Computer Controlled Portable Frost Simulator for Field Studies of Frost Effects on Wild Blueberries

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SUMMARY. Two commercial freezers were modified to provide an inexpensive chamber system to investigate frost effects on wild, lowbush blueberries (*Vaccinium angustifolium*) under field conditions. A computer control system was developed with software written in Visual Basic 6.0 for MSWindows, which precisely controlled temperature in the plant canopy when the chambers were placed over blueberry plants in the field. Frost events (with temperatures ranging from -2 to -15 °C (28.4 to 5.0 °F)) were simulated by user input to control the cooling and warming rates, and minimum temperatures. The system records temperature set points, and current temperature in the plant canopy, or elsewhere in the plant environment, and provides a graphical display of key parameters. Trials have verified the reproducibility of temperature profiles and the chambers have been used to provide preliminary information on the effects of frost at bloom on fruit set and development.

The wild blueberry is a major horticultural crop in eastern Canada and the New England states (Kinsman, 1993), and is well adapted to the climate and soil conditions of the region (Eaton, 1994). Climatic

factors can have dramatic effects on fruit yield. Flowers that open in middle to late May are sensitive to frost and are damaged at temperatures of -3.5 °C (25.70 °F) or lower (Hall et al., 1971; Olson and Eaton, 2001). Even the early stages of fruit development (in late May and early June) are sometimes jeopardized by a particularly late frost. Frost events are responsible each year for reductions in yield that vary from minor to nearly complete crop loss in certain locations (Kinsman, 1993), yet there is very little information on the specific in-situ effects of freezing temperatures during bloom. The lack of experimental data are directly related to the unpredictability of frost events. To study the in-situ effects of frost on blueberry plants at various stages of development it has been necessary to develop a system that allows control of ambient temperature around plants in experimental field plots. While previous researchers have designed and reported on computer-controlled frost chambers, these designs have all involved lab-based systems ranging from the very small (e.g., for plant tissue exotherm analysis; Cappiello and Dunham, 1994; Wample et al., 1990) to those suitable for freezing

containerized plants and trees (Johnson et al., 1987; Robotham et al., 1978). The requirements of wild blueberry field research necessitated development of a system that shared many design criteria with these lab-based systems (including control of cooling rate, low minimum temperatures, and data acquisition and storage), but which was also fully portable, inexpensive, and capable of being deployed quickly in field situations. This paper describes the design, construction and use of such a system.

Materials and methods

The goal of the project was to develop a two-chamber system capable of independent temperature control and datalogging by a single computer. Two pre-owned retail food freezers (one measuring $60 \times 100 \times 55$ cm ($23.6 \times 39.3 \times 21.7$ inches) and the other $50 \times 83 \times 55$ cm ($19.7 \times 32.7 \times 21.7$ inches) (inside dimensions)) were chosen as the basic chambers. Each incorporated a small, externally mounted compressor [0.25 kW (1/3 horsepower)] and adequate wall insulation [7 cm (2.8 inches) urethane foam insulation] to ensure even cooling from ground to a height of 30 cm (11.8 inches; the maximum

Fig. 1. A schematic of the portable frost simulator used in field studies of frost effects on wild blueberries: 1) DyanRes Dr80 data acquisition board analog to digital card (IOtech, Inc. Cleveland, Ohio), 2) parallel control line, 3) terminal board (T71-TC), 4) 5-V direct current control, 5) ground, 6) solid state relay, 7) 110-V alternating current source, 8) 110-V alternating current load, 9) line voltage, 10) neutral, 11) compressor, 12) bypass valve, 13) capillary tube, 14) condenser, 15) fan, 16) thermocouples.

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Fig. 2. Two freezing chambers in place over blueberry plants in the field. A shelter containing the computer is visible in the background.

height of lowbush blueberry plants). Additional flexible insulation may also be placed around the chamber in place in the field to reduce air and heat leakage. The freezers were inverted so the compressor was relocated to the top (Figs. 1 and 2). A copper-constantan four-junction thermopile, suspended on a wooden dowel tree extending 5 cm (2.0 inches) below the interior ceiling of the chamber, gave an average chamber temperature. During operation, the thermopile was aspirated continuously by a small horizontal air flow fan. Figure 1 shows with a dashed line the modification to the refrigerant flow to improve temperature control. It included a bypass valve that allows hot refrigerant to enter radiator coils located inside the chamber on demand. In this manner the computer control system can continuously monitor, and heat or cool, the chamber to maintain a close temperature control.

Output from the thermopile is directed to a DynaRes data acquisition board (IOTech Inc., Cleveland, Ohio) connected to a Windows-compatible computer. Control software [compiled in Visual Basic 6.0 for Windows (Microsoft Corp., Bellevue, Wash.) with drivers provided in the Analog Connection Development System software (Campbell, Calif)] re-balances compressor cold and hot gas flows each 15 s based on sensor temperature and keyboard-selected rate of temperature change. Control is within 0.5 °C (0.90 °F) of setpoint over a range of 0 °C to -15 °C (32.0

°F to 5.0 °F) The software is capable of logging and graphing chamber temperatures and set points continuously; verification of temperatures achieved in the air above the plants and at canopy level is achieved through the use of redundant sensors and a datalogger not associated with the control circuitry. When used in the field, the computer is housed in a prefabricated shelter. Principal input to the Windows program includes 1) the temperature

at the end of each hour for up to 30 h 2) the desired data logging frequency and data file information.

Direct output to the screen, in a colored graphical display, consists of chamber cooling or chamber warming temperature indicators, current set points, current temperature, and the temperature of auxiliary sensors. A linear temperature decline at an initial rate of 3 °C/h (5.4 °F/h; hours 3 to 5) followed by a 2° C/h rate (3.6 °F/h; hours 5 to 11) and a holding temperature of -5° C (23.0 °F) for the next 3 h is shown as an example profile in Fig. 3. Maximum cooling and heating rates are 0.5 °C/min at 14° C (57.2 °F). Trials of the units were conducted under a range of ambient temperature conditions including those considerably above freezing (Fig. 3). Temperature profiles can be varied widely depending on investigator requirement, but most experiments are likely to be run where relatively low optimum nighttime temperatures have been forecast. This avoids the need for rapid, or very extended temperature decline profiles and allows realistic simulation of frost events in lowbush blueberry production areas where minimum temperatures generally occur during the 0200 to 0500 HR period (Agriculture and Agri-Food Canada, 2002).

Field trials with both freezers were

Fig. 3. A typical temperature profile obtained for an overnight trial in late May at the Nova Scotia Wild Blueberry Institute, Debert, N.S. (v) outside temperature; (x) air temperature within the plant canopy temperature (inside freezer); (o) freezer setpoint; °F = 1.8 (°C) + 32.

conducted during the blueberry bloom period (typically late May to early June) at the Nova Scotia Wild Blueberry Institute, Debert, Nova Scotia (lat. 45° 55' N, long. 63° 27' W). The two freezers were installed at dusk on five dates (27 and 28 May and 1, 2, 3, and 6 June) over different parts of the same clone. Lowbush blueberry clones frequently spread over extensive areas with above-ground stems linked by underground rhizomes. Flower buds had previously been counted on four individual tagged stems of similar size in the area covered by each chamber. Separate trials were conducted with minimum canopy temperatures of 1.0, -3.5, -6.0, -7.5, and -8.0 °C (33.80, 25.70, 21.20, 18.50, and 17.60 °F), respectively. Outside ambient temperatures varied between -3 °C (26.6 °F) and 14 °C over the five dates. Minimum temperatures were assigned at random to the chambers over the five date experimental period to complete the full set of treatments. Each minimum temperature was sustained for 3 h. In the system trials each tagged stem had flower buds at various stages of development ranging from closed (with petal color showing) to fully open (Hicklenton et al., 2002). At 0700 HR the following day, the freezers were removed and samples of buds and blossoms were examined visually for frost damage. All tagged stems were monitored throughout the remainder of the spring and summer to assess fruit set, and berry yield percentages based on all flowers present at the time of the trial.

Results and discussion

Percent fruit set (from flowers at all stages of development) declined curvilinearly with temperature (Fig. 4), approaching zero at temperatures of -8 °C. The percentage of fruit maturing following each temperature exposure (Fig. 5) fell below that of fruit set indicating that postset abortion occurs. The pattern of decline with temperature, however, corresponded closely with the fruit set data suggesting that rates of abortion were not influenced by minimum temperatures experienced by the flowers. While the objective of these trials was to test the system and not to provide definitive information on blueberry flower frost sensitivity, we note that the decline in fruit set with temperature corresponds to that observed in laboratory freezing studies with lowbush blueberry at time of

bloom (Hicklenton et al., 2002).

The tests with minimum temperatures of -3.5 °C resulted in little immediate observable damage to blossoms while increased damage was noted following tests at -8 °C (data not shown). The greatest reductions in

fruit set and fruit for harvest occurred at the lowest night time temperatures (-7.5 and -8 °C), temperatures that are not uncommon during the late May to mid June period in the blueberry-producing areas of Nova Scotia. The observed effects on fruit set confirm earlier

Fig. 4. The percentage fruit set recorded 3 weeks after freezing trials on wild blueberry plants exposed to various temperatures for 3 h (see Fig. 3). Data are means based upon total numbers of flowers on eight branches (two chambers) shown $\pm$ SE; $^{\circ}\text{F} = 1.8 (^{\circ}\text{C}) + 32$.

Fig. 5. The percentage of mature blueberries harvested at the end of the season for plants exposed to various temperatures for 3 h (see Fig. 3 for typical temperature profile). Data are means based upon total numbers of flowers on eight branches (two chambers) shown $\pm$ SE; $^{\circ}\text{F} = 1.8 (^{\circ}\text{C}) + 32$.

reports by other researchers (Hall et al., 1971, Jackson et al., 1972; Olson and Eaton, 2001). Similarly, flowers of the saskatoon berry (*Amelanchier alnifolia*) are rendered sterile by night time temperatures of -3°C (Olson and Steeves, 1983), whereas highbush blueberry (*Vaccinium corymbosum*) flowers are killed by temperatures as high as 0°C (Gough, 1994).

The study of the effects of frost events on plants in the field pose special problems for researchers. Frosts, while predictable by short term weather forecasts, occur too rarely to allow the planned conduct of replicated experiments at particular phenological stages. The portability, precision and flexibility of the system we have described makes it a valuable tool in investigations into frost effects at bloom or any number of other developmental stages. The limitations of the system relate primarily to the type of frost conditions that can be simulated. The chambers reproduce the mass movement of cold air that creates conditions of advective frost in the field. They do not control air moisture content, though, and so chamber frosts may be either white in saturated air, or black in air of lower moisture content. Neither are they capable of reproducing the relatively common radiation frost that occurs on clear nights as plant tissues lose heat to the sky. The bulk cooling of the air inside the chamber means that all parts of the covered plants experience similar temperature conditions so vertical temperature gradients that develop in the canopy under radiation frost conditions are not simulated. Still, these limitations are not serious when effects of low temperatures on individual organs are the focus of the experiment. Overall the system is efficient and relatively inexpensive to construct, especially using preowned refrigeration units. The computer program provides nearly unlimited flexibility to design temperature regimes that simulate various frost events, including the sometimes precipitous decline in temperature that occurs frequently in the Canadian maritime climate. Extended periods at low temperature are also possible. With relatively minor modifications this system could be used to control on the basis of tissue temperature. Copies of the software and additional programming and engineering details are available from the senior author on request.

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Yield Potential of Selected Medicinal Herbs Grown at Three Plant Spacings in New Mexico

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SUMMARY. Field studies were conducted to determine the production potential of echinacea (*Echinacea purpurea*), valerian (*Valeriana officinalis*), mullein (*Verbascum thapsus*) and yerba mansa (*Anemopsis californica*) medicinal herbs at two sites in New Mexico. Las Cruces, N.M., is at an elevation of 3,891 ft (1,186 m) and has an average of 220 frost free days per year, whereas Alcalde, N.M., is at an elevation of 5,719 ft (1,743 m) and averages 152 frost-free days per year. In-row plant spacings of 12, 18 and 24 inches (30.5, 45.7, and 61.0 cm) were compared at both locations. The corresponding plant densities for the 12, 18 and 24 inch spacings were 14,520 plants/acre (35,878 plants/

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