Journal of Bio-Environment Control, 15(4):340~345, (2006)

Effect of Root Zone Cooling on Growth Responses and Tuberization of Hydroponically Grown 'Superior' Potato (*Solanum tuberosum*) in Summer

Dong Chil Chang[1]*, Jin Cheol Jeong[1], and Yong Beom Lee[2]

[1]*National Institute of Highland Agriculture, Rural Development Administration, Pyeongchang 232-954, Korea*

[2]*Department of Environmental Horticulture, University of Seoul, Seoul 130-743, Korea*

Abstract. A potato (*Solanum tuberosum* L. cv. Superior) cultivar was grown in aeroponic cultivation system to investigate the effect of root zone cooling in summer. Based on their nutrient uptake, growth responses, and tuberization, the possibilities for potato seed production were determined. Although shoot growth and early tuberization increased in the conventional non-cooling root zone system (root zone temperature of 25±2°C), stolon growth, photosynthesis, transpiration rate and number of tubers produced were higher in the cooling root zone system (20±2°C) than in the non-cooling system. Increasing root zone temperature above 25°C stimulated absorption of K more than T-N, P, Ca, Fe and Mn. On the other hand, root zone temperatures in the range of 20°C to 25°C did not affect Mg contents. The lower uptake and supply to leaves of T-N, Fe and Mn at the high root zone temperature promoted early tuberization and advanced haulm senescence. The results stress the importance of keeping root zone temperature to as low as below 20, particularly in summer under temperate zone.

Key words : hydroponic system, potato, root zone temperature, tuberization

*Corresponding author

Introduction

Since its introduction to Korea, potato cv. Superior has been a principal cultivar widely cultivated for tablestock. Seed potato production of the Superior is mostly based on hydroponic cultivation systems using in vitro plantlets. Some responses of the Superior to hydroponic systems (Kang et al., 1996) and nutrient solution properties (Chang et al., 2005) such as electrical conductivity and pH have been investigated. However, relatively little information is available for solution temperatures (or root zone temperatures), although potato has good adaptability to low temperatures (Beukema and Van der Zaag, 1979).

In an earlier paper (Chang et al., 2001) we reported the effects of nutrient solution temperature on the growth response of two potato cultivars, especially during winter season. High nutrient solution temperatures (20~25°C) promoted haulm growth and early tuber formation of the Superior cultivar. Generally, root zone temperature of potato is crucial to the onset of tuberization and to the subsequent tuber growth. According to Epstein's report (1971) with soil experiment, low soil temperature (5°C) enhanced tuber formation more than high temperature (29°C). The effect of root zone temperature on crop growth also has been reported in other horticultural crops such as cutted rose (Lee et al., 2004), tomato (Lee et al., 2002), and cucumber (Lee et al., 2001).

Plant roots are known to function best at a temperature between the high teens and the mid twenties (Barry, 1996). Under hydroponic conditions, nutrient solution temperature affects the nutrient uptake and translocation, and the production rate of hormones in the roots (Papadopoulos and Tiessen, 1987). The temperature induced physiological changes presumably affect level of induction to tuberize (Ewing, 1995). Particularly, high nutrient solution temperatures influence water uptake by affecting the changes in root structure (Al-harbi and Burrage, 1992). Therefore, growth enhancement is assumed to be related to higher water and nutrient uptake under high solution temperature.

As a cool climate crop, potatoes are often produced in cool regions (or season) in preference to warm production areas (or season). However, there have been possibilities that potatoes could be produced in warmer areas (or season) by optimizing the temperatures around certain parts of the potato plant (Struik et al., 1989b). This research is focused on monitoring the growth responses of hydroponically grown Superior cultivar of potato as well as on the accumulation of plant nutrients as influenced by root zone temperatures during the summer season.

Materials and Methods

Plant material & growing conditions

Trials were conducted in 2002 and 2004 at the National Institute of Highland Agriculture (NIHA), Pyeongchang, Korea. Superior (medium-early season) potato (*Solanum tuberosum* L.) plantlets, which account for 60% of the certified seeds in Korea (Chang et al., 2005), were initiated from small tuber sprouts and grown in a recirculating aeroponic system with half strength potato solution (Chang et al., 2000). A randomized complete block design with three replications was employed. Each plot had 36 plants with 25 cm spacing between plants. All experiments were conducted in single spanned glasshouse under mean air temperature of 24°C and 16 hr daylength. Thirty days after transplanting (DAT), daylength was changed from 16 hr to 12 hr to induce tuber initiation. Insects and diseases were controlled as in seed potato production.

Treatment of root zone temperature

Root zone temperature was controlled by cooling the nutrient solution with a coil of flexible copper tubing through which ground water was circulated. The warm root zone temperatures (non-cooling treatment), measured every 30 minutes with an automatic temperature recording meter (TR-71S, T&D, Japan) in the center of the culture bed, were 25.5±1.4°C and 25.1±1.5°C in the light and dark, respectively. The cool root zone temperatures were 21.5±1.0°C and 20.0±0.9°C in the light and dark, respectively. Cooling of nutrient solution was maintained from 20 to 40 DAT (mid July to early Aug.). Solution EC was controlled to 1.0±0.2 $dS{\cdot}m^{-1}$, while pH of the nutrient solution was not adjusted.

Analysis plant growth & plant tissues

Plant growth was expressed as leaf chlorophyll content, shoot weight, and stolon growth. Chlorophyll content was measured 40 DAT on recently matured leaves in upper canopy using a portable chlorophyll meter (SPAD-502, Minolta, Japan) and expressed as relative values. Potato plants were also sampled at 55 DAT for determining shoot and stolon growth and mineral uptake. Stolon growth was measured as the number of primary stolons longer than 5 cm and the length of the longest stolons. After determining fresh shoot weight, leaves were separated out of the shoots and were oven-dried for 48 hr at 85°C. Each plant tissue (leaves and roots) was finely ground in a homogenizer and was ashed by the H_2O_2-H_2SO_4 method in an electric heating block at 420°C for 24 hr. Total-N concentration was determined by the distillation method using automatic nitrogen analyzer (Vapodest, Gerhardt, Germany). Inorganic phosphorus (P) was determined by spectrophotometer (U-2000, Hitachi, Japan). For cations K, Ca, Mg, Fe and Mn atomic absorption spectrophotometer (Z-6000, Hitachi, Japan) with air-acetylene flame was used. All analyses were reported on a dry matter basis.

Tuberization

Tuberization means the first visible swelling of at least one stolon tip (Krauss and Marschner, 1982). Tuberization ratio was calculated as the percentage of tuberized plants over total transplanted plants. After harvest 75 DAT, tubers heavier than 1 g weight were counted and weighed.

Phtosynthesis & transpiration rate

Diurnal measurement of the photosynthetic rate, stomatal resistance and transpiration rate were performed on recently matured leaves in upper canopy using a photosynthesis system (LI-6400, Li-COR, USA) and a steady state porometer (LI-1600, Li-COR, USA), respectively.

Results and Discussion

Nutrient uptake

Table 1 shows the mineral contents of Superior potato leaves and roots as affected by root zone temperature in summer. Mineral contents of potato plants were higher in leaves than in roots, except for P, Mg, Fe and Mn. Total-N content in leaves and roots showed opposite tendency.

Table 1. Mineral contents of hydroponically grown potato cv. Superior as affected by root zone temperature in summer.

Root zone temp.(°C)	T-N	P	K	Ca	Mg	Fe	Mn
	(% dry wt)					(mg·kg^{-1} dry wt)	
				Leaves			
20±2	6.49 a^z	0.65 a	2.84 b	0.99 a	0.66 a	80 a	90 a
25±2	6.14 b	0.53 a	2.93 a	0.97 b	0.66 a	60 a	70 b
				Roots			
20±2	3.75 b	1.14 a	1.93 a	0.69 a	0.76 a	320 b	1,970 b
25±2	3.89 a	1.03 b	1.87 b	0.62 b	0.76 a	330 a	2,040 a

^{z}Mean separation within columns of leaves and roots by *t*-test at $P = 0.05$.

Increasing root zone temperatures from 20°C to 25°C, resulted to decrease in T-N content in Superior leaves from 6.49% to 6.14%. On the other hand, T-N of roots increased from 3.75% to 3.89% with increased root zone temperature. Insufficient supply of nitrogen from the roots to leaves and thereby nitrogen deficiency may have resulted in light green leaves (figure not shown) and early tuberization (Fig. 1) as indicated by previous papers (Krauss and Marschner, 1982; Kang et al., 1996).

Potassium contents in potato leaves and roots showed opposite results to T-N. This result was supported by the role of K in the cation-anion balance in plants: K^+ is a dominant counterion for NO_3^- in long-distance transport in xylem as well as for storage in vacuoles (Marschner, 1995). Contents of P and Ca followed the same pattern (Table 1). Both elements decreased in the leaves and roots with increased root temperature. Coincidence with the Epstein's results (1971), the P content of roots was higher than in leaves at the two root zone temperatures. Magnesium content in both leaves and roots was unaffected by root zone temperatures. It was higher in the roots than in the leaves for both root zone temperatures.

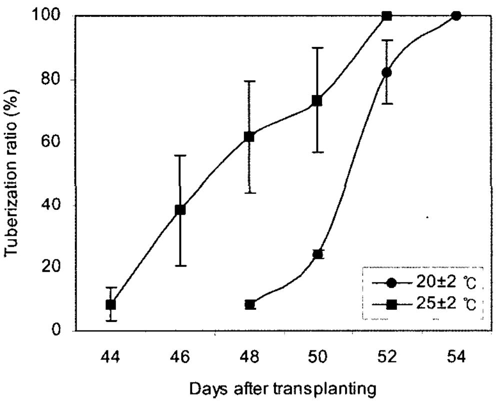

Fig. 1. Evolution of tuber formation in potato cv. Superior under different root zone temperatures during summer. Tuberization ratio was calculated as the percentage of tuberized plants over total transplanted plants. Vertical bars represent SE of treatment means at the times noted.

Contents of Fe and Mn were higher in roots than in leaves at the two root zone temperatures (Table 1). Both micro-elements decreased in the leaves and increased in the roots with increased temperature. The lower uptake and supply of the micro-elements at the high root zone temperature was assumed to cause the early haulm senescence expressed as light green leaves (figure not shown).

Photosynthesis & transpiration rate

Stomatal resistance did not differ significantly in plants grown at root zone temperatures between 20°C and 25°C (Table 2). On the other hand, plants grown at the root zone temperature of 25°C showed decreased photosynthetic activity. This reduction of photosynthesis was apparent above 25°C root zone temperature, particularly in medium-early maturing Superior cultivar (data not shown). Under field conditions, Burton (1972) also estimated that net assimilation for potato plants falls to zero at about 30°C. For these reasons, the optimal temperature for photosynthesis of potato plants has been estimated as extending from 15 to 20°C or 16 to 25°C (Ewing, 1981). Transpiration rate also significantly decreased from 25.4 μg·cm^{-2}·s^{-1} at 20°C root zone temperature to 23.7 μg·cm^{-2}·s^{-1} at 25°C (Table 2). There is, however, general agreement that high root temperatures reduce the resistance to water flow through the root (Epstein, 1971; Moorby and Graves, 1980). This effect is caused by the reduction in root cortex and formation of large xylem vessels resulting from increased root temperature.

Table 2. Effect of root zone temperature on photosynthesis, stomatal resistance and transpiration rate in potato cv. Superior.

Root zone temp. (°C)	Photosynthesis[z] ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Stomatal resistance ($s \cdot cm^{-1}$)	Transpiration rate ($\mu g \cdot cm^{-2} \cdot s^{-1}$)
20±2	16.7±0.77 a[y]	0.88±0.07 a	25.4±0.33 a
25±2	16.3±1.28 b	0.75±0.28 a	23.7±0.15 b

[z] Measuring conditions were 20°C leaf temp. and 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PPF.
[y] Mean separation within columns by *t*-test at $P = 0.05$.
[y] Values denote mean ± SE.

Table 3. Effect of root zone temperature on leaf chlorophyll content, shoot weight, and number of stolons and tubers in potato cv. Superior.

Root zone temp.(°C)	Leaf chlorophyll (SPAD)[z]	Shoot fresh wt. (g/plant)	Stolon length (cm)	No. of stolons/plant	No. of tubers/plant
20±2	43.4±0.4 a[y]	493± 3.5 b	56.8±0.9 a	7.7±1.0 a	11.5±1.1 a
25±2	34.1±1.1 a	515±12.6 a	27.3±5.0 b	6.7±1.0 b	5.8±0.4 b

[z] Leaf chlorophyll was measured 40 DAT by a portable SPAD meter.
[y] Mean separation within columns by *t*-test at $P = 0.05$.
[y] Values denote mean ± SE.

Plant growth

Plant growth measured as shoot weight, leaf chlorophyll and number of stolons was affected by root zone temperature (Table 3). Shoot fresh weight of Superior was higher in plants grown at 25°C root zone temperature than at 20°C. Although potatoes have been classified as a cool season crop, the development of above-ground plant parts is restricted at low temperature (Epstein, 1971). The same results have also been found in other cool season crops (Collier and Tibbitts, 1984; Thompson and Langhans, 1998). Lettuce growth was slower in lower temperatures (15°C or 17°C) than in higher temperatures (23.5°C or 24°C).

In the present experiment, potato leaves of Superior grown at the root zone temperature of 25°C produced more light green leaves (figure not shown) and showed rapid senescence (data not shown) than in 20°C possibly due to the decreased absorption or translocation of T-N, Fe and Mn (Table 1). The results were consistent with the data of Struik et al. (1989a). According to their experiment which allowed temperatures of the shoot, root, and stolon environments to be varied, haulm longevity significantly decreased by high shoot temperature (28°C) combined with high root temperature (28°C). In the experiment, increased stolon temperature also advanced haulm senescence. There was no significant difference in leaf chlorophyll content between the two temperature regimes (Table 3). In an experiment with lettuce, Dale (1965) also confirmed that leaves on plants grown at 15°C appeared greener than comparable leaves grown at 25°C.

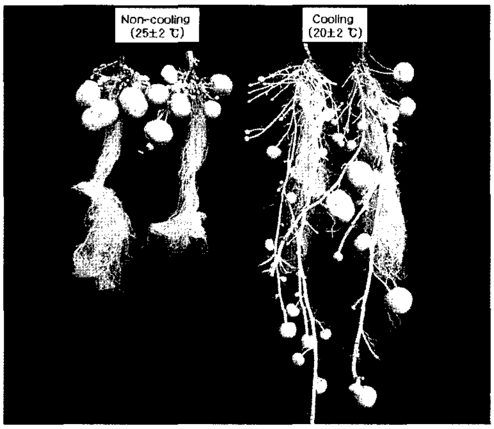

Fig. 2. Effect of root zone temperature on growth of stolons and tubers in potato cv. Superior grown under hydroponic conditions in summer. Picture was taken at final harvest 75 DAT.

Stolon growth, as indicated by the number of primary stolons and the length of the longest stolon, was severely inhibited in the high root zone temperature above 25°C (Table 3 and Fig. 2). The results support two distinct and subsequent physiological responses that were expressed as early tuberization (Fig. 1) and small number of tubers (Table 3). Struik et al. (1986b) reported that high root zone temperature combined with high air temperature reduced stolon number. The influence of high temperature on the development of stolon is assumed to be associated with a production of gibberellins, since gibberellins have been known to promote stolon formation and stimulate stolon elongation.

Tuberization & tuber production

Under present hydroponic conditions, the first indications of tuber formation were observed 44 DAT in root zone temperature of 25°C (Fig. 1). At root zone temperature of 20°C, however, tuber formation was delayed by 4 days compared with tuber formation at root zone temperature of 25°C. These relatively early tuberization in the non-cooling root zone treatment (25°C) could be explained by the nitrogen deficiency (Table 1). The phenomenon also shows the importance of mechanical stress on roots or stolons by high root zone temperature. Because high root zone temperatures (or nutrient solution temperatures) could directly affect the changes in root structure (Al-harbi and Burrage, 1992), and indirectly affect the production rate of hormones in the roots (Papadopoulos and Tiessen, 1987). At root zone temperature of 20~25°C in summer, tuberization of Superior was completed 52 to 54 DAT (Fig. 1). On the other hand, tuberization in winter was completed 39 to 40 DAT (Chang et al., 2001). These differences in time of tuber formation were associated with differences in the pattern of shoot growth (Slater, 1968); high root zone temperatures, particularly in hot climate, can promote potato shoot growth and thereby delay tuber formation in hydroponic conditions.

Because of hot temperature, tuber numbers of Superior were lower in summer than in other growing seasons. Chang et al. (2001) reported 20 to 24 Superior tubers (above 1 g weight) per plant in winter season, particularly in the range of root zone temperature 20~25°C. In the present experiment conducted in summer, however, there was significant decrease in tuber production (6 to 12 tubers per plant) at the same root zone temperatures (Table 3). Struik et al. (1989c) reported that number of tubers depended on the number of potential tuber sites and on the relative tuber set. Particularly, the relative tuber set was extremely low when both the air and root temperature were high. For these reasons, potato production in summer with high temperatures was low. Therefore, above results emphasize the importance of keeping root zone temperature to as low as below 20°C during the summer season in temperate zones.

Conclusions

Our data show that an increased temperature around the root zone stimulate the development of the shoot when the air temperature is high such as in summer season. As indicated by Struik et al. (1989a), the combined high air and root zone temperature causes a severe stress and delays, impedes or even inhibits tuber formation. These stress conditions cause the root system to function so poorly that a certain nutrient (particularly, T-N, Fe and Mn) deficient plant is stunted with light green or yellowing leaves, and shows rapid senescence. Therefore, our study show the importance of root zone cooling on nutrient uptake, growth and tuberization of hydroponically grown potato plants during the summer in temperate zones.

Literature Cited

1. Al-harbi, A.R. and S.W. Burrage. 1992. Effect of root temperature and Ca level in the nutrient solution on the growth of cucumber under saline condition. Acta Hort. 323:61-73.
2. Barry, C. 1996. Nutrients-The handbook to hydroponic nutrient solutions. Casper, Australia. p. 33-49.
3. Beukema, H.P. and D.E. Van der Zaag. 1979. Potato improvement. some factors and facts. International Agricultural Center, Wageningen, The Netherlands. p. 81-90.
4. Burton, W.G. 1972. The response of the potato plant and tuber to temperature. p. 217-233. *In:* A.R. Rees, K.E. Cockshull, D.W. Hand, and R.G. Hurd (ed.): Crop processes in controlled environments. Academic Press, London and New York.
5. Chang, D.C., C.S. Park, J.G. Lee, J.H. Lee, J.M. Son, and Y.B. Lee. 2005. Optimizing electrical conductivity and pH of nutrient solution for hydroponic culture of seed potatoes (*Solanum tuberosum*). J. Kor. Soc. Hort. Sci. 46:26-32.
6. Chang, D.C., J.C. Jeong, Y.H. Yun, C.S. Park, S.Y. Kim, and Y.B. Lee. 2005. Tuber number, size, and quality of 'Superior' potato (*Solanum tuberosum*) grown in hydroponics as affected by harvest time. J. Kor. Soc. Hort. Sci. 46:21-25.
7. Chang, D.C., S.Y. Kim, J.C. Jeong, K.Y. Shin, and

Y.B. Lee. 2001. Solution temperature effects on potato growth and mineral uptake in hydroponic system. Acta Hort. 548:517-522.

8. Chang, D.C., S.Y. Kim, K.Y. Shin, Y.R. Cho, and Y.B. Lee. 2000. Development of a nutrient solution for potato (*Solanum tuberosum* L.) seed tuber production in a closed hydroponic system. Kor. J. Hort. Sci. & Technol. 18:334-341.
9. Collier, G.F. and T.W. Tibbitts. 1984. Effects of relative humidity and root temperature on calcium concentration and tipburn development in lettuce. J. Amer. Soc. Hort. Sci. 109:128-131.
10. Dale, J.E. 1965. Leaf growth in *Phaseolus vulgaris* II. Temperature effects and the light factor. Ann. Bot. 29:293-307.
11. Epstein, E. 1971. Effect of soil temperature on mineral element composition and morphology of the potato plant. Agron. J. 63:664-666.
12. Ewing, E. E. 1995. The role of hormones in potato (*Solanum tuberosum* L.) tuberization. p. 698-724. In: P.J. Davies (ed.): Plant hormones: Physiology, biochemistry and molecular biology. Kluwer Academic Publishers, the Netherlands.
13. Ewing, E. E. 1981. Heat stress and the tuberization stimulus. Amer. Potato J. 58:31-49.
14. Kang, J.G., S.Y. Kim, H.J. Kim, Y.H. Om, and J.K. Kim. 1996. Growth and tuberization of potato (*Solanum tuberosum* L.) cultivars in aeroponics, deep flow technique, and nutrient film technique culture systems (in Korean). J. Kor. Soc. Hort. Sci. 37:24-27.
15. Kang, J.G, S.Y. Yang, and S.Y. Kim. 1996. Effects of nitrogen levels on the plant growth, tuberization and quality of potatoes grown in aeroponics (in Korean). J. Kor. Soc. Hort. Sci. 37:761-766.
16. Krauss, A. and H. Marschner. 1982. Influence of nitrogen nutrition, daylength and temperature on contents of gibberellic and abscisic acid and on tuberization in potato plants. Potato Res. 25:13-21.
17. Lee, H.J., Y.B. Lee, and J.H. Bae. 2004. Effect of root zone temperature on the growth and quality of single-stemmed rose in cutted rose production factory (in Korean). J. Bio-Env. Con. 13:266-270.
18. Lee, J.H., J.G. Kwon, O.G. Kwon, Y.H. Choi, and D.G. Park. 2002. Cooling efficiency and growth of tomato as affected by root zone cooling methods in summer season (in Korean). J. Bio-Env. Con. 11:81-87.
19. Lee, S.G., K.C. Seong, K.D. Ko, and K.Y. Kim. 2001. Effect of Soil Heating and Lateral Branching in White Spined Cucumbers (in Korean). J. Bio-Env. Con. 10: 155-158.
20. Marschner, H. 1995. Mineral nutrition of higher plants. 2nd ed. Academic Press, San Diego, CA, USA. p. 299-310.
21. Moorby, J. and C.J. Graves. 1980. Root and air temperature effects on growth and yield of tomatoes and lettuce. Acta Hort. 98:29-43.
22. Papadopoulos, A.P. and H. Tiessen. 1987. Root and air temperature effects on the elemental composition of tomato. J. Amer. Soc. Hort. Sci. 112:988-993.
23. Slater, J.W. 1968. The effect of night temperature on tuber initiation of the potato. Eur. Potato J. 11:14-22.
24. Struik, P.C., J. Geertsema, and C.H.M.G. Custers. 1989a. Effects of shoot, root and stolon temperature on the development of the potato (*Solanum tuberosum* L.) plant. I. Development of the haulm. Potato Res. 32: 133-141.
25. Struik, P.C., J. Geertsema, and C.H.M.G. Custers. 1989b. Effects of shoot, root and stolon temperature on the development of the potato (*Solanum tuberosum* L.) plant. II. Development of stolons. Potato Res. 32:143-149.
26. Struik, P.C., J. Geertsema, and C.H.M.G. Custers. 1989c. Effects of shoot, root and stolon temperature on the development of the potato (*Solanum tuberosum* L.) plant. III. Development of tubers. Potato Res. 32:151-158.
27. Thompson, H.C. and R.W. Langhans. 1998. Shoot and root temperature effects on lettuce growth in a floating hydroponic system. J. Amer. Soc. Hort. Sci. 123: 361-364.