Improving Water and Nutrient Use Efficiency of Potato by Partial Root-Zone Drying Irrigation in a Semi-Arid Area in China: A Field Experimental Study

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Abstract — Partial root-zone drying irrigation (PRD) has been established as an efficient technology to save water without sacrificing crop yield, but its effectiveness in saving nutrients and reducing the impact on soil and water environment is less well understood. In this paper, we present the results of a field experimental study with potatoes to demonstrate that PRD can save not only water but also nitrogen. It keeps soil water at 90% of the field capacity, alternately keeping half of the roots dry in both subsurface-drip and furrow PRD. The measurements of soil nitrogen after harvest revealed that the residual mineral nitrogen in the soil from 0 to 30cm deep reduced by 29.72% and 17.05% respectively under drip PRD and furrow PRD compared to the corresponding full irrigation. Similarly, for soil in depth from 30 to 60cm, these increases to 13.52% and 33.17% respectively under drip full irrigation and furrow full irrigation compared to the corresponding PRD irrigation. It indicates a significant decrease in nitrogen leaching when irrigated using drip PRD.

Keywords - potato; nitrogen uptake; residual nitrogen; partial root-zone drying; subsurface drip irrigation; furrow irrigation

I. INTRODUCTION

China is the biggest potato producing country in growing area and yield in the world, with the output of potatoes approximately 730×108 kilogram per year, close to one fourth of total tuber yield of the world [1]. Due to its sparse and shallow root system, soil water deficit obviously influences tuber yield [2]. Thus, supplementary irrigation is always needed to produce high yielding plants in a semi-arid area. Until now, however, knowledge is unavailable on how to improve irrigation water-use efficiency (IWUE) and nitrogen efficiency of potato by PRD. PRD has been reported to enhance WUE while maintaining the yield in several crops [3]. The PRD method is to irrigate the plants alternately on different zones of the root system and alternately part of the plant root exposed to drying soil. [4]. As stated above, many studies have been conducted to assess the influence of fertilizer, irrigation strategies, plant species and other factors on the nitrogen uptake and WUE by potato [5], but the response of soil nitrogen residual as well as uptake to different irrigation management strategies under semi-arid environmental conditions is still not fully understood. The objective of this study was that how to affect the nitrogen cycle and water use efficiency in the soil-plant system during the whole growth cycle of potato with the approach of PRD, deficit irrigation (DI) and full irrigation (FI). The study results might be useful in the areas where deficit irrigation and soil quality maintenance are needed in crop production.
content (Θ) in the root zone was 0.439 and 0.089 m³/m³, respectively.

Figure 1. Daily means of temperature (a), vapor pressure deficit (b), radiation (c) and potential evapotranspiration (d) during the experimental period in 2007 and 2008

B. Experimental Design and Irrigation Treatment

In 2007, the field trial was a randomized complete block design with two subsurface drip irrigation treatments (full irrigation (FI1), partial root-zone drying (PRD1) and two furrow irrigation treatments (full irrigation (FI2), partial root-zone drying (PRD2)). Irrigation scheduling was based on soil water measured with a Time Domain Reflectometer (TDR). Three TDR probes groups were installed in line with the drip lines close to a plant and to both sides halfway to the neighboring plants (Figure 2a and b). The full irrigation treatment was irrigated daily to maintain the soil water content at 5–10 mm below field capacity during the whole growing season. The PRD treatment received 70% of the irrigation water volume of FI at each irrigation event in which half of the root zone was irrigated while the other half was dried out. PRD was started after tuber initiation, 36 days after planting (DAP) and lasted until maturity, 97 DAP. Up to 36 DAP, PRD was irrigated as FI. For more details, see Li Ping et al.

In 2008, the field trial was a fully randomized design with three replicates of three subsurface drip irrigation treatments [full irrigation (FI1), partial root-zone drying (PRD1), deficit irrigation (DI1, 70% irrigation amount of FI1)] and two furrow irrigation treatments [fully irrigation (FI2), partial root-zone drying (PRD2)]. The FI treatment was irrigated daily to maintain the soil water content at 5–10 mm below field capacity during the whole growing season. The PRD treatment received 70% of the irrigation water volume of FI at each irrigation event in which half of the root zone was irrigated while the other half was dried out. PRD was started after planting (36 DAP) and lasted until maturity (97 DAP). DI and PRD treatments received 70% of the irrigation water amount of FI in each irrigation event during the whole growing season. In PRD treatments the irrigation was alternated between the two sides of the rows at 5–10 days interval in 2007 and weekly in 2008. Subsurface drip lines for irrigation were installed in the middle of the ridge 10 cm below the soil surface. For the PRD treatments the drip lines were placed in parallel, positioned at the same depths as in the FI and DI treatments (Figure 2c). Other management practices during the whole growth season were completely uniform.
C. Fertilization

In 2007, fertilizers were applied by ploughing (tractor, YTO-600) at rates of 168.86N, 58P, 58 K (kg/hm²) as the base fertilizer. Initial N content of the in the top soil (0-60cm) was 3.18 kg/hm². In 2008, fertilizers were applied by ploughing at rates of 158.33N, 62.5P, 62.5K (kg/hm²) as the base fertilizer. At the period of tuber initiation, fertilizers were applied by irrigation at rates of 37.5N, 30P, 17.25K (kg/hm²). At the period of the beginning of flowering, fertilizers were applied by irrigation at rates of 37.5N, 30P, 17.25K (kg/hm²). Initial N content of the root zone was 4.30 kg/hm². Initial N content was measured by the Key Laboratory of High-Efficient and Safe Utilization of Agriculture water Resources of the CAAS.

D. Crop Management

Seedbed preparation was conducted during the early spring. Seed tubers of the Jinyan were pre-conditioned at 14-16°C for about 2 weeks under dim light until they had 5 mm long shoots. They were planted as soon as possible with temperature of at least 8°C at 10 cm depth in the middle of the day (usually early March). They were then placed at a distance of 30 cm apart, 17 cm below ridge level. Subsequently, the drip lines were placed 10 cm below the top of the ridges. Because of a delay in the installation of the irrigation system (laid down late April and operational in May), tubers at the Xinxiang site were planted in early April and some measurements were missed.

E. Plant Sampling and Measurements

Plant samples were taken after harvest (3 samples per plot), stored at room temperature and analyzed for NO3-N, NH4-N, Total Nitrogen (TN), Available P (AP), and potassium (AK) in stem and leaf. Tubers were stored at room temperature and analyzed for NO3-N, NH4-N, Total Nitrogen (TN), Available P (AP), potassium (AK), starch, deoxidized sugar and total acidity in the tuber. The measurements were done according to standard methods of plant analysis.

F. Soil Sampling and Measurements

Soil samples (5 samples per plot) were taken by the soil auger with a standard 3.5 cm in the bit diameter from soil layers after key growth stage of potato, stored at room temperature and analyzed for NO3-N, NH4-N, Total Nitrogen (TN), Total Organic Carbon (TOC), Available P (AP), and potassium (AK), pH, Bulk Density (BD), and CaCO3(Figure 3). The measurements were done according to the standard methods described in the methods of soil analysis.

G. Statistical analysis

Analysis of variance (ANOVA) was performed using the general linear model univariate procedure from DPS7.05 software. ANOVAs were done with irrigation method and fertilization level as the main effects and their interaction. All the treatment means were compared for any significant differences using the Duncan’s multiple range tests at significant level of P<0.05 with the DPS7.05 for Windows software package.

III. RESULTS

A. Irrigation and Water Use Efficiency

Table 1 shows the irrigation amount and irrigation water use efficiency of different treatments in 2007 and 2008. In 2007, during the PRD treatment period, the full subsurface drip irrigation treatment and full furrow irrigation treatment were irrigated with 58.91mm. For the whole growing season the FI and PRD treatments received 85.30 and 103.77 mm, respectively. The tuber yield of PRD1, FI1, PRD2, FI2 was 9.62, 9.64, 7.48, 6.31 tons per hectare, respectively. The PRD treatments were not significantly different from full irrigation (p<0.05). The irrigation water use efficiency of PRD1, FI1, PRD2, FI2 was 112.82, 92.87, 87.75, 60.85 kg/hm²/mm, respectively. The WUE or the PRD treatments was significantly higher than that of FI (p<0.05). In 2008, the PRD1, FI1, DI1, PRD2 and FI2 treatments received 131.9, 174.5, 131.9, 166.1 and 219.3 mm during the growing season, respectively. The tuber yield of PRD1, FI1, DI1, PRD2, FI2 was 18.65±1.69, 20.88±2.95, 18.37±3.36, 16.24±2.19, 18.57±1.87 tons per hectare, respectively. The tuber yield of the PRD treatments was not significantly different from that obtained under full irrigation (p<0.05). The irrigation water use efficiency of PRD1, FI1, DI1, PRD2, FI2 was 141.42±12.81, 119.65±16.94, 139.29±25.49, 97.8±13.18, 84.7±8.54 kg/hm²/mm-1, respectively. The PRD treatments had significantly higher IWUE than FI by 18.19% and 16.41%, respectively. The PRD2 treatments had significantly higher IWUEs than FI2 by 16.97% (p<0.05).
### B. Total Mineral Nitrogen (Nmin) Content in Potato

Total Nmin content in tuber, stem and leaf of all of irrigation treatments are shown in Figure 4. In 2008, total residual Nmin for PRD1, FI1, DI1, PRD2 and FI2 were 84.85±7.91, 93.47±13.23, 86.33±15.8, 88.86±10.74 and 97.21±9.51 kg/hm2, respectively. The residual Nmin for PRD1, DI1 and PRD2 treatments was not significantly different when compared with FI1 and FI2 (p < 0.05). It can be concluded that roots of potato enhanced soil N absorbance after water sup pleasantly under water deficit press.

![Figure 4. The residual Nmin content in plants after harvest for different treatments in 2007 and 2008](image)

### C. Residual N in Soil

The NO3-N, NH4-N and mineral N content in 2007, 2008 of different treatments measured are shown in Figure 5 and Figure 6. The residual NO3-N and NH4-N in soil layers were measured for all treatments at the end of the season. The residual NO3-N in different soil layers in 2007 is shown in Figure 5a. In the top layer (0-30cm) soil residual NO3-N content for PRD1, FI1, PRD2 and FI2 was 23.73% and 15.02%, respectively. In the deeper layer(30-60cm), residual NO3-N content for PRD1, FI1, PRD2 and FI2 was 86.5, 99.12, 64.16 and 88.64 kg/hm2, respectively. The residual NO3-N content of the deeper soil layer for PRD1 and PRD2 was lower than FI1 and FI2, 12.73%, 27.62%, respectively. The residual NO3-N in different soil layers in 2008 is shown in Figure 6a. In the top layer (0-10cm) , the maximum and minimum residual NO3-N content was 180.78 and 39.93 kg/hm2, which was found in FI1 and FI2. Residual NO3-N content in PRD1 and PRD2 was significantly lower in the top layer compared with the FI1, DI1 and FI2 treatments (p < 0.05). Residual NO3-N content in PRD1 and PRD2 was significantly lower in the second, third and fourth layer(10-20, 20-30, 30-40cm) compared with the FI1 and FI2 (p < 0.05). It can be conclude that the soil residual NO3-N in FI1 treatments is higher than that in PRD and DI treatments.

The residual NH4-N in different soil layers during 2007 is shown in Figure 5b. In the top layer (0-30cm) soil residual NH4-N content for PRD1, FI1, PRD2 and FI2 was 7.56±0.93, 6.56±0.8, 6.00±1.17 and 9.78±1.19 kg/hm2, respectively. The ratio of NH4-N with NO3-N range in the upper layer(0-30cm) was 2.16% to 3.17%, the ratio of NH4-N and NO3-N range in the deeper layer was 7.33% to 16.07%. The residual NH4-N in different soil layers during 2008 is shown in Figure 6b. In the top layer (0-10cm) soil residual NH4-N content for PRD1, FI1, DI1, PRD2 and FI2 was 0.19±0.07, 0.09±0.07, 0.29±0.08, 0.29±0.07 and 0.16±0.1 kg/hm2, respectively. The ratio of NH4-N with NO3-N range in the soil layer was 0.05% to 1.05%. For all soil layers, residual NH4-N content for PRD1, DI1 and PRD2 was not significantly different compared with the FI1, DI1 and FI2 treatments (p < 0.05).

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatments</th>
<th>Pre-irrigation /mm</th>
<th>First event /mm</th>
<th>Second event /mm</th>
<th>Third event /mm</th>
<th>Total amount /mm</th>
<th>The yield /t·hm-2</th>
<th>IWUE /kg·(hm2·mm)-1</th>
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<tr>
<td>2007 50mm*</td>
<td>PRD1</td>
<td>34.72</td>
<td>10.14</td>
<td>15.94</td>
<td>24.50</td>
<td>85.30</td>
<td>9.62a</td>
<td>112.82a</td>
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<td></td>
<td>FI1</td>
<td>34.72</td>
<td>10.14</td>
<td>22.78</td>
<td>36.13</td>
<td>103.77</td>
<td>9.64a</td>
<td>92.87b</td>
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<tr>
<td></td>
<td>PRD2</td>
<td>34.72</td>
<td>10.14</td>
<td>15.94</td>
<td>24.50</td>
<td>85.30</td>
<td>7.48a</td>
<td>87.75a</td>
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<tr>
<td></td>
<td>FI2</td>
<td>34.72</td>
<td>10.14</td>
<td>22.78</td>
<td>36.13</td>
<td>103.77</td>
<td>6.31a</td>
<td>60.85b</td>
</tr>
<tr>
<td>2008 38.9mm*</td>
<td>PRD1</td>
<td>22.50</td>
<td>35.20</td>
<td>30.80</td>
<td>43.40</td>
<td>131.90</td>
<td>18.65a</td>
<td>141.42a</td>
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<tr>
<td></td>
<td>FI1</td>
<td>22.50</td>
<td>46.00</td>
<td>44.00</td>
<td>62.00</td>
<td>174.50</td>
<td>20.88a</td>
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<td>DI1</td>
<td>22.50</td>
<td>35.30</td>
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<td>131.90</td>
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<td>PRD2</td>
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<td>43.90</td>
<td>47.80</td>
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<td>166.10</td>
<td>16.24a</td>
<td>97.80bc</td>
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<td></td>
<td>Full2</td>
<td>22.50</td>
<td>54.20</td>
<td>68.40</td>
<td>74.20</td>
<td>219.30</td>
<td>18.57a</td>
<td>84.70c</td>
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</table>

The residual Nmin of 2007 and 2008 in different soil layers is shown in Figure 5c and Figure 6c respectively. Based on the above results the total residual Nmin content decreased from the topsoil to the deeper layers in subsurface drip irrigation. However, the maximum residual Nmin content for PRD2 and FI2 appeared in the third layer (20-30 cm), 76.92±8.4, 82.88±4.18 kg/hm2, respectively. The minimum residual Nmin content for PRD2 and FI2 appeared in the top layer, 62.23±10.15 and 39.93±4.24 kg/hm2, respectively. The residual Nmin in upper layers (0-10, 10-20, 20-30, 30-40 cm) for PRD1 and PRD2 has significantly lower than that for the FI1 and FI2 treatments.

The N balance variables determined in 2007 and 2008 for different treatments are shown in Table 2. The residual Nmin after harvest in 2007 for PRD1, FI1, PRD2 and FI2 was 399.35±20.43, 415.98±21.33, 313.15±16.75 and 338.54±19.97 kg/hm2, respectively. The residual Nmin after harvest in 2008 for PRD1, FI1, DI1, PRD2 and FI2 were 486.32±14.85, 603.51±50.35, 488.09±4.31, 297.55±40.83 and 355.58±29.65 kg/hm2, respectively. The residual Nmin after harvest in 2007 and 2008 with deficit irrigation was significantly lower than that with full irrigation. The physiological N use efficiency (PNUE) and agronomic N use efficiency (ANUE) for PRD1 were not significantly different compared with FI1. However, the physiological N use efficiency (PNUE) for PRD2 was significantly higher than for FI2.

Figure 5. Residual NO3-N(a), NH4-N(b) and mineral N[Nmin](c) content in different soil layers in 2007 with PRD1, FI1, PRD2 and FI2

Figure 6. Residual NO3-N(a), NH4-N(b) and mineral N[Nmin](c) content in different soil layers in 2008 with PRD1, FI1, DI1, PRD2 and FI2
Partial root-zone drying (PRD) and deficit irrigation (DI) had been proven effective water-saving irrigation strategies (Kang and Zhang, 2004). The irrigation water use efficiency (IWUE) was calculated as the ratio of total fresh tuber (TFT) weight to irrigation water amount (IWA) for the whole growth season, IWUE = IFT/IWA (kg/mm). In this study, PRI and DI slightly reduced the total dry mass under the same fertilization level compared with the FI treatment. But PRD saved water consumption of potato by 24.41% to 32.03%, and thus increased IWUE by 15.47–18.19%. Our results are in agreement with some previous reports. Kang et al. indicated that PRD reduced water consumption of maize by 35% with a slight reduction in total biomass compared with conventional watering. The mechanism of PRD alternates wetting and drying of the soil profile in the root-zone, by which it allows the plant to explore root-sourced ABA signaling to regulate plant physiology, stimulates root growth which it allows the plant to explore root-sourced ABA signaling to regulate plant physiology, stimulates root growth and thus increases microbial activity. In other words, PRD might have avoided the potential in a suitable range which increases microbial activity. Under optimum ratios of inorganic to organic nitrogen fertilizers. Therefore, PRD might have avoided the potential in a suitable range which increases microbial activity.

In this study, the residual NO3-N and mineral N with sub-surface drip irrigation decreased from top layer to lower layers. This might be due to furrow irrigation which enhanced the nitrogen transfer to lower layers under larger irrigation amounts compared with sub-surface irrigation.

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## IV. DISCUSSION

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## V. CONCLUSION

Potato is very sensitive to water deficit and tuber yield would be reduced by soil water stress. But in Henan province, potato is grown with supplementary irrigation under low rainfall conditions. Based on 2 years field experiments on sandy loam soil under semi-arid environment we conclude that:

1. **PRD treatment can improve IWUE and soil mineral N availability, and maintain tuber yield if a suitable irrigation schedule and alternate cycle are applied.**
2. **Furrow irrigation strategies, whether PRD or FI, can transfer more soil residual nitrogen to lower layers compared with sub-surface drip irrigation.** This might involve the risk of soil nitrogen leaching and shallow groundwater pollution.

## ACKNOWLEDGMENT

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### TABLE 2. NITROGEN BALANCE IN THE PLANT–SOIL SYSTEM AND NITROGEN USE EFFICIENCY OF DIFFERENT TREATMENTS IN 2007 AND 2008 KG·HM-2

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatments</th>
<th>N uptake by plant</th>
<th>Residual Nmin after harvest</th>
<th>Nmin before planting</th>
<th>Fertilizer</th>
<th>N content in water</th>
<th>PNUE</th>
<th>ANUE</th>
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PNUE equal to ratio of yield with plant uptake N. ANUE equal to ratio of yield with total N supplied.
REFERENCES


