Heating Soil with Hot Air Improves Early Yield and Quality of Greenhouse Tomatoes

Martin P.N. Gent[1] and
Vincent Malerba[2]

Additional index words. *Lycopersicon esculentum* Mill., root temperature

Summary. The soil within a greenhouse was heated by blowing hot air from a forced-air heater through drainage pipes buried beneath raised beds. This warmed the soil from 50F (10C) to 68F (20C) after 1 week of heating in mid-March. Soil in unheated beds did not warm to this temperature until May. The yield of tomato (*Lycopersicon esculentum* Mill.) planted in heated beds was higher than in unheated beds by 16% over the season in 1992, and by 14% as of early July 1993. The weight fraction of highest-quality fruit also were 11% greater in 1993. This simple method of soil heating involved negligible additional expense

Heating the soil is not a standard practice for producing greenhouse tomatoes in New England (Boulton, 1991). This is due in part to a perceived lack of benefit in terms of higher yields and, in part, to the extra cost involved in heating the soil.

Typically, the air in a greenhouse is heated beginning a few days before transplanting tomato seedlings in March. The soil temperature may be 50 to 60F (10 to 15C) initially, and it warms slowly due to poor heat transfer with the air. As long as the temperature of the root zone is cooler than 68F (20C), the optimal temperature for growth of tomato seedlings (Harsemma, 1977), it may slow growth and development of the seedlings. Although heating the root zone enhanced vegetative growth of tomato plants (Ganmore Neumann and Kafkafi, 1980; Gosselin and Trudel, 1983; Maletta and Janes, 1987), the effect on yield was inconsistent. Warming the soil to 70F (21C) from the ambient temperature of 57F (14C) increased yield by 47% in spring, but had no effect in fall in Quebec (Trudel and Gosselin, 1982). In Ontario, warming the soil from 70 to 81F (21 to 27C) had no effect on yield in spring or fall (Papadopoulos and Tiessen, 1983). In England, warming roots from 59 to 81F (15 to 27C) increased total yield by ≈10%, but had no effect on earliness (Hurd and Graves, 1983).

The common techniques used to heat the soil, such as buried tubing heated with circulating hot water or buried electric heating cables (Elwell et al., 1985), are a substantial and expensive modification of the typical greenhouse. An additional heating and control system is required. Such methods are unlikely to be used by growers if there is only marginal benefit in terms of increased yield.

We describe here a simpler method for heating soil that makes use of the forced-hot-air furnace that is used to heat the greenhouse air. The only modification to the greenhouse was burial of air ducts underneath raised beds. Blowing air through ducts in the soil can moderate the variation from day to night of air temperatures within a greenhouse (Boulard et al., 1989; Mavraganopolis and Kyritis, 1986). As we showed in a preliminary report (Gent and Malerba, 1993), this method also can be used to heat the soil and increase the yield and quality of greenhouse tomatoes.

Materials and methods

Growth conditions and plant material. The experiment was conducted in a greenhouse at Malerba's Farm in Norwich, Conn. The greenhouse area was 30 × 96 feet (7.6 × 29.2 m), covered with a double layer of 6-mil polyethylene film supported by steel hoops at a 4-foot (1.2-m) spacing. It was heated by a 90-kW oil-fired, forced-air furnace located in the southwest corner of the greenhouse. The furnace was activated by a thermostat if the air in the greenhouse cooled below 61F (16C). Fans that generated a horizontal air flow helped maintain a uniform air temperature throughout the greenhouse.

The soil was heated by blowing air from the furnace through buried air ducts (Fig. 1). The soil was formed into raised beds, 0.5 foot high × 4 feet wide (0.15 m × 1.2 m), which were covered with black polyethylene film. The beds were arranged along the north–south axis of the greenhouse and separated by 2-foot- (0.6-m-) wide aisles. Two 96-foot (30-m) lengths of 4-inch- (10-cm-) diameter, black polyethylene, corrugated drainage tubing were buried 1 foot (0.3 m) deep and 2 feet (0.6 m) apart under each of the heated beds. The unheated beds had no drain pipe. The furnace had three outlet ducts, two of which were directed into the air. One duct was attached to 1-foot- (0.3-m-) diameter polyethylene-film tubing, which served as a manifold for distribution of forced hot air to the tubing in the soil. The amount of heat going through the soil could be reduced if necessary by constriction of the manifold. The air was exhausted from the drain pipes into the north end of the greenhouse.

Experiments were conducted in the spring of 1992 and 1993. Seeds of the tomato cultivars Jetstar (Harris Moran, Rochester, N.Y.), and Buffalo (Stokes, Buffalo, N.Y.) were germinated on 1 Feb. 1992. Seedlings were transplanted into the raised beds in the production greenhouse on 21 Mar. 1992, and heating of the soil and the air began on the same day. Seeds of the tomato cultivars Caruso and Buffalo (Stokes, Buffalo, N.Y.) were germinated on 15 Jan. 1993. The production greenhouse was heated for 5 days before transplanting on 17 Mar. 1993.

Cultural methods were the same in 1992 and 1993. The seeds were germinated in flats of peat–vermiculite at 21C. After emergence, the seedlings were transferred to 4-inch- (10-cm-) diameter pots and grown on at 21C. After they were set in the raised beds, plants were pruned to a single stem and supported by string. Plants were watered by drip irrigation with a complete nutrient solution [Peters 15–16–17 (N–P_2O_5–K_2O), W.R. Grace Co, Cambridge, Mass.]. The concentration of nutrients was increased from 50 ppm N shortly after planting to 200

---

[1] Department of Forestry and Horticulture, The Connecticut Agricultural Experiment Station, POB 1106 New Haven, CT 06504.

[2] Malerba's Farm, 634 New London Turnpike, Norwich, CT 06360.

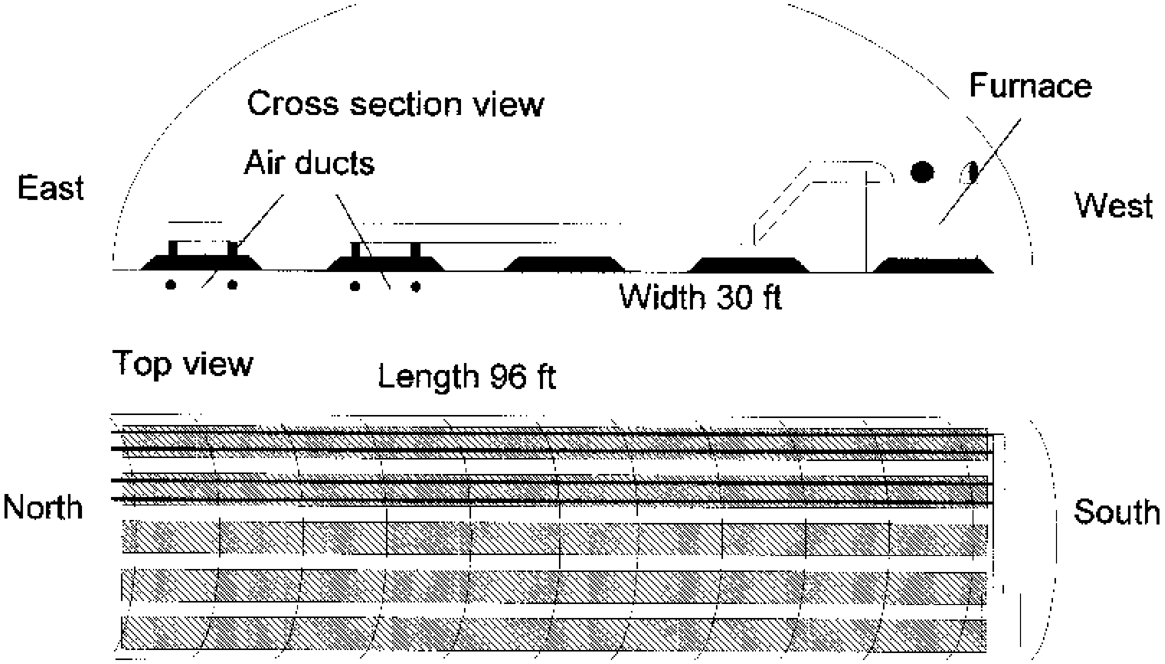

Fig. 1. *A schematic diagram of a greenhouse with a forced-air furnace connected to buried drainage pipes used to heat the soil.*

ppm during fruit production.

Experimental design and measurements. Each raised bed was planted with one cultivar of tomato. The plants were set into the raised beds in two rows spaced 2 feet (0.6 m) apart and separated by 2 feet (0.6 m) within the row. Four raised beds were used for the experiment. The two beds on the east were heated and the beds on the west were not. The two cultivars were assigned at random to a heated and an unheated bed. Another bed on the west was used as a border, and was not part of the experiment.

Soil temperatures were measured at 0800 HR EST, daily for the first 2 weeks, then at weekly intervals. A thermometer was inserted to a depth of 4 inches (10 cm) in the center of the raised bed. Heated and unheated beds were measured at two locations, halfway between the mid-point and the end of the bed, in the north section away from the furnace, and in the south section, near the furnace. Maximum and minimum air temperatures were also recorded.

The rows were divided into south and north sections for harvesting. Each half-row contained 21 plants. Fruit was picked at 2- to 4-day intervals and weighed. The highest-quality (number one) fruit were selected and weighed. In 1992, harvests were combined for adjacent half-rows before weighing. In 1993, the weight of the harvest was recorded for each half-row, but harvests of north and south sections were combined before selecting grade #1 fruit. The accumulated yield and yield of #1s were calculated as well as the weight fraction of #1 fruit. One of the heated rows of 'Jetstar' in 1992 and 'Caruso' in 1993 was adjacent to the east side-wall of the greenhouse. This row, which yielded 16% more than the adjacent row in the raised bed, was treated as a border row and not included in the analysis. There were border rows on the west that were not part of the experiment.

Analysis of variance treated soil heating as a block effect with cultivars assigned at random within the blocks, and section as an independent effect. Neither the soil heating by section, nor the cultivar by section interactions, were significant, and they were combined in the error term.

Results

Temperatures. The soil temperature was 59F (15C) at planting on 21 Mar. 1992. The soil in the south section of heated beds, near the furnace, warmed to 66F (19C) in 1 day, and 68F (20C) in 1 week. The soil in the north section of the heated beds, away from the furnace, was about 5F (3C) cooler. The soil in the unheated beds remained at 59F (15C) for the week after planting. In Apr. 1992, the soil in the south section of the heated beds averaged 68F (20C), and it was 2 to 3F cooler in the north section. The unheated beds were 61F (16C) in the first week and 63F (17C) for the rest of April. In May, the heated beds cooled from 68 to 66F (20 to 19C) because the furnace was used much less for heating. The unheated beds had an average soil temperature of 64F (18C) in May.

The soil temperature was 50F (10C) when heating began on 12 Mar. 1993. At planting, on 17 Mar. 1993 and, for the first 10 days thereafter, the heated beds were 70F (21C) in the south section and 66F (19C) in the north section (Fig. 2). The unheated beds warmed from 59 to 64F (15 to 18C) during this period. The end of March was warm and cloudy, and the furnace was used less for heat. Consequently, the soil in the heated beds cooled to 64F (18C). In April, the soil in the south section of the heated beds averaged 72F (22C), and it was 1F cooler in the north section. The south section of the unheated beds warmed from 60 to 64F (16 to 18C) during April. The north section was 2 to 3F cooler. Minimum air temperatures were nominally 61F (16C), but cooled to 57F (14C) on some nights in March. Maximum air temperatures, which were as low as 70F (21C) in mid-March, tended to increase to 86F (30C) in May and 95F (35C) in June

Tomato production. In 1992,

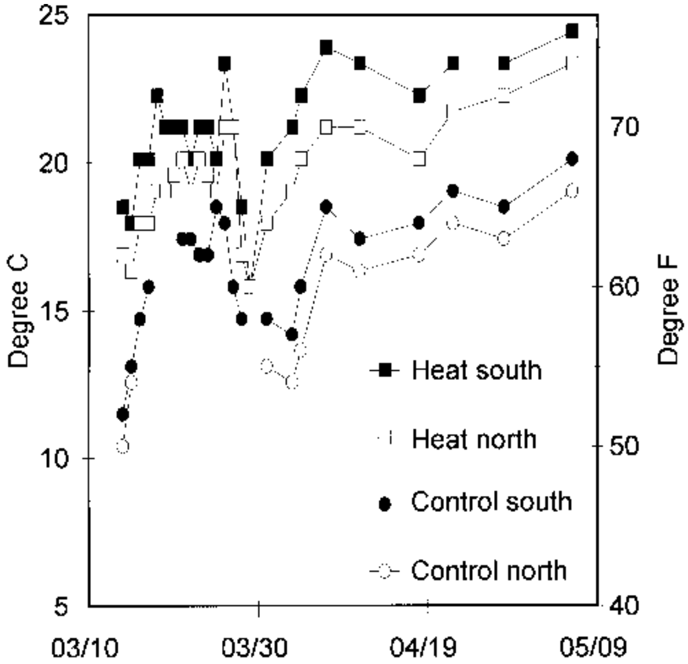

Fig. 2. *Soil temperatures in heated and unheated beds measured at a 10-cm depth in sections close to (south) and distant from (north) the furnace.*

heating the soil increased the total yield of tomatoes. The heated beds were more productive than the unheated beds throughout the season, resulting in a 16% greater overall yield (Table 1). Ripe fruit was picked from plants in the heated beds 3 days earlier than in unheated beds, a statistically insignificant difference.

'Jetstar' yielded more than 'Buffalo' throughout the 1992 season, and continued producing in August, when 'Buffalo' declined (Fig. 3). Heating the soil increased yields of both 'Jetstar' and 'Buffalo', but, for 'Jetstar', this increase was small until mid-July. The difference in yield between heated and unheated beds was greater in the south section of the greenhouse, near the furnace, than in the north section (data not shown).

Although heated beds produced more high-quality tomatoes than did unheated beds, the weight fraction of #1 fruit was not significantly greater (Table 1). The early production of 'Buffalo' had higher-quality tomatoes than 'Jetstar'.

In 1993, heating the soil increased the early yield as well as the total yield, but it did not advance ripening of the first fruit (Table 2). By 30 June 1993, early production of the heated beds was 14% greater than that of the unheated beds. There was no difference in production between heated and unheated heated beds in July, so the differences in total yields reflected the differences in early production.

'Caruso' yielded more than 'Buffalo' over the 1993 season, and heating the soil increased yield of 'Caruso' more than 'Buffalo' (Fig. 4). The south sections yielded more than the north sections (data not shown). In the south sections, the difference in production between heated and unheated beds occurred in June. In the north section, the difference developed in July.

In 1993, the tomatoes from the heated beds were of better quality than those from unheated beds. Over the season, 82 w/w% of tomatoes picked from the heated beds were rated #1, compared to 72 w/w% from the unheated beds. The difference in quality between heated and unheated beds was similar for both cultivars in 1993.

Discussion

Our results showed that blowing hot air from a forced-air furnace through buried air ducts could heat

Table 1. *Effect of heating the soil on ripening, yield per plant, and quality of greenhouse tomatoes in 1992.*

Factor	Date of first ripe fruit	Early yield 2 July lb	kg	Total yield 3 Sept. lb	kg	Fraction #1s 2 July w/w%	3 Sept. w/w%
Heated	11 June	3.7	1.7	15.6	7.1	0.82	0.83
Unheated	14 June	3.5	1.6	13.9	6.3	0.79	0.79
Buffalo	15 June	3.3	1.5	13.2	6.0	0.87	0.83
Jetstar	10 June	3.7	1.7	16.3	7.4	0.74	0.79
North	13 June	3.3	1.5	14.1	6.4	0.81	0.82
South	12 June	3.7	1.7	15.4	7.0	0.79	0.80
Significance							
Soil heat	NS	NS		**		NS	NS
Cultivar	*	*		**		NS	NS
Section	NS	*		**		NS	NS

NS,*,** Not significant or significant at P ≤ 0.05 or 0.01, respectively.

Table 2. *Effect of heating the soil on ripening, yield per plant, and quality of greenhouse tomatoes in 1993.*

Factor	Date of first ripe fruit	Early yield 30 June lb	kg	Total yield 4 Aug. lb	kg	Fraction #1s 30 June w/w%	4 Aug. w/w%
Heated	1 June	5.5	2.5	10.1	4.6	0.80	0.82
Unheated	1 June	4.8	2.2	9.5	4.3	0.70	0.72
Buffalo	2 June	4.8	2.2	9.0	4.1	0.75	0.77
Caruso	31 May	5.7	2.6	10.6	4.8	0.73	0.75
North	2 June	4.6	2.1	9.3	4.2	NA	NA
South	31 May	5.7	2.6	10.1	4.6	NA	NA
Significance							
Soil heat	NS	**		*		**	**
Cultivar	NS	**		**		NS	NS
Section	*	**		NS		NA	NA

NS,*,** Not significant or significant at P ≤ 0.05 or 0.01, respectively.

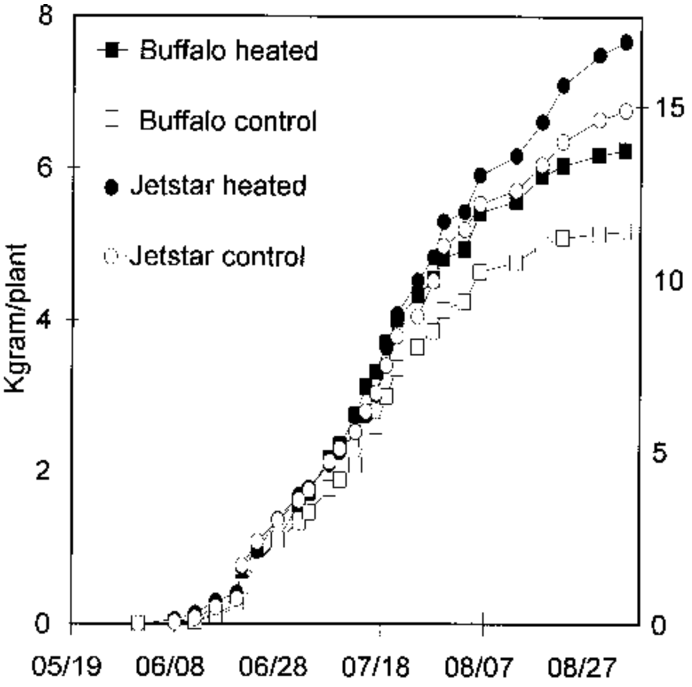

Fig. 3. *Accumulated yield of ripe tomatoes picked from the cultivars Buffalo and Jetstar grown in heated or unheated beds in a greenhouse in 1992.*

the soil quickly within the root zone. However, there were two drawbacks of this method that would not occur in a system that heated the air and soil independently. During a period of warm weather in 1993, the furnace was idle at a time when heating the soil would have been beneficial. Due to the one-way flow of air, the soil near the furnace was warmed more than that at the other end of the greenhouse. Despite these drawbacks, this method increased the yield of tomatoes in trials in 2 years.

Costs were low for this method of heating the soil. The material costs for the air duct, at $0.25 per foot, would be $250 for a 25 × 96-foot greenhouse. With a tractor to make furrows, the installation can be completed in a few hours. Soil heating would increase energy cost due to a greater loss of heat from the soil through the perimeter of the greenhouse. Perimeter insulation was not used in this study. It would reduce heat loss from the soil and help raise the soil temperature, with or without soil heating. However, far more energy is used to heat the air in a greenhouse than to heat the soil, so the increased energy costs for soil heating would be a small fraction of the total.

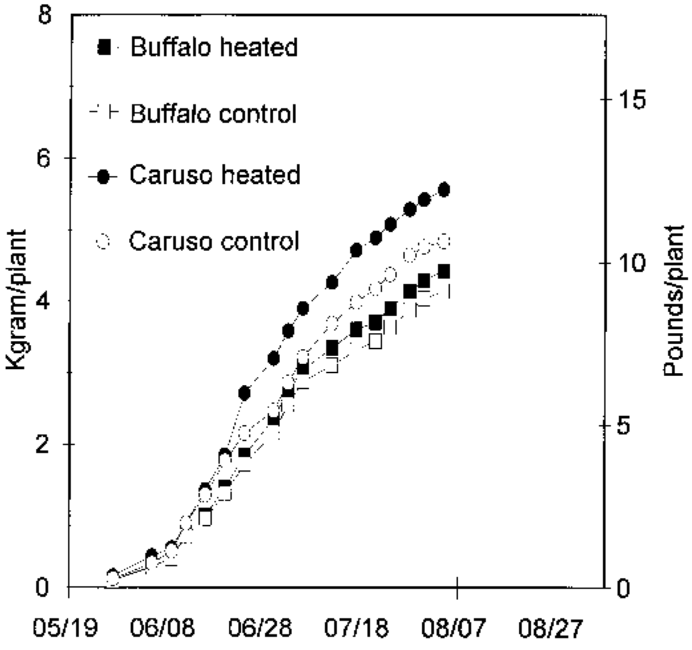

Fig. 4. *Accumulated yield of ripe tomatoes picked from the cultivars Buffalo and Caruso grown in heated or unheated beds in a greenhouse in 1993.*

The increase in yield due to heating the root zone warrants its use in greenhouse tomato production in the northeastern United States. When planted in March, the ambient temperature of the soil was sufficiently cool to limit tomato production. In other experiments with successive plantings, soil temperatures did not seem to limit greenhouse tomato production in Connecticut after mid-April (Gent, 1991; 1992). Thus, there may be little benefit to heating the soil for tomatoes transplanted later than we did in this study. Sub-surface heating also may have less effect in bag-and-trough culture or with the nutrient-film technique, because in these situations the temperature of the root medium follows that of the air more closely than the temperature of the soil mass under the greenhouse. Conversely, root-zone heating has been found to increase yield in unheated or minimally heated greenhouses more than in heated greenhouses (Cholette and Lord, 1989; Moss, 1983).

In our study, warming the root zone had little effect on the rate of plant development or the earliness of ripening. This was noted in other studies, in which differences in root-zone temperature were maintained throughout production (Gosselin and Trudel, 1983; Hurd and Graves, 1985). The main effect of warming the root zone was to increase yield and fruit size or quality. In our study, the differences in yield between heated and unheated beds developed long after differences in soil temperatures had dissipated.

In conclusion, blowing hot air from a forced-air furnace through ducts beneath raised beds heated the soil rapidly. This method of heating the soil resulted in greater yields and a higher quality of greenhouse tomatoes than if the soil was not heated.

Literature Cited

Boulard, T., E. Razafinjohany, and A. Baille. 1989. Heat and water vapor transfer in a greenhouse with an underground heat storage system: I. Experimental results. Agr. For. Meteorol. 45:175–184.

Boulton, E.L. (ed.). 1991. New England vegetable production recommendations. Coop. Ext. Serv., New England. p. 68–70.

Cholette, C. and D. Lord. 1989. Night air temperature effects on yields of greenhouse tomato produced in soil and NFT. Can. J. Plant Sci. 69:317–320.

Elwell, D.L., M.Y. Hamdy, W.L. Roller, A.E. Ahmed, H.N. Shapiro, J.J. Parker, and S.E. Johnson. 1985. Soil heating using subsurface pipes. Ohio Agr. Res. Dev. Center Res. Bul. 1175.

Ganmore Neumann, R. and M. Kafkafi. 1980. Root temperature and percentage NO_3/NH_4 effect on tomato plant development: I. Morphology and growth. Agron. J. 72:758–761.

Gent, M.P.N. 1991. High tunnels extend tomato and pepper production. Conn. Agr. Expt. Sta. Bul. 893.

Gent, M.P.N. 1992. Effect of planting date, ventilation and soil temperature on growth and nutrition of tomato in high tunnels. Plant & Soil 145:81–91.

Gent, M.P.N. and V. Malerba. 1993. A simple method of soil heating that improves earliness and yield of greenhouse tomatoes. Conn. Greenhouse Nwsltr. 174:17–23.

Gosselin, A. and M.J. Trudel. 1983. Interactions between air and root temperatures on greenhouse tomato: I. Growth, development and yield. J. Amer. Soc. Hort. Sci. 108:901–905.

Harssema, H. 1977. Root temperature and growth of young tomato plants. Meded. Landbou. Wageningen 77-19.

Hurd, R.G. and C.J. Graves. 1985. Some effects of air and root temperatures on the yield and quality of glasshouse tomatoes. J. Hort. Sci. 60:359–371.

Maletta, M. and H.W. Janes. 1987. Interrelationship of root and shoot temperatures on dry matter accumulation and root growth in tomato seedlings. J. Hort. Sci. 62:49–54.

Mavroganopoulos, G.N. and S. Kyritis. 1986. The performance of a greenhouse heated by an earth-air heat exchanger. Agr. For. Meteorol. 36:263–268.

Moss, G.I. 1983. Root zone warming of greenhouse tomatoes in nutrient film as a means of reducing heating requirements. J. Hort. Sci. 58:103–110.

Papadopoulos, A.P. and H. Tiessen. 1983. Root and air temperature effects on the flowering and yield of tomato. J. Amer. Soc. Hort. Sci. 108:805–809.

Trudel, M.J. and A. Gosselin. 1982. Influence of soil temperature in greenhouse tomato production. HortScience 17:928–929.

Evaluation of an Energy Storage Module as the Primary Heat Source for Greenhouse Production of Bedding Plants

Richard H. Merritt[1] and
K.C. Ting[2]

Additional index words. energy conservation, low night temperatures

Summary. A phase change material (PCM) energy storage unit operating in a greenhouse from 29 Oct. through 21 Dec. 1992 cooled it on the average 1.7C in the day and warmed it 2.2C at night due to both sensible and latent heat absorbed, released, and circulated. *Tagetes patula* 'Mighty Marietta' and 'Early Queen Sophia' marigolds and *Viola* × *Wittrockiana* 'Yellow Blotch' and 'Blue Blotch' pansies were grown in a PCM and a control (no PCM) greenhouse. Temperatures went below 0C 10 days in the control greenhouse and 4 days in the PCM greenhouse. The lowest temperature of –7.8C killed the marigolds in the control greenhouse. Neither marigolds nor pansies were killed in the PCM greenhouse, which attained a low temperature of –3.3C. On 4 Dec., plants were destructively harvested. Morphologically the marigolds were taller, and had more leaf area and dry matter when grown in the PCM greenhouse as compared to the control, but pansies were taller, and had more leaf area and dry matter when grown in the control greenhouse, as compared to the PCM greenhouse.

Heating and cooling greenhouses is usually accomplished by heat from fossil fuels and cooling using exhaust fans. Other heating and cooling techniques are the use of rock storage (Willits and Peet, 1987) or a phase change material (PCM) energy storage device. PCMs have been reported to absorb solar heat in the daytime hours and release the heat energy during cool nighttime hours (Ting et al., 1990). The purposes of this study were: a) to evaluate the effectiveness of a redesigned PCM system to improve its performance to heat and cool a greenhouse, and b) to compare growth and development of marigold and pansy in a greenhouse with a PCM system vs. an unheated unvented greenhouse.

A PCM energy storage unit constructed by the Westech Co. (New Brunswick, N.J.) was installed in a 8.5 × 14.6-m plastic greenhouse in East Brunswick, N.J., and evaluated from 29 Oct. through 21 Dec. 1992 as a source of daytime cooling and nighttime heating for the production of bedding plants. A second plastic greenhouse of the same size adjacent to the PCM greenhouse was used as the control. Both greenhouses were covered by air-inflated double polyethylene (colorless 6-mil Nutrigro by Visqueen plastic). Neither greenhouse received supplemental heat or venting during the entire study, and the only difference between them was that one had the PCM unit in operation. The phase change material was Glauber's salt ($Na_2SO_4\cdot10H_2O$), sodium carbonate decahydrate ($Na_2CO_3\cdot10H_2O$)—nucleating and stabilizing agents. The mixture had a design phase change temperature of 16C to enable the PCM to collect and store solar energy during daytime hours and to release this heat energy to the greenhouse during nighttime hours. Previous studies (Giacomelli et al., 1990; Wu, 1991) have evaluated plant growth in PCM-heated and -cooled greenhouses. The performance of this unit was evaluated for its effect on greenhouse temperature and its capability in storing and releasing thermal energy. The PCM unit contained 660 kg of phase change material packaged in 44 tube-sheets in a design similar to the unit described by Ting et al. (1990). A 250-W fan (Dayton Venture) ($0.25\ kWh\cdot h^{-1}$) was installed and operated continuously to provide an airflow of $1.274\ m^3\cdot s^{-1}$ through the

---

Cook College, Rutgers University, New Brunswick, NJ 08903-0231.

[1] *Dept. of Plant Science.*

[2] *Dept. of Bioresource Engineering.*

New Jersey Agricultural Experiment Station Paper No. D-03232-26-93. Supported by the Center for Controlled Environment in Agriculture and State funds. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement *solely to indicate this fact.*