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Is Partial Root-Zone Drying More Appropriate than Drip Irrigation to Save Water in China? A Preliminary Comparative Analysis for Potato Cultivation

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Abstract China is the largest worldwide potato producer where around half of the crops is planted in the semi-arid region frequently affected by water restriction. While innovative methods are needed for water-saving irrigation methods, the use of low-cost and environmental-friendly technology must be prioritised. In this study, potato production under drip irrigation (DI, commonly adopted to save water) was compared with partial root-zone drying furrow irrigation (PRD) using the same water volume per irrigation, in both methods. Two initiation timings (early and late) were tested under

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shelter and field conditions, the water supplied during every irrigation being 50% of the crop water demand calculated for furrow full irrigation (FI, as control). The comparison of both methods was done through the assessment of tuber fresh-yield and estimated economic and environmental (carbon footprint and irrigation water use efficiency, WUE_i) benefits. Late PRD and DI produced the highest WUE_i without significant yield reduction. PRD produced 3.1% higher net benefit than DI with an estimated CO_2 emission of 3659 kg ha^{-1} CO_2 (14% lower than DI). The input-output ratio (total input costs/yield output) for PRD was 0.4, which was 10% lower than DI. The study's results suggested that PRD, with no less than 50% of the water applied in FI per application, not only maintained yield but could also increase revenues while saving water and reducing CO_2 emissions, compared to DI. Such results might help reduce the pressure on the water reserves in semi-arid potato-producing areas in China. Notwithstanding, a scaling-up of PRD technology must be tested in those regions to substantiate the findings of this preliminary study.

Keywords Carbon footprint · Economic benefit · Irrigation methods · Irrigation water use efficiency · *Solanum tuberosum*

Introduction

Potato (*Solanum tuberosum* L.) is the fourth most important food crop after maize, rice and wheat, and is cultivated widely in the world, with China as the largest potato-producing country accounting for 26.3% of global production (FAO 2018). In 2015, the government of China implemented a policy to push potato as a staple food, to guarantee food security and improve human nutrition and health requirements. The aim was to expand potato planting to more than 6.7 million ha by 2020 (CHNMOA 2015). This might exacerbate the current pressure on the use of water resources, since about 50% of potatoes cultivated in this country are grown under irrigation in semi-arid areas (Luo et al. 2015). Moreover, potato is considered sensitive to drought stress due to a shallow and inefficient root system (Stalham et al. 2007). Thus, the expansion of potato cultivation in water-scarce environments poses important research challenges.

In China, declining water resources have raised great public attention in agriculture, so innovative irrigation strategies are developed to save water and increase water use efficiency (WUE) in comparison to conventional irrigation methods (Qin et al. 2013; Zhang and Guo 2016; Giuliani et al. 2016). The government subsidises the implementation of Hi-Tech irrigation systems such as drip irrigation (DI), which in potato reduces soil moisture evaporation and prevents weed growth by supplying water mainly to the root zone (Wang et al. 2007; Qin et al. 2011; Xue et al. 2017). The adoption of DI in several crops has generated benefits such as yield increments (Deng et al. 2009; Kruzhilin et al. 2016), water saving by 30–70% (Zhao and Wang 2016; Ibrahim et al. 2016) and reduced fertiliser application by 10–40% (Li 2008, 2016) compared to furrow irrigation. However, the costs of DI are higher than those of furrow irrigation, when the whole system itself plus maintenance costs are included in the analysis (Shen et al. 2011). Furthermore, after harvest, some plastic residues (pipes, tubes) that are kept in the field become brittle polluting the environment (Yang et al. 2011). Moreover, it has been reported that because system maintenance demands a lot of time, mainly when canopy cover is at maximum, farmers are not able to detect water leaks (caused by insects or other factors) on time which may cause water loss and have a negative effect on plant growth (Chen and Du 2011). On the other hand, partial root-zone drying furrow irrigation (PRD) is considered a deficit irrigation strategy (Perry et al. 2017), which allows half of the root system to be irrigated while keeping the other half dry in each irrigation event, before rewetting the root zone by shifting irrigation to the dry side (Kang et al. 1997). PRD has been successfully applied to potato, reducing water by 30–50% with an increased WUE, without tuber yield reduction (Liu et al. 2006a, b; Saeed et al. 2008; Jovanovic et al. 2010; Xie et al. 2012; Yactayo et al. 2013, 2017). However, challenges for PRD include finding the appropriate timing, duration and intensity of the water restriction management in potato that stimulates some tolerance mechanism to avoid yield reduction (Monneveux et al. 2013). Recent findings, working in potatoes under pot (Saeed et al. 2008) and field (Xu et al. 2011; Yactayo et al. 2013, 2017) conditions, highlight that an early timing of the water restriction (starting at 6 weeks after planting) with PRD using 50% of the amount of water applied with full irrigation allows high WUE with no significant yield reductions through the activation of drought tolerance traits like osmotic adjustment.

While the benefits of furrow versus Hi-Tech irrigation methods have been reported in potato, these studies have not used the same amount of water (Erdem et al. 2005, 2006; Ati et al. 2012) or irrigation frequency (Kumar et al. 2009) in the comparisons. In this study, DI and PRD irrigation techniques were compared using similar amounts of water per equivalent treatments, under sheltered (to avoid unexpected rainfall effect which can bias the results) and field conditions. The metrics used for the comparative assessment included agronomic parameters and economic and environmental (estimated carbon footprint, irrigation WUE-WUE_i) costs. Since the timing for initiating water restriction is an underexplored topic in potato water management (Monneveux et al. 2013), we made the aforementioned comparisons testing early and late DI and PRD initiation treatments. We hypothesised that PRD could show similar benefits in terms of water saving and tuber yield to DI but in a more economic and environmental friendly manner.

Materials and Methods

Experimental Site

The field experiments were conducted from May 16 to September 13, 2013, in the experimental station of Zhangjiakou Academy of Agricultural Sciences (41° 04′ N, 114° 42′ E, 1505 masl), Zhangbei County, China. The climate is semi-arid with 4.0 ± 11.9 °C and 385.8 ± 20.4 mm of average annual temperature and precipitation, respectively, January (−14.6 ± 2.0 °C) and July (19.8 ± 1.0 °C) being the coldest and hottest months, respectively (2003–2014; Zhangjiakou Academy of Agricultural Sciences Meteorological Station). During the study period, the average, minimum and maximum daily temperatures and humidities were 16.3 ± 2.5 °C, − 4.5 °C and 31.2 °C and 66.8 ± 12.6% (Table 1). The soil texture was clay loam with field capacity and bulk density of 0.19 (*w*/*w*) and 1.44 g cm^{-3}, respectively.

Table 1 Monthly average values (± standard error) of meteorological variables from May to September in 2013 in the study area

Month	Minimum temperature (°C)	Maximum temperature (°C)	Average temperature (°C)	Atmospheric humidity (%)	Vapour pressure deficit (kPa)	Precipitation (mm)
May	− 4.9	26.8	14.4 ± 3.0	36.6 ± 16.0	0.6 ± 0.3	7.3
June	5.0	27.5	17.2 ± 2.2	58.6 ± 18.6	1.1 ± 0.3	67.7
July	11.1	29.7	19.2 ± 1.3	72.7 ± 9.6	1.6 ± 0.2	116.8
August	5.8	31.2	18.5 ± 2.6	69.0 ± 8.5	1.4 ± 0.3	71.3
September	− 4.5	24.1	12.5 ± 2.9	60.1 ± 12.4	0.9 ± 0.3	21.4

Experimental Design

The potato cultivar tested was Shepody (CIP code 801079) which is considered drought sensitive (Zhou and Zhang 2015). The experiment was carried out under open field and rain-proof shelter conditions, the latter installed to avoid interference with tested water treatments from potential rainfall water. For both conditions, there were five blocks with five plots (5×3.5 m^2) per block. Each plot had five ridges (0.7 m apart from each other). Potatoes were planted at a distance of 0.3 m resulting in a plant density of 4.8 plants m^{-2}. The irrigation treatment was randomly assigned to each plot in the block (randomised block design). The irrigation treatments (details below) were as follows: full furrow irrigation (FI) supplying 100% of the water demand; early PRD and early DI with 50% water amount of FI (E-PRD$_{50}$ and E-DI$_{50}$), starting the irrigation after but close to tuber initiation onset (TIO around 43 DAP); and late PRD and late DI with 50% water amount of FI (L-PRD$_{50}$ and L-DI$_{50}$), starting the irrigation 2 weeks after TIO. Tuber initiation was visually detected by removing and replacing soil from randomly chosen border plants.

Irrigation Management

Twenty transparent plastic water tanks (300 L of capacity, graduated at 5 L) placed at 1.5 m height were used for both open field and shelter conditions. Four tanks were placed per block, one for FI, one for PRD and two for DI plots. The water supply for the tanks came from a water reservoir (10,000 L capacity) placed 40 m from the experiment. From planting to the beginning of the irrigation treatment period, the only water supplied was 34.7 mm from a rainfall event after which the rain-proof shelter was used and the treatments were initiated. When the water treatment started, both PRD and DI received the same amount of water in each irrigation event. Water demand was assessed to define the required irrigation quantity (I, mm) in FI every 10 days, as follows:

$$I = \frac{[((\theta_{FC} \times BD) - (\theta_{act} \times BD)) \times RD]}{10} \times WA \quad (1)$$

Where θ_{FC} is gravimetric soil moisture at field capacity (0.19), θ_{act} is actual gravimetric soil moisture (%), BD is soil bulk density (1.44 g cm^{-3}), RD is root depth (0.25 m), and WA is wetted area (distance between rows/wetted perimeter) (see Fig. 1). Before each irrigation, two representative soil samples in every FI plot were collected from the middle of the two plants in the respective centre ridges at 0.25 m depth to calculate θ_{act}. This soil sampling depth assumed that the main roots were distributed between 0.2–0.3 m and that the soil water potential at a depth of 0.25 m could represent the trend of 0–0.5 m in depth (Guo et al. 2015). Soil samples were weighed and dried (at 105 °C for 24 h) and re-weighed. Then, the water demand for FI treatment was calculated using Formula (1) and water was pumped (pump of 7.5 kW, 380 V, 52 m lift and 20 $\mathrm{m}^3\ \mathrm{h}^{-1}$ capacity, Tianjin Weiyi Electrical Machinery Factory, Tianjin, China) from the reservoir to the tanks. For volumes less than 5 L, a small container (15 L, graduated every 1 L) was used to add the remaining quantity of water to the tank. After the water amount for FI was estimated, 50% of this quantity was provided to the tanks which supplied water for plots under PRD and DI irrigation treatments in tandem.

Plastic barriers were buried in the soil in the perimeter of the sheltered area and down to 30 cm among plots to avoid lateral water flow. PRD consisted in irrigating only one side of the root system, while keeping the other side dry in each irrigation event, alternating sides every 10 days. A drip irrigation system was installed in plots with DI treatments consisting of drip taps with emitters (with a flow rate of 1.38 L h^{-1}) spaced at 0.3 m on the top of the ridge. As in furrow irrigation, 50% of estimated FI water demand was placed in the respective reservoirs and delivered through the DI system.

The rain-proof shelter was 90 m long and 8.5 m wide, but the actual area used for the experiment was 88.2 × 5 m^2 to avoid boundary effect. The shelter was made of two aluminium arched frames (1.5 mm thick) which consisted of a shoulder (1.6 m height) and roof (2.5 m top height) (see Fig. 2). Only the roof from 0.8 m above the ground was covered by a transparent plastic film to prevent rainfall, and a nylon net (0.425 mm) was used for the whole frame to reduce the entrance of pest and disease vectors. The plastic

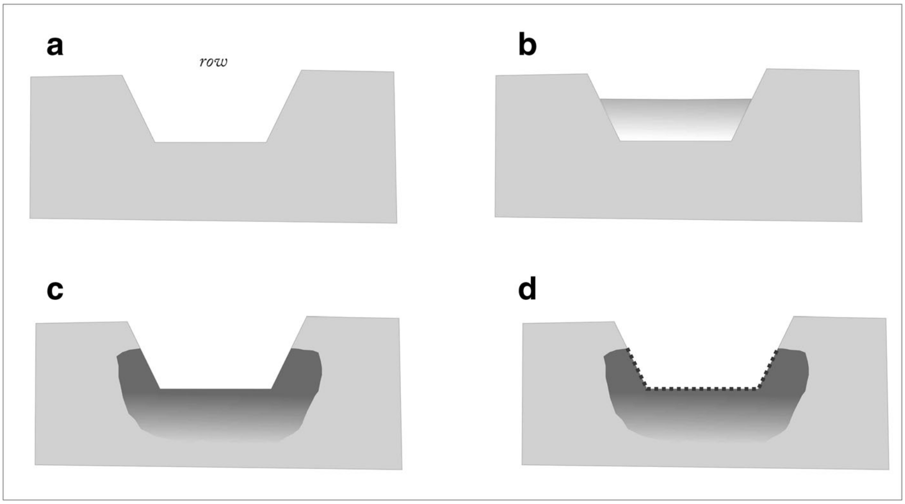

Fig. 1 Schematic representation of the measurement of the average wetted perimeter. Transversal image of a row: **a** before irrigation; **b** during irrigation; **c** immediately after the irrigation where it is possible to distinguish the wetted part of the row (dark colour); **d** measure of the wetted perimeter using a flexible metric tape up to 20 sampling points or rows (blue dotted line) in the plot, the average value can be used as the plot wetted perimeter

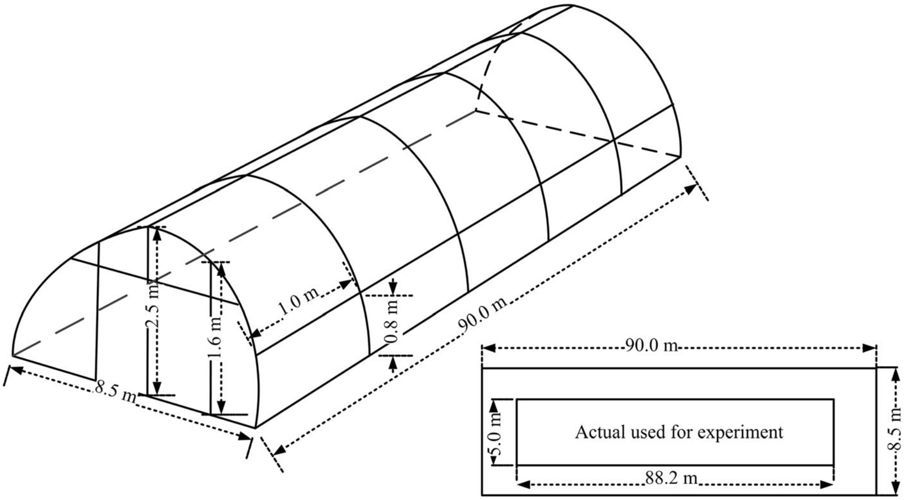

Fig. 2 Rain-proof shelter frame for the experiment

film was also buried to 0.3 m depth inside the frame and kept 0.65 m away from the border of the frame to prevent entry of outside water.

Agronomic Practices

Compound fertiliser (15:15:15) was applied at a rate of 495 kg ha^{-1} before planting, giving 74.3:74.3:74.3 kg ha^{-1} of N:P_2O_5:K_2O. To avoid soil-borne disease affecting emergence, seed tubers were treated with 70% of thiophanate methyl wettable powder: talcum powder (1:25) at a dose of 6 kg ha^{-1}. Late blight disease was controlled by 75% mancozeb wettable powder (Hebei Shuangji Co., Ltd., Shijiazhuang City, China) and 75% metalaxyl-mancozeb wettable powder (Zhejiang Heben Pesticide & Chemicals Co., Ltd., Wenzhou City, China) applied (1.5 kg ha^{-1}) to the canopy on July 5 and August 5, 2013, respectively.

Response Variables

Tuber Yield and Components

The final harvest was conducted on September 13, 2013, with yields recorded from the centre two rows of the plot to avoid border effects. Marketable tuber (per tuber fresh weight > 150 g) yield (MTY) and total fresh tuber yield (FTY) were measured.

Irrigation WUE (WUE_i, kg m^{-3}) was calculated by dividing the total tuber dry biomass by the amount of water received by each treatment, including the contribution from rainfall, for open field conditions. Total tuber dry biomass was determined by FTY multiplied by tuber dry biomass of 100 g tuber fresh biomass (100 g sample of fresh tuber was taken from three representative tubers and then dried in an air forced oven at 75 °C (Kheirandish and Harighi 2015) until the weight was constant).

Environmental and Economic Indicators

Carbon footprint was calculated using the online model "Cool Farm Tool" developed by the University of Aberdeen and the Sustainable Food Lab (CFA 2013) and based on field information about yield, seed amount, planting and harvest date, soil texture, fertiliser amount, fungicide amount, above ground biomass, irrigation and pumping energy use and fuel for field management (see details in Haverkort and Hillier 2011). For the economic comparison, net benefit was calculated based on the costs including fixed assets and operation. The input-output ratio (total input costs/yield output) for all treatments was determined by the total input costs and yield output data. Depreciation of DI and PRD was different due to the irrigation system. The useful life of the irrigation system was based on the experience of the irrigation equipment company (Dayu Water-saving Group, Wuwei, China; see Table 2).

Data Analysis and Statistics

Statistical analysis was performed by ANOVA using a randomised block design. Dunnett's multiple range test was applied to compare water restriction treatments against control (FI), then Duncan's test was applied to all measured parameters in order to assess differences among irrigation treatments. All the statistical analyses were run with SPSS v20.0 software (SPSS, Inc., Chicago, IL, USA).

Results

Yield Components and WUE_i

There were no significant differences ($P > 0.05$) among the treatments for MTY and FTY in shelter and open field conditions (Table 3). In general, FTY and MTY in open

Table 2 Irrigation system annual depreciation of drip irrigation (DI) and partial root-zone drying under furrow irrigation (PRD)

Irrigation method	Item	Cost (RMB ha^{-1})	Useful life (years)	Depreciation (RMB $year^{-1}$)
DI	Head	450	10	45
	Main pipe line	2085	20	104
	Sub pipe line	1425	5	285
	Accessories	534	5	107
	Drip line	1665	0	1665
	Total			2206
PRD	Head	2805	10	281
	Main pipe line	2243	20	112
	Sub pipe line	652.5	10	65
	Total			458

Table 3 Results of the analyses of variance assessing marketable and total fresh tuber yield and irrigation water use efficiency (WUE_i) under shelter and open field conditions

Variable	Factor	DF	Shelter F-value	Open Field F-value
Marketable tuber yield	Treatments	4	2.2 $^{n.s.}$	1.4 $^{n.s}$
	Blocks	4	1.2 $^{n.s}$	0.7 $^{n.s}$
Total fresh tuber yield	Treatments	4	1.1$^{n.s}$	0.0 $^{n.s}$
	Blocks	4	2.2 $^{n.s}$	1.2 $^{n.s}$
WUE_i	Treatments	4	6.2 **	0.5 $^{n.s}$
	Blocks	4	2.1$^{n.s}$	1.4 $^{n.s}$

DF degree of freedom

$^{**}P < 0.01$, $^{n.s}P > 0.05$

field condition (38.1 and 25.7 Mg ha^{-1}, respectively) were 21.8 and 7.0% higher than shelter condition (31.3 and 24.0 Mg ha^{-1}, respectively) (Fig. 3). Under both conditions, the higher FTY and MTY were obtained by E-PRD_{50} and E-DI_{50} and the lower FTY and MTY were obtained by L-PRD_{50} and L-DI_{50} (Fig. 3). Similar to yield components, there were no significant differences ($P > 0.05$) among treatments in WUE_i for open field conditions whereas in shelter conditions this trait showed significantly ($P < 0.01$) higher values under late treatments (5.6 kg m^{-3} on average) and lower values for the control (FI, 2.8 ± 0.3 kg m^{-3}) (Table 3, Fig. 3). In general, WUE_i in open field conditions (2.6 kg m^{-3}) was 45.9% lower than under shelter conditions (4.8 kg m^{-3}) (Fig. 3). Due to the water contribution from rainfall (253.1 mm), the irrigation in open field conditions required 78.3% less irrigation water than in shelter conditions in FI (Table 4).

Economic Benefit Analysis

Under shelter conditions, the net benefit for FI was 19,246 RMB ha^{-1} (as a reference for the reader, 1 RMB = 6.5 US$), which was the highest followed by E-DI_{50} > L-PRD_{50} > E-PRD_{50} > L-DI_{50} (Table 5). Although the cost of DI was 10.6 and 16.3% higher than FI and PRD, respectively, the net benefit of E-DI_{50} was relatively high (18,379 RMB ha^{-1}) i.e. only 4.5% less than FI (Table 5). In open field conditions, E-PRD_{50} produced the highest net benefit (24,743 RMB ha^{-1}) followed by L-PRD_{50} > L-DI_{50} > FI > E-DI_{50}, but the amplitudes of the net benefits among all the treatments were smaller than those under shelter conditions (Table 5). The average value showed that the irrigation system cost for DI was 4.8 times higher than for PRD and FI, where extra costs were mainly associated with pipelines and filter systems (Table 2), machinery and laying and drip line collection (Table 5). The yield output was higher in FI (35,516 RMB ha^{-1}) than DI followed by PRD (35,304 and 33,722 RMB ha^{-1}, respectively, Table 5). The other costs including seed, chemicals and fertilisers were the same for all the treatments whereas the net benefits for PRD and DI were only reduced by 5.3 and 0.6%, respectively, compared with FI (Table 5). PRD produced 3.1% higher net benefit than DI through low costs for irrigation system and machinery. The input-output ratios for FI and PRD (0.4) were 10% lower than DI (Table 5).

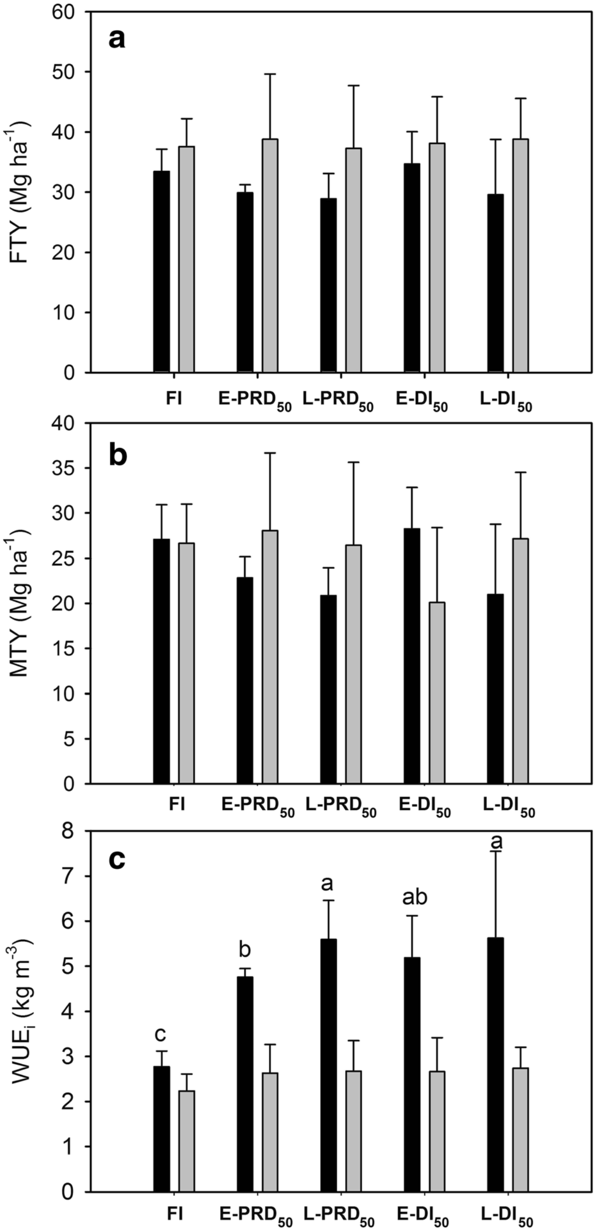

Fig. 3 Average total fresh tuber yield (FTY), marketable tuber yield (MTY) and WUE$_i$ under shelter (dark bar) and open field condition (grey bar). Different letters mean significant differences in ANOVA at $P < 0.05$

Carbon Footprint as an Environmental Indicator

CO_2 emissions from fertiliser and soil/fungicides were the same for both treatments, but CO_2 emissions from the energy use of DI were 19% higher than that of PRD as well as from crop residue and seed production (Table 6). In general, the total CO_2 emission of

Table 4 Total amount of water used under full irrigation (FI), drip irrigation (DI) and partial root-zone drying (PRD) systems under both environmental tested conditions. Early (E-PRD$_{50}$; E-DI$_{50}$) and late (L-PRD$_{50}$; L-DI$_{50}$;) treatments of the initiation of PRD and DI were tested using 50% of water demand of FI

Treatment	Shelter	Open field	
	Irrigation (mm)	Irrigation (mm)	Precipitation (mm)
FI	241.3	71.7	253.1
E-PRD$_{50}$	120.6	35.9	253.1
L-PRD$_{50}$	88.6	27.1	253.1
E-DI$_{50}$	120.6	35.9	253.1
L-DI$_{50}$	88.6	27.1	253.1

PRD was 3659 kg ha^{-1} (109 kg CO$_2$ Mg fresh potato^{-1}) which was 14% lower than DI through less crop residue (above ground biomass) and energy use (lay and collect pipe line) (Table 6).

Discussion

In this study, both PRD and DI were irrigated with the same amount of water which was 50% of the water used in FI. In spite of the sizable reduction in irrigated water, tuber yields did not differ from the control (FI). This finding was in agreement with that of other studies (Foti et al. 1995; Erdem et al. 2005; Yactayo et al. 2013, 2017) showing the usefulness of both methods to save water in potato cultivation. The results confirmed the hypothesis that PRD produced no significant difference in tuber yield and WUE$_i$ compared to DI, but in an economically and environmentally friendly manner, under both tested conditions.

Table 5 Economic benefit of different irrigation methods (RMB ha^{-1})

Condition	Treatment	Yield[1] output	Irrigation[2] water	Irrigation system	Machinery	Labour	Other[3] costs	Net benefit
Shelter	FI	33,449	162	458	1800	4200	7584	19,246
	E-PRD$_{50}$	29,902	81	458	1800	4200	7584	15,779
	L-PRD$_{50}$	28,875	59	458	1800	3000	7584	15,973
	E-DI$_{50}$	34,700	81	2206	2250	4200	7584	18,379
	L-DI$_{50}$	29,562	59	2206	2250	3000	7584	14,463
Open field	FI	37,583	48	458	1800	4200	7584	23,493
	E-PRD$_{50}$	38,809	24	458	1800	4200	7584	24,743
	L-PRD$_{50}$	37,302	18	458	1800	3000	7584	24,442
	E-DI$_{50}$	38,146	24	2206	2250	4200	7584	21,882
	L-DI$_{50}$	38,807	18	2206	2250	3000	7584	23,749
Average	FI	35,516	105	458	1800	4200	7584	21,370
	PRD	33,722	46	458	1800	3600	7584	20,234
	DI	35,304	46	2206	2250	3600	7584	19,618

[1] The average price was 1.0 RMB kg^{-1}

[2] The price of the water was 1.5 RMB mm^{-1}

[3] Including seed, chemicals and fertiliser

Table 6 Average carbon footprint of drip irrigation (DI) and partial root-zone drying under furrow irrigation (PRD) in both conditions

Item	Total CO_2 eq/kg ha^{-1}	
	DI	PRD
Energy use (field)	1413.4	1189.7
Fertiliser production*	795.7	795.7
Soil/fertiliser	304.0	304.0
Fungicides	61.5	61.5
Crop residue management	1432.2	1079.3
Seed production	255.4	228.9
Total	4262.3	3659.1

*Calculated with validated default values for fertiliser production

PRD and Drip Irrigation Did Not Penalise Tuber Yield and Improved WUE_i

In both conditions, fresh tuber yield for all the treatments did not show significant differences. In the open field, the response was hindered by the supplementary water from rainfall which offset the benefit of FI. However, under the shelter, the advantages of the PRD and DI treatments were evident in that FTY and MTY were not significantly decreased compared with FI. PRD irrigation can positively affect the soil temperature and water uptake, consequently preventing significant tuber yield reduction (Karandish and Shahnazari 2016). Our results were in agreement with studies testing alternate deficit irrigation or PRD (Wang et al. 2009; Xie et al. 2012; Yactayo et al. 2013, 2017; Abdelraouf 2016) and deficit irrigation (Erdem et al. 2005; Wang et al. 2009) in which potato yield was not significantly reduced using 50% of the water supplied in FI. No significant ($P > 0.05$) reductions in potato tuber yield have been reported in studies comparing furrow versus drip irrigation when the latter used the same criteria as the former (Erdem et al. 2005, 2006; Kumar et al. 2009; Ati et al. 2012). Similar to our results, Erdem et al. (2005) reported that DI at 50% of soil water demand showed similar tuber yield to FI irrigated at 100% of soil water demand. An increased soil moisture frequency and aeration effectiveness in the root zone, a reduction in nutrient leaching and percolation, an enhanced nutrient efficiency and evapotranspiration or water consumption reduction are attributed advantages of DI compared to FI in potato (Erdem et al. 2006; Kumar et al. 2009) and other Solanaceous crops (Tagar et al. 2012). However, we could not find studies in the literature comparing alternate deficit irrigation or PRD versus DI in potato or other crops using 50% of water amount of FI. Nevertheless, when these two irrigation techniques were compared in other crops, PRD produced higher yields (similar to control) than DI, probably associated with differences in water volumes used per method (Sezen et al. 2014). The absence of significant differences ($P > 0.05$) in tuber yield found in the present work between PRD and DI requires future study to understand the physiological mechanisms and strategies in this crop under these two irrigation conditions (see for example Kachwaya et al. 2016).

WUE_i under shelter conditions (range 2.8–5.6 kg m^{-3}) was higher than that in open field conditions (range 2.2–2.7 kg m^{-3}), and previously reported values in potato (0.6–2.6 kg m^{-3}; Monneveux et al. 2013), thus showing the water-saving potentiality of PRD and DI. In this study, FI produced the lowest WUE_i under both conditions compared with PRD and DI, which coincides with findings of other studies in potato (Erdem et al. 2006; Shahnazari et al. 2007; Kumar et al. 2009; Ati et al. 2012). Ahmadi et al. (2010) also reported similar results but depending on soil type, i.e. lower water productivity in FI under sandy loam and coarse sand conditions but not in loamy sand conditions. In general, as the water amount decreased, WUE_i increased, which was in agreement with the results reported by Ahmadi et al. (2014) and de Lima et al. (2015) in potato. Notwithstanding, WUE_i response depends on cultivars, soil texture, root distribution, weather condition and water amount (Ahmadi et al. 2010; Xie et al. 2012; Ahmadi et al. 2014; El-Abedin et al. 2017). For example, there were other studies which reported lower WUE_i under PRD furrow irrigation (Ahmadi et al. 2014) and PRD drip irrigation treatments (El-Abedin et al. 2017) compared to FI. El-Abedin et al. (2017) also reported that potato under deficit drip irrigation with 50–70% of the water supplied for drip full irrigation resulted in similar WUE_i compared to FI.

The results of this study showed that irrigation treatments initiated 2 weeks after TIO for both DI and PRD, with only 36% of the total water amount applied to FI, did not significantly reduce yield, which was in agreement with other studies in potato (Jovanovic et al. 2010; Xie et al. 2012; Yactayo et al. 2017). The findings showed that both water restriction timing and water amount must be considered when water-saving technologies are implemented in potato. Late treatments, starting 2 weeks after TIO, produced higher WUE_i without significant tuber yield reduction. Since this stage is considered the most water-sensitive stage (van Loon 1981), exposing the plant to drought stress in the early growth period causes a priming effect after which plants are more prepared to tolerate the next water restrictions events. Short-term water stress memory improvement after PRD treatments has been reported in potato (Xu et al. 2011; Yactayo et al. 2013) and this study supports these findings, but further research is required to understand the underlying mechanisms (epigenetic effects, protein signalling).

PRD Showed Economic Benefits and Lower Carbon Footprint than Drip Irrigation

Although the average yield output of DI was 4.7% higher than PRD, the costs of the former were 16.3 and 10.6% higher than PRD and FI, respectively, caused by filter systems, pipe lines and their management, including laying, maintenance and cleanup (Table 5). This result was in agreement with economic comparisons in potato (Kumar et al. 2009) and other crops like cotton and wheat where the DI costs were reported to be 8.3 and 36% higher than FI, respectively, with similar yield output in both irrigation systems (Huang 2005; Li 2012). However, while in cabbage, tomato, cucumber, eggplant and pepper the costs of FI were 4% higher than DI, this was attributed to the fact that the calculations did not include the head and pipeline used in the DI system (Zheng et al. 2010). Also, in this study, FI generated the highest net benefit followed by PRD and DI, which was partly in accordance with the result in pepper where the net benefit of DI from the output was reduced mainly due to the higher cost of the irrigation system (Sezen et al. 2015). Furthermore, PRD was a more environmentally friendly technology producing a total average CO_2 emission of 109 kg CO_2 Mg fresh potato^{-1}, which was 10% lower than that emitted by DI (Table 6). The CO_2 emission values reported in this study (109–121 kg CO_2 Mg fresh potato^{-1}) were in the range (71–310 kg CO_2 Mg fresh potato^{-1}) of others reported in potato cropping systems (Röös et al. 2010; van Evert et al. 2013; Haverkort et al. 2014; Steyn et al. 2016). However, as the fertilisers were only applied once before planting, the most important contributors (energy and crop residual) of CO_2 emissions in this study were different to the most important factor (fertiliser-induced emissions) in the aforementioned works.

Conclusion

The application of water-saving irrigation technologies like partial root-zone drying (PRD) or drip irrigation (DI), starting 2 weeks after tuber initiation onset (TIO), can save 50% of the water used per irrigation in common irrigation practices like furrow irrigation (FI), thus avoiding significant tuber yield reduction while raising irrigation water use efficiency (WUE_i). PRD maintained yield, improved WUE_i, saved 2198 RMB ha^{-1} and reduced 12 kg CO_2 Mg fresh $potato^{-1}$ of carbon emissions, compared to DI. However, more studies are necessary to test these preliminary findings in other environments with commonly used water stress tolerant potato cultivars, especially in the semi-arid regions of China. Such studies would nurture the scaling-up of irrigation methods like PRD which appears to be of lower cost and more environmentally friendly than DI. To further this scaling-up process, the involvement of local farmers and governmental efforts are required to achieve success in the adoption of this technology. The potential revenues in terms of reducing the pressure on the limited water resources available, fully justify such an undertaking.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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