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COMMENTS ON THE COLORADO STATE UNIVERSITY CLIMATE SYSTEM

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Since the installation of the climate control system in the Colorado State University 'heat' houses in 1985 (CGGA Bul. 420), the system has undergone continuous revision in the software code to enhance environmental control and obtain additional information on what is going on inside the greenhouses. Some of the methods incorporated are described here.

For the past five years, CGGA research bulletins have documented work with computer controls at the Colorado State University research range (CGGA Bul. 396, 407, 420, 430). The difficulty we run across in development is the lack of much meaningful comparison with the innumerable systems available to Colorado growers. These "computer" systems are proprietary, and the particulars may not be fully explained so the grower has some idea of what is going on. They may not be suitable for Colorado climate, which is unique when compared with any other location in the world. What I attempt here is an explanation of how climate is controlled in the Colorado State system which uses Hewlett-Packard's version 3.0 of the BASIC language. Other languages such as FORTRAN, PASCAL or FORT are employed in many of the systems available, and have their own particular advantages. However, the advanced BASIC used in the Colorado State system compares favorably with FORTRAN 77. The system has been documented in detail and copyrighted. Manuals are available with a complete code listing.

Temperature

To reduce the criticality of sensor position in the greenhouse, three aspirated sensors are located at crop height in each house, the system reading each sensor individually, and averaging them; to which the adjusted setpoint is compared at each execution of the program. A basic setpoint is stored and then modified appropriately prior to actual comparison — for example, 62 F nights and 72 F days. Setpoint adjustment then proceeds:

1. If the outside air temperature is below the average air temperature inside, the setpoint is adjusted upward as noted in **Fig. 1.** The value for adjusting is determined by the temperature difference, inside to outside, and a constant unique to the greenhouse and its heating system. This type of setpoint regulation has been available for a number of years with the majority of control systems, and tends to maintain the desired setpoint regardless of heating load.
2. With low outside air temperatures, the cooling system is locked out at night. Otherwise, cooling will occur if the

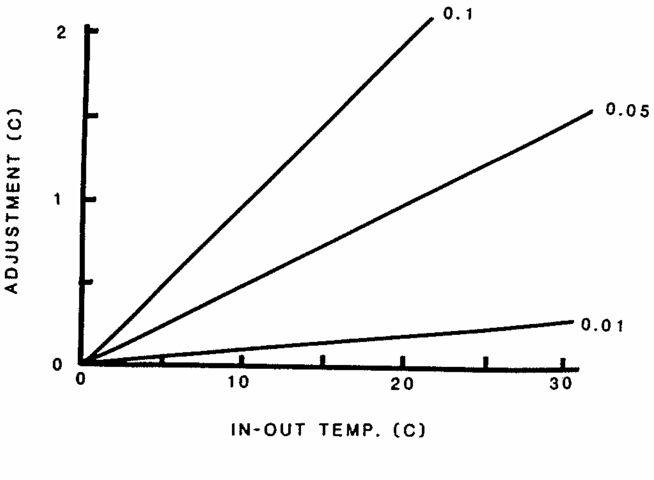

Fig. 1: The effect of temperature differential (in-out) on air temperature setpoint modification. The adjustment is added to the basic setpoint if the differential (in-out) is positive.

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inside average temperature rises by more than a minimum value above the basic setpoint as determined by the operator. This setpoint-plus-staging value is further adjusted upward as outside temperature drops **(Fig. 2);** so that, if the temperature differential (outside-to-inside) exceeds 30 degrees F, the system will not cool regardless of solar radiation conditions in this climate. This cooling setpoint adjustment is not available at night.

3. As we depend upon fan-and-evaporative pad cooling, fans are staged according to a separate constant. Under summer conditions, the basic setpoint (72 F day) is adjusted downwards since high CO_2 concentration will not be available (CGGA Bul. 461), and the crop should be grown as cool as possible for maximum quality. The main ventilator and pads are controlled separately. Ventilators, which are hinged at one side, are particularly sensitive to air movement during the first few inches of opening. The Colorado State University system utilizes a separate staging constant in conjunction with a timing command which positions the ventilator open or close in very small increments. Water in the pads is determined by outside radiation and outside air temperature — a method which we have utilized at Colorado State University for more than 20 years. We find this prevents sudden temperature changes, and we can control mildew diseases more effectively than where pad water is staged along with the fans. Pads can be shut off manually, and ventilators can be closed permanently for winter operation.
4. Heating utilizes a separate staging constant, depending upon whether hot air or hot water is employed. Hot water systems, with suitable mixing valves, have greater potential for precision control as compared to staged hot air. The mixing valves in our system use a non-linear algorithm **(Fig. 3)** so that heating occurs in very small increments during initial opening. If there is no change in the temperature differential over time, the control code will tend to reduce the differential to zero — or the adjusted setpoint. The boilers are maintained at operating temperatures (190-220 F), based upon an anticipatory system that takes into account temperature differential, radiation and outside wind velocity, insuring that hot water is always available for heating under cloudy or windy conditions. If the greenhouse has a hot water system, the original hot air, fan jet, equipment is employed as backup during severe weather.
5. We have known for several years that photosynthesis in many species becomes increasingly temperature dependent at high radiation and CO_2 levels. For roses, Frank Coker (CGGA Bul. 456) showed that maximum photosynthesis occurred at 86 F under clear sky conditions and 500 ppm CO_2. Under cloudy conditions, the temperature effect was much less. The cooling set-point (No. 2 above) allows higher temperatures above the basic setpoint if there is sufficient radiant energy. This is a semi-automatic temperature adjustment we have found to be easily implemented, resulting in higher rose yield under Colorado winter conditions. Recently, we have deliberately implemented a control sequence that will increment the day setpoint as a function of CO_2 level and radiation. This adjustment is in addition to the change made in No. 1 above, and requires a minimum radiation level of 100 watts/sq.m. and 45 Pascals CO_2 (ca 530 ppm). These levels, as well as the amount of adjustment, can be controlled by the operator. As we are already into an experiment for the 1988-89 winter

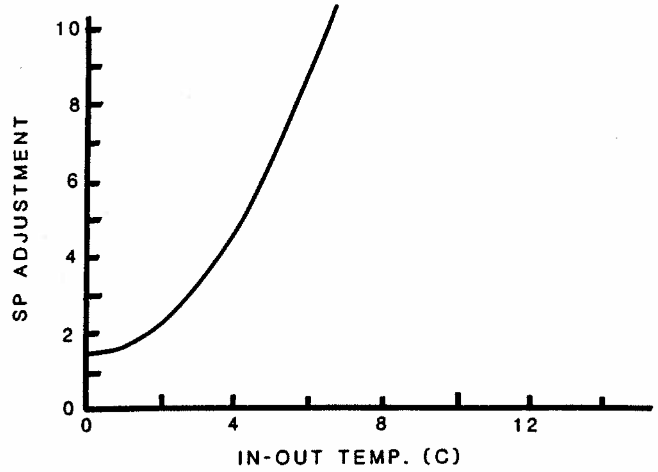

Fig. 2: The effect of temperature differential (in-out) on cooling setpoints. With this particular curve, first stage cooling cannot come on unless the temperature is at least 1.5 C above the basic heating setpoint (0 in-out). As outside temperature drops, the cooling setpoint increases non-linearly.

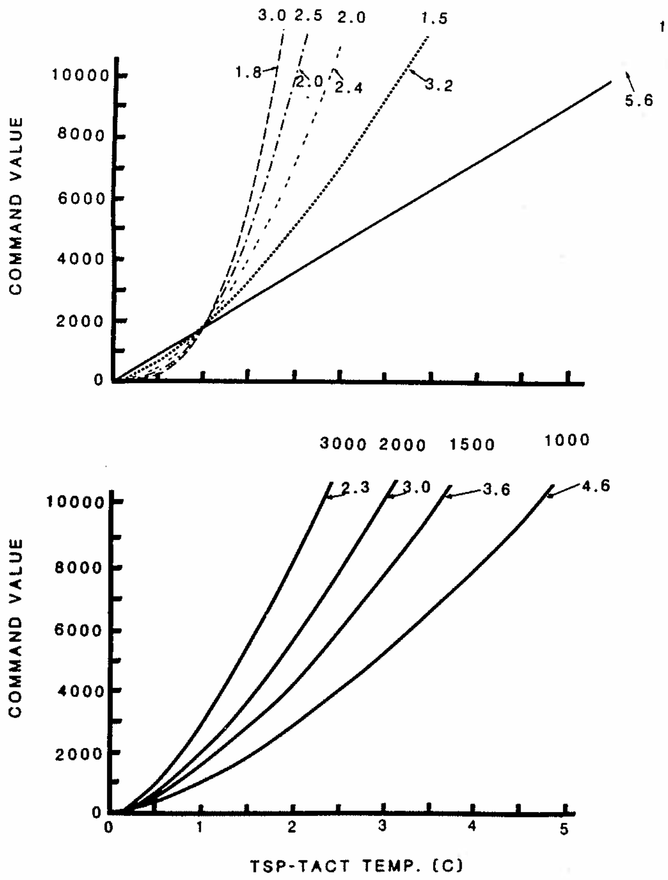

Fig. 3: The effect of changes in constants on mixing valve control for a hot water system. The equation is (command value) = AX^B, where X is the difference between adjusted setpoint and actual average air temperature. The upper graph is the effect of "B" at A = 1800, whereas the lower is the effect of "A" when "B" = 1.5. The arrows show the maximum temperature range of the valve when full open.

season, this change is equally applied in all houses, and the effect of the algorithm on yield and gas consumption is planned for the 1989-90 heating season.

Staging of cooling and hot air systems does not employ differentials between **ON** and **OFF** of a particular stage. "Chattering", often occurring when a sensor is too sensitive, is avoided by the fact that an operation is delayed by the timing between program execution; and by the staging constants set by the operator. The latter determines the temperature differential between stages **ON** or **OFF**.

The control algorithm outlined in No. 5, is a modification of an original attempt by Korns and Holley in 1962 (CFGA Bul. 150). This was unsuccessful, largely due to equipment available at the time. It represents a different approach to climate control, based upon the literature and experience, as contrasted to basic plant model development at the University of Guelph, Davis, Penn State and Michigan State University.

Humidity

We have chosen to control humidity in the Colorado State University system by calculating the actual, absolute water vapor concentration (pressure terms = millibars), and then setting the system to maintain a known vapor pressure deficit (VPD) such as 3, 5 or 10 millibars. This avoids problems inherent in relative humidity as discussed in CGGA Bul. 420. The effect of a constant VPD on relative humidity over the usual rose temperature range is plotted in **Fig. 4.** Thus, if the operator sets a VPD of 10 mb, the RH (%) at 52 F would be zero — which never occurs in a greenhouse full of plants. The actual situation during a heavy heating load is indicated in **Fig. 5** in which two houses are being controlled at 3 mb and two at 15 mb VPD. At humidities much greater than 5 mb VPD, the actual humidity will vary in accordance with heating system and outside weather conditions. Only at high humidities (>80% RH) is it possible to maintain a known humidity level in greenhouses by means of a misting system (CGGA Bul. 461).

Since, during Colorado winters, the outside absolute humidity frequently drops below 3 mb, it would be simple to set dehumidification VPD at a higher value (e.g. 10 mb versus present value of 0.5). This would be extremely costly and does not appear to be a viable option except for experimental purposes. The dehumidification cycle in the Colorado State University system requires at least one heating stage and one cooling fan stage whenever the VPD is less than 0.5 mb (ca 98% RH). We have not had any powdery mildew on roses for more than a year.

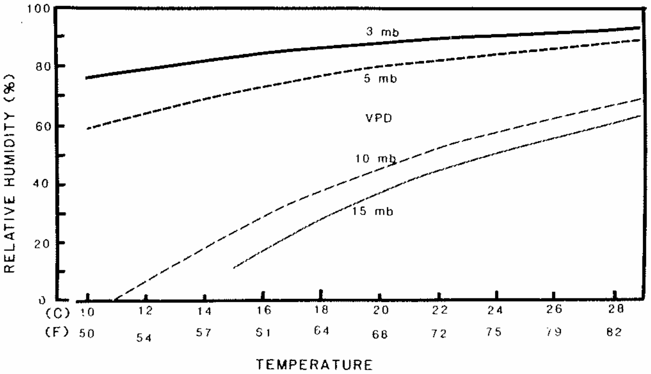

Fig. 4: The effect of temperature on relative humidity for different vapor pressure deficit (VPD) settings. For any particular VPD, the absolute difference between saturation (100% RH) and actual vapor concentration remains the same. The relative humidity variation results from the fact that absolute vapor concentration at 100% RH decreases as temperature falls.

Although the Colorado State University system has wet bulb thermometers for measuring humidity, we do not maintain them or use the data. We use capacitance probes which are now commonly available, and these are calibrated monthly. Frequent calibration is a necessity as we have found capacitance probes to drift significantly inside greenhouses. Capacitance probes outside the greenhouse have been found to be very stable, and, of course, wet bulbs are not much good below freezing.

Carbon dioxide

Due to elevation at Fort Collins, a CO_2 concentration in parts per million (ppm) at this location is 16% less absolute concentration than the same ppm at sea level. We have chosen, therefore, to calibrate and measure CO_2 levels in absolute pressure terms — Pascals (CGGA Bul. 421). A CO_2 concentration of 350 ppm at Ft. Collins is 29 Pascals (Pa). The system attempts to maintain a basic 45 Pa (537 ppm) up to radiation levels of 100 W/sq.m. Above 100 W/sq.m., the minimum CO_2 is increased 0.2 Pa per watt. At 300 W/sq.m., concentrations will be in the range of 900 to 1000 ppm. Control is complicated by the fact that air samples must be brought considerable distances from the greenhouse to the analyzer. The system requires time for purging of the sample lines so that actual concentrations

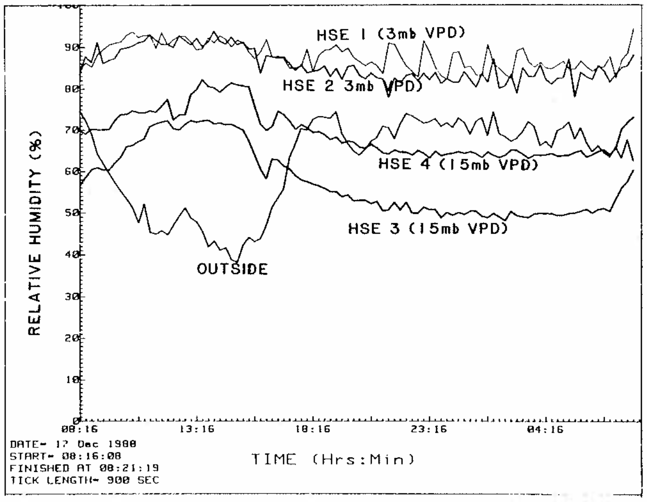

Fig. 5: Typical winter relative humidity values in four greenhouses, two set to vapor pressure deficits (VPD) of 3 millibars (mb) and two set to VPDs of 15 mb. Houses 1 and 3 use hot air, fan jet heating with constant air circulation, whereas Houses 2 and 4 have hot water systems with no positive air circulation. The higher infiltration in House 3, due to positive air movement, results in a lower humidity at a 15 mb VPD setting. The higher outside relative humidity at night is meaningless since actual vapor concentration will usually be less than 3 mb at temperatures below freezing as compared to vapor pressures above 10 mb inside the greenhouses.

are recorded every 10 to 15 minutes. Under these conditions, CO_2 injection rates are critical. If too high, the resulting situation is depicted by **Fig. 6,** which shows the considerable variation that may occur. There are also problems of condensation in the sample lines, and growers contemplating analyzer installation should keep sampling lines as short as possible without subjecting them to low temperatures. Centrally located analyzers in large commercial ranges are not desirable. On the other hand, the greenhouse environment is not the best situation for electronic equipment.

As CO_2 analysis does not occur at night, all values are set to zero, and time is allowed in the mornings for the system to purge before beginning control. Attempting to maintain CO_2 levels beyond first stage cooling is uneconomical in Colorado, and a delay in injection after cooling fans go off is mandatory. Although the newer analyzers are very stable, provision should be made for calibration at quarterly intervals.

Radiation

Previous work (CGGA Bul. 449, 454, 455) has shown that attempts to reduce stress on roses with a 40% shade cloth will reduce rose yield under fiberglass and double greenhouse covers. The controlled greenhouses at Colorado State University have the capability of closing shade screens during the day, based upon inside energy. These screens can also be deployed at night for energy conservation, regardless of day-time settings. The latter results in a highly significant energy saving. But, the presence of screens, even when open, measurably reduces total inside energy. It may be that screens with less shading, in the range of 10 to 20% reduction, would be beneficial during the day in Colorado. In European greenhouses, it is not unusual to see two separate screens, one opaque for night energy conservation, the other for shading during the day.

The system switches day-night at an outside radiation level of 50 W/sq.m. However, under partially cloudy conditions, a single value results in rapid environmental changes. A "toggle" mechanism has been incorporated so that the system switches to night at 10 W/sq.m. and returns to day settings at 70 W/sq.m. Experience over the last three years shows this range to be adequate for Colorado conditions.

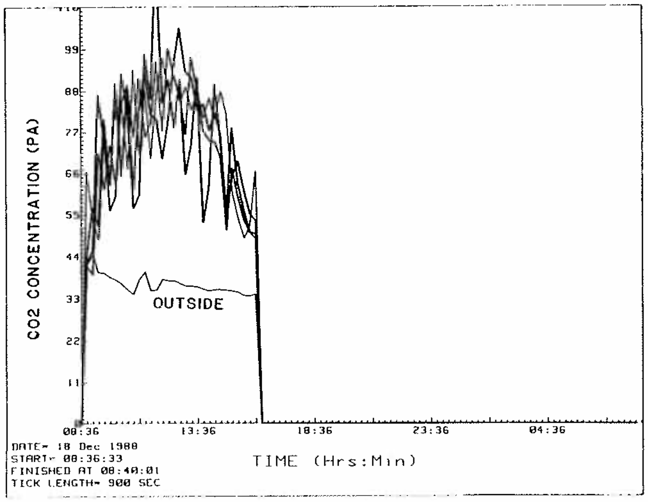

Fig. 6: Typical example of excessive CO_2 injection rates. These variations can be reduced by lowering injection rate or reducing sampling time — such as locating the analyzer in the environment to be controlled, thereby eliminating the purging requirements.

To avoid rapid, maximum heating at the night-to-day switchover, the program code causes the system to step to the day setpoint in small increments over a period determined by the operator. If there is sunshine, the greenhouse will come to daytime operating conditions with little requirement on the part of the heating system. Some growers will attempt to conserve energy by allowing their system to stay at night settings if there is no significant radiation (i.e. $< 100\ W\ m^{-2}$). Observation indicates that this is a dangerous practice, resulting in considerable delay and severe flower malformation, especially in carnations. Day temperatures on most cut flower and flowering pot plants should always by higher than night settings regardless of available radiation level.

What we do find is that "single point" radiation sensors are difficult to locate properly. A number of investigators get around problems of intermittent shading by locating the sensor directly under south facing roofs. As most Colorado greenhouses are oriented north-south, this leads to some difficulty, given Colorado's frequently cloudy afternoons. Linear sensors (3 ft. long) are available, but expensive, and these would do much to reduce variability in light measurements in greenhouses. They could be located above the crop for better total radiation measurement as contrasted to directly under the roof.

Irrigation

If cut flowers are grown in the ground (soil), the possibilities for automatic irrigation are severely limited. At this time, reliable methods for soil moisture determination are very expensive or extremely bothersome. The appropriate irrigation cycle must be determined by testing and observation, with a good understanding of the situation in the particular greenhouse. But, if the grower has appropriate training, a good quality water supply, and an appropriate fertilizer injection system, most crops can be grown in soilless media such as gravel, scoria or rockwool. It becomes possible, as we have been able to do, to automatically irrigate plants based upon accumulated solar radiation. Occasional overwatering is not critical with an appropriate soilless medium. The Colorado State University system accumulates radiation in each greenhouse, and initiates a watering cycle when the accumulated energy exceeds a set value. If this is combined with a suitable trickle system for application, there should be no problem with physical injury or disease. One is assured of an adequate water and nutrient supply.

Summary

The Colorado State University system incorporates a number of methods to record and summarize data which may not be required by the usual grower. The potential for complete automatic data on the crop is there, and which growers can use to fine-tune their environment for maximum return. There appears to be no limitation as to what can be done. The main problem is the external climate as determined by greenhouse location. However, any of these systems require someone capable of becoming familiar with them — especially in maintaining sensors and analytical equipment. As the cliche goes: "Garbage in, garbage out". Systems will certainly give garbage if growers expect to install them and forget about them. Cleaning and recalibration on a regular basis should have some thought, with care to see that it is done properly.

Abstracts from the American Society for Horticulture Science Annual Meeting, 1988, Michigan State University

THE EFFECTS OF PHOTOPERIOD AND HIGH-PRESSURE SODIUM LIGHTING ON *PRIMULA VULGARIS*

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The effect of photoperiod and supplementary lighting on flowering date and plant size was studied on an early and a late strain of Primula vulgaris, namely 'Saga' and 'Joker' respectively. The photoperiod treatments of 8 hours (SD) and 16 hours (LD) day lengths were given with or without high pressure sodium (HPS) lighting at 49 μ mole/m^2/sec and compared with ambient conditions. These treatments were started at transplanting and lasted 4 weeks. Plants were then subdivided into the 5 lighting regimes, also for 4 weeks, resulting in 25 lighting combinations. After lighting treatments plants were kept under ambient conditions until flowering. Two seedling dates (July 1 and 29) were used. Transplanting took place six weeks after seeding. Plants were grown in glass greenhouses with a minimum set air temperature of 10C.

Flowering date was not affected by any lighting treatment. The LD treatment in combination with HPS lighting resulted in plants with the largest leaves when measured one week after the end of the second treatment period but there was no effect on leaf size of any lighting treatment at time of flowering.

EFFECT OF HUMIDITY CONTROL ON GREENHOUSE ENVIRONMENT

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Air humidity in the greenhouse was controlled using a high pressure fog system. The effects on certain environmental parameters and plant variables were compared to a greenhouse with no humidity control. Under humidity control the air temperature was reduced by up to 6°C, light intensity was reduced by up to 5%, relative humidity was maintained at 80%, maximum transpiration was reduced by 50%, maximum water stress was reduced by 50% and leaf-air temperature difference was also reduced. The implications of humidity control based on relative humidity feedback compared to absolute vapor pressure feedback are discussed.

EFFECT OF DIURNAL TEMPERATURE FLUCTUATIONS ON STEM ELONGATION CIRCADIAN RHYTHMS

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Previous research has shown that final stem length is a function of the relationship between day and night temperature. A cooler day than night reduces stem elongation while a warmer day than night promotes stem elongation. The diurnal variation in stem elongation under different day/night temperature regimes has not been quantified. Therefore, the diurnal variation in stem elongation rate of *Lilium longiflorum, Dendrothema grandiflora,* and *Cucumis sativus* was determined using angular displacement transducers. Thermoperiod and photoperiod interacted to affect stem elongation of these species. Stem elongation occurred during both the photoperiod and scotoperiod when the day temperature was warmer than the night temperature. In contrast, stem elongation occurred only during the scotoperiod when the day temperature was cooler than the night temperature. These data suggest that the effect of the day/night temperature relationship on stem elongation is associated primarily with stem elongation during the photoperiod.

CHANGES IN FRESH WEIGHTS OF VARIOUS FLORAL PARTS DURING SENESCENCE OF CUT CARNATIONS AS AFFECTED BY SILVER THIOSULFATE

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Greenhouse-grown 'White Sim' carnations were harvested at the open stage and pulsed with distilled water (control) and 4 mM silver thiosulfate (STS) for 30 min, and then kept in distilled water at 21°C under continuous light. Each day flowers were separated into petals, ovary, styles, receptacle, and calyx, and fresh weights of each part were measured. STS extended flower longevity by 92% over the control (6.2 days). Fresh weight of petals in control flowers increased gradually until day 2, and then diminished. After petals began to wilt and showed the ethylene peak at day 6, fresh weight of petals decreased rapidly. Fresh weight of STS-treated petals, however, increased until day 3, and then stayed similar until day 12. Fresh weight of ovary in control flowers gradually increased until day 11, when petals senesced completely, though fresh weight in STS-treated flowers did not change until day 7 and then diminished gradually. Fresh weights of styles and receptacle in control flowers changed as a similar pattern, gradual increase until initial wilting of petals and then gradual decrease, but those in STS-treated flowers did not change from harvest to senescence. Fresh weights of calyx in control and STS-treated flowers decreased gradually.

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