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Deficit Irrigation as an Effective Way to Increase Potato Water Use Efficiency in Northern China: A Meta-Analysis

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Abstract: Water scarcity poses a significant threat to the sustainable production of crops in Northern China. Despite this, the effect of water management practices, such as deficit irrigation, on the yield and WUE of potatoes has been rarely explored. Based on the meta-analysis of field experiment data, this study evaluated the influence of deficit irrigation on potato yield, evapotranspiration (ET), water use efficiency (WUE) and irrigation water use efficiency (IWUE) under variable soil types, water-saving ratio, irrigation methods, soil organic carbon (SOC) content, and fertilizer rate in Northern China. Here, we determined that potato WUE and IWUE were significantly increased by 10.0 and 31.6%, respectively, under deficit irrigation, while ET was significantly decreased by 26.3% compared to full irrigation. Conclusively, deficit irrigation significantly reduced potato yields by 16.4% compared to full irrigation. Furthermore, SOC content played a vital role in improving the WUE and alleviating potato yield losses under deficit irrigation. Our study suggested that maximum WUE with lower potato yield losses under deficit irrigation can be achieved in the Central Plains region of China or in yellow loam soil, brown soil, and meadow soil under alternate root-zone irrigation when the water-saving ratio was less than 45% and fertilizer application rates were 300 kg N ha⁻¹, >240 kg P₂O₅ ha⁻¹, and 181–300 kg K₂O ha⁻¹. Overall, these findings highlight the need for a comprehensive understanding of various agricultural management practices and local environmental conditions to optimize the benefits of deficit irrigation in potato-growing regions across Northern China.

Keywords: potato; deficit irrigation; yield; water use efficiency; meta-analysis



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1. Introduction

In the arid and semiarid regions of Northern China, where water resources are limited, implementing appropriate water irrigation management strategies is essential to boost crop yields and meet food demand. Globally, approximately 70% of the freshwater extracted is used to irrigate 25% of the world's croplands (399 million hectares), which produce 45% of the global food supply [1]. China leads the world in water usage for irrigated agriculture, utilizing over 60% of its total freshwater resources [1,2]. Although Northern China contains 60% of the nation's arable land, it only has 19% of the country's total freshwater resources [3]. This imbalance in water distribution between the northern and southern regions of China poses significant challenges related to water scarcity in Northern China [4]. In recent years, with the increase in water demand for domestic and industrial usage, agricultural water consumption further decreased due to overpopulation. Extensive groundwater is used as a basic irrigation source for agricultural production. Soil groundwater tables are persistently declining in different regions worldwide [2]. This urgently requires saving water resources and improving water use efficiency (WUE; expressed as tuber yield per

unit of water consumed). This suggests that efficient water management approaches are needed to recover IWUE or WUE.

Among sustainable agricultural practices, efficient water management such as deficit irrigation is crucial for conserving water and maximizing its productivity potential. Deficit irrigation is a sustainable technique designed to enhance WUE while minimizing yield losses [5]. Deficit irrigation is regarded as less water needed for crop uptakes rather than needed water use [2]. Under deficit irrigation, crops are subjected to a controlled level of drought stress by applying irrigation at specific growth stages and reducing the amount of irrigation water, either during a certain period or throughout the growing season. Consequently, crops under deficit irrigation enhance WUE and IWUE while accepting a manageable yield reduction under optimal conditions [6]. The deficit irrigation systems have been successfully implemented in various crops [2,7].

The plant response to deficit irrigation depends upon timing, duration, and the magnitude of water restriction [5,8]. Study results exhibited that wheat growth stages, i.e., stem elongation, booting, and grain filling stages are more sensitive to water stress corresponding to grain yields under subtropical climates [9]. However, highest grain yield and WUE were observed under mild water deficit in seedlings, while initial stem-elongation stages and severe soil water stress were observed at the maturity stage in the Loess Plateau of Northwest China [10]. Another study documented the efficacy of water stress on pepper plants, the 60% irrigation treatment provided a higher WUE by 34 and 4.4% compared to the 100 and 75% treatments, respectively [11]. Under greenhouse conditions, it was found that the highest yield of eggplant grown was at 100% ET_c, while the highest WUE was found under 75% ET_c [12]. These research findings revealed that deficit irrigation is an advantageous approach to increasing WUE for various crops without causing severe yield reductions [13,14].

Potato (*Solanum tuberosum* L.) is the fourth major crop after rice, maize, and wheat [15]. It is one of the most important staple food crops in China. China leads the world in potato production and consumption, with over 5.6 million hectares planted and a yield of approximately 10 million tons [16,17]. The northern region of China, particularly the northwest, is a key potato-growing area, significantly contributing to the country's food security. Adequate water supply is crucial for successful potato production, with water requirements ranging from 300 to 800 mm depending on environmental conditions, soil type, and developmental stage [1,18]. Traditional irrigation leads to a significant waste of water resources, exacerbating regional water scarcity, especially in Northern China. Also, uncertainty in the availability of water resources poses a challenge to traditional irrigation approaches. It is widely believed that improving WUE is the key to mitigating water shortage. However, there is a lack of comprehensive reviews on the potential for improving WUE under deficit irrigation at the national or regional scale. Furthermore, there is little knowledge on how potato productivity, ET, WUE, and IWUE respond to various deficit irrigation methods. Our study utilized a meta-analysis technique to address the following research questions: (1) how do potato yield, WUE, and IWUE respond to the deficit irrigation, SOC content, soil type, or NPK-based fertilizer rate and (2) how does the water-saving ratio of deficit irrigation affects potato yield, WUE, and IWUE? Here, we hypothesized that (1) deficit irrigation will enhance WUE compared to full irrigation; (2) high SOC content could be more effective in enhancing potato WUE; and (3) potato yield and WUE were significantly different from alternate root-zone irrigation and conventional deficit irrigation methods (i.e., uniform irrigation at fixed locations).

2. Materials and Methods

2.1. Literature Search and Data Collection

A comprehensive survey was carried out to search for scientific literature from 1970 to 2022 via Web of Science, PubMed, Scopus, and China Knowledge Resource Integrated dataset. Keywords for multiple databases were “potato”, “deficit irrigation”, “yield”, or “WUE”. To prevent biases, the data were chosen based on the following criteria: (1) only

field trial data were selected; (2) research mainly focused on deficit irrigation treatment and a full irrigation control; (3) means, standard deviations, and sample size of relevant factors were directly available or measured by following past research. After careful examination of the search results, 672 observations were selected for inclusion in the meta-analysis (Figure 1).

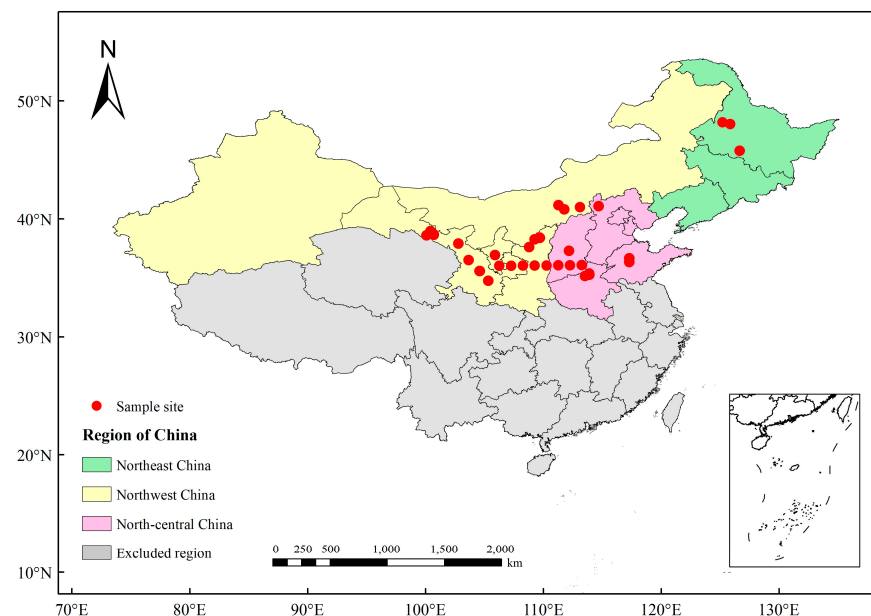


Figure 1. Site location of field experiments in Northern China.

Study sites were categorized into three regions: (1) Northeast China (NE), (2) Northwest China (NW), and (3) Central Plains region of China (CP). The N, P, K fertilizer rates were classified as 0–60, 60–120, 120–180, 180–240, 240–300, and >300 kg ha^{−1}. Based on soil types, the studied soil was characterized as aeolian sandy soil, chestnut soil, sierozem, meadow soil, gray desert soil, Huangmian soil, yellow loam soil, brown soil, and chernozem (Gong, 2001), soil properties of experimental sites are shown in Table 1. Deficit irrigation methods were divided into conventional deficit irrigation (i.e., uniform irrigation at fixed locations) and alternate root-zone irrigation (i.e., alternate partial root-zone irrigation). The SOC content (%) was categorized as <0.5, 0.5–1.0, 1.0–1.5, 1.5–2.0, 2.0–2.5, and 2.5–3.0 (%). For deficit irrigation subgroups, water-saving ratio of deficit irrigation was classified as 0–10, 10–25, 25–45, 45–65, and >65%.

Table 1. Soil properties of experimental sites used in this study.

Soil Types	Soil Textures	pH	Field Capacity (%)	Soil Organic Matter (%)
Chernozem	sandy loam	7.0–8.5	30–33	2.0–8.0
Brown soil	sandy loam	5.5–7.0	25–30	5.0–6.0
Yellow loam soil	clay loam	4.0–6.0	30–40	1.0–2.0
Huangmian soil	sandy loam	7.5–8.5	20–28	0.3–1.0
Gray desert soil	sandy loam	8.0–9.0	17–20	0.6–1.5
Meadow soil	sandy loam	8.0–10.0	20–23	2.0–2.5
Sierozem	sandy loam	8.0–9.5	20–25	1.1–2.0
Chestnut soil	sandy loam	7.5–8.5	17–20	1.5–2.5
Aeolian sandy soil	sandy soil	8.0–9.0	15–18	0.1–1.0

2.2. Statistical Analysis

Irrigation water use efficiency (IWUE), expressed as tuber yield per unit of irrigation water, was calculated as

$$IWUE = \frac{Y_t}{I} \quad (1)$$

where “ Y_t ” is the potato yield and “ I ” is the irrigation amount (mm).

In the current meta-analysis, we used the natural logarithm of response ratio (lnR) as the effect size [6]:

$$\ln R = \ln\left(\frac{X_d}{X_f}\right) = \ln X_d - \ln X_f \quad (2)$$

where “ X_d ” is the average of potato yield, ET, or WUE in deficit irrigation treatment and “ X_f ” is the average of potato yield, WUE, or ET in full irrigation control. If the $\ln R > 0$, it represents that treatment showed a positive impact on each dependent variable.

The weighting factor (W_i) and weighted response ratio ($\ln R+$) were measured by following the previous studies [1,3,6,19]. The average effect sizes and 95% confidence intervals (CIs) were recorded via bootstrapping (9999 iterations). The values were determined with statistical software MetaWin 2.1 (Systat Software, Inc., San Jose, CA, USA). A random model was utilized to assess the impact of deficit irrigation on each dependent variable. For data interpretation, the percent change in potato yield, ET, and WUE was determined as $(R - 1) \times 100\%$. Means of the different categorical variables were considered significantly different from one another if their 95% bootstrapping CIs did not overlap. A positive percentage change indicated an increase in the respective variable with deficit irrigation relative to full irrigation, while a negative value indicated a decrease. In addition, significance in differences between means for each dependent variable was established if their 95% bootstrapping CIs did not intersect each other.

3. Results

3.1. Overall Response of Potato Yield, ET, and WUE to Deficit Irrigation

Yield and evapotranspiration (ET) for deficit irrigation significantly decreased by 16.4 and 26.3% compared to full irrigation, respectively. Compared to full irrigation, WUE and IWUE of potatoes were significantly increased by 10.0 and 31.6%, respectively, under deficit irrigation (Figure 2).

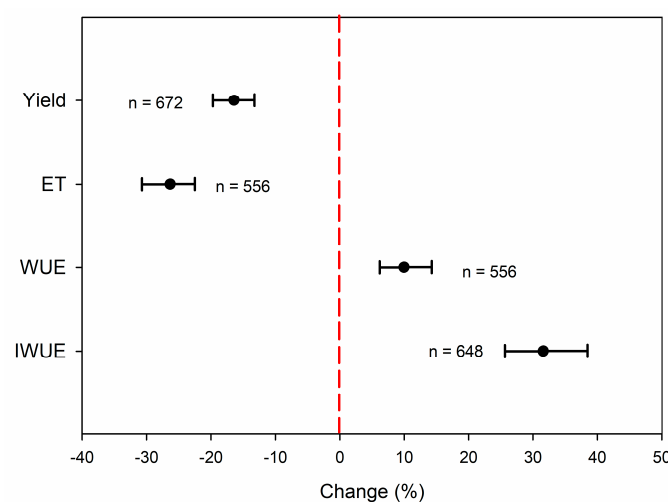


Figure 2. Overall response of change in potato yield, evapotranspiration (ET), water use efficiency (WUE), and irrigation water use efficiency (IWUE) to deficit irrigation compared to full irrigation in Northern China. Error bars represent 95% confidence intervals. The values for “n” represent the corresponding number of comparisons.

3.2. Response of Potato Yield, ET, WUE, and IWUE to Deficit Irrigation in Different Regions

The effect of deficit irrigation on potato yield, ET, WUE, and IWUE varied with different regions of Northern China (Figure 3). The greatest reduction in potato yield was found in Northwest China (19.3%), followed by Northeast China (12.0%), whereas the Central Plains region of China slightly increased potato yield by 5.2% ($p > 0.05$). The negative effect of deficit irrigation on ET was greatest in Northeast China (35.8%), followed by Northwest China (26.9%) and Central Plains region of China (12.6%). The greatest increase in potato WUE was observed in Northeast China (30.1%), followed by Northwest China (9.3%) and Central Plains region of China (8.4%). The positive effect of deficit irrigation on IWUE was 65.4% in Central Plains region of China and 24.1% in Northeast China, respectively.

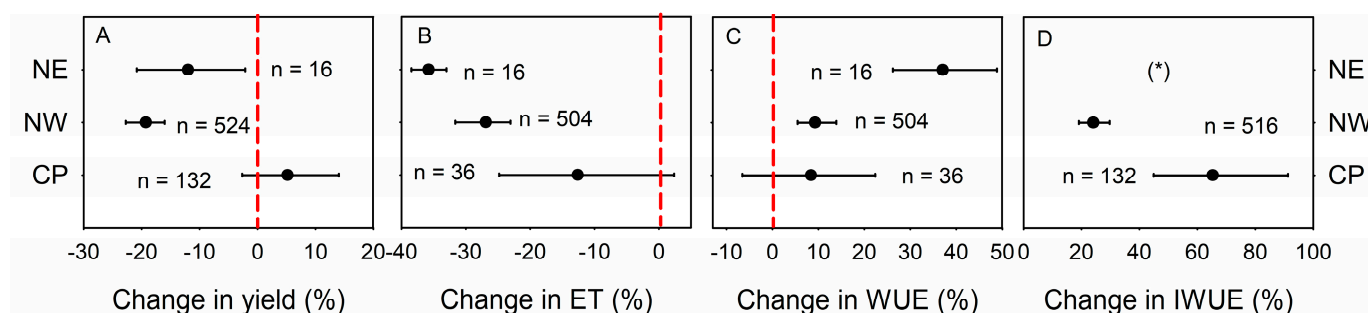


Figure 3. Response of change in potato yield (A), evapotranspiration (ET) (B), water use efficiency (WUE) (C), and irrigation water use efficiency (IWUE) (D) to deficit irrigation compared to full irrigation control in different regions of Northern China. Error bars represent 95% confidence intervals. The values for “n” represent the corresponding number of comparisons. Asterisks represent the response for a group with less than 3 comparisons. NE, Northeast China; NW, Northwest China; CP, Central Plains region of China.

3.3. Response of Potato Yield, ET, WUE, and IWUE to Deficit Irrigation in Different Soil Types

Soil type significantly affected the effect of deficit irrigation on potato yield, ET, WUE, and IWUE ($p < 0.05$) (Figure 4). Altogether, the variations in yield are parallel with the trend of ET values except for sierozem, meadow soil, and chernozem, where a lower decrease in ET correlated with a lower yield reduction. Deficit irrigation significantly increased WUE by 47.8, 44.7, 37.1, 16.0, 8.1, and 5.9% in meadow soil, Huangmian soil, chernozem, sierozem, yellow loam soil, and gray desert soil, respectively, but deficit irrigation did not significantly affect WUE in aeolian sandy soil, chestnut soil, and brown soil. The WUE was not significantly different among aeolian sandy soil, chestnut soil, brown soil, yellow loam soil, and gray desert soil. Similarly, the positive effect of deficit irrigation on IWUE was greatest in meadow soil (120.6%), followed by yellow loam soil (102.8%), sierozem (59.4%), Huangmian soil (46.7%), brown soil (30.3%), aeolian sandy soil (20.4%), chestnut soil (18.4%), and the lowest in gray desert soil (12.4%).

3.4. Response of Potato Yield, ET, WUE, and IWUE to Deficit Irrigation in Different Soil Organic Carbon Content

In Northern China, the soil organic carbon (SOC) content significantly affected the effect of deficit irrigation on potato yield, ET, WUE, and IWUE (Figure 5). Except for an SOC that is less than 0.5%, the increase in SOC significantly alleviates the opposite effect of deficit irrigation on yield, while the positive influence on WUE and IWUE was greatly increased with SOC increment. Deficit irrigation significantly reduced potato yield by 30.0% when SOC was 0.5–1.0%. The mean decrease in yield with deficit irrigation ranged from 12.0 to 17.9% for sites with 1.0–3.0% SOC. Deficit irrigation did not significantly affect potato yield when SOC was less than 0.5%. Among all SOC subgroups, deficit irrigation significantly reduced ET by 20.3–35.8%. A strongly positive response of deficit irrigation on

water use efficiency was found when SOC was 2.5–3.0% (average 37.1%), followed by SOC of 2.0–2.5% (average 21.6%) and 1.5–2.0% (average 15.7%), and least (11.9–14.3%) when SOC was less than 1.5%. Deficit irrigation significantly increased IWUE by 49.6% at <0.5% SOC, by 22.3–29.5% at 0.5–2.0% SOC, and by 5% for sites with 2.0–3.0% SOC.

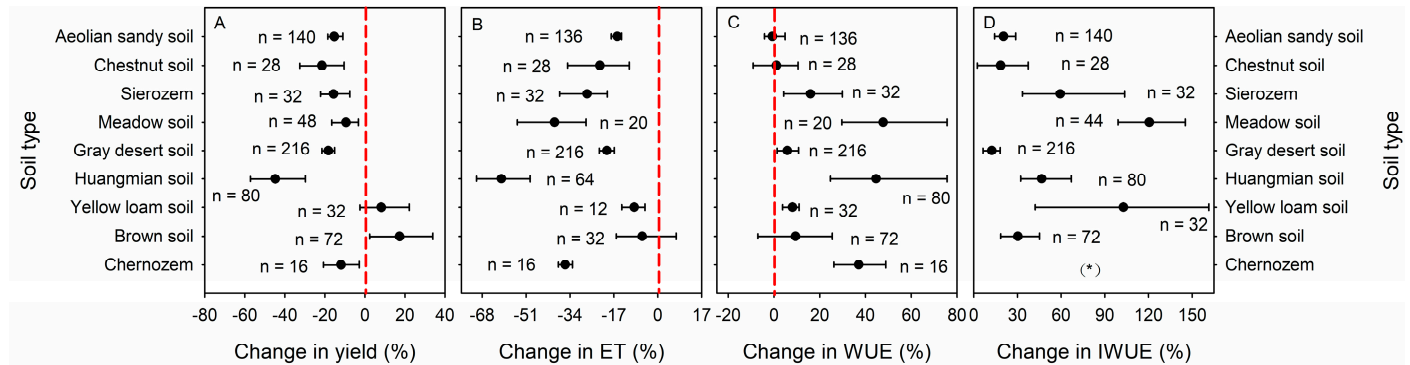


Figure 4. Response of change in potato yield (A), evapotranspiration (ET) (B), water use efficiency (WUE) (C), and irrigation water use efficiency (IWUE) (D) to deficit irrigation compared to full irrigation control in different soil types. Error bars represent 95% confidence intervals. The values for “n” represent the corresponding number of comparisons. Asterisks represent the response for a group with less than 3 comparisons.

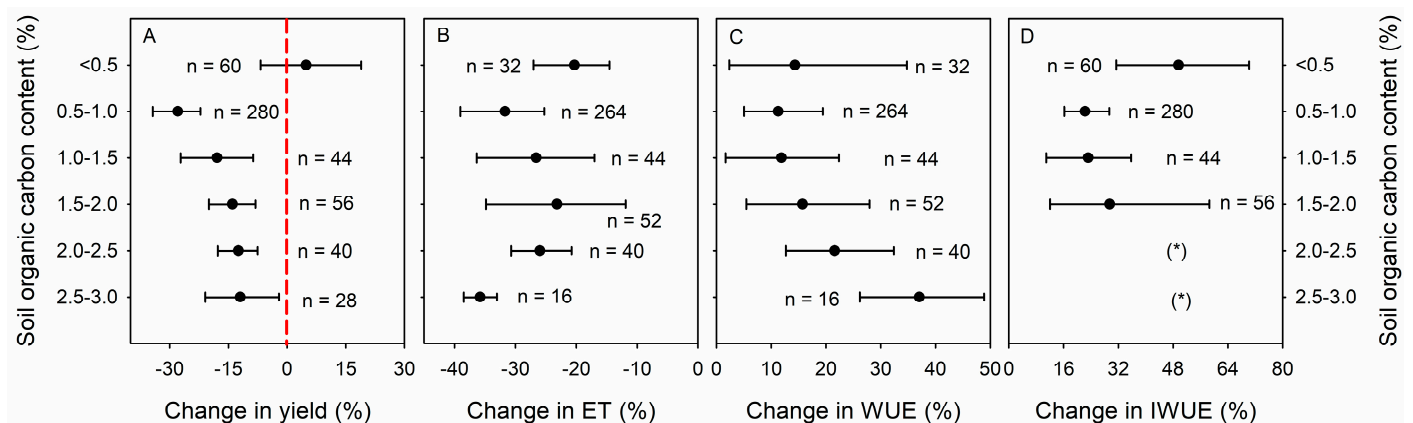


Figure 5. Response of change in potato yield (A), evapotranspiration (ET) (B), water use efficiency (WUE) (C), and irrigation water use efficiency (IWUE) (D) to deficit irrigation compared to full irrigation control at various soil organic carbon concentrations. Error bars represent 95% confidence intervals. The values for “n” represent the corresponding number of comparisons. Asterisks represent the response for a group with less than 3 comparisons.

3.5. Response of Potato Yield, ET, and WUE, IWUE to Deficit Irrigation as Affected by Water-Saving Ratio

Compared to full irrigation, deficit irrigation significantly reduced potato yield when the water-saving ratio exceeded 65%, but it did not significantly affect potato yield when it was less than 65% (Figure 6). In all water-saving ratio subgroups, deficit irrigation significantly reduced ET by 8.9–47.9%. With the increase in water-saving ratio, WUE and IWUE showed a gradually increasing trend. The greatest increase in WUE (102.3%) was found when the water-saving ratio was 65%, followed by a water-saving ratio of 45–65% (66.1%), 10–25% (45.8%), and 25–45% (23.1%), and the lowest increase in WUE (7.3%) was found when it was 0–10%. Compared to full irrigation, the change in IWUE was −7.8, 37.5, 58.2, 149.6, and 235.6% under 0–10, 10–25, 25–45, 45–65, and >65% water-saving ratios, respectively (Figure 6).

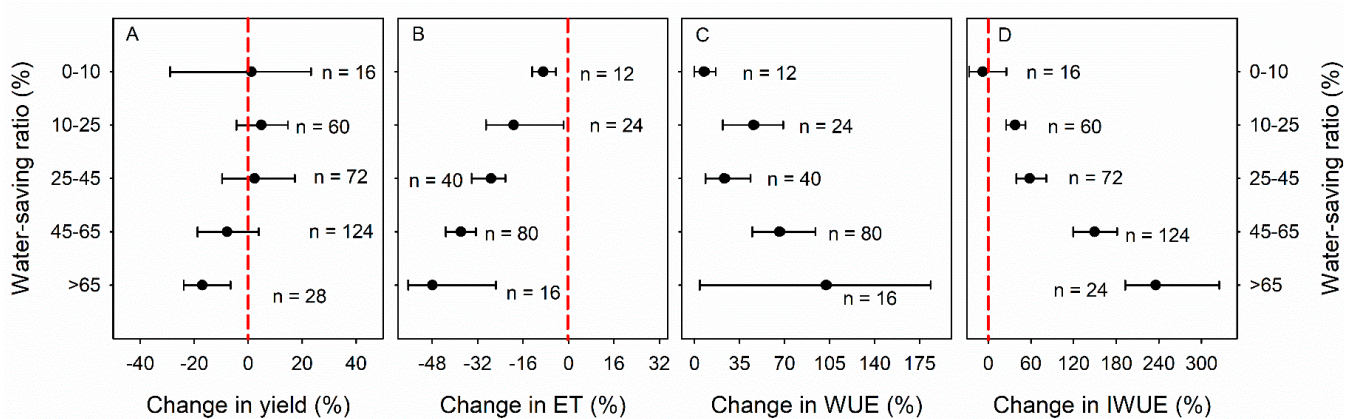


Figure 6. Response of change in potato yield (A), evapotranspiration (ET) (B), water use efficiency (WUE) (C), and irrigation water use efficiency (IWUE) (D) to deficit irrigation compared to full irrigation at different water-saving ratios. Error bars represent 95% confidence intervals. The values for “n” represent the corresponding number of comparisons.

3.6. Response of Potato Yield, ET, and WUE, IWUE to Deficit Irrigation as Affected by Fertilization Rate

There were distinct results of irrigation on potato yield, ET, WUE, and IWUE, depending on N application (Figure 7). Deficit irrigation massively reduced potato yield by 13.7, 34.9, 15.6, and 18.3% when N fertilizer was applied at 61–120, 121–180, 181–240, and 241–300 kg N ha⁻¹, respectively, when compared to full irrigation ($p < 0.05$). When N dose rate was less than 60 or more than 300 kg N ha⁻¹, deficit irrigation did not significantly affect potato yield. Deficit irrigation markedly reduced potato ET by 15.6–38.2% under all N rates compared to full irrigation. Deficit irrigation remarkably raised water use efficiency by 10.3 and 25.1%, respectively, under a N applied rate of 121–180 and >300 kg N ha⁻¹. Compared to full irrigation, deficit irrigation did not significantly affect WUE under <60 and 181–300 kg N ha⁻¹. Similarly, deficit irrigation strongly increased IWUE by 22.9, 56.7, 23.8, 16.8, 66.2, and 92.2% when N input rates were 0–60, 61–120, 121–180, 181–240, 241–300, and >300 kg N ha⁻¹, respectively, compared to full irrigation.

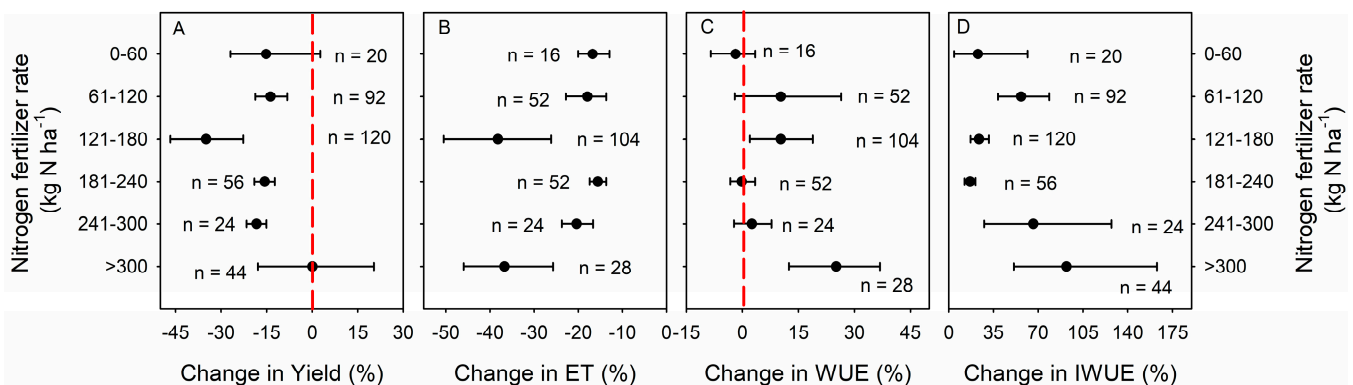


Figure 7. Response of change in potato yield (A), evapotranspiration (ET) (B), water use efficiency (WUE) (C), and irrigation water use efficiency (IWUE) (D) to deficit irrigation compared to full irrigation at different levels of nitrogen fertilizer rate. Error bars represent 95% confidence intervals. The values for “n” represent the corresponding number of comparisons.

The influence of deficit irrigation on ET, WUE, IWUE, and potato yield was varied with P rate (Figure 8). When P fertilizer rate was less than 240 kg P₂O₅ ha⁻¹, potato yield was significantly reduced by 23.8–37.1% for deficit irrigation as compared to full irrigation. When P fertilizer rate was more than 300 kg P₂O₅ ha⁻¹, potato yield under deficit irrigation was significantly increased by 88.4% than that of full irrigation, but there was no difference

in yield between deficit irrigation and full irrigation using 241–300 kg P_2O_5 ha⁻¹ P dose rates. Moreover, ET under deficit irrigation was reduced by 13.3–44.9% among all P fertilizer rates compared to full irrigation. Compared to full irrigation, deficit irrigation extensively improved water use efficiency by 15.9, 19.2, and 28.3%, respectively, under P fertilizer rates of 0–60, 181–240, and 241–300 kg P_2O_5 ha⁻¹. During a phosphatic fertilizer addition of more than 300 kg P_2O_5 ha⁻¹, the deficit irrigation significantly reduced WUE by 30.8% compared to full irrigation, whereas no difference was observed in water use efficiency between deficit irrigation and full irrigation when P fertilizer rate was 61–180 kg P_2O_5 ha⁻¹. The increase in IWUE under deficit irrigation was 23.1, 19.6, 26.1, 30.7, 153.7, and 134.2%, respectively, compared to full irrigation under P added at rates of 0–60, 61–120, 121–180, 181–240, 241–300, and >300 kg P_2O_5 ha⁻¹.

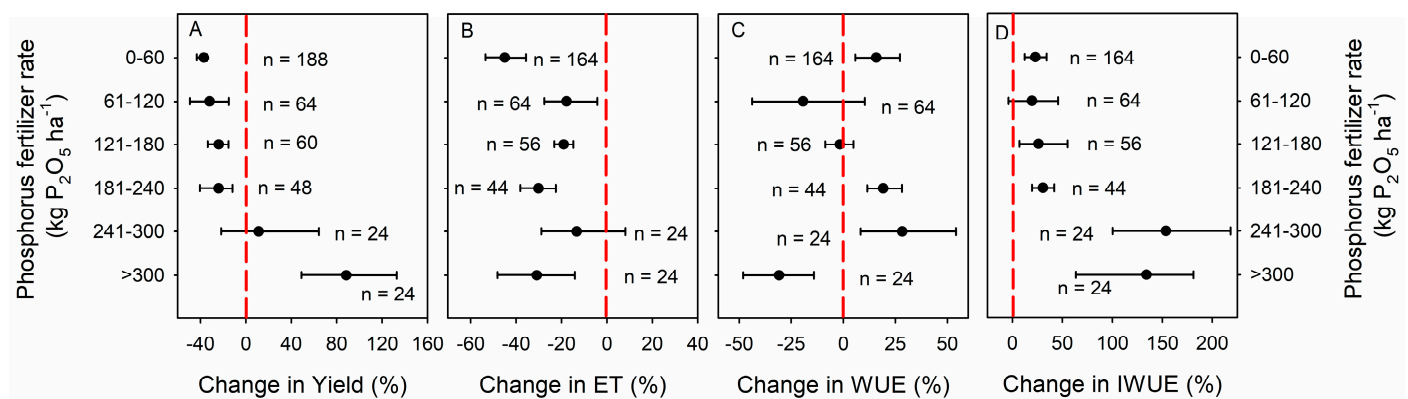


Figure 8. Response of change in potato yield (A), evapotranspiration (ET) (B), water use efficiency (WUE) (C), and irrigation water use efficiency (IWUE) (D) to deficit irrigation compared to full irrigation at different phosphorus fertilizer rates. Error bars represent 95% confidence intervals. The values for “n” represent the corresponding number of comparisons.

Under deficit irrigation, the potato yield, ET, and WUE, IWUE were influenced by potassium (K) fertilization rate (Figure 9). When K applied rate was less than 180 and more than 300 kg K_2O ha⁻¹, deficit irrigation significantly reduced potato yield by 22.6–49.8% compared to full irrigation. However, potato yield under deficit irrigation was slightly decreased by 11.8–12.7% compared to full irrigation when K fertilization rate was 181–300 kg K_2O ha⁻¹. ET under deficit irrigation was reduced by 12.4–56.3% among all K fertilization rates compared to full irrigation. As the amount of potassium fertilizer increases, WUE shows a gradually increasing trend. Compared to full irrigation, the deficit irrigation significantly increased potato WUE by 28.32 and 21.5%, respectively, under 181–240 and >300 kg K_2O ha⁻¹. the positive effect of deficit irrigation on IWUE was greatest under 241–300 kg K_2O ha⁻¹ (80.9%), followed by 121–180 kg K_2O ha⁻¹ (79.6%), >300 kg K_2O ha⁻¹ (59.7%), 181–300 kg K_2O ha⁻¹ (49.2%), and 0–60 kg K_2O ha⁻¹ (27.2%), and was lowest under 61–120 kg K_2O ha⁻¹ (16.0%).

3.7. Response of Potato Yield, ET, and WUE, IWUE to Deficit Irrigation as Affected by Irrigation Methods

The potato yield, ET, WUE, and IWUE to deficit irrigation were diverse with selected watering techniques (Figure 10). Compared to fixed irrigation followed by the same water quantity, deficit irrigation with alternate irrigation did not markedly raise potato yield and WUE, while ET of potato was significantly reduced by 5.6% under alternate irrigation methods corresponding to the fixed irrigation method. In addition, under alternate irrigation, the potato IWUE was significantly increased by 30.7% in response to fixed irrigation practice.

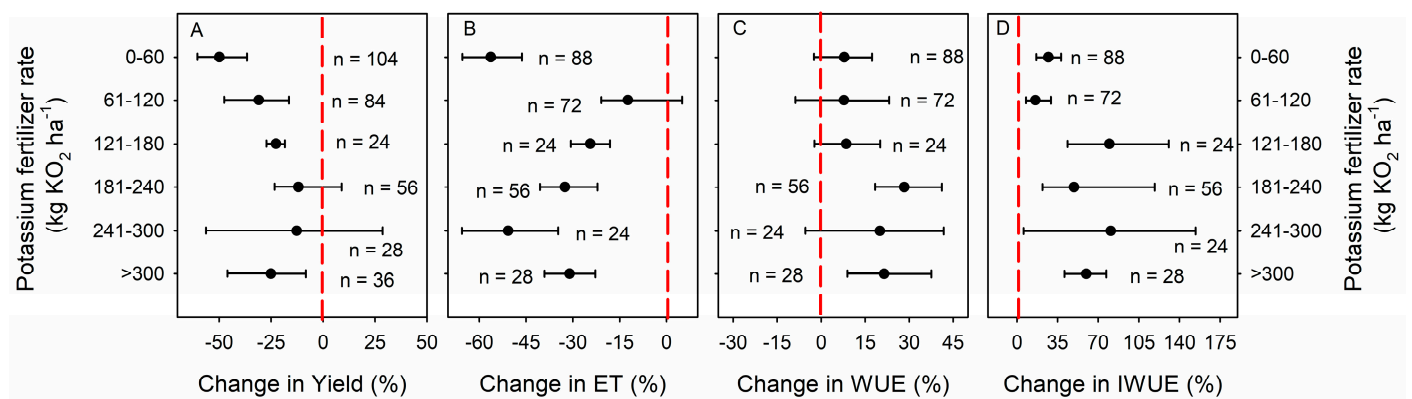


Figure 9. Response of change in potato yield (A), evapotranspiration (ET) (B), water use efficiency (WUE) (C), and irrigation water use efficiency (IWUE) (D) to deficit irrigation compared to full irrigation at different potassium fertilizer rates. Error bars represent 95% confidence intervals. The values for “n” represent the corresponding number of comparisons.

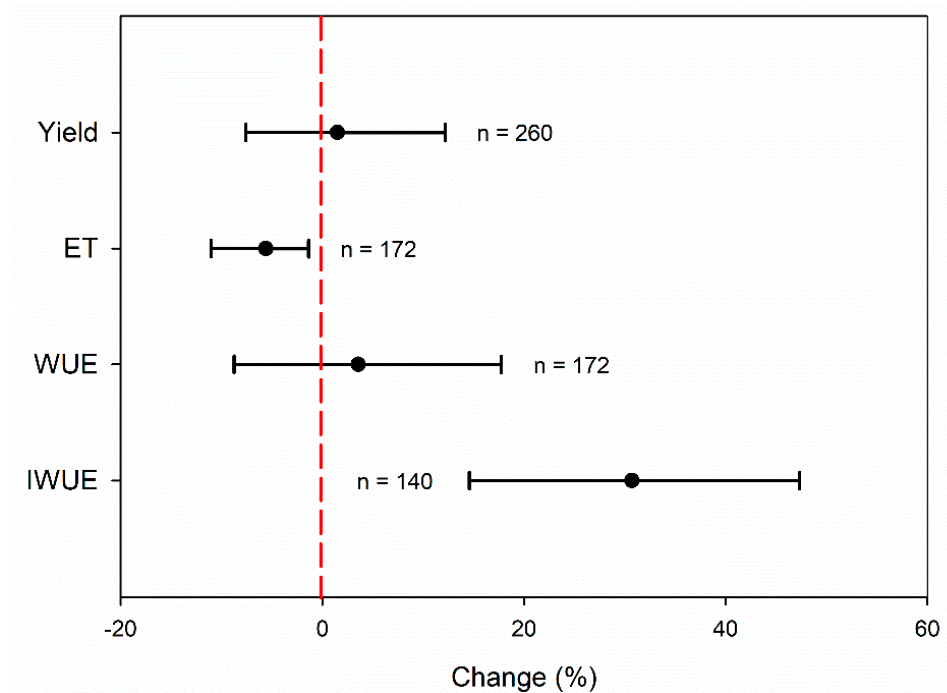


Figure 10. Response of change in potato yield, evapotranspiration (ET), water use efficiency (WUE), and irrigation water use efficiency (IWUE) under deficit irrigation with alternate root-zone irrigation (i.e., alternate partial root-zone irrigation and/or partial root-zone drying irrigation) compared to conventional deficit irrigation (i.e., uniform irrigation at fixed locations) under the same irrigation amount and the same experiment. Error bars represent 95% confidence intervals. The values for “n” represent the corresponding number of comparisons.

4. Discussions

4.1. Overall Response of Potato Yield and WUE to Deficit Irrigation

Deficit irrigation significantly reduced potato yield, mainly because ET was significantly reduced under deficit irrigation, thus reducing photosynthesis, stomatal conductance, and transpiration, leading to a decrease in leaf area and biomass accumulation, thereby reducing tuber yield of potato [20–24]. However, deficit irrigation significantly increased WUE and IWUE [20,21,25]. This is likely due to the reduction in photosynthesis and transpiration rates to varying extents under deficit irrigation, which significantly

lowers transpiration, thus enhancing transpiration efficiency and improving instantaneous WUE [21,25].

4.2. Response of Potato Yield and WUE to Deficit Irrigation as Affected by Irrigation Methods and Growing Region

In the last decade, the deficit irrigation technique has been extensively evaluated and a water-saving ability for agronomic and horticultural plants has been determined [26]. The question of whether alternating irrigation methods can enhance yield compared to traditional deficit irrigation has been a key research focus. Some studies have shown that techniques like alternate partial root-zone drying irrigation can significantly boost crop yields and WUE compared to conventional deficit irrigation [2,24,26]. However, other studies have found that with the same amount of irrigation, alternate root-zone irrigation does not significantly enhance crop yields and WUE compared to conventional deficit irrigation [21,22,24]. In this study, potato yield and WUE were not different between conventional deficit irrigation and alternate root-zone irrigation, but alternate root-zone irrigation significantly reduced ET and enhanced IWUE. This result partially supports our first hypothesis, suggesting that under the same irrigation amount, alternate root-zone irrigation has greater potential for effective water-saving conservation and utilization efficiency.

Therefore, deficit irrigation in Northwest China results in significant yield losses, resulting in a relatively small increase in IWUE; this might be due to poor water retention capacity in drought-stressed soils. The irrigation supply in the Central Plains region is relatively large for the potato crops, but this is due to the high temperatures in summer, which is not conducive to potato production [17,27]; therefore, deficit irrigation did not reduce yield, but greatly promoted IWUE. In the case of Northeast China soils, deficit irrigation slightly decreased the potato yield due to high soil fertility.

4.3. Response of Potato Yield and WUE to Deficit Irrigation as Affected by Soil Types, Soil Organic Carbon Content, and Water-Saving Ratio

The results of the current study indicated that potato yield and WUE are influenced by soil texture. In yellow loam and brown soils, deficit irrigation positively impacted potato yield and WUE due to their high water retention capacity, which mitigates the negative effects of deficit irrigation. Chernozem soil, with its high fertility, experienced less negative impact from deficit irrigation, significantly enhancing WUE. In contrast, aeolian and chestnut soils, which are common in the arid regions of the north and have low fertility and poor water retention, saw a significant reduction in potato yields under deficit irrigation. On the contrary, supplementary irrigation can promote potato yield in aeolian sandy soil and chestnut soil [1]. The decrease in potato yield for deficit irrigation was lower and resulted in a greater WUE and IWUE in meadow soil than other soil types, suggesting the suitability of promoting deficit irrigation techniques in meadow soil.

Whether increasing SOC can increase yield and WUE and enhance the water-saving potential of irrigated agriculture always remained a hot research topic in dryland agriculture. In present study, as the SOC increased, the adverse influence of deficit irrigation on yield gradually decreased, while the remarkable effect on WUE slowly raised, which is similar to recent studies [1,19]. Our findings implied that increasing SOC gained much importance in improving yield and water-saving irrigation in agricultural systems.

Effective irrigation practices are critical to benefiting cost-effective yields and balancing water use efficiency for crops [28]. The water-saving ratio poses a beneficial effect on potato output and water use efficiency [6,24]. Appropriate water-saving ratio potentially improved biomass accumulation [21,26], consequently maintaining potato yield and enhancing WUE. Although a higher water-saving ratio (>45%) greatly improved WUE and IWUE, it exposed the risk of reduced potato yield, especially when the water-saving ratio exceeded 65%, which can lead to a significant decrease in potato yields. To maximize win-win effects and minimize tradeoff between yield and WUE, we found that deficit irrigation is most appropriate when the water-saving ratio was less than 45%. While a study found that in wheat crops, the water-saving ratio was more than 20%, deficit irrigation significantly

reduced yield [6]. The above study results reflect that deficit irrigation not only depends on crop yield but also on crop species.

4.4. Response of Potato Yield and WUE to Deficit Irrigation as Affected by Fertilizer Application Rate

Fertilization is important to boost yield and improve WUE for sustainable crop productivity [29]. Appropriate fertilizer input induces optimum WUE and yield [19,29]. Optimal response in potato yields and WUE for deficit irrigation is noticed at low and high N rates <60 and >300 kg N ha⁻¹, respectively. This might be possible due to limited potato growth and yield output under an imbalanced N fertilizer supply. Due to the increased P fertilizer rate, the inhibitory effect of deficit irrigation on yield slowly becomes limited, especially under high P fertilizer >300 kg P₂O₅ ha⁻¹. Furthermore, deficit irrigation demonstrated a significant trend in increasing potato yield, likely because potatoes are P-loving crops, and appropriate P fertilizer management is crucial for improving yield, especially in the alkaline soils of Northern China. Increasing P fertilizer application improved potato WUE, aligning with previous findings [17]. Similarly, as potassium fertilization rates increased, potato yield losses under deficit irrigation gradually decreased, while WUE gradually increased. This may be because K fertilizer enhances crop drought resistance [30–32], thereby improving yield and WUE. Our study highlights the importance of managing P and K fertilizers in potato production for synergistically enhancing yield and WUE.

5. Conclusions

This meta-analysis study was based on field experiments on various soils and growing environments in Northern China, underscoring the significant potential of deficit irrigation to enhance the WUE of potato plants. The findings indicate that the response of potatoes to deficit irrigation is influenced by factors such as soil type, SOC content, water-saving ratio, irrigation method, growing region, and fertilizer application rate. We found that deficit irrigation performed better for improving WUE and lowering yield losses in the Central Plains region of China or yellow loam soil, brown soil, and meadow soil with alternate root-zone irrigation when the water-saving ratio was less than 45% and fertilizers were applied at 300 kg N ha⁻¹, >240 kg P₂O₅ ha⁻¹, and 181–300 kg K₂O ha⁻¹. Our study also suggested that SOC plays an important role in increasing WUE and reducing yield loss under deficit irrigation. These findings emphasize the potential of deficit irrigation for water-saving in potato production, achieving higher WUE with lower yield losses when appropriate methods and local conditions are carefully taken into account.

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