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Research Paper

Regulation effects of water and nitrogen on potato dry matter and nitrogen accumulation and partitioning

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Abstract. In order to maximize potato tuber yield and nitrogen uptake, it is important to optimize the management practices related to dry matter (DM) and nitrogen (N) accumulation and partitioning. To evaluate the effects of water and N level on DM and N accumulation and partitioning during the tuber bulking stage in the potato, a pot experiment was conducted with three water levels (90%, 70%, and 50% of field capacity) and three N levels (0, 85.5 and 171 kg N ha^{-1}). The results showed that potato tuber yield and tuber N uptake were significantly affected by the water levels, N levels, and the interaction between water and N. Under the watered and moderate N conditions (90% of field capacity and 85.5 kg N ha^{-1}), the tuber yield and N uptake were the highest. Watered conditions, moderate N conditions, and the watered combined with moderate N condition increased the tuber yield and tuber N uptake by increasing the accumulation of total DM and N in the plant, while not by increasing the partitioning of DM and N to tubers. Therefore, these results suggest that optimizing water and N management to improve DM and N accumulation is the key to ensuring high tuber yield and N uptake in the potato.

Keywords: Potato, water, nitrogen, dry matter, accumulation, partitioning.

INTRODUCTION

Potato (*Solanum tuberosum* L.) is an important food crop that is grown in many regions throughout the world. The tuber is an important source of starch in human diets and contains large amounts of nutritious compounds, such as vitamin C, several B vitamins, vitamin A and potassium (Camire *et al*., 2009). It is also an industrial material that can be used to produce ethanol (Srichuwong *et al*., 2009). Thus, there is growing demand for potatoes for food, feed, and industrial products (Birch *et al*., 2012). Understanding the patterns of dry matter (DM) and nitrogen (N) accumulation and partitioning in potato plants is useful in the improvement of potato yield and N uptake (Alva *et al*., 2002).

Water is essential for plant growth and it dramatically affects potato growth and yield (Bélanger *et al*., 2001). The potato is sensitive to water stress, even slight water shortage can cause a reduction in tuber yield, especially during the tuber bulking stage (an Loon, 1981). Previous studies showed that water level significantly affects potato plant DM and N accumulation, while its effect on the partitioning of DM to tubers is conflicting: some studies reported that there was no significant difference in the partitioning of DM to tubers under different water levels whereas others put forth that water deficiency

Table 1. Water and nitrogen levels in different treatments.

Water	Nitrogen
Watered (90% of field capacity)	Low nitrogen (0 mg N added to per kg soil) Moderate nitrogen (200 mg N added to per kg soil) High nitrogen (400 mg N added to per kg soil)
Moderate stress (70% of field capacity)	Low nitrogen (0 mg N added to per kg soil) Moderate nitrogen (200 mg N added to per kg soil) High nitrogen (400 mg N added to per kg soil)
Droughted (50% of field capacity)	Low nitrogen (0 mg N added to per kg soil) Moderate nitrogen (200 mg N added to per kg soil) High nitrogen (400 mg N added to per kg soil)

increased DM partitioning to tubers (Wolfe *et al*., 1983; Bélanger *et al*., 2001; Liu *et al.*, 2015). Thus, how water level affects DM and N accumulation and partitioning and influences potato yield and N uptake remains unclear.

N is also an important crop management consideration that affects tuber yield in potato production (Badr *et al*., 2012). Potato is sensitive to N stress. Deficient and excess N conditions result in a low yield (Geary *et al*., 2015). Many studies reported that although there was an increase in the amount of total DM and N that the plant accumulated with more N available, the partitioning of DM to tubers was not affected by N levels, and the proportion of N recovered in tubers decreased with increased N level (Kleinkopf *et al.*, 1981; Millard et al., 1989; Vos, 1997; Sharifi *et al*., 2005). How the N level affects DM and N accumulation and partitioning to influence potato yield and N uptake remains poorly understood.

In agricultural production, water and N often interact (Sadras *et al*., 2016; Kunrath *et al*., 2018). As dynamic processes in plant growth and development, DM and N accumulation and partitioning are often influenced by it (Chen and Setter, 2012; Fernandes *et al*., 2015). The effect of water and N on the DM and N accumulation and partition, and subsequently on the yield and N uptake during the tuber bulking stage in the potato is unclear. Therefore, the objective of this study was to evaluate the effect of water and N levels on the DM and N accumulation and partitioning during the tuber bulking stage in the potato, and to examine the effects of these different patterns on tuber yield and N uptake.

MATERIALS AND METHODS

Plant material and experimental conditions

The pot experiment was conducted in Yangling, Shaanxi province, China (34°12′N, 108°7′E, and altitude 530 m). On April 11, 2014, virus-free plantlets of the potato cultivar Atlantic, with uniform height (approximately 20 cm), were transplanted into plastic pots (diameter 30 cm, height 30 cm). There was one plantlet per pot, and each pot was filled with 9.5 kg air-dried loessal soil and placed in a field under a transparent rainfall shelter to exclude natural precipitation. The loessal soil contained 2.4 g kg^{-1} organic matter, 0.32 g kg^{-1} total N, 0.68 g kg^{-1} total P, 19.6 g kg^{-1} total K, 16.91 mg kg^{-1} NO_3^--N, and 38.72 mg kg^{-1} NH_4^+-N, with a pH of 8.27. Soil gravimetric water content was maintained at 90% of field capacity by adding sufficient water at 18:00 h every day in all pots before the beginning of tuber bulking (26 days after transplanting [DAT]).

The experiment comprised nine treatments, representing all combinations of three water levels and three N levels (Table 1). For three water levels, soil gravimetric water content was maintained at 90% of field capacity for the watered group, 70% for the moderate stress group and 50% for the droughted group. Each water level was imposed from 26 DAT and was achieved by withholding watering based on weighing pots every day. N levels (designated as low, moderate, and high) were chosen on the basis of our preliminary experiment to allow unlimited growth at the moderate level and to limit growth at the low and high levels. Three N levels, 0, 200, and 400 mg N kg^{-1} soil, were equivalent to 0, 85.5 and 171 kg N ha^{-1}, since potato are planted at a density of 45,000 plants ha^{-1} generally. N fertilizer was applied according to each treatment using urea (46% N). Phosphate and potassium fertilizers were applied at a rate of 200 mg P_2O_5 and 100 mg K_2O per kilogram soil for every treatment (equivalent to 85.5 kg P_2O_5 ha^{-1} and 42.8 kg K_2O ha^{-1}), in the form of $Ca(H_2PO_4)_2$ and K_2SO_4, respectively. N, phosphate, and potassium fertilizers were evenly incorporated with soil before transplanting. Every treatment had 45 pots, and different treatments were displayed in a randomized complete block design. At 69 DAT, the experiment was terminated.

Plant sampling

At 26, 36, 47, 58, and 69 DAT, eight plants were sampled

Table 2. Tuber yield and tuber N uptake under different water and N levels.

Treatment		**Tuber yield (g plant^{-1})**	**Tuber N uptake (mg plant^{-1})**
	Low N	174 ± 4^{c}	219 ± 5^{e}
Watered	Moderate N	273 ± 14^{a}	546 ± 27^{a}
	High N	216 ± 8^{b}	361 ± 14^{cd}
	Low N	164 ± 3^{cd}	179 ± 3^{e}
Moderate stress	Moderate N	257 ± 10^{a}	413 ± 16^{bc}
	High N	200 ± 11^{b}	416 ± 23^{b}
	Low N	147 ± 2de	175 ± 2^{e}
Droughted	Moderate N	207 ± 8^{b}	403 ± 15^{bc}
	High N	135 ± 12^{e}	313 ± 28^{d}
ANOVA			
Water level		**	**
N level		**	**
Water × N		**	**

Values are presented as the mean ± SE of eight replicates. Values followed by the same letter in the columns were not significantly different according to Duncan's test at $P = 0.05$; ** Significant at the 0.01 probability level.

per treatment. Whole plants were harvested, divided into plant shoots (leaves and stems), roots, and tubers, and washed to remove soil residues. Tubers larger than 1 cm in diameter were weighed and then sliced thinly. Plant shoots, roots, and tuber slices were then dried at 70°C until they reached a constant weight for DM determination. The dried samples were then ground, passed a 40-mesh screen, and analyzed for N concentration. The concentration of N in different plant parts was measured by the standard macro-Kjeldahl method according to Nelson and Sommers (1973).

Tuber yield was calculated as the tuber fresh weight per plant at 69 DAT. Tuber N uptakes were calculated by multiplying the tuber dry weight by the tuber N concentration at 69 DAT. The total DM accumulation of the whole plant was calculated as the sum of the dry weight of plant shoots, roots, and tubers. The amount of N accumulated in each plant portion was calculated by multiplying the N concentration by the dry weight of each plant part. Then, the values obtained in each plant portion were added up to determine the total N accumulation in the plant. DM partitioning to tubers was determined from the tuber dry weight as a percentage of whole plant dry weight, that is, the harvest index. N partitioning to tubers was determined from the amount of N accumulated in tubers as a percentage of the amount of total N accumulated in the plant, that is, the N harvest index. The specific equations were as follows:

Total plant dry weight (g/plant) = Shoots dry weight + Roots dry weight + Tubers dry weight

Total N content (mg/plant) = Shoots dry weight × N concentration in shoots + Roots dry weight × N concentration in roots + Tubers dry weight × N concentration in tubers

Harvest index (%) = Tubers dry weight / Total plant dry weight

N harvest index (%) = Tubers N content / Total N content

Statistical analysis

Statistical analyses were performed using the SPSS statistical software (Version 19.0 for Windows, SPSS, Chicago, USA). Analysis of variance (ANOVA) was used to assess the effect of water, N, and their interaction on the related parameters. Treatment means were compared using the Duncan's test at a 5% level of significance.

RESULTS AND DISCUSSION

Among the environment factors that can be modified by farmers, water and N levels are the two main ones affecting plant growth (Gonzalez-Dugo *et a*l., 2010). Several studies have demonstrated that crop yield is directly related to water and N levels in soil (Mueller *et al*., 2012). In our study, potato tuber yield and N uptake were both significantly affected by water levels, N rates, and the interaction between water and N (Table 2). Among three water levels, there was an increase in tuber yield and N uptake with the application of moderate N compared with low N. While high N level did not further increase tuber yield and N uptake, it resulted in a lower yield and N uptake. This suggests that the N fertilizer

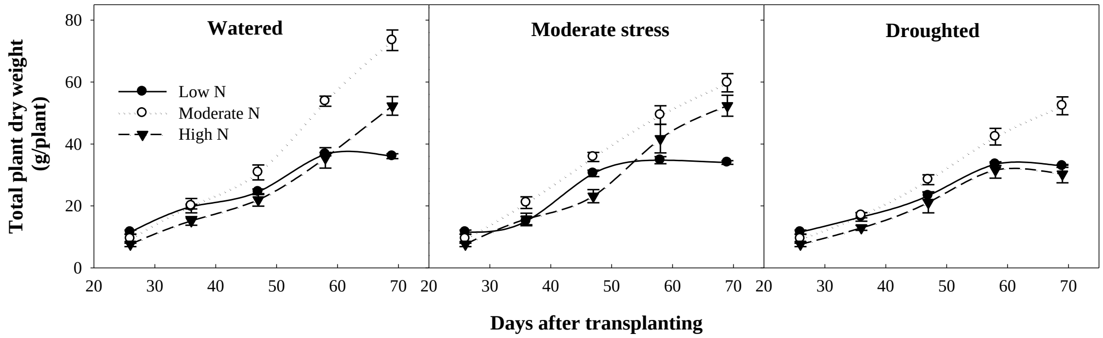

Figure 1. Total DM accumulation in potato plants at different days after transplanting under different water and N levels. Data are presented as the mean ± standard error (SE, n = 5).

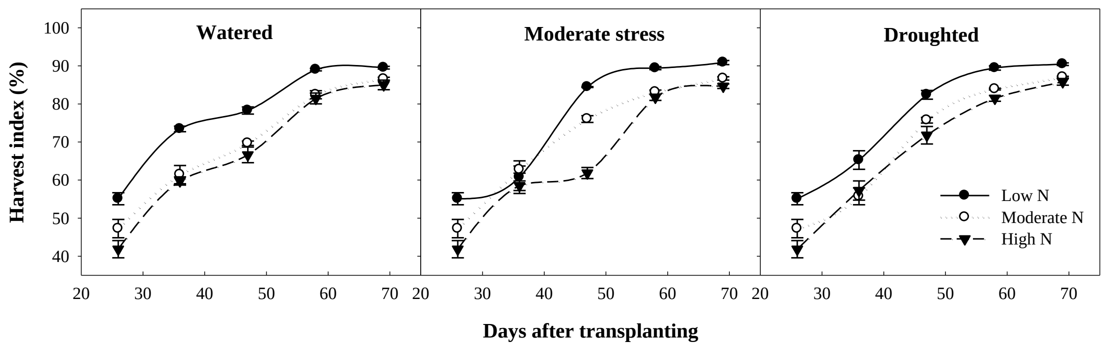

Figure 2. Harvest index for tubers in potato plants at different days after transplanting under different water and N levels. Data are presented as the mean ± SE (n = 5).

dose is not the more the better for the potato yield and N uptake. Moderate N rate (85.5 kg N ha^{-1}) was beneficial for potato production, while low (0 kg N ha^{-1}) or high (171 kg N ha^{-1}) N rates would restrict tuber yield and N uptake. Among three N rates, watered plants (90% field capacity) had higher tuber yield and N uptake than plants under water stress (70 and 50% of field capacity). It suggests that the growth of potato requires a great deal of water, water deficiency would restrict potato growth and N uptake, and then result in a low yield. In water combined with N conditions, tuber yield and N uptake was highest under the watered combined with moderate N condition. This means that watered, moderate N and watered combined with moderate N conditions were beneficial for tuber yield and N uptake improvement. This is in agreement with the findings of Ierna *et al*. (2011), who reported that the highest potato yield was achieved under irrigation at 100% of the maximum evapotranspiration (ETM) and a medium fertilization level (100 kg ha^{-1} of N).

Potato yield depends on the amount of total DM the plant accumulates and the amount of DM that is partitioned to the tubers, that is, the harvest index (Jenkins and Mahmood, 2003). In our study, in terms of tuber bulking, the total DM accumulation and harvest index in the potato plant increased with time under all water and N levels although the amounts differed with different treatments (Figures 1 and 2). Among the three water levels, although there was no apparent difference in the harvest index, watered plants accumulated more total DM than plants under water stress, which resulted in a higher yield (Table 2; Figures 1 and 2). This suggests that watered conditions are beneficial for potato DM accumulation, it increased tuber yield by increasing the accumulation of total DM but not by increasing the partitioning of DM to tubers. This is consistent with the findings of Wolfe *et al*. (1983). Among the three N levels, plants with moderate N accumulated the highest amount of total DM and tuber yield, but the harvest index was not highest under this condition (Table 2; Figures 1 and 2). Under low N levels, although the harvest index was the highest, the amount of total DM the plant accumulated was lower, which resulted in a lower yield. Under high N levels, because both the total DM accumulation and harvest index were lower, plants had a lower tuber yield. Thus, the highest tuber yield with moderate N was attributed to the highest amount of total DM the plant accumulated. Millard and Marshall (1986) also reported similar results that potato yield increases were due to the

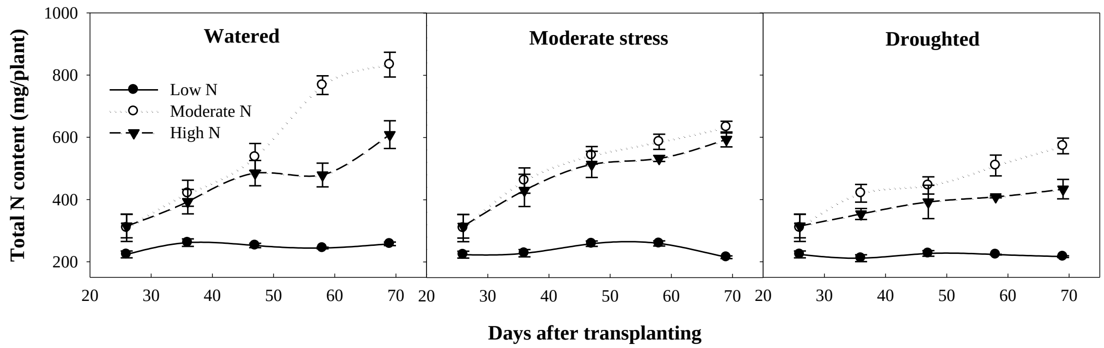

Figure 3. Total N accumulation in potato plants at different days after transplanting under different water and N levels. Data are presented as the mean ± SE (n = 5).

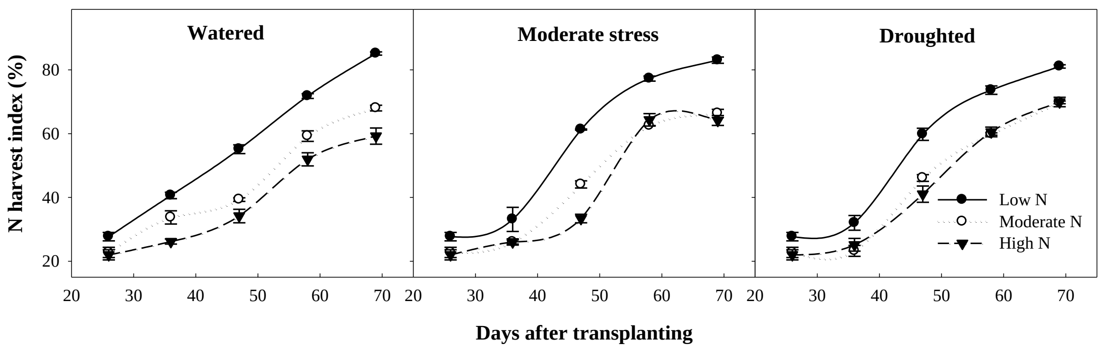

Figure 4. Harvest index for N in potato plants at different days after transplanting under different water and N levels. Data are presented as the mean ± SE (n = 5).

increased accumulation of total DM. In water combined with N conditions, the total DM the plant accumulated, and tuber yield were both highest under the watered combined with moderate N condition, but the harvest index was not highest under this condition. This suggests that the watered combined with moderate N condition is beneficial for potato DM accumulation, but it did not promote the partitioning of DM to tubers. Thus, the increased tuber yield under this condition was due to the increased accumulation of total DM in the plant but not to the increased partitioning of DM to tubers.

Nitrogen is an essential element for maintaining the physiological activities of plants. Understanding the patterns of plant N accumulation and partitioning is important for increasing crop N uptake (Hirel *et al*., 2007). For tuber bulking, the amount of total N the plant accumulated increased with time under moderate and high N conditions for all the three water levels, but the amount of total N in low N plants did not change obviously (Figure 3). This may be because, under low N conditions, the plants could not accumulate more N because of soil N deficiency. The N harvest index increased with time for all water and N levels (Figure 4). This indicated that more N in the potato plant was translocated into the tubers during tuber bulking phase. Among the three water levels, since N is taken up with water, the amount of total N the plant accumulated under water stress was lower than that under watered conditions, though there was no significant difference in the N harvest index (Figures 3 and 4). This suggests that the higher tuber N uptake under watered conditions resulted from the higher accumulation of total N in the plant. Among the three N levels, plants with moderate N accumulated the most N, but the N harvest index was not highest under this condition (Figures 3 and 4). At low N levels, as in Millard *et al*.'s report (1989), the N harvest index was higher than it was at moderate N and high N levels, but the accumulation of plant total N was the lowest. Under high N levels, the total N the plant accumulated and the N harvest index were lower. This suggests that the higher tuber N uptake with moderate N was due to the higher amount of total N the plant accumulated. In water combined with N conditions, plants with watered and moderate N accumulated the most total N, but these plants did not have the highest N harvest index. This means that the highest tuber N uptake under the watered combined with moderate N condition was due to the highest accumulation of total N in the plant.

Therefore, like tuber yield, the increased tuber N uptake is attributed to the increased accumulation of total N in the plant.

On the whole, the patterns of plant DM and N accumulation and partitioning were obviously affected by the water and N levels. Understanding the changes of these patterns under different water and N levels is important for improving potato yield and N uptake. Watered and moderate N conditions (90% of field capacity and 85.5 kg N ha^{-1}) were beneficial for potato yield, N uptake, DM and N accumulation during the tuber bulking stage, but were not beneficial for the partitioning of DM and N to tubers. Thus, watered conditions, moderate N conditions, and the watered combined with moderate N condition increased the tuber yield and tuber N uptake by increasing the accumulation of total DM and N in the plant, but not by increasing the partitioning of DM and N to tubers. Therefore, optimizing water and N management to improve the accumulation of total DM and N during the tuber bulking stage is important for increasing tuber yield and N uptake in potato production.

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