regions was defined as the difference between optimal irrigation amount and predetermined irrigation quota. Regional fresh yield, WUE, and HYW of potato under each combination of planting date, cultivar maturity, and irrigation schedule were calculated by averaging the simulated values of all sites in each region.

3. Results

3.1. Potential yield, rainfed yield, and yield gap

Y_p, Y_r, and Y_g ranged from 22 to 70.2 t ha^{-1}, from 0 to 31.8 t ha^{-1}, and from 5.4 to 69.7 t ha^{-1} respectively across China's potato planting regions (Fig. 4). Averaged Y_p were 51.5, 36.6, 26, and 29.2 t ha^{-1}, respectively, in NS, CD, SW, and SWM (Fig. 4a). Simulated potential yields were close to the high yield records from regional high-yield experiments under optimal agronomic management level (Table S5), which suggested the reliability of simulated potential yields (Fig. S5a). Actual fresh potato yields accounted for 42%, 61%, 76%, and 64% of the potential yields, respectively, in NS, CD, SW, and SWM during 2005–2015 (Fig. S5b). Y_r was highest with the value of 21.7 t ha^{-1} in CD followed by NS, SW, and SWM with the values of 18.4, 14.9, and 13.2 t

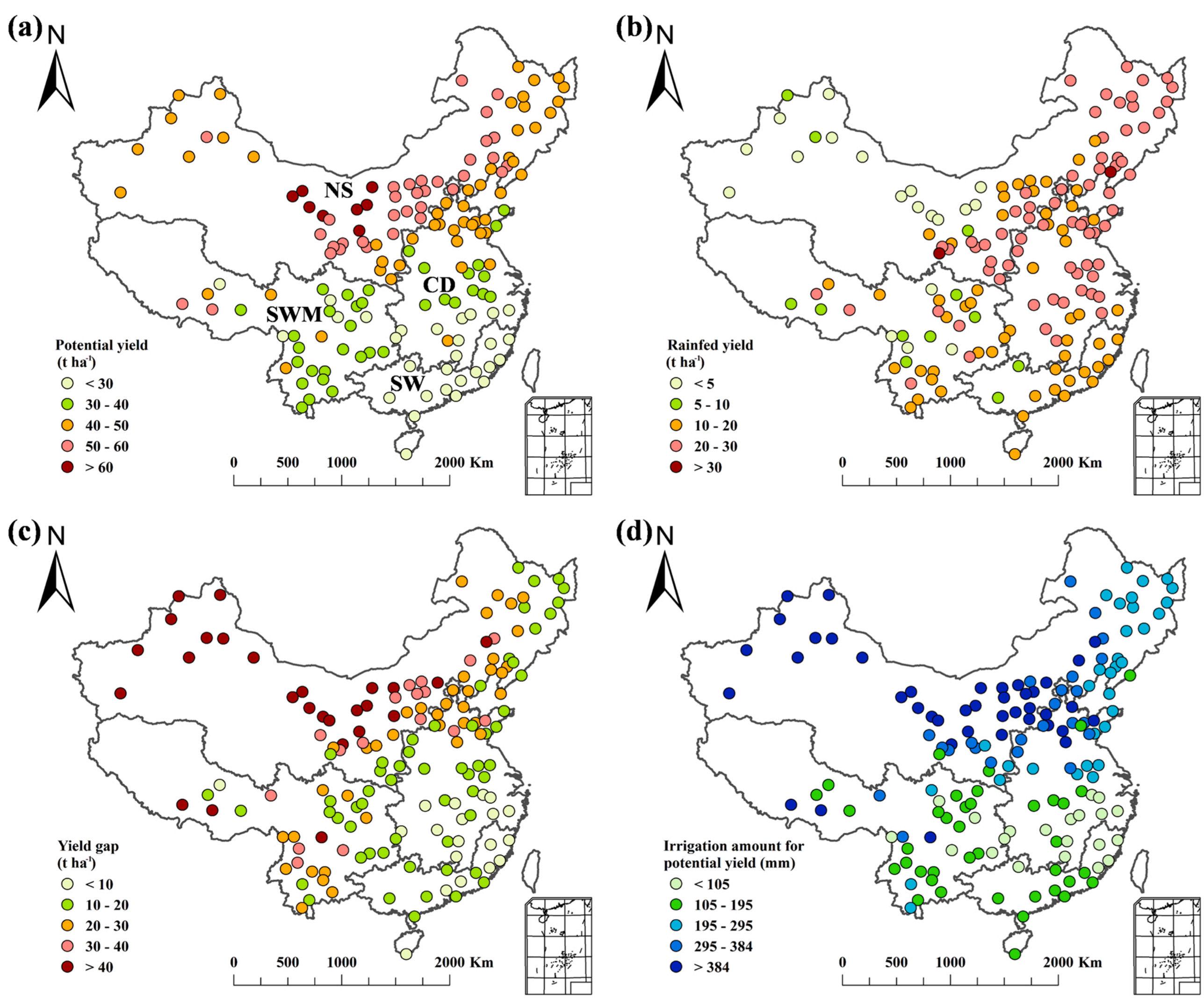

Fig. 4. Simulated potential yield (Y_p) (a), rainfed yield (Y_r) (b), yield gap (Y_g) (c) of potato, and irrigation amount for achieving potential yield (d) for each site across China's potato planting regions. NS, CD, SW, and SWM represent North Single planting region, Central Double planting region, South Winter planting region, and Southwest Mixed planting region, respectively.

ha^{-1}, respectively (Fig. 4b). Consequently, Y_g was highest in NS with the value of 33.1 t ha^{-1} while the values of CD, SW, and SWM were, respectively, 14.9, 11.1, and 16 t ha^{-1} (Fig. 4c). For achieving the potential yield, 381 mm, 173 mm, 196 mm, and 126 mm of irrigation amounts, respectively, were needed in NS, SWM, CD, and SW (Fig. 4d).

3.2. Optimal combinations of planting date and cultivar maturity under irrigation quota

Simulated fresh potato yield based on the predetermined irrigation quota ranged from 0.6 to 46.7 t ha^{-1} across China's potato planting regions. Averaged fresh potato yield in NS was highest among all regions (Fig. 5). Late-maturing cultivar with early-planting produced highest yield (33.9 t ha^{-1}) in NS while middle-maturing cultivar with late-planting was the optimal combination in CD. The middle-maturing cultivar with early-planting could obtain highest yield of 17.6 t ha^{-1} in SW while middle-maturing cultivar with late-planting could achieve higher fresh yield (23.1 t ha^{-1}) than other combinations in SWM.

Highest fresh yield of potato under optimal combinations of planting date and cultivar maturity ranged from 10.6 to 46.7 t ha^{-1} across China's potato planting regions with a decreasing trend from north to south. Averaged fresh potato yields were 34.1, 27.6, 17.9, and 23.3 t ha^{-1}, respectively, for NS, CD, SW, and SWM (Fig. 6a). Accordingly, potato WUE ranged from 7.6 kg m^{-3} to 11.9 kg m^{-3} with an increasing trend from north to south. Averaged WUE in NS, CD, SW, and SWM was 8.2, 9.4, 10.8, and 8.7 kg m^{-3}, respectively (Fig. 6b). The middle to late maturing cultivar was recommended to plant in most China's potato planting regions (Fig. 6c). For the selection of optimal planting date, early-planting was recommended in NS and SW while late-planting was recommended in CD and SWM (Fig. 6d).

3.3. Water-saving potential in China's potato planting regions

Simulated fresh potato yield increased with increasing irrigation amount in NS and CD, but not for SW and SWM, with the mean values $\pm$ standard deviations of 24.8 ± 3.4, 23.9 ± 1.7, 16.6 ± 0.6, and 18.8 ± 2.3 t ha^{-1}, respectively (Fig. 7). Accordingly, simulated potato WUE increased with increasing irrigation amount in NS and CD, with the mean values of 8.2 ± 0.3 and 9.4 ± 0.2 kg m^{-3}, respectively. However, simulated potato WUE (10.8 ± 0.5 kg m^{-3}) decreased with increasing irrigation amount in SW. For most combinations of planting date and cultivar maturity, potato WUE (8.6 ± 0.3 kg m^{-3}) did not change significantly in SWM.

In NS, early-planting with late-maturing cultivar irrigated at planting, emergence, earlytuber, and senescing could achieve highest HYW with lowest variation of 1.96 ± 0.11 (Fig. 8a). Middle-maturing cultivar under late-planting irrigated at planting, emergence, earlytuber, and senescing achieved highest HYW with lowest variation of 1.98 ± 0.01 in CD (Fig. 8b). In SW, middle-maturing cultivar under early-planting had a better performance than other combinations, which achieved a higher HYW with a lower variation of 1.97 ± 0.03 and only needed irrigating at planting (Fig. 8c). Late-maturing cultivar under late-planting irrigated at planting, emergence, earlytuber, and senescing could achieve a higher HYW with a lower variation of 1.94 ± 0.05 than other combinations (Fig. 8d).

Fig. 9 showed the predetermined irrigation quota, optimal irrigation amount and water-saving potential in different potato planting regions. Average predetermined irrigation quota was 305 ± 135, 233 ± 113, 307 ± 82, and 205 ± 137 mm, respectively in NS, CD, SW, and SWM. Compared with irrigation quota, the irrigation amount could be decreased in all the regions with average reduction amount of 123 mm (40%), 69 mm (29%), and 202 mm (66%), and 102 mm (49%), respectively, in NS, CD, SW, and SWM.

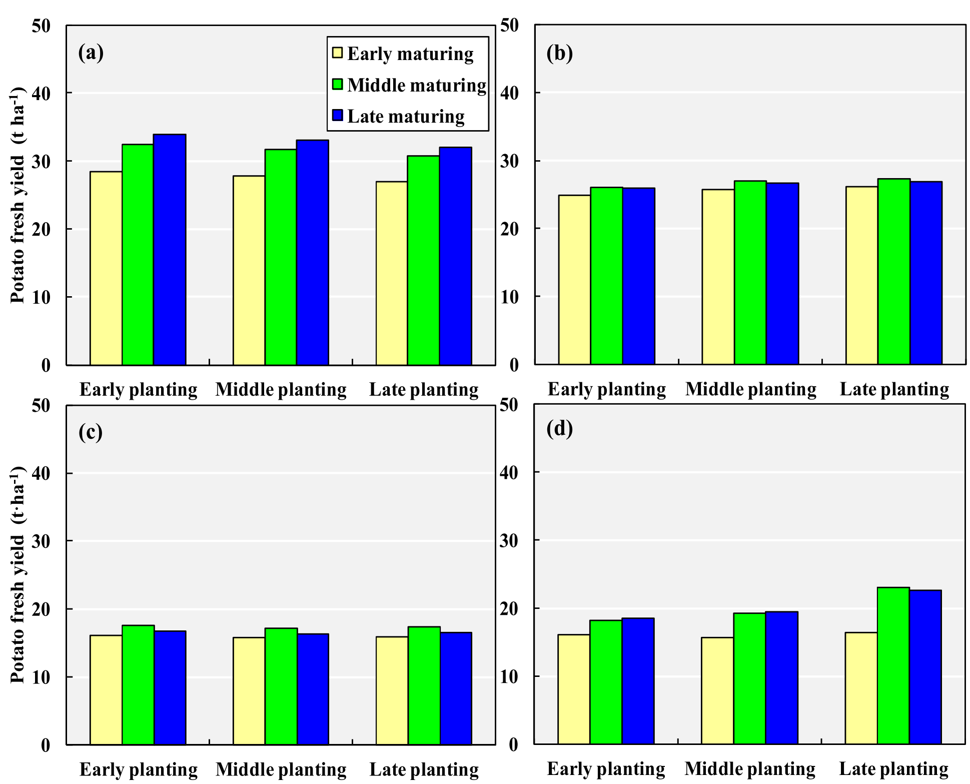

Fig. 5. Simulated fresh yield of potato for each combination of planting date and cultivar maturity based on predetermined irrigation quota in NS (a), CD (b), SW (c), and SWM (d) during 1981–2015. NS, CD, SW, and SWM represent North Single planting region, Central Double planting region, South Winter planting region, and Southwest Mixed planting region, respectively.

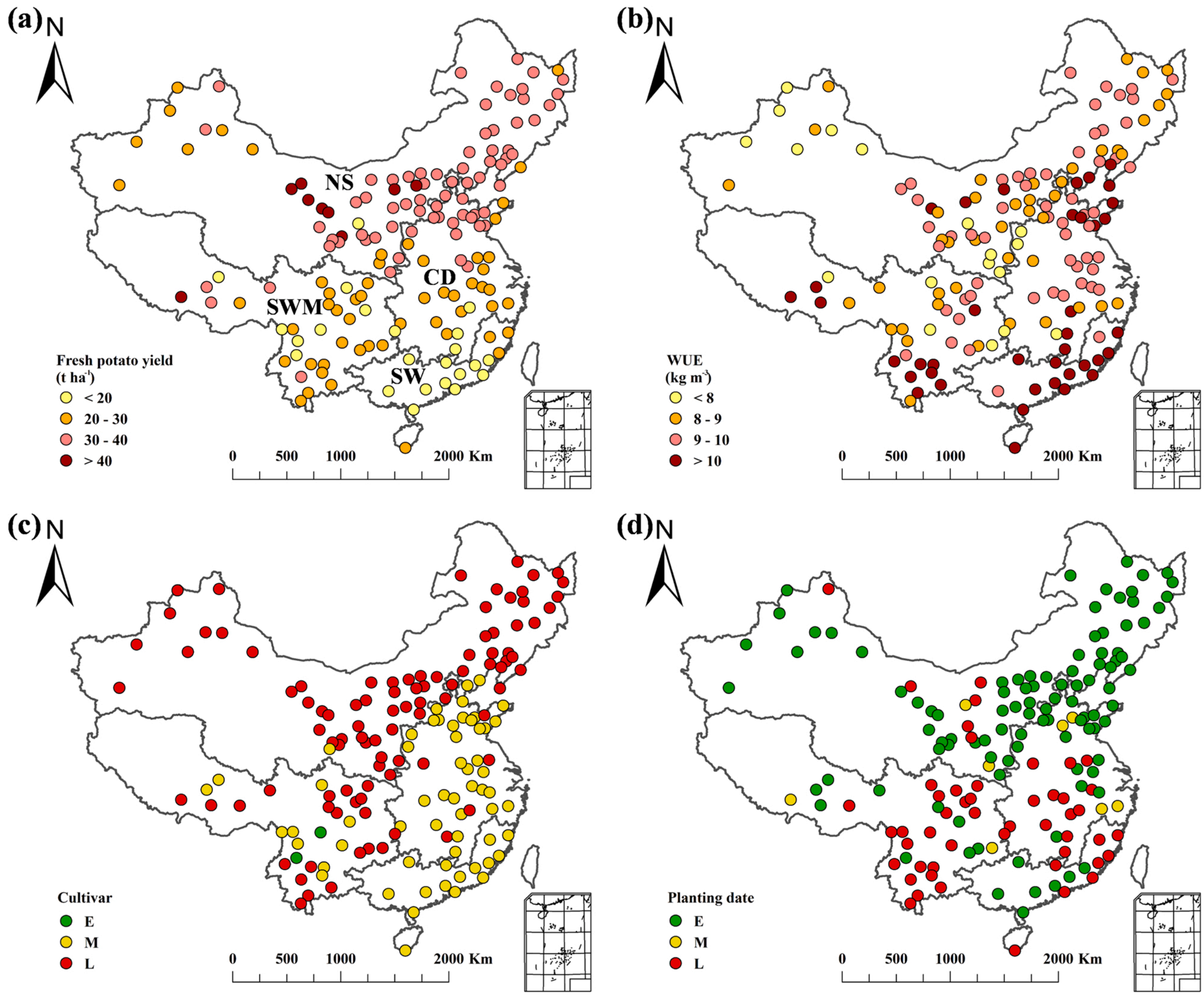

Fig. 6. The fresh yield (a) and WUE (b) of potato under optimal combination of cultivar maturity (c) and planting date (d) across China's potato planting regions. NS, CD, SW, and SWM represent North Single planting region, Central Double planting region, South Winter planting region, and Southwest Mixed planting region, respectively.

4. Discussion

We found that the potential yield was highest in NS, which was 28.8%, 49.5%, and 43.2% higher than that of CD, SW, and SWM due to higher solar radiation (Jansky et al., 2009; Yang et al., 2018; Tang et al., 2019). Rainfed yield only reached 35.6%, 59.2%, 57.2%, and 45.1% of the potential yield, respectively, in NS, CD, SW, and SWM due to water limitation (Wang et al., 2018). We did not compare actual potato yield from the statistical data with our simulation because there were lack of detailed records for cultivars and agronomic management practices in the statistical yearbooks. However, the performance of APSIM-Potato model in simulating the growth and development, water consumption, and fresh yield in response to climate, cultivar, and agronomic management has been tested widely in previous studies (Brown et al., 2011; Tang et al., 2019, 2020; Li et al., 2021).

Irrigation can greatly increase potato yield, however, limited freshwater resources constrain the application of irrigation in China (Rosa et al., 2018). Therefore, the government formulated the irrigation quota based on crop water requirement and available water resources to guide agricultural irrigation (Sun and Kang, 2000; Wu and Zhao, 2010). Average irrigation quota for potato production ranged from 205 to 307 mm across China's potato planting regions. With such amount of irrigation, simulated fresh potato yield was 26.1 ± 8.1 t ha^{-1} and the yield under irrigation quota was close to the potential yield in some regions, implying that the irrigation quota could meet the water requirement of potato under current planting date and cultivar maturity. However, actual potato yields were lower than the simulated values in these regions due to low irrigation efficiency, and improper agronomic management practices such as low quality of seed potato, weeds, insect pests, and disease (Jansky et al., 2009; Tang et al., 2019; Li et al., 2019b). Optimizing planting date and cultivar maturity could effectively decrease hydrothermal stress by adjusting potato growth period to obtain suitable solar radiation, temperature, and precipitation (Van Duinen et al., 2015; Zhang et al., 2019). We demonstrated that adjusting planting date, cultivar maturity, and irrigation schedule could further improve yield and water use efficiency of potato and therefore could realize the water-saving potential by reducing the irrigation amount based on the current irrigation quota. We found that potato WUE increased with increasing irrigation amount in NS and CD while decreased with increasing irrigation amount in SW and SWM. This was because there was a low precipitation amount and high evaporation amount during potato growing season in NS and CD while the natural precipitation was sufficient for potato growth in SW and SWM (Jansky et al., 2009; Chen et al., 2018).

Devising strategies to make use of the current water resource in an efficient way is of importance to save water and increase crop yield

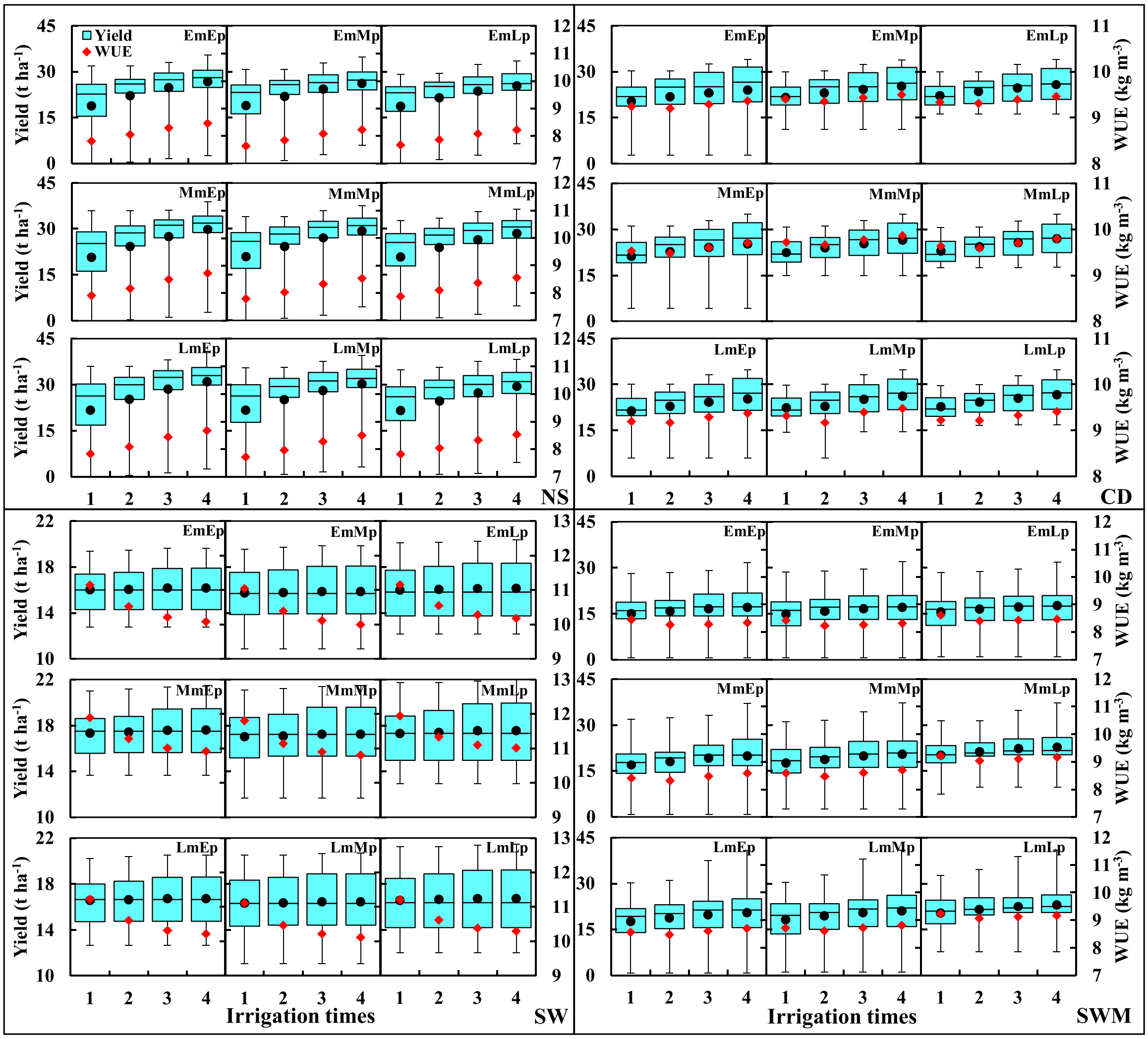

Fig. 7. Simulated fresh yield and WUE of potato under different combinations of planting date, cultivar maturity, and irrigation time in China's potato planting regions. Em, Mm, and Lm represent early-, middle- and late-maturing cultivars, respectively. Ep, Mp, and Lp represent early-, middle- and late-planting, respectively. NS, CD, SW and SWM represent North Single planting region, Central Double planting region, South Winter planting region and Southwest Mixed planting region, respectively. The box whiskers show the maximum and minimum values; the upper and lower box edges of boxes show the 75th and 25th percentiles, respectively; the interior horizontal bar shows the median.

(Shan and Xu, 1991; Van Duinen et al., 2015; Davis et al., 2017b). For boosting water use efficiency, potato cultivars with higher yield and less water consume should be selected firstly. However, the yield and water consume of potato is determined by the interaction of climate, genotype and agronomic management (Zhang, 2018; Tang et al., 2019; Li et al., 2020). Currently, there are no cultivars that could achieve high yield and low ET simultaneously under any climates and agronomic management practices. Thus, for achieving a win-win of yield and water use efficiency, the HYW index was used to realize a trade-off between the fresh yield and water use efficiency of potato. The statistical analysis showed that fresh yield and water use efficiency (WUE) of potato responded differently to potato evapotranspiration (ET) (Fig. S6). Due to various hydrothermal conditions in each region, different agronomic management options had large differences in the relative contribution rate to potato yield enhancement and water-saving potential. Adjusting irrigation schedule contributed more to yield increase and water-saving potential than adjusting planting date and cultivar maturity in NS and CD while in SW and SWM the latter contributed more than adjusting irrigation schedule. Moreover, we analyzed the temporal variations of fresh yield, WUE, and HYW of potato and found they did not change significantly. This was because the determining meteorological factors of fresh yield, WUE, and HYW of potato did not change significantly during the simulation period (data not shown).

Irrigation is widely applied in most China's potato planting regions, especially in NS (Wang et al., 2018). Our results found that the current irrigation quota was higher than the irrigation amount required for approaching potential yield in most China's potato planting regions, which meant the irrigation quota could be reduced dramatically. Compared with irrigation quota, the irrigation times needed not change in NS, CD, and SWM although the average irrigation amount could be reduced by 40%, 29%, and 49% respectively in NS, CD, and SWM by optimizing planting date and cultivar maturity. In SW, reducing the irrigation times from three times to one time could reduce the irrigation amount by 66%. The study results based on the field experiments showed that the optimal irrigation amounts in NS, CD, SW, and SWM were 240 mm, 267 mm, 121 mm, and 157 mm, respectively, which were similar with our simulation results (Wang et al., 2013; Zhang et al., 2013; Li et al., 2019a; Lu et al., 2019). Based on the optimized planting date, cultivar maturity, and irrigation schedule, the average fresh potato yield could increase 59%, 21%, 3%, and 19%, respectively, in NS, CD, SW, and SWM, compared with actual potato yield (Fig. 10). Our study results reveal a large water-saving potential across China's potato

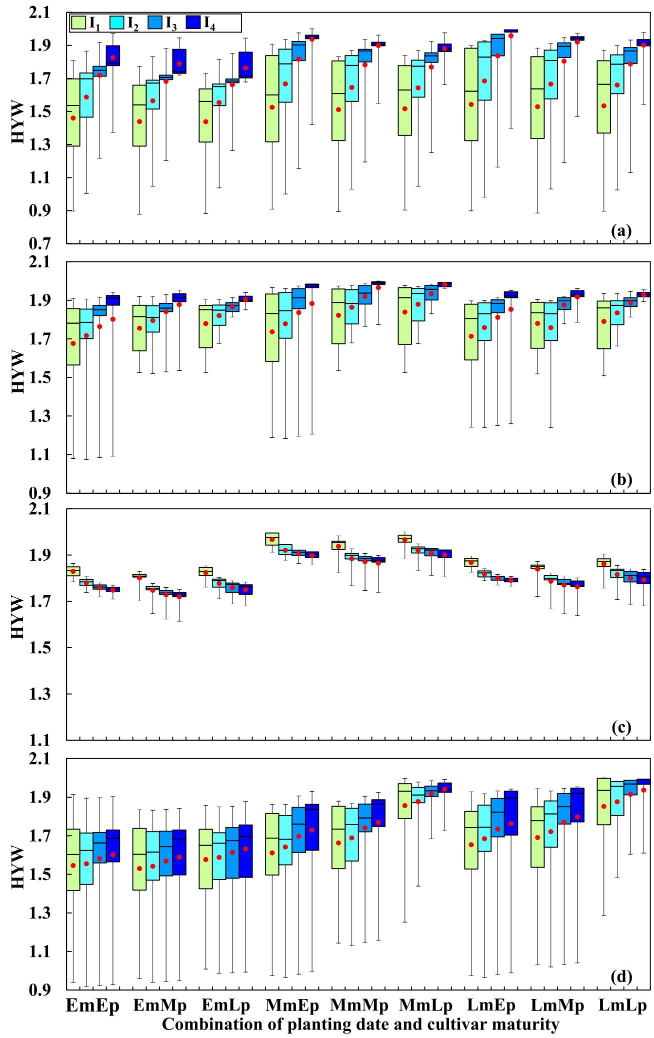

Fig. 8. HYW of potato for different combinations of planting date and cultivar maturity in NS (a), CD (b), SW (c), and SWM (d). Em, Mm, and Lm represent early-, middle-, and late-maturing cultivars, respectively. Ep, Mp, and Lp represent early-, middle-, and late-planting, respectively. NS, CD, SW, and SWM represent North Single planting region, Central Double planting region, South Winter planting region, and Southwest Mixed planting region, respectively. The box whiskers show the maximum and minimum values; the upper and lower box edges of boxes show the 75th and 25th percentiles, respectively; the interior horizontal bar shows the median.

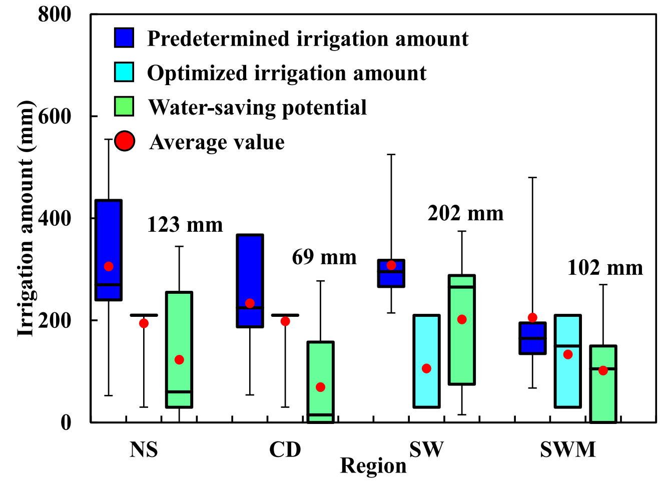

Fig. 9. The water-saving potential, optimal irrigation amount, and predetermined irrigation quota across China. NS, CD, SW, and SWM represent North Single planting region, Central Double planting region, South Winter planting region, and Southwest Mixed planting region, respectively. The box whiskers show the maximum and minimum values; the upper and lower box edges of boxes show the 75th and 25th percentiles, respectively; the interior horizontal bar shows the median.

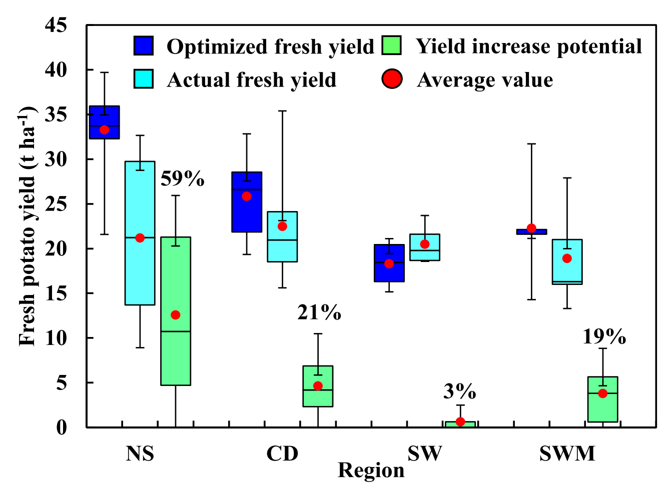

Fig. 10. The yield-increasing potential under optimized planting date, cultivar maturity, and irrigation schedule relative to actual yield across China during 2005–2015. NS, CD, SW, and SWM represent North Single planting region, Central Double planting region, South Winter planting region, and Southwest Mixed planting region, respectively. The box whiskers show the maximum and minimum values; the upper and lower box edges of boxes show the 75th and 25th percentiles, respectively; the interior horizontal bar shows the median.

planting regions, which provides an important reference for guiding regional agricultural water resources management (Yang et al., 2012). Water saved from current irrigation could be used for recovering groundwater or irrigating new farmland (Davis et al., 2017b; Wang and Mei, 2017).

There were several limitations in our simulation results. Firstly, the water-saving measures for potato production only considered the optimization of planting date, cultivar maturity and irrigation schedule. Actually, other agronomic managements such as film mulch and conservation tillage and selecting drought-resistance cultivars could also increase water-saving potential (Saluzzo et al., 1999; Carter and Sanderson, 2001), which needed to be considered in the future study. Secondly, the limitation of nitrogen fertilizer on potato production was not considered. Yield and WUE of potato would change with nitrogen application rate if the interaction effects of water and nitrogen on yield and WUE of potato were considered (Lisson and Cotching, 2011). Thirdly, the irrigation quota did not change with time during our simulation. Actually, government may adjust the irrigation quota according to supply and demand of local agricultural water resource. However, the aim of our study was to investigate the water-saving potential under the current irrigation quota. The last but not the least, the policy of the government would have significant impacts on the water-saving potential of potato production (Yang et al., 2012).

5. Conclusion

Large yield gaps between potential and rainfed yields exist in China's potato planting regions. Increasing irrigation amount could improve potato yields in most China's potato planting regions. However, water resources shortage limits the further development of irrigation potato production in China. Reducing irrigation amount by optimizing planting date, cultivar maturity and irrigation schedule based on current predetermined irrigation quota is of importance for the sustainable development of potato production in China. Our simulation results show that there is a large water-saving potential in most China's potato planting regions, especially in SW, SWM, and NS. Optimizing planting date, cultivar maturity and irrigation schedule could realize win-win of yield and water use efficiency and provide a scientific support for water-saving potato production in China.

CRediT authorship contribution statement

Yang Li: Writing - review & editing, Methodology, Writing - original draft, Formal analysis and data processing. **Jianzhao Tang:** Writing - review & editing, Methodology, Writing - original draft. **Jing Wang:** Writing - review & editing, Methodology, Supervision, Conceptualization. **Gang Zhao:** Methodology, Conceptualization. **Qiang Yu:** Methodology, Conceptualization. **Yixuan Wang:** Visualization. **Qi Hu:** Investigation, Resources. **Jun Zhang:** Investigation, Resources. **Zhihua Pan:** Conceptualization, Funding acquisition. **Xuebiao Pan:** Conceptualization, Funding acquisition. **Dengpan Xiao:** Investigation, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2021.126450.

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