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Shoot and Root Temperature Effects on Lettuce Growth in a Floating Hydroponic System

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Abstract. **'Ostinata' Butterhead lettuce (*Lactuca sativa* L.) was used to study lettuce production at varied shoot (air) and root (pond) temperatures. A floating hydroponic system was used to study the influence of pond temperature on lettuce growth for 35 days. Pond water temperature setpoints of 17, 24, and 31 °C were used at air temperatures of 17/12, 24/19, and 31/26 °C (day/night). Pond temperature affected plant dry mass, and air temperature significantly affected growth over time. Maximum dry mass was produced at the 24/24 °C (air/pond temperature) treatment. Final dry mass at the 31/24 °C treatment did not differ significantly from the 24/24 °C treatment. The 24 °C pond treatment maintained market quality lettuce head production in 31 °C air. Using optimal pond temperature, lettuce production was deemed acceptable at a variety of air temperatures outside the normal range, and particularly at high air temperatures.**

Hydroponic system designs are constantly being refined for greenhouse use. The pond system used in this research was first described by Massantini (1976). These deep-flow hydroponics, or hydroponic ponds, provide a uniform root environment in which nutrients, pH, dissolved oxygen, and temperature can be closely controlled.

Wurr et al. (1992) identified temperature ranges of 17 to 28 °C (day) and 3 to 12 °C (night) as suitable temperatures for outdoor production of lettuce. Marsh (1987) used 'Ostinata' lettuce in her greenhouse experiments and identified 24 °C as an optimal daytime growing air temperature.

Shoot and root temperatures impact a variety of physiological processes. According to Salisbury and Ross (1992), the deleterious effects of high air temperatures on plants occur primarily in photosynthetic functions and the thylakoid membranes. Most enzymes are also influenced by temperature and effects on rubisco and other enzymes of carbon metabolism most directly impact growth (Berry and Raison, 1981). Wien (1998) reported temperature as the main factor determining the rate of growth of lettuce during the early seedling period.

Marsh (1987) and Seginer et al. (1991) reported higher temperatures promoted larger leaf area. Wolfe (1991) observed a significant reduction of leaf area ratio for many crop species when grown at cooler temperatures, which resulted in visibly thicker leaves. Dale (1965) confirmed that leaves on plants grown at 15 °C appeared greener, thicker and more leathery in texture than comparable leaves grown at 25 °C.

Challa et al. (1995) reported that root zone heating had a positive effect on crop production. They ascribed this positive effect to a reduction in root resistance to water flow and hence to an improved water balance of the crop. Berry and Raison's (1981) findings also correlated inhibition of water uptake at low temperature with an immediate inhibition of leaf growth.

Root zone climate control was used in traditional greenhouse lettuce production and some varieties responded well to soil warming (Large, 1981). Hicklenton and Wolynetz (1987) reported increased root temperature in a hydroponic system resulted in increased values for specific leaf area, leaf area ratio, and leaf weight ratio at final harvest. Jensen and Malter (1995) also found that cooling the nutrient solution in nutrient film systems dramatically reduced bolting and decreased the incidence of the fungus *Pythium aphanidermatum*.

This study explores the potential of optimizing root zone conditions to grow a normally cool crop, lettuce, in warmer air temperatures. If possible, greenhouse production of lettuce could spread to nontraditional lettuce producing regions.

Materials and Methods

The 'Ostinata' Butterhead lettuce used in this study exhibits tolerance to bolting, tip-burn, and bitterness (Large, 1972). Rooting media for seeding production consisted of one volume part dolomitic limestone and 239 volume parts each of sphagnum peat and horticultural vermiculite. One environmental growth chamber (2.5 × 3.6 × 2.1 m) was used for germination, and contained one ebb-and-flow bench (1.2 × 2.4 m), a solution tank (265 L), and an aspirated sensor housing box. Cool-white fluorescent lamps provided 60 to 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ continuously for the first 24 h, which was increased to 200 to 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ thereafter. Temperature in the chamber was 20 °C for 24 h, and was then raised to 25 °C. Seedling selection for uniformity took place on day 6. About 30% of the seedlings were rejected.

Plants were transplanted as plugs from the growth chamber to ponds 11 d after seeding. The glass greenhouse which contained the ponds measured 7.6 × 10.7 m. The greenhouse contained three ponds each measuring 4.9 × 1.2 m internally, with a depth of 0.2 m. A pump, along with a system of pipes, kept the water, nutrients and dissolved oxygen (DO) mixed and evenly distributed within each pond. Sensors measuring DO concentration, combined with a computer control program developed by Cornell's Controlled Environment Agriculture (CEA) group, maintained a constant DO concentration of 8.4 $mg \cdot L^{-1}$ in the water. Adjustments were made outside the 8.3 to 8.5 $mg \cdot L^{-1}$ range by adding O_2 or purging with N_2. Composition of nutrient solution is listed in Table 1 and was regulated by measuring electrical conductivity (EC), which was maintained at 1.2 $mS \cdot cm^{-1}$ (with adjustments outside the 1.15 to 1.25 $mS \cdot cm^{-1}$ range). The pH was maintained at 5.8 (adjusted

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Table 1. Mineral composition of the nutrient solution.

Macronutrients	($mol \cdot m^{-3}$)	Micronutrients	($mmol \cdot m^{-3}$)
N	8.93	Fe	16.82
P	1.00	Mn	2.55
K	5.50	B	14.81
Ca	2.09	Cu	0.47
Mg	0.99	Zn	1.99
S	1.09	Mo	0.31

outside the 5.7 to 5.9 range) and water levels were kept constant by addition of fresh nutrient solution or distilled water.

High-pressure sodium (HPS 400 Watt) lamps together with natural sunlight provided a total 17.6 $\mu mol \cdot m^{-2} \cdot d^{-1}$. The level of supplemental lighting was ≈200 $\mu mol \cdot m^{-2} \cdot s^{-1}$. A lamp installation was designed to obtain uniform lighting. Lighting was controlled by an environmental control computer system developed by Cornell's CEA group that provided supplemental lighting when sunlight levels were below 17.6 $\mu mol \cdot m^{-2} \cdot d^{-1}$ on a particular day. Greenhouse shading was used to avoid light excesses.

The temperature at the growing point was measured using 30 gauge copper-constantan thermocouples and an infrared thermometer. When plants were transplanted thermocouples were attached to the shoot meristem of two plants in each pond, and the infrared thermometer was placed 3 cm above one of the plants in each pond. Temperature was measured at the growing meristems until final harvest.

Each crop cycle had a constant day/night air temperature. Air temperature setpoints centered on 24 °C, the optimal air temperature for lettuce growth (Marsh, 1987). Air temperature setpoints were (day/night) 17/12, 24/19, and 31/26 °C. The air temperature treatments were not randomized, instead the 17 °C daytime temperature treatments were used consecutively during the coldest months (December and January) and the 31 °C daytime temperature treatments during the warmer months (October and March), with 24 °C daytime temperature treatments falling in between (November and February), to minimize environmental control fluctuations. Pond temperatures of 17, 24, and 31 °C were maintained for each 35-d growth study. Ponds were randomly selected for water temperature setpoint for each air temperature study. The study consisted of six experiments, two at each air temperature regime.

Environmental factors, light, nutrient solution and dissolved oxygen, were closely controlled to ensure that any dry mass differences were only due to air and pond temperature treatments. Ambient CO_2 levels were used. Harvests occurred at 7, 11, 14, 21, 28, and 35 d after seeding. Sixty plants (shoots only) were taken each harvest (48 plants on harvest day 28), dried and weighed. Data presented are from these masses, variation was low due to seedling selection and accurate environmental control.

The dry mass data were analyzed using a split-plot design to examine combined effects of air and pond temperatures. The main plot treatment was air temperature applied to a greenhouse, subplots were water temperatures applied to individual ponds. This structure allowed for analysis of the subplot (pond) after accounting for effects of the level above (air).

Results

Individual treatments were recorded as (daytime air/pond) temperature combinations and were as follows: 17/17, 17/24, 17/31, 24/17, 24/24, 24/31, 31/17, 31/24, and 31/31 °C. The dry mass from each harvest is listed in Table 2 (R1 being the first replicate, R2 being the second replicate). Analysis used the mean values of R1 and R2. The maximum final dry mass mean in treatment 24/24

Table 2. Dry mass (g/plant) and standard deviations at 14, 21, 28, and 35 d after seeding of lettuce for first and second replications (R1 and R2) of the nine air and pond treatments.

Air temp day/night (°C)	Water temp (°C)	Dry mass (g/plant) ± SD 14 Day	21 Day	28 Day	35 Day
17/12[z]	17 R1	0.09 ± 0.01	0.57 ± 0.06	2.14 ± 0.27	4.69 ± 0.36
	17 R2	0.09 ± 0.01	0.51 ± 0.07	1.92 ± 0.21	4.41 ± 0.33
	24 R1	0.10 ± 0.01	0.63 ± 0.05	2.59 ± 0.15*	5.21 ± 0.35*
	24 R2	0.10 ± 0.01	0.62 ± 0.07	2.38 ± 0.22*	5.11 ± 0.43*
	31 R1	0.11 ± 0.01	0.70 ± 0.07	2.43 ± 0.17	4.67 ± 0.37
	31 R2	0.09 ± 0.01	0.48 ± 0.08	1.88 ± 0.4	5.38 ± 0.59
24/19[y]	17 R1	0.12 ± 0.01	0.78 ± 0.09	2.94 ± 0.28	5.43 ± 0.37
	17 R2	0.09 ± 0.09	0.45 ± 0.19	1.96 ± 0.37	5.95 ± 0.75
	24 R1	0.14 ± 0.02	0.89 ± 0.09*	3.38 ± 0.26*	6.00 ± 0.64*
	24 R2	0.09 ± 0.02	0.62 ± 0.09*	3.00 ± 0.22*	7.00 ± 0.51*
	31 R1	0.14 ± 0.02	0.84 ± 0.01	2.91 ± 0.36	5.58 ± 0.59
	31 R2	0.09 ± 0.01	0.48 ± 0.08	1.88 ± 0.40	5.38 ± 0.59
31/26[x]	17 R1	0.16 ± 0.02	0.87 ± 0.10	2.95 ± 0.46	5.25 ± 0.54
	17 R2	0.11 ± 0.01	0.74 ± 0.08	3.02 ± 0.25	5.85 ± 0.45
	24 R1	0.15 ± 0.02	0.85 ± 0.10	3.30 ± 0.35*	5.27 ± 0.69*
	24 R2	0.12 ± 0.02	0.86 ± 0.11	3.46 ± 0.32*	6.49 ± 0.62*
	31 R1	0.16 ± 0.02	0.86 ± 0.12	2.67 ± 0.48	4.26 ± 0.84
	31 R2	0.11 ± 0.01	0.65 ± 0.18	2.00 ± 0.43	4.30 ± 0.68

[z]R1, December 1995; R2, January 1996.
[y]R1, November 1995; R2, February 1996.
[x]R1, October 1995; R2, March 1996.
*The 24 °C pond (mean of R1 and R2) was significantly greater than other ponds within that air temperature ($p = 0.05$).

Table 3. Split-plot analysis of dry mass including all nine air and pond temperature treatments and all harvest dates (day 14, 21, 28, and 35).

Effect	P	Conclusion
Light	0.7115	NS
Air	0.4964	NS
Pond	0.0154	*
Air × pond	0.2612	NS
Harvest	0.0001	*
Air × harvest	0.0001	*
Pond × harvest	0.0001	*
Air × pond × harvest	0.1131	NS

NS,*Nonsignificant or significant at $p = 0.05$.

°C is 9% greater than the second greatest final dry mass mean, treatment 31/24 °C, and 13% greater than the third greatest 24/17 °C treatment mean.

Among ponds, the final mean dry mass of plants from 24 °C pond tested significantly greater than mean mass from the 17 or 31 °C ponds at each air temperature. Treatments in which the 24 °C pond mean mass is significantly greater within an air temperature are indicated in Table 2 (*) for each harvest.

Results of split-plot analysis of variance with dry mass as the response variable are shown in Table 3. The negative test (p = 0.2612) of air × pond interaction indicates the effect of pond temperature on dry mass was not influenced by the level of air temperature, so air and pond effects can be examined separately. Pond water was significant ($p = 0.0154$) as a main effect contributing to differences in dry mass. Although air tested negatively as a main effect, possibly because high and low air temperatures produced similar final dry masses, the air temperature definitely influenced growth over time (air × harvest $p = 0.0001$, pond × harvest $p = 0.0001$).

Contrast tests compared each of the nine air/pond treatments' final mean dry masses. The maximum final dry mass was produced in the 24/24 °C air and pond treatment. Using contrast comparisons the final dry mass produced at 31/24 °C was found not to differ statistically from the maximum 24/24 °C ($p > 0.10$). These mean weights are shown in bold in Table 2. The pond effect (in air and pond treatment 31/24 °C) was strong enough to produce a dry mass at an elevated air temperature that rivaled the dry mass produced under optimal conditions (24/24 °C). This is the only final harvest from which the maximum 24/24 °C treatment did not differ.

Average growing point temperatures for the second experimental replicate are shown in Table 4. The averages include day/night fluctuations. As shown, growing point temperature measured by the thermocouples paralleled air temperature. The 31 °C air treatment's lower meristem temperature may have been due to increased transpiration at 31 °C, but did not vary significantly with pond treatments. Pond temperature had an insignificant effect on the meristem temperature.

Visual observations showed a marked effect of root temperature on leaf initiation and development (head and leaf size). Head size increased with air and pond temperature, until affected by 31 °C air and pond temperatures. Although 31/31 °C plants were stunted due to root damage, using a root zone temperature of 24 °C allowed the 31/24 °C treatment to develop a marketable head size.

The effect of air temperature on leaf thickness was moderated by pond temperature. Leaf thickness decreased from the 17 to the 31 °C pond within each air temperature. Yellowing of leaves decreased with lower pond temperatures within the 31 °C air treatment. Overall, lower air and pond temperatures produced darker green and thicker leaves.

Root damage and disease existed in all 31 °C pond treatments, but was nonexistent in 24 °C ponds. Wilting and browning of outer leaves paralleled the root damage in the 31/31 °C treatment.

Discussion

The 31 °C air treatments produced significantly larger heads until the day 35 harvest (Table 2). These 31 °C air final harvest plants were visibly stressed, either stunted or wilted, in the 17 and 31 °C ponds. Although a beneficial effect can be seen in the early plant growth in 31 °C ponds, it is only by using the 24 °C pond temperature that the 31 C air temperature can produce marketable plants at final harvest.

The presence of root disease in 31 °C ponds and poorly formed roots in the 17 °C pond contributed to the reduced size of 17 °C and the decline of 31 °C pond plants. The elevated pond temperature may have affected the activity of pathogens in the water. Pathogenic symptoms occurred at 31 °C in the same nutrient solution that had produced disease free plants before, and disease symptoms disappeared when water temperature was dropped for a following experiment.

High final mass, marketability and uniformity of the crop are the primary attributes sought for production of consistent quality crops in controlled environment agriculture. Visual observations confirmed the superiority of lettuce grown at a 24 °C pond temperature. Head size, leaf color and thickness, and root structure were best in 24 °C ponds, regardless of air temperature.

The positive effects of the 24 °C pond were due to impacts on the root zone physiology. Temperature at the growing point, as measured by thermocouples, was not affected by pond temperature, instead growing point temperature paralleled the air temperature. Differences in the 24 °C ponds were due to the pond temperature effect on the root zone itself, not due to a temperature gradient between pond and air.

The benefit of growing in 24 °C pond temperature, instead of 17 or 31 °C, is apparent in Table 2. The final harvest mean dry mass is greater in the 24 °C pond at every air temperature. The optimal 24 °C pond temperature allowed quality lettuce growth at elevated temperatures. The 31/24 °C dry mass equaled the optimal 24/24 °C crop, shown in highlights in Table 2. These 31/24 °C heads were also as marketable as the 24/24 °C plants. An air temperature of 31 °C is well outside the range of standard lettuce production (Wurr et al., 1992), but when combined with optimized root conditions produced a marketable lettuce crop.

Conclusions

The importance of optimal air temperature is widely recognized, but the importance of optimizing root as well as air temperature in lettuce production was demonstrated in this study. By using 24 °C root temperature in hydroponic systems lettuce crop growth was maximized, and variations and damage minimized, even with elevated air temperatures. Lettuce is traditionally grown as a cool

Table 4. Growing point mean temperatures for each air and pond treatment.

Pond	Day/night air temp (°C)		
temp (°C)	17/12	24/19	31/26
17	12.7 ± 2.5	19.3 ± 2.4	20.3 ± 1.5
24	14.7 ± 1.6	18.7 ± 2.3	20.7 ± 1.2
31	13.9 ± 2.5	20.3 ± 4.4	21.7 ± 1.5

climate crop but, by optimizing root zone temperature, lettuce production could be grown in warmer geographic areas. Root environment control is already being used for lettuce production in some southern climates (Jensen and Malter, 1995). Root zone temperature is an essential parameter to include in a systems approach to crop production.

Literature Cited

Berry, J.A. and J.K. Raison. 1981. Responses of macrophytes to temperature, p. 277–338. In: O.L. Lange, P.S. Nobel, C.B. Osmond, and H. Zeigler (eds.). Encyclopedia of plant physiology. ns. vol 12A. Springer-Verlag, Heidelberg.

Challa , H., E. Heuvelink, and U. van Meeteren. 1995. Crop growth and development, p. 62–84. In: J.C. Bakker, G.P.A. Bot, H. Challa, and N.J. van de Braak (eds.). Greenhouse climate control. Wageningen Pers.

Dale, J.E. 1965. Leaf growth in *Phaseolus vulgaris* II. Temperature effects and the light factor. Ann. Bot. 29(114):293–307.

Hicklenton, P.R. and M.S. Wolynetz. 1987. Influence of light- and dark-period air temperatures and root temperature on growth of lettuce in nutrient flow systems. J. Amer. Soc. Hort. Sci. 112:932–935.

Jensen, M.H. and A.J. Malter. 1995. Protected agriculture, A global review. World Bank Tech. Paper No. 253. The World Bank, Washington D.C.

Large, J.G. 1972. Glasshouse lettuce. Grower Books, London.

Large, J.G. 1981. Lettuce under glass. Grower Guide No. 21. Grower Books, London.

Marsh, L.S. 1987. A model of greenhouse hydroponic lettuce production: Daily selection of optimum air temperatures and comparison of greenhouse covers. PhD diss. Cornell Univ., Ithaca, N.Y.

Massantini, F. 1976. Floating hydroponics; A new method of soilless culture, p. 91–98. 4th Intl. Congr. on Soilless Culture, Las Palmas, 25 Oct. to 1 Nov.

Salisbury, F.B. and C.W. Ross. 1992. Plant physiology. Wadsworth, Belmont, Calif.

Seginer, I., G. Shina, L. Albright, and L. Marsh. 1991. Optimal setpoints for greenhouse lettuce. J. Agr. Eng. Res. 49(3):209–226.

Wien, H.C. 1998. Lettuce. In: H.C. Wien (ed.). Veg. Crop Physiol. CAB International. (In press.)

Wolfe, D.W. 1991. Low temperature effects on early vegetative growth, leaf gas exchange and water potential of chilling-sensitive and chilling-tolerant crop species. Ann. Bot. 67:205–212.

Wurr D.C.E., J.R. Fellows, and A.J. Hambidge. 1992. Environmental factors influencing head density and diameter of crisp lettuce cv. Saladin. J. Hort. Sci. 67(3):395–401.