Chapter 20
Potato Evapotranspiration and Productivity as Affected by Drip Irrigation Frequency and Soil Matric Potential

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Abstract Drip irrigation has been shown to be an effective method for achieving high potato yields. Soil matric potential (SMP) and irrigation frequencies are two important factors in optimizing potato production and tuber quality. This chapter reviews and discusses a case study of potato evapotranspiration (ET) and productivity in drip irrigated potato systems in the North China Plain in 2001 and 2002, as affected by SMP and irrigation frequency. The experiment in this case study included five treatments for SMP: F1 (−15 kPa), F2 (−25 kPa), F3 (−35 kPa), F4 (−45 kPa) and F5 (−55 kPa) and six treatments for irrigation frequency: N1 (daily irrigation), N2 (2 day intervals), N3 (3 day intervals), N4 (4 day intervals), N6 (6 day intervals) and N8 (8 day intervals). In general, ET was reduced at lower SMP, as F5 had the lowest ET (150 mm) among the five treatments, and F2 had the highest (208 mm). F1 experienced somewhat waterlogged conditions. Potato ET losses declined as SMP dropped from −25 to −55 kPa. Higher frequency of irrigation enhanced both potato tuber growth and water use efficiency (WUE). Reducing irrigation frequency from N1 to N8 resulted in significant yield reductions by 33.4% and 29.1% in the 2001 and 2002 growing seasons, respectively. Based on the results, the authors of this case study suggested a SMP threshold of −25 kPa, and an irrigation frequency of once a day for the as a target for drip irrigation management for potato production in the North China Plain.

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20.1 Introduction

Arid and semi-arid areas account for one third of the land area of the Earth's surface. Semi-arid regions are defined as transition zones between arid and sub-humid belts, where precipitation is less than the potential evaporation (ET) (Huang et al. 2010). One of these regions is the Northern Area of China. As China is a country not only with a shortage of water resources, but also supporting a large population with great food needs, the development of sustainable and economically viable food production techniques is important in order to achieve security of both food and water resources. Research on water-saving and high-efficiency agriculture in China has been primarily focused on five aspects: (1) biological water-saving technologies such as identification and creation of water-efficient and draught-tolerant plant species, (2) development of technologies that can recycle and utilize inferior water resources such as brackish and reclaimed irrigation water, (3) creation of highly efficient water using technologies for dry farming, (4) development of water saving irrigation technology and equipment, and (5) creation of comprehensive technologies that meet regional needs for high-efficiency water-saving agriculture (Wu 2010). There has been a significant body of research conducted towards these efforts. For example, the effects of different planting pattern on water use and yield performance of winter wheat were examined in the Huang-Huai-Hai plain of China, and the furrow irrigated raised bed-planting was recommended as a sound opportunity for sustainable farming in that region (Zhang et al. 2007). The technique of micro-rainwater harvesting with ridges and furrows for potato production in semi-arid areas of China was evaluated (Wang et al. 2008). In addition to this chapter, Chap. 22 reviews the effect of plastic mulch on reduction of water loss and soil temperature regulation for potato growth. Chapter 23 reports the development of the transgenic potato plants with improved tolerance to drought and salinity stresses.

Efficient water delivery systems can contribute towards increasing higher crop yields and improved water and fertilizer use efficiency (WUE) (Badr et al. 2010; Jensen et al. 2010). Drip irrigation has been shown to be an effective method for achieving high potato yields (Eldredge et al. 2003; Yuan et al. 2003). However, precise irrigation management is essential to ensure the most efficient attainment of optimal yield and quality, as water storage under drip irrigation conditions is generally less than that for surface and sprinkler irrigation techniques, and most roots are concentrated in the wetted soil volume near each emitter or along each lateral line (Kang et al. 2004). Soil matric potential (SMP) and irrigation frequencies are two important factors in optimizing the potato production and quality (Wilson et al. 2001; Shock and Wang 2011). Based on published data (Kang et al. 2004; Wang et al. 2006, 2007), this chapter reviews and discusses a case study of potato ET and productivity in drip irrigated potato systems in the North China Plain affected by the SMP and irrigation frequency.

20.2 Irrigation Management and Precipitation

Field experiments were conducted at Luancheng (Hebei Province) Agro-ecosystem Station (LAES), Chinese Academy of Sciences, during the 2001 and 2002 growing seasons (Kang et al. 2004; Wang et al. 2006, 2007). Annual precipitation in the area is about 480 mm. and is normally concentrated between July and September, as precipitation is very rare in the spring and early summer. The dominant soil type is loam, with an average bulk density of 1.53 $g\,cm^{-3}$ for the upper 30 cm soil layer. The mineral content of the groundwater is less than 0.5 $g\,L^{-1}$, with the water table about 28 m below the surface. The drip irrigation system was installed after the experimental field was ploughed and bedded. Thin-wall drip tapes with a flow rate of 3.72 $L\,m^{-1}\,h^{-1}$ at 0.042 MPa were placed in the center of the raised beds. Dripper spacing was 30 and 20 cm, respectively, in the 2001 and 2002 growing seasons.

The six treatments for irrigation frequency were: daily (N1), and at intervals of every 2 days (N2), 3 days (N3), 4 days (N4), 6 days (N6), and 8 days (N8). In 2001, due to the lack of information on potato ET under drip irrigation the N1 treatment was irrigated according to SMP readings, weather broadcasts, and visual observation of potato growth. In 2002, the irrigation depth of N1 was determined from the previous day's ET, as measured by a lysimeter on the SMP (−25 kPa) treatment conducted at the same site and time. Irrigation quantities for N1 and precipitation after potato emergence are listed in Fig. 20.1. The total amount of irrigation was 192 and 142 mm

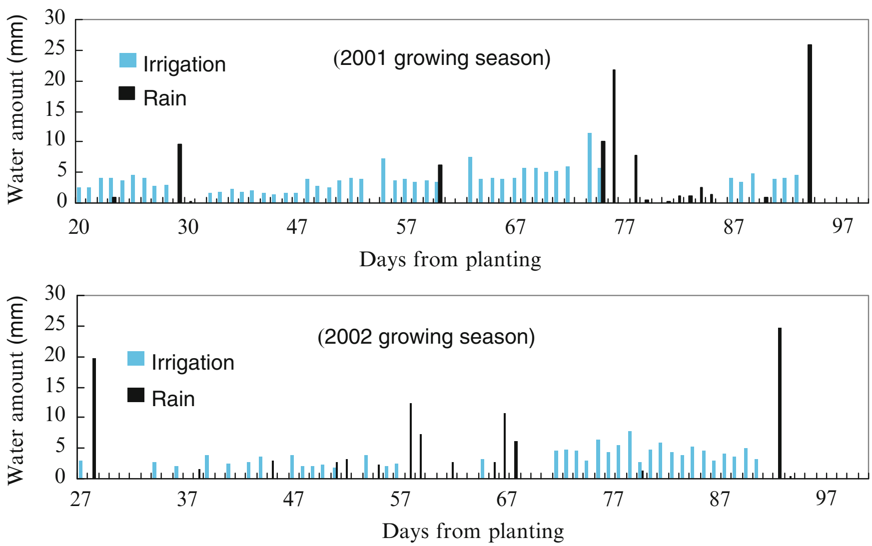

Fig. 20.1 Total amount of water received from daily irrigation (*N1*) and precipitation following potato emergence (Wang et al. 2006)

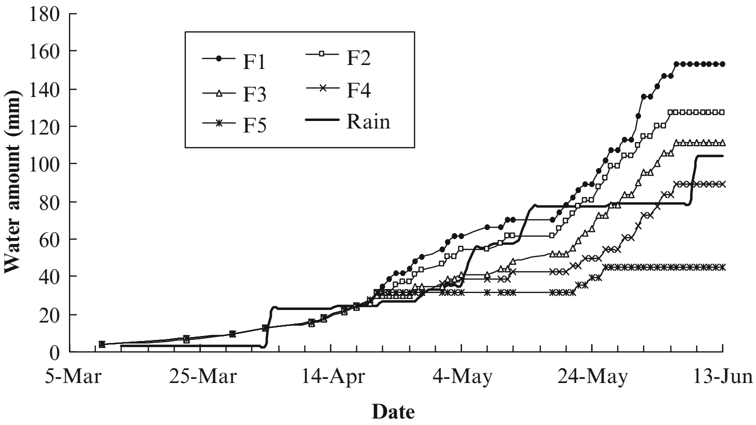

Fig. 20.2 Cumulative precipitation and irrigation water for potatoes in the 2002 growing season under different soil matric potentials: −15 kPa (F1), −25 kPa (F2), −35 kPa (F3), −45 kPa (F4) and −55 kPa (F5) with rain precipitation (Kang et al. 2004)

during the 2001 and 2002 growing seasons, respectively. Total rainfall was 77 and 104 mm, respectively, for the two seasons (Wang et al. 2006). Irrigation water in the other treatments was taken as the cumulative value of N1 treatment. When it rained, effective rainwater was subtracted from irrigation application. Before the potatoes sprouted, all treatments plots were well irrigated with the same quantity of water, at the same frequency, in order to ensure a uniform germination rate. After that, each plot was irrigated according to prescribed frequency treatments.

SMP was measured at 0.2 m, immediately under the drip emitter, and the 5 SMP treatments were: −15 kPa (F1), −25 kPa (F2), −35 kPa (F3), −45 kPa (F4) and −55 kPa (F5). Irrigation was applied only when the SMP reached the targeted values for F1, F2, F3, F4 and F5. The depth of water for each irrigation event of all the SMP treatments (the constant) was constantly changing during the growing season and varied from about 3 to 6 mm. Seasonal total applied irrigation for F1, F2, F3, F4 and F5 was 153, 132, 111, 89 and 45 mm, respectively (Fig. 20.2).

20.3 Potato Evapotranspiration

Evapotranspiration from growing plants is one of the essential parameters that must be assessed in order to achieve optimal irrigation management (Timlin et al. 2007). Badr et al. (2010) conducted a field investigation on the effects of drip irrigation and ET on yield and yield components, using four irrigation levels representing 100%, 80%, 60% and 40% of potato ET. Marutani and Cruz (1989) found that 3 to 5 mm of water per day is necessary to fulfill ET requirements and maintain optimal soil water potential (−50 to −10 kPa) for growing potatoes in the tropics. For a sub-humid region in India under furrow irrigation conditions, Kashyap and Panda (2001, 2003) evaluated ET estimation methods, and developed the crop-coefficients for potato. They found that the maximum and average daily ET of potatoes was 4.24 and 2.49 mm, respectively. Under hot dry conditions in northeastern Portugal, peak ET rates reached 12 to 13 mm per day on days immediately following irrigation, but then declined logarithmically to about 3 mm per day within 5 days following sprinkler irrigation (Ferreira and Carr 2002).

In this case study, the ET varied from 275.6 mm (N4) to 293.0 mm (N3) in the 2001 season, and from 192.1 (N8) to 214.5 mm (N1), among the six irrigation frequency treatments. The differences between the two seasons revealed a 74.4 mm higher average ET of the six irrigation frequency treatments in 2001 than that in 2002. However, it should be pointed out that the differences in ET between treatments in both growing seasons were statistically insignificant at $P = 0.05$ (Wang et al. 2006).

In the 2002 growing season, the highest ET value for the SMP treatments was 63.4 mm greater than that for the lowest SMP, representing a decrease of 32.1%. A drip-irrigation frequency of 4 days or less had little effect on potato ET; however, irrigation frequencies of 6 and 8 days resulted in ET values were lower than in the other frequency treatments. The highest ET value was 36.7 mm (19.2%) more than the lowest value. As potato ET is affected by SMP and irrigation frequency, Kang et al. (2004) proposed that potatoes would sustain severe water stress and reduced crop ET when the SMP was below −45 kPa. Further analysis indicated that total ET was a function of SMP and irrigation frequency. The relationships are ET (mm) $= 0.0216P^2 - 0.1217P + 205.7$ (P, −KPa; $R^2 = 0.987$) and ET (mm) $= 0.6076D^2 + 0.1945D + 187.81$ (D, days; $R^2 = 0.843$), for the ET and SMP, respectively. These relationships indicate that total ET decreases significantly as SMP and irrigation frequency decrease.

Based on the observations in the work, a SMP threshold of −25 kPa and an irrigation frequency of once a day were suggested for potato drip-irrigation scheduling in the North China Plain (Kang et al. 2004). This suggestion was further fine tuned by Wang et al. (2007). In the later analysis, F5 had the lowest ET among the five treatments (150 mm), while F2 had the highest ET (208 mm). The difference was 48 mm (30%) higher with F2 than with F5. Although F1 had the highest irrigation frequency and greatest depth percolation (14.7 mm), the lower ET of F1 than F2 suggested that the F1 experienced somewhat waterlogged conditions. This observation implied that plant performance and water uptake could have been constrained by leaching of nutrients from the rooting zone, and a decrease in root activity due to poor soil aeration. ET values declined as SMP dropped from −25 to −55 kPa, with the sharpest reduction (22 mm) occurring when the SMP dropped from −45 to −55 kPa. This suggests that potatoes sustain notable water stress at SMP values below −45 kPa. In other words, an SMP of −25 kPa (F2) was the most favorable criterion for potato production and water use efficiency (WUE), whereas −15 kPa (F1) was too wet and −45 kPa (F4) too dry, leading to severe water stress.

20.4 Potato Root Distribution

Based on the root length density (RLD) and root weight density (RWD) data (Tables 20.1), researchers concluded that potato roots were concentrated in the top 40 cm of the soil layer for all treatments. The highest root density appeared between 0 and 10 cm, where about 26–41% and 63–82% of the total root density was concentrated based on RLD and RWD, respectively. For the entire soil profile (0–60 cm) the data revealed the trend of increasing RLD but decreasing RWD with the more irrigation frequency. This inconsistency between RLD and RWD has been reported previously for irrigated cotton plants (Plaut et al. 1996). For this reason, some researchers use RLD only to characterize root systems (Coelho and Or 1999).

In the SMP experiment Wang et al. (2007) found that RWD had a tendency to increase gradually as SMP dropped from −15 to −35 kPa in the 0–30 cm soil layer, reaching a maximum at F3 (−35 kPa) and then declining as SMP decreased from −35 to −55 kPa (Fig. 20.3). One exception was observed with the F4 (−45 kPa) treatment at the depth of 0–10 cm, and could perhaps be due to sampling errors. It was clear that most potato roots grew in the upper 0 to 40 cm of the soil, with only a few roots growing deeper than 40 cm. The affect of SMP on RWD in the horizontal direction of root growth (Fig. 20.3b) was similar to that vertically (Fig. 20.3a), with few roots extending more than 30 cm from the potato plant. Previously, Lahlou and Ledent (2005) reported that the average root length of four potato cultivars whose root dry mass had been reduced by drought were all below 38.5 cm, under either well irrigated or water-stressed conditions. It was recently proposed that partial rootzone drying (PRD) is one technique that offers potential for reducing the

Table 20.1 Effects of potato root distribution under different irrigation frequencies in the 2001 growing season. Irrigation frequency treatments were: once every day (N1), once every 2 days (N2), once every 3 days (N3), once every 4 days (N4), once every 6 days (N6), and once every 8 days (N8) (Wang et al. 2006)

	Soil layer					
Treatment	0–10 (cm)	10–20 (cm)	20–30 (cm)	30–40 (cm)	40–60 (cm)	0–60 (cm)
(a) Root length density (cm cm^{-3})						
N1	0.227	0.153	0.160	0.172	0.083	0.146
N2	0.193	0.139	0.137	0.136	0.065	0.122
N3	0.276	0.102	0.111	0.108	0.042	0.113
N4	0.255	0.107	0.111	0.115	0.040	0.112
N6	0.268	0.110	0.096	0.097	0.044	0.110
N8	0.246	0.107	0.109	0.103	0.048	0.110
(b) Root weight density (mg cm^{-3})						
N1	0.883	0.178	0.109	0.154	0.043	0.235
N2	1.030	0.108	0.099	0.087	0.081	0.248
N3	1.486	0.237	0.186	0.150	0.072	0.367
N4	1.614	0.132	0.097	0.122	0.051	0.345
N6	1.924	0.166	0.127	0.074	0.029	0.392
N8	2.175	0.221	0.125	0.106	0.090	0.468

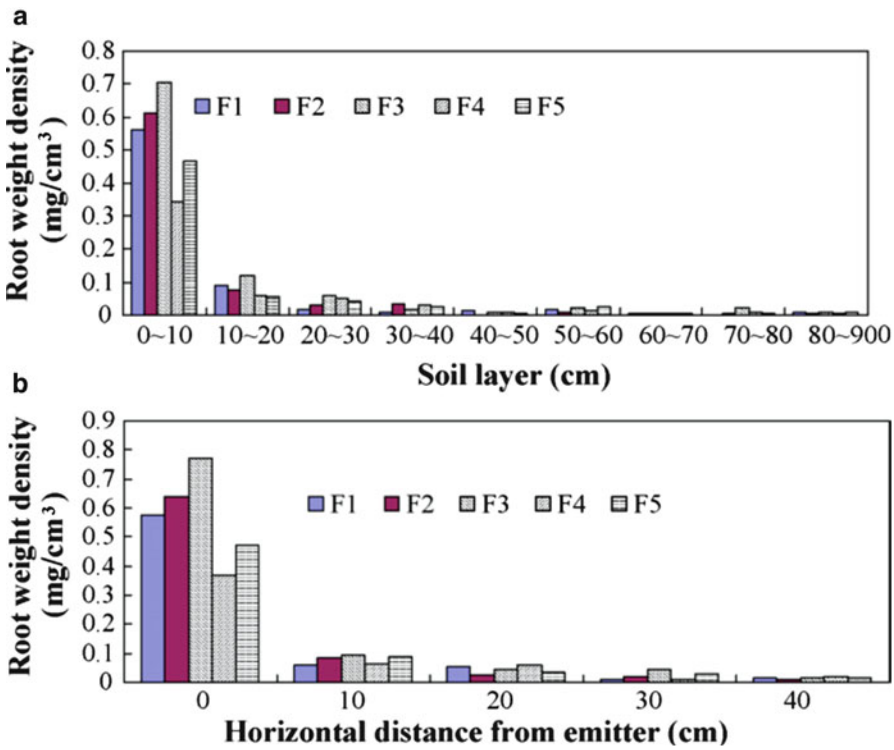

Fig. 20.3 Root weight density at (**a**) different soil depths and (**b**) different horizontal distances from crop base. The five soil matric potential treatments were: −15 kPa (F1), −25 kPa (F2), −35 kPa (F3), −45 kPa (F4) and −55 kPa (F5) (Wang et al. 2007)

use of irrigation water (Saeed et al. 2008). PRD may have potential in achieving sustainable potato production in the North China Plain. However, more field research on the impacts of drip irrigation parameters on root growth is needed prior to its widespread implementation, in order to ensure conservation of irrigation water with minimal loss of potato yield.

20.5 Potato Yields and Water-Use Efficiency (WUE)

Although the absolute tuber yield values were different in 2001 and 2002, tuber yield decreased as irrigation frequency declined (Table 20.2). In both season, the yields with irrigation frequency of N2, N3, and N4 were very close, whereas there was a sharp yield reduction with N6 and N8. In the 2001 season, the yield of potato tubers ranged from 14,139 to 21,234 kg ha^{-1}. The highest yield was with N1, and was 50.2% higher than the lowest yield produced (N8); however, differences among treatments were not significant according to F-test ($P > 0.05$). In the 2002 season,

Table 20.2 Potato tuber yields, water use efficiency (WUE) and irrigation water use efficiency (I_{WUE}) with soil matric potential treatments of −15 kPa (F1), −25 kPa (F2), −35 kPa (F3), −45 kPa (F4) and −55 kPa (F5), and irrigation frequency of once every day (N1), once every 2 days (N2), once every 3 days (N3), once every 4 days (N4), once every 6 days (N6), and once every 8 days (N8)

	Tuber yield (kg ha^{-1})		WUE (kg ha^{-1} mm)		I_{WUE} (kg ha^{-1} mm)	
	2001	2002	2001	2002	2001	2002
N1	21,234	28,241	77	132	–[a]	–
N2	16,750	25,307	59	125	–	–
N3	16,889	25,405	58	120	–	–
N4	16,872	24,109	61	114	–	–
N6	14,176	21,157	50	103	–	–
N8	14,139	20,000	51	104	–	–
F1	–	22,590	–	115	–	−194
F2	–	26,660	–	128	–	155
F3	–	23,410	–	122	–	126
F4	–	20,640	–	113	–	38
F5	–	18,980	–	119	–	–

Data are adapted from Kang et al. (2004) and Wang et al. (2006, 2007)
[a] No data available

potato tuber yield ranged from 20,000 to 28,241 kg ha^{-1}. The yield for the six treatments were in order of N1 > N3 > N2 > N4 > N6 > N8, and differences among treatments was significant ($P < 0.05$). Tuber yield was significantly higher with N1 than with N6, and N1 was 41.2% higher than N8. The yield difference between any other two treatments was insignificant ($P = 0.05$) (Wang et al. 2006). The SMP data for the 2002 season revealed that total tuber yield for the different SMP treatments followed the order of F2 > F3 > F1 > F4 > F5 (Table 20.2). It is assumed that tuber growth in treatments F4 and F5 were restrained to some extent by a soil water deficit, while tuber growth at F1 was restrained by soil water excess (Wang et al. 2007). Statistical analysis ($P = 0.05$) indicated that treatment F2 resulted in a significantly higher yield than treatments at F1, F4 and F5. F3 also had a significantly higher yield than F5 (Wang et al. 2007).

The cumulative irrigation for each drip irrigation treatment was 192 and 142 mm during 2001 and 2002 growing seasons, respectively. Cumulative rainfall was 77 and 104 mm, respectively, for the two seasons (Wang et al. 2006). In 2001, the change in soil water content that occurred between planting and harvesting of each treatment was negative, indicating that the soil became drier at the end of the growing season. In 2002, the change was positive, suggesting that the soil became wetter. Perhaps due to this difference in soil moisture content, the values of WUE were nearly twice as high in 2002 than 2001: however, despite higher WUE values in 2002, the effects of irrigation frequency on WUE and tuber yield for both seasons displayed the same general pattern.

Wang et al. (2007) noticed that WUE at the F1 SMP treatment was higher than that at F4, implying that WUE was not a good criterion for evaluating the effectiveness of irrigation in that particular experiment; therefore, an improved parameter, irrigation water use efficiency (I_{WUE}) was introduced as an additional factor. This parameter is defined as:

$$I_{WUE_i} = \frac{Y_i - Y_{i-1}}{I_i - I_{i-1}}$$

where Y_i and Y_{i-1} are yield at irrigation levels I_i and I_{i-1}, respectively.

Evaluation of this factor revealed that the F2 SMP treatment had the highest I_{WUE}, and suggested that a SMP of −25 kPa should be an irrigation target (Table 12.2). F1 had a negative I_{WUE} value consequent with lower tuber yield than F2. Furthermore, F3 had a higher I_{WUE} than F4, implying that the irrigation increase for F3 was more worthwhile than that for F4. Based on both the WUE and I_{WUE} analysis, the authors concluded that both F2 and F3 are good SMP thresholds for favorable potato production, with F2 superior due to both higher WUE and I_{WUE} values.

20.6 Potato Tuber Quality

In the 2001 season, the total tuber number per plant varied between 4.0 and 6.9 among the drip irrigation treatments (Table 20.3). Treatments N1, N2, N3, N4 and N6 resulted in more tubers per plant than did N8; however, the difference among the six treatments were not significant ($P > 0.05$) (Wang et al. 2006). In contrast, there were significant differences in the number of marketable tubers among these treatments, with N2 producing the most, N1 producing the second, and N8 producing the lowest quantity of tubers that were over 50 g in weight. Overall, irrigation frequency increased the number of marketable tubers, as N1, N2, N3, N4 and N6 all had significantly higher marketable tuber yield than N8. In 2002, the effects of irrigation frequency on tuber quality was more significant than in 2001, with significant differences found in total tuber number per plant among the treatments. The difference in marketable tuber number among the treatments was also highly significant ($P < 0.05$), and N1 produced significantly more marketable tubers than the other treatments. While the marketable tuber yield of N2 and N3 were very similar, irrigation frequency did increase production, and N3 was significantly higher than the N6 treatment. In summary, data for both the 2001 and 2002 growing seasons suggest that potato tuber production was optimized under the N1 irrigation frequency (daily irrigation), and that potatoes grown under the N8 (once every 8 days) irrigation regime had lower total tuber and marketable tuber yield than potatoes grown with higher irrigation (Wang et al. 2006).

In 2002, while the total number of tubers produced per plant was not affected by SMP, both the number of marketable tubers and the marketable tuber weight were significantly affected by SMP (Table 20.3). Treatments of SMP at F2 and F3 produced more marketable tubers per plant than potatoes grown at F4 and F5. The marketable tuber weight per plant was also significantly affected by SMP,

Table 20.3 Potato tuber quality impacted by soil matric potential treatments of −15 kPa (F1), −25 kPa (F2), −35 kPa (F3), −45 kPa (F4) and −55 kPa (F5), and irrigation frequency of once every day (N1), once every 2 days (N2), once every 3 days (N3), once every 4 days (N4), once every 6 days (N6), and once every 8 days (N8)

	Total tubers ($plant^{-1}$)		Marketable tubers ($plant^{-1}$)*		Marketable tuber weight (g $plant^{-1}$)	
	2001	2002	2001	2002	2001	2002
N1	6.9a**	7.3a	3.3ac	3.9a	–***	–
N2	6.7a	5.2b	3.5a	3.3ab	–	–
N3	6.0a	6.1ab	2.7ac	3.3ab	–	–
N4	6.1a	5.4b	2.7ac	2.9b	–	–
N6	6.6a	4.5b	2.6ac	2.5b	–	–
N8	4.0a	4.4b	1.7b	2.6b	–	–
F1	–	5.2a	–	3.0ab	–	311.3ab
F2	–	6.4a	–	3.5ac	–	385.9a
F3	–	6.4a	–	3.7a	–	355.5ab
F4	–	5.3a	–	2.6b	–	271.2b
F5	–	4.5a	–	2.3b	–	225.6b

Data are adapted from Wang et al. (2006, 2007)
*Tuber weight not less than 50 g each
**For each treatment, values within a column followed by the same letter are not significantly different (P = 0.05)
***No data available

with F2 producing a much greater mass than the F4 and F5 treatments. Wilson et al. (2001) suggested that management of soil moisture deficit during tuber initiation and early development was important for the optimization of net and marketable tuber yields, as they found marketable tuber yield was better at −25 and −35 kPa than at −55 and −75 kPa. Lynch and Tai (1989) showed that marketable potato yield decreased as soil water potential dropped from −30 to −120 kPa. The observations in the field studies of Wang et al. (2006, 2007) for potato production in the North China Plain are consistent with the two previous studies.

20.7 Conclusions

In Northern China, potatoes are generally planted in raised beds and furrow-irrigated. Due to regional water shortages, farmers in this region are currently encouraged to adopt drip irrigation techniques to maximize water conservation. This chapter reviewed a field experiment that compared the effects of different drip irrigation frequencies and SMP thresholds on potato ET and productivity in a loam soil in the North China Plain. Potato ET increased as irrigation frequency and SMP increased, with the highest ET 63.4 mm (32.1%) more than the lowest ET value. Analysis of potato growth and productivity data revealed that a SMP of −25 kPa is most favorable for potato production, while a SMP of −15 kPa is too high and a

SMP of −45 kPa or more leads to notable water stress. Based on irrigation frequency treatments, the highest ET was 36.7 mm (19.2%) more than the lowest value. Drip irrigation frequency also affected root growth, as higher irrigation frequency resulted in a higher root length density. Increasing the irrigation frequency enhanced potato tuber growth, yield of marketable tubers, and water use efficiency. Based on these results these researchers recommend that a SMP threshold of −25 kPa and an irrigation frequency of once a day, could be used as a target reference for drip irrigation management for potato production in this region.

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