J. For. Res. 5:205–208 (2000)

Short Communication

A Soil Temperature Control System for Ecological Research in Greenhouses

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We designed and tested a soil temperature control system for plant ecophysiological experiments in greenhouses and growth chambers. The system consists of a plywood box, polyethylene liner, insulation, seedling containers, a water pump, and a flow-through heater or chiller. One hundred and twelve seedling containers (11cm diameter, 13.5 cm high) are mounted in the plywood box. There is a hole at the bottom center of each container to allow the free drainage of irrigation water and fertilizer solution. The space between containers is filled with water that is circulated through the chiller/heater. The water is also circulated within the plywood box by a water pump to increase the uniformity of temperature. The system was tested for three soil temperatures (5, 20, and 30°C) over a period of four months. The containers were filled with a peat-moss vermiculite mixture and planted with tree seedlings. The test showed that the soil temperature was almost equal to the water temperature for all three soil temperatures (regression slop = 0.99, intercept = 0.12, $r^2 = 1.00$). The average soil temperatures were within (0.41°C of the set values. The soil temperature of the 112 containers within the same box followed a normal distribution with a small standard deviation (0.34°C for the 30°C treatment). There was a temperature gradient from the top to the bottom of the container ($<$ 1°C). The direction of the temperature gradient was determined by the direction of temperature difference between the soil and the ambient air. When the soil temperature was lower than air temperature, the soil temperature decreased from the top to the bottom of the container, and vise versa. The soil temperature was higher during the day than at night (difference < 1.5°C).

Key words: greenhouse experiment, plant ecophysiology, soil temperature control

Various techniques have been used to control soil temperatures in tree ecology and silvicultural research. Different soil temperatures in the field were achieved by site selection (Balisky and Burton, 1997), different methods of site preparation (Brand, 1990), or by using different mulching materials (Brand, 1990). Heating cables were used to increase soil temperature in the field (Van Cleve *et al.*, 1990; Peterjohn *et al.*, 1993).

The following techniques have been used to regulate soil temperatures in greenhouse and growth chamber experiments. For a small sample size, soil temperatures were controlled by inserting pots into an air-conditioned box (DeLucia *et al.*, 1992). Under-bench heaters were used to increase soil temperature (Landis *et al.*, 1992). Plants were grown in nutrient solutions (hydroponic system) where the solution temperature was regulated using a waterbath (Running and Reid, 1980; Lorenzen *et al*, 1998). In aeroponic systems (mist-chambers), root temperature was controlled by circulating temperature-controlled antifreeze through copper coils (R.D. Buy, personal communication). However, hydroponic and aeroponic systems create a root environment substantially different from that of soils. Consequently, the result may not be as applicable to field conditions.

The use of waterbaths is by far the most common technique for controlling soil temperature in greenhouse and growth chamber experiments. For example, soil temperatures were regulated by circulating temperature-controlled antifreeze through copper coils enclosing plant pots (Turner and Jarvis, 1975; Lawrence and Oechel, 1983; Ziska, 1998). However, the heat exchange between the pot and the coil is not efficient because of the small proportion of coil surface in contact with the pot. The most efficient heat exchange can be achieved by the direct contact between the pot and the temperature regulating fluid. Some researchers (Heninger and White, 1974; Lopushinsky and Max, 1990; Brissette and Chambers, 1992; Camm and Harper, 1991; Landhausser and Lieffers, 1994; Landhausser *et al.*, 1996) submerged pots with no or sealed drainage holes directly in the waterbath. An inherent problem with this system is the lack of drainage, which can cause water-logging and salt accumulation. To alleviate this problem, Borges and Channey (1989) placed pots with drainage holes into pots without holes and then submerged the double-walled system into a waterbath. While this setup allows limited drainage, the double-layered wall significantly reduced the heat exchange between the soil and the solution. Additionally water will accumulate in the space between the two pots and the system will lose the draining capacity over time. Recently Landhausser and Lieffers (1998) developed a system that allows free drainage. They enclosed seedling containers in plastic bags and placed a hollow spacer between the bottom of the container and the bag. Excess water drained into the bag and was removed using a syringe. The drainage capability of this system represents a significant improvement in the design of soil temperature control apparatus, but water removal using syringes becomes very cumbersome as the number of containers increases. They only used five containers per treatment. Furthermore, the efficiency and spatial and temporal variation of soil temperatures in the above designs are not well documented. This paper presents a new design that allows the free drainage of the growing medium and the efficient regulation of soil temperature and can accommodate a large number of seedling containers (112 in our tests). We also report the diurnal pattern and spatial variation in soil temperature within and between containers.

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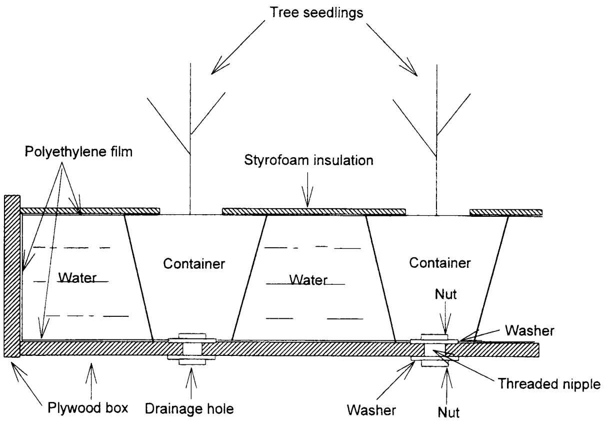

Fig. 1 Partial cut-away view of the soil temperature control system.

Materials and Methods

1 Design

The system consists of a large polywood box, polyethylene liner, polystyrene insulation, seedling pots, and a flow-through chiller or heater (Fig.1). The internal dimensions of the plywood box are 112-cm wide, 196-cm long and 16-cm deep. Since the plywood used was not waterproof, heavy-duty polyethylene film (Emballagea Cascades Inc., Yamachiche, Quebec, Canada) was used to line the inner surface of the box. The top of the box is open. Food containers of 13.5-cm tall, 11-cm top diameter and 9.5-cm bottom diameter were used as seedling containers. Each plywood box contains 112 containers. A drain-hole (1.3-cm diameter) was drilled at the bottom center of each container and through the bottom of the plywood box. To avoid water leakage from the container to the plywood box or from the plywood box into the container, the containers are fixed to the plywood box using threaded nipples, stainless steel washers and nuts (3-mm thick, Fig. 1). This design effectively prevents the direct contact between the temperature regulating fluid and the growing medium. We also tried to use water-resistant glues and a combination of sealant and wood screws to fix and seal the seedling container to the plywood box but none of the products purchased from construction or automotive stores worked.

The containers in our tests are filled with peat-vermiculite growing medium. The space between containers in the plywood box is filled with water. The water is circulated through a flow-through heater (model 210) or chiller (model KR-30A, PolyScience, Nile, Illinois, USA), depending on the greenhouse temperature and the desired soil temperature. We tested three soil temperatures: 5, 20, and 30°C. Because the chiller did not have a built-in temperature controller, a White-rodgers thermostat (Emerson Electric Co., Louis, Mo., USA) was used to control the chiller. To prevent soil particles and fertilizer solution from falling into the water and to minimize water evaporation from the box, the top of the plywood box is sealed with heavy-duty polyethylene film with holes (smaller than the opening of the container) cut for each container. To minimize the heat exchange between the water in the plywood box and the ambient air, the top of the plywood box is covered with polystyrene board insulation (Fig. 1). A hole of 5-cm diameter is cut through the polystyrene insulation around each seedling to facilitate irrigation, fertilization and the gas exchange between the growing medium and the ambient air. A water pump (model AC-2CP-MD, March Manufacturing, Inc., Glenview, Illinois, USA) stirs the water to ensure a uniform water temperature and thus a uniform soil temperature throughout the box. The inlet and outlet to the pump are installed at the two different ends of the plywood box to further improve the uniformity of water and soil temperatures.

2 Testing

The following tests were conducted: (1) the relationship between soil temperature at the center of the container and water temperature outside the container, (2) temperature variation among containers, (3) variation of soil and water temperatures with depth from the surface, (4) diurnal variation of water and soil temperatures. The system was tested for three soil temperatures: 5, 20, and 30 °C. Soil temperatures were measured at the center of the container at 7-cm depth in all the tests except the one examining temperature variation with depth. Soil and water temperatures were monitored using copper-constantan thermocouples connected to an SCXI-MS100 temperature system (National Instruments Corporation, Austin, Texas, USA) and a Pentium computer. Temperatures were logged every 10 min. To examine the temperature variation among containers, all the 112 containers in the 30 °C treatment were measured.

The tests were conducted in the Lakehead University greenhouse. The ambient environmental conditions during the tests were set at 22/16 day/night temperatures and 16-h photoperiod. The temperature in the greenhouse generally fluctuated around the setpoint. The daytime temperature was generally above the setpoint, particularly on sunny day. The relative humidity was not controlled and generally varied between 55 and 75 %. One-year old seedlings of aspen (*Populus tremuloides* Michx.), jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea Mariana* (Mill.) B.S.P.) and white spruce (*Picea glauca* (Moench) Voss.) were planted at the beginning of the test. The seedlings were irrigated with fertilizer solution every two days.

3 Statistical analysis

The relationship between water and soil temperature was analyzed using regression analysis (data combined for the three soil temperatures). Chi square test was used to examine the distribution of soil temperature among containers in the same plywood box:

$$\eta = \sum_{i=1}^{m} \{(V_i - n \times P_i)^2 / n \times P_i\}$$

where V_i is the actual number of samples having the same temperature value t; P_i is the probability for a normal distribution; $n \times P_i$ is the theoretical number of samples having temperature t; m is the total number of temperature values in the test.

Analysis of variation was used to test the difference in the magnitude of diurnal temperature fluctuation among the three temperature treatments. Standard deviation was used as a measure of the magnitude of the diurnal fluctuation. Since ANOVA showed significant differences between the three temperature treatments, multiple-comparison (q-test) was used to identify which temperature treatment was significantly different from which treatment (Fu, 1979; Mason *et al.*, 1989).

Results and Discussion

1 Relationship between soil temperature and water temperature

Soil temperature (T_{soil}) was strongly correlated to water temperature (T_{water}). This was almost a 1 to 1 relationship ($T_{\text{soil}} = 0.99\ T_{\text{water}} + 0.12$, $r = 0.999$, $n = 25$) but the soil temperature was significantly greater than water temperature (intercept = 0.12). The results suggest that the heat exchange between the growing medium and the water outside the container was highly effective in the system. The accuracy of soil temperature control therefore will solely depend on the accuracy of the water temperature control.

2 Temperature variation among containers

The soil temperature was very uniform among containers within the system except a few containers at one end where the soil temperature was higher (Fig. 2). This was probably attributed to the steam heater located at that side of the greenhouse.

Chi-square test showed that the soil temperature of all containers within the system followed a normal distribution with a mean of 30.5, a small standard deviation of 0.36 ($\eta = 5.11 < \chi^2\ 0.05\ (15) = 25.00$) for the 30°C test. This suggests that soil temperature measurements from a few containers can provide a reliable estimate of the average soil temperature of the treatment. For example, the average of measurements from two containers provided an estimate of the average soil temperature for the 30°C treatment with a 95% confidence.

3 Temperature variation with depth from the surface

There was a temperature gradient from surface to bottom of the container and the direction of the gradient varied with temperature (Fig. 3). In the 5°C and 20°C tests, soil temperature generally decreased from the top to the bottom of the container (Fig. 3A and B). In the 30°C test, on the other hand, soil temperature increased from the top to the bottom of the container (Fig. 3C). The opposite direction of the temperature gradient was related to the direction of heat exchange between the ambient air and the surface of the system. The soil temperatures in the 5 and 20°C tests were generally lower than air temperature. Therefore, the system gained heat from the air, resulting in higher temperatures at the surface than deeper levels. On the other hand, the soil temperature in the 30°C test was generally higher than air temperature. The heat loss from the surface of the system caused the temperature at the surface to be lower than deeper layers. However, the temperature gradient was small (< 1°C). A better mixing and stirring of the water and/or better insulation should produce even smaller temperature gradients, but better insulation may be less effective because relatively large holes have to be cut through the insulation to facilitate irrigation, fertilization and the aeration of the growing medium. Therefore we recommend to use water pumps with a higher flow rate or more than one pumps to further reduce the temperature gradient.

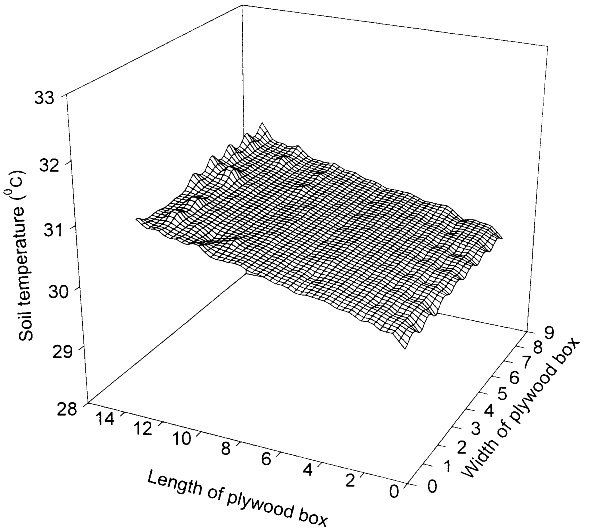

Fig. 2 Horizontal distribution of soil temperature.

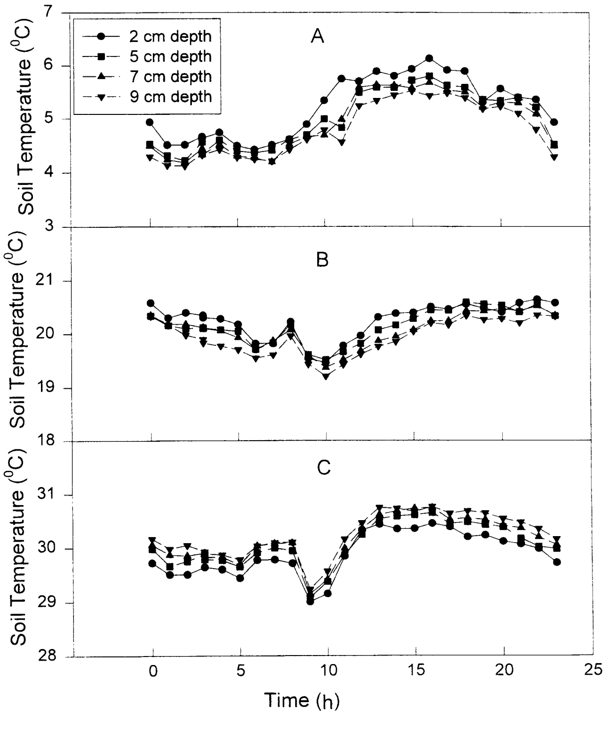

Fig. 3 Diurnal variations of soil temperature at different depth from the surface in the (A) 5°C, (B) 20°C, and (C) 30°C treatments.

4 Diurnal variations of soil and water temperatures

Soil temperature decreased at night and increased during the day (Fig. 3) and water temperature followed the same pattern (data not shown). The soil temperature range (max–min)

Table 1 Multiple-comparison for the magnitude of diurnal fluctuation in soil and water temperature between the 5, 10, and 30°C treatments.

Water temperature	T_i	T_i–$T_{30°C}$	T_i–$T_{20°C}$
5°C	0.6132	0.2244*	0.2582*
20°C	0.3550	0.0338	
30°C	0.3888		
Soil temperature	T_i	T_i–$T_{30°C}$	T_i–$T_{20°C}$
5°C	0.6891	0.2941*	0.3191*
20°C	0.3700	0.0250	
30°C	0.3950		

* Significant at 95 %. $D=q0.05^{(a,f)} \times (S^2_w/m)^{0.5}=0.1682$, where D is the critical value; a is for the number of treatments (=3); f is degree of freedom in the test (=21); $q0.05^{(a,f)}=3.58$ (from statistical q table); m is the number of samples within a temperature treatment ($m=8$ in this experiment), S^2_w is the mean sum of squares soil or water temperature (=0.018 in this experiment). T_i in the table is the magnitude of diurnal fluctuation for temperature treatment i ($i=5$, 20, 30°C). T_i–$T_{30°C}$ and T_i–$T_{20°C}$ are the difference in the magnitude of diurnal temperature fluctuation between temperature treatment i and the 30°C and 20°C treatment, respectively.

was 1.5, 0.8, and 1.0°C, respectively, for the 5, 20, and 30°C tests. The diurnal variation was probably attributed to a combination of light energy input and the heat exchange between the system and the ambient air. Since the change in soil temperature followed the change of water temperature closely, the diurnal variation in soil temperature can be further reduced by using a higher capacity temperature controller.

The magnitude of daily temperature fluctuation was significantly greater in the 5°C test than the 20 and 30°C tests (Fig. 3, Table 1). The greater fluctuation in the 5°C test was probably resulted from the lower resolution (± 1.9°C) of the thermostat used to control the chiller. The temperature controlling device on the other two systems has much better resolution (± 0.5°C).

It should be noted that the sudden drop in soil temperature in the morning (Fig. 3) was not part of the normal diurnal variation. It resulted from the addition of fertilization solution to the growing medium and the refill of water in the system. The temperature of tap water was below 15°C. The addition of the cold water caused an immediate decline in both water and soil temperatures. The system needed to be refilled very 1–2 weeks to replace the lost water. Recharging the system more often (thus smaller amount of water each time) can minimize the magnitude of temperature drop. An automatic recharge device to keep the water level more constant should minimize this effect.

Funding for this research was provided by Lakehead University, CFI, ORDCF, and NSERC research grants to Dang, and an NSERC PGS A to Cheng.

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(Accepted May 8, 2000)