THESIS

IMPROVED QUALITY AND WATER USE BY SCHEDULING IRRIGATION FOR GREENHOUSE PRODUCTION OF *ROSA HYBRIDA* L.

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY STEVEN E. WOERNER ENTITLED "IMPROVED QUALITY AND WATER USE BY SCHEDULING IRRIGATION FOR GREENHOUSE PRODUCTION OF ROSA HYBRIDA L." BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

IMPROVED QUALITY AND WATER USE BY SCHEDULING IRRIGATION FOR GREENHOUSE PRODUCTION OF ROSA HYBRIDA L.

Ground water contamination from greenhouse and nursery operations is a cause for concern owners, neighbors and governmental agencies alike. In fact, the state of Colorado has passed legislation that will directly effect greenhouse growers: these growers may eventually be mandated to control their waste water pollution. One way to reduce the amount of waste water produced while maintaining product quality is to schedule irrigation, rather than manually irrigating and overwatering. Four irrigation scheduling techniques for greenhouse production of three cultivars of hybrid tea rose, *Rosa hybrida* L., were examined for their effect on bloom quality and production over time. The irrigation scheduling techniques developed for use in this study included: a time clock based method; an accumulated radiation based method; an accumulated vapor pressure deficit (VPD) based method; and a combination method, which used an accumulated combination of VPD and radiation. Results from the study indicate that the time clock method had poorer quality roses in three quality measurements: length, fresh weight, and dry weight. The other three treatments did not differ in a discernable pattern for their effect on the quality measurements. We hypothesize that the time clock method, while putting on as much or more water, was not able to apply water at the right *time*. Other researchers have shown that the timing of irrigations is critical, and we believe that because the other techniques were based on environmental parameters directly involved in plant processes (photosynthesis, translocation of mass flow solutes, etc.), they were able to respond more appropriately to the water needs of the plants. The treatment effect on numbers of blooms produced was highly variable, and the statistical analysis indicated that the variability within treatments was too great to allow for appropriate analysis.

The methods did differ significantly on the amount of water that they applied to benches, as the VPD method supplied as much as 60% less water during the Valentine's Day harvest period, and as much as 80% less water during the Mother's Day harvest, without reductions in quality. This was mainly due to the selection of the trigger values, and future research could focus on increasing those trigger values and reducing the amount of water applied to benches.

Implementation of these irrigation scheduling techniques may not be prohibitively expensive, as growers could use current sensors and computer facilities to accomplish these methods. Growers should look at return on investment when considering using these methods, and they should consider factors such as labor savings, flower quality and production efficiency improvements, and reduced cost for both water and fertilizer.

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INTRODUCTION

Justification

The importance of water quality preservation and management is becoming increasingly prominent, and the floriculture industry will be under scrutiny for its contribution to ground and surface water pollution, as well as misuse of available water supplies. Historically, water was considered a relatively inexpensive, abundant, renewable and clean resource. However, since the 1960's and 1970's, people have started to re-examine this assumption and take a good look what was happening with our water. The Environmental Protection Agency (EPA) was formed in 1970 as a watchdog/enforcement body, with the purpose of protecting and preserving our natural resources, while maintaining a balance between industry and economic growth. The EPA and congress are currently reworking the federal Clean Water Act of 1965 (and its 1987 revision) to be stricter and better enforced. Because of this, state EPA's (or other equivalent governing bodies) have also undertaken revision of state water quality control measures to come in line with what will be new federal standards.

The Pacific northwest has long been a leader in environmental protection: California, Oregon and Washington all have some of the stricter regulations on contamination of water sources. Oregon has mandated that every greenhouse or nursery must file an "Intent to Discharge" if they will be discharging any agricultural chemical from their operations after May 1, 1992, with plans to eliminate all discharge by June 1, 1993 (Anonymous, 1991). If they produce discharge after June 1, 1993, they must purchase an annual "Water Pollution Permit". Cost has yet to be determined, but it is speculated that the Water Pollution Permit will be relatively expensive. In Colorado, there is a long history of water rights laws based on mining that have traditionally left water use and water misuse up to private water owners, unfettered by government regulation. However, since the induction of the 1990 revision of the 1966 Colorado Water Quality Control Act, called Senate Bill 90-126 (Norton et al., 1990), the state government has been granted greater power to implement groundwater pollution control. This law mainly addresses agricultural chemical use, from the agricultural chemical producer on down to the end user of the chemical. This act defines agricultural chemicals as any commercial pesticide or fertilizer applied to agricultural product. A portion of the act calls for, "development of rules and regulations for bulk storage facilities and mixing/loading areas where 55,000 pounds of finished agricultural chemical product (tank mix) are handled in one calendar year." Another portion of the act directly addresses the management of contamination of groundwater with agricultural chemicals by an agricultural chemical applicator. Thus, under this section of the law, these new regulations are applicable to anyone who applies any pesticide or fertilizer to any crop.

The act is designed to have a three-tiered response to any potential or actual groundwater pollution due to agricultural chemicals. The first level of response is prevention efforts such as education and training, monitoring, classification of high risk "Agricultural Management Areas" (AMA) or areas where there is a high risk of contamination, and development of Best Management Procedures (BMP), or recommended practices that prevent or remedy the introduction of the chemicals into the groundwater. Some of the BMPs include soil testing, use of slow release nitrogen fertilizers, and irrigation management, including irrigation scheduling. The second tier of response is mandated practices. If the prevention efforts are ineffectual in dealing with a contaminator, the Agriculture Department can adopt regulations that mandate use of BMPs by polluters, "to the extent technically and economically practical" (Walker, unpublished document). The third level of response occurs when continued detection of contamination is discovered, and calls for a range of possible reactions from cease and desist orders to daily accumulated fines. This act may appear to be quite restrictive, but the primary concern of the act is to protect Colorado's groundwater from contamination with agricultural chemicals, and it "favors and stresses voluntary compliance and educational methods" (Walker, unpublished document). Although this act will affect greenhouse producers, voluntary compliance and initiative (use of BMPs) will eliminate the painful side effects of non-compliance.

Many greenhouse producers could be affected by this act; in fact, one randomly placed monitoring system that was downstream from a greenhouse near the Platte River has shown that nitrogenous pollutant levels were up to 1000 times higher in that area (Waskom, 1992). Greenhouse property owners will also have to pass environmental audits by governmental or private agencies before selling properties, and groundwater contamination with pesticide and fertilizer wastes may deem a property unsalable and condemnable, resulting in severe economic hardships for greenhouse/nursery owners (Eskilson, 1992). For these reasons, greenhouse and nursery operations will be held responsible not only for their waste water practices, but also for controlling the amount of water used.

Although, this portends future economic problems for greenhouse owners due to governmental regulation, there are benefits that can be received from these new restrictions. Planning for reducing greenhouse waste is always a benefit because it increases overall efficiency. As a simple example, reducing over-application of water to a crop by scheduling irrigations rather than using trial and error will not only reduce water costs, but also quite possibly improve crop quality and reduce labor costs. If growers approach these new challenges as opportunities to become more efficient, it may prove to be to their advantage.

Background

Several approaches can reduce both waste water contamination and waste water production. Some cultural practices have been examined and found to limit runoff, or eliminate runoff by leachate collection and recirculation. Biernbaum et al. (1991) have suggested such methods as the use of appropriate, well-drained media, slow release fertilizers, and wetting agents and gels as ways to improve watering efficiency. They have also researched using pot covers as a technique of reducing non-consumptive evaporation. Another current trend in greenhouse irrigation uses collection troughs and tanks with recirculation pumps to enable waste water collection and reuse. Variations range from simple bench lining with plastic sheets and consequent leachate collection and recirculation, to sophisticated ebb and flood benches, which utilize classic field subirrigation as a model. These benches fill at irrigation time with nutrient solution from a holding tank, allow time for the plants to uptake the solution, and then drain the solution back into the holding tank. Nutrient levels and pH are adjusted prior to irrigation. These benches are a semi-closed system, water only leaving the system through evapotranspiration and consumptive use by the plants, and no waste water enters groundwater or sewage systems. Tsujita (1991), Vernooij (1991), and Molitor (1990) have examined recirculation systems and many of the parameters associated with these systems. However, these methods may prove to be logistically impractical or economically prohibitive at the present time for many of the larger production facilities in the United States.

Irrigation scheduling, on the contrary, is an alternative method of reducing or eliminating the amount of waste water produced from irrigation by calculating or estimating the appropriate amount and/or time to apply irrigation water. For agronomic, vegetable, and orchard crops, researchers have developed many irrigation scheduling techniques for controlling not only the timing of irrigations, but also the amount applied, thereby reducing over-application and possible leaching problems. Classic field irrigation scheduling techniques employ various methods such as tensiometers, neutron probes, infrared thermometry, and empirical water balance and potential evapotranspiration (ET) equations to schedule both irrigation timing and amount. Penman, in his now famous 1948 paper on estimating evapotranspiration by plants, developed a mathematical equation which predicts a reference ET from a open-water surface based on wind and vapor pressure deficit (Penman, 1948), and suggested the use of this reference ET amount to model actual ET of the plant. His equation was based on radiation, soil heat flux, wind, and vapor pressure deficit:

$$E_{tp} = [\,\Delta / (\Delta+\gamma)]\cdot[(R_n + G)/L] + [\gamma / (\Delta+\gamma)\cdot f(U)\cdot(VPD)] \qquad [1]$$

where Δ is the slope of the saturation vapor pressure-temperature curve, γ is the psychometric constant, R_n is the net radiation, G is the soil heat flux, L is the latent heat of vaporization, VPD is the vapor pressure deficit and f(U) is a wind function, given as

$$f(U) = 2.63 + 1.38\,U \qquad [2]$$

where U is the daily mean wind speed.

Since his initial paper, there has been a multitude of developments based upon the "Penman" or "combination" equation, and the Penman equation has been modified for different conditions many times, not limited to the Food and Agriculture Organization (FAO) Doorenbos-Pruitt modified Penman models (Doorenbos and Pruitt, 1977; Batchelor, 1984), which uses a modified wind function; and the Penman-Monteith (Monteith, 1965), who developed a much more complex, aerodynamically based modified Penman equation. Other researchers have developed similar but slightly differing models for

ET: the Jensen-Haise (Jensen and Haise, 1963) model uses only daily mean temperature and solar radiation plus long-term temperature records to calculate a reference ET; the Priestly-Taylor (Priestly and Taylor, 1972) model, which modified the Penman equation by assuming that there is a strong correlation between the radiation and aerodynamic components of the Penman equation, allowing for the development of a modifying constant, α; and the Blaney-Criddle method, which calculates a monthly ET from monthly temperature, daylength and other empirically derived correlation coefficients (Blaney and Criddle, 1950).

Steiner et al (1991) evaluated several ET prediction models and assessed their accuracy based on comparison with lysimeter data. They found that the modified Penman-Monteith model provided the best predictions of potential ET across the range of measured ET. They also noted that the simple modified Penman, the Jensen-Haise, and the Priestly-Taylor all overestimated ET, but performed satisfactorily after adjustments to the equations were made. Stegman and Ness (1974) also performed a comprehensive comparison of some of the ET-estimation, irrigation scheduling schemes for simulated sprinkler irrigation of alfalfa, including a rare economic analysis. These schemes included the Jensen et al (1970) scheduling model, the Hiler-Clark stress day index method (Hiler and Clark, 1971), the average ET scheme, the mass curve technique (Woodruff et al., 1972; Chu 1972) and the precipitation supplementation scheme. They found that the Jensen-Haise method had the greatest economic advantage at the time of the study. Braunworth and Mack (1987) examined three different irrigation scheduling methods for sweet corn, including: a) irrigation when 46% and 57% of available water was depleted according to neutron probe data; b) irrigation when 50% of available water was depleted as estimated by the FAO modified Penman equation; and c) irrigation at three growth stages. Conclusions from this study indicated that both the modified Penman and irrigation by growth stage methods would provide good, low-input solutions for scheduling, while the neutron probe method was not as successful. When developing scheduling techniques for use under greenhouse conditions, direct use of any of these methods may be inappropriate because of their dependence on long-term data, precipitation data, wind measurements, or soil properties data. These are not always easily or commonly measured parameters, but with modification of the equations and assumptions of the methods, they will prove very useful in development of appropriate techniques for greenhouse use.

Irrigation scheduling of horticultural field crops has also been developed. Smittle et al (1990) assessed an irrigation scheduling model for use on field production of snap bean. The model was based on the water balance method of Stegman et al (1980), and the parameters of the model included crop age, useable soil water, precipitation, and irrigation. They found the model to significantly improve both overall production and yield, and also marketable yield over a two year study period. Moore and McSay (1990) produced an irrigation scheduling model that used a modified Bellani atmometer (as described in Broner and Law, 1991) to provide reference ET data for timing of onion irrigation. Modification and evaluation of any of these techniques for use under greenhouse conditions could provide methods for control of irrigation waste water from horticultural production.

Traditionally, greenhouse irrigation scheduling has not been a concern for greenhouse growers, since water was abundant and measurement of media moisture was conducted by sight or touch. Water management became more sophisticated with the incorporation of solenoids with timing controllers, but even today much of the irrigation is applied by hand. As computers have become more prevalent and accepted, the ability to effectively control water use is available, but has not been fully exploited. Systems of irrigation control have been developed for greenhouse crops based on weight or soil moisture tension. Read et al. (1962) developed a self-watering greenhouse pot as far back as 1962, which involved the use of some rather intricate machinery including vacuum pumps and filter cylinders, but allowed for a more automatic control of soil moisture. Schwaegerle (1983) developed another simplistic method for maintaining soil moisture availability for potted plants. This method entailed placing a plant on a modified triple beam balance and as the pot dried out, the balance would shift and the beam would close a relay that energized the watering system. As the plant gained moisture, the balance would shift back, opening the relay and turning off the water. The weight (and soil moisture content) at which the balance would shift was adjustable. Hunter and Tonks (1979) also developed a slightly more complex system, utilizing the tilting siphon principle to irrigate plants in much the same manner. Critical to these methods if they were to be used for large production facilities would be the use of "representative" plants, which are supposed to be average plants in close proximity to the other plants controlled by the scheme. Because this assumption of appropriate representation could easily be violated, these methods do not lend themselves to control of large numbers of plants, or very easily to computer interfacing.

Lieth and Burger (1989) developed a technique for irrigation scheduling using soil moisture tension as the basis for both timing and quantity of irrigation. The system was based on earlier work by researchers who utilized soil moisture tensiometer readings to assist in making decisions about when and how much to irrigate. Lieth and Burger's system employed solid-state transducers connected to ceramic cup tensiometers allowing for digital voltage measurement of soil moisture tension. Two such modified tensiometers were placed in representative plants in each treatment group, one in the lower level of the container level, and one in the upper level of the container. These tensiometers were then tied into a computer system that made irrigation decisions based on the tension readings, irrigating when tensions reached specified levels, and irrigating until the tension in the lower tensiometer read zero (container capacity). They found that this system of irrigation control in peat-based media used up to 43% less water than traditional time-clock controlled irrigation, with no loss of water as leachate and no significant loss of bloom quality for chrysanthemums. Once again, this method relies on representative plants, which may include problems of representation, but perhaps if enough representative plants are used and results averaged, this problem may be avoided. Also, this system has proven to increase the efficiency of water application and will be very useful in the future, but this technique may not be applicable to new, highly porous media due to lack of complete media-tensiometer contact. Tjosvold and Schulbach (1991) examined a modified field technique of scheduling irrigation based on a calibrated evaporation pan. By using a readily available wash tub as an evaporation pan, and calibrating both when and the amount to irrigate with soil tensiometers, they were able to reduce the amount of water applied by almost 50% without a reduction in numbers of blooms produced (although no comparison to manual irrigation was provided). Scheduling irrigation using internal and external leaf resistances to vapor and heat transport has been suggested (Stranghellini, 1988) but not fully investigated. Further, comparisons between different irrigation scheduling techniques for greenhouse crops and their effect on production and/or quality have not been conducted. Because all horticultural product must be irrigated in some fashion, appropriate irrigation scheduling techniques may be tested and accepted for use on many crops in production, not only allowing growers to produce more efficiently, but satisfying governmental regulations and protecting our environment as well. One objective of the study, then, was to develop irrigation scheduling techniques based on historical combination and/or radiation, ET-estimating equations that were appropriate for use under greenhouse conditions. I further wanted to compare these techniques to a control treatment, and evaluate the methods studied based on their effect on rose quality and production.

MATERIALS AND METHODS

Development of Greenhouse Irrigation Scheduling Techniques

This study examined four irrigation scheduling techniques and determined their impact on rose production and quality. A commonly used time clock method was used as a control with which the performance of the other three techniques was evaluated. Initial attempts at developing methods appropriate for greenhouses considered the Penman combination equation and Jensen-Haise methods, but found most field ET estimation techniques required possibly difficult or expensive measurement of environmental parameters. We sought to develop simple, but appropriate, scheduling methods that looked at basic, easily measured greenhouse parameters as driving variables for estimating evapotranspiration. To look at the effect of radiation, a second method was based only on accumulated photosynthetic photon flux (PPF). Because the Penman equation involved vapor pressure deficit (VPD), a third method was based only on accumulated vapor pressure deficit. A more Penman-like, but still very simple, fourth method was developed and based on a combination of accumulated PPF and accumulated vapor pressure deficit. Each method is discussed in detail below.

Study Description

The irrigation scheduling study was undertaken in the winter and spring of 1992, for Valentine's Day and Mother's Day harvests, two economically important dates for greenhouse rose growers. Four similar, unconnected, quonset greenhouses covered with fiberglass reinforced panel (FRP) were used for this study. Each house measured 6.1 m by 15 m, oriented north-south, and contained five benches, two of which were used for this project, for a total of eight benches. Each bench measured 120 cm by 360 cm, and contained approximately 18 to 20 cm of 100% rockwool media (Partek, N. America, Englewood, CO). All benches were equipped with a solenoid controlled, twin-wall drip irrigation system (Chapin Watermatics, Watertown, NY). The same ambient solar radiation, CO_2, fertilizer solution (Colorado State University nutrient solution as described in Appendix A), and water pressure were available in all houses; temperatures differed as described below. All benches in all houses were watered at least once daily at dawn for 2 minutes.

The two benches in the study in each house were planted with fifteen XXX and XX plants of three different cultivars of hybrid tea rose (*Rosa hybrida* L.): 'Royalty' (XXX; DeVor Nurseries, Inc., Chico, CA), 'Emblem', and 'Samantha' (XX; Jackson and Perkins Roses, Medford, OR). The location of each cultivar in the study benches was randomly designated, and the final layout of the houses and benches is shown in Fig. 1. Planting for the benches took place 12 August 1991. Each rose plant was pruned of any dead tissue, dipped in an antifungal agent, and then planted directly in the bench. Each bench was then watered to saturation, and covered with 6-mil white plastic. The purpose of tenting the benches was to increase the relative humidity surrounding the plants, and to reduce the incident radiation on the plants. The plastic reduced radiation levels to 30% of the light in the rest of the house. Plants were watered to saturation daily to ensure adequate water availability during rooting and bud break. When plants began to break bud, tents were opened gradually over the course of a week to allow the plants to acclimate to the lower relative humidity levels and higher radiation levels, after which plastic tents were removed from the benches. To simulate grower practices, plants were pinched on 22 October 1991 to time for a Christmas harvest (10-12 December 1991), and 13 March 1992 for a Mother's Day harvest (1-3 May 1992), respectively. The Christmas 1991 harvest period was used as the pinch for the Valentine's Day harvest (5-7 February 1992).

Four separate treatments, each a different irrigation scheduling technique, were applied to the study benches on 2 January 1992. Because of commitments to other research projects, two of the four houses had a 23C/18C day/night temperature regime, and the other two had a 26C/16C day/night regime. Each treatment was applied to two different benches within each of the two different temperature regimes. However, the effect of the temperature difference was removed by blocking in the statistical analysis as described in the section below. The "time clock" (TC) method employed a computer-based time-clock attached to a solenoid valve controlling those benches and was set to initiate irrigation every three hours during daylight hours. The time-clock is minimally associated with environmental conditions and the associated water use by plants, while the other three scheduling methods examined were based on environmental parameters. The irradiance-based (PPF) method utilized an existing computer subroutine (Hanan et al., 1987), which used accumulated photosynthetic photon flux (PPF) levels to initiate an irrigation event. To examine an effect of both humidity and temperature, the VPD method utilized another existing subroutine to calculate instantaneous VPD and used accumulated VPD to initiate an irrigation event. The combination (COMB) method used a subroutine written for the computer that scaled the PPF and VPD values, added and accumulated them, and initiated irrigations based on this accumulated combination value. A discussion of vapor pressure deficit and the combination value and how each was calculated in this study can be found in Appendix B.

Irrigation events were initiated by an Hewlett-Packard HP9920S Computer Control System, with computer code written in HP BASIC as described by Hanan et al (1987). Raw voltages from environmental sensors and control signals sent to equipment were handled by a digital acquisition/control (IDAC) board, which relayed the voltages to and from the HP9920S system upon execution (once per minute). Accumulated values (time, PPF, VPD, and COMB) were used to initiate events as described above. When any accumulated value surpassed the threshold value designated for that treatment (Table 1), the HP9920S caused the appropriate solenoids for those benches to be opened (irrigating) for two minutes. HP BASIC code and a discussion of the control program and its procedures for accumulating and initiating irrigation can found in Appendix C. Threshold values for the three irrigation scheduling treatments were obtained from the literature, or from simulations using IRRMOD, an irrigation scheduling modeler, which estimated the threshold values based on user defined greenhouse conditions. ANSI C code and an explanation for IRRMOD is given in Appendix D.

Because irrigation was only applied during daylight hours when plants were photosynthesizing, all measured values over the course of a day are dependent on daylength. The time-clock method's only variable during the study was daylength, because the interval between irrigations was set at a constant 3 hours, but the number of irrigations increased as the number of 3 hour periods during the day increased seasonally. The other methods did not directly use time as a variable, but as daylengths increased, so did the amount of time values accumulated, and thus the *potential* for increased number of irrigations increased for these methods as well. The control program determined the start and end of the day period based on actual outside solar radiation levels (measured at a weather station on top of the headhouse); the night to day switchover occurred as irradiance levels reached 70 $W \cdot m^{-2}$; day to night switchover occurred when irradiance dropped to 10 $W \cdot m^{-2}$. The actual recorded daylengths for each day during the study are shown in Figure 2. The response appears to be the expected sine curve response, with deviations from that curve due to overcast conditions delaying day switchover or expediting night switchover.

Sensing of temperature was accomplished using aspirated thermocouples (Type T) located near the two benches in each house. Figure 3 shows the actual daily mean temperatures (measured in °C) for each house over the entire study period. Cosine-corrected quantum sensors (model LI-190SZ, Li-Cor, Inc., Lincoln, NE) measured incoming radiation in the 400-700nm waveband (PPF) just above canopy level near each bench; Figure 4 gives the daily accumulated PPF values (measured in $mol \cdot m^{-2} \cdot day^{-1}$) for houses 1 through 4 for the entire study period. Sensing of humidity was accomplished using aspirated, thin-film capacitance probes (Lee Integer, N.A., Chicago, IL); Figure 5 shows the actual daily accumulated vapor pressure deficit values (measured in kPa) for houses 3 and 4 for the entire study period. The combination value was determined as described in Appendix B, and the actual recorded accumulated combination values in houses 3 and 4 for the duration of the study are shown in Figure 6.

Data Acquisition

To examine treatment effects, one tagged bloom from each plant of each cultivar (=15 blooms/cultivar =45 blooms/bench) was cut at flower, and fresh weight, length, grade, and dry weight were recorded for each bloom. To simulate grower practices, each stem was cut to 2 five-leaflet leaves for the Valentine's Day harvest, but while growers would probably cut to the knuckle for the Mother's Day harvest, stems were still cut to 2 five-leaflets leaves to maintain consistency of length and weight measurements during data acquisition. To examine the treatment effect on total production over time, the untagged blooms were cut and graded according to industry standards. Daily numbers for each cultivar and grade were recorded. Total numbers of irrigation events for each day, as well as all associated environmental parameters, were reported by the HP9920S at the end of each day. Because treatments were applied initially on 2 January 1992, data from the Christmas harvest were considered "pre-treatment" and will not be considered in the discussion of results.

Statistical Approach

Overall experimental design was a randomized complete block; temperature was considered a block, while irrigation scheduling technique was the treatment. Each bench was split into cultivar subplots (Fig. 1), which were analyzed separately. Statistical analysis was performed using the Analysis of Variance procedure (ANOVA) of SAS (SAS Institute, Carey, NC). Mean separations were accomplished using the Student-Neuman-Keuls test for differences in SAS, and means and significance reported in tables arise from the output of this procedure.

RESULTS AND DISCUSSION

Actual Recorded Parameters

The plots in Fig. 3 show that the actual recorded temperatures for these houses were close to the aforementioned temperature setpoints, with day temperatures deviating more because they are more difficult to maintain. Spikes in temperatures are most likely due to actual heating system complications, with the majority of the peaks being found in houses 3 and 4 early in the year. This observation agrees with problems that were occurring in those houses at that time of the year. On an annual basis, the daylength (Fig. 2) and light levels (Fig. 4) exhibited the expected sine curve response, and deviations from this curve were due to overcast or cloudy conditions on particular days. As an observation, the prolonged (~ 7 day) depression in daylength beginning around day 100, coincides with a recorded depression in the accumulated PPF values for each house at that same time. Similar but smaller depressions can be seen around day 62 and again around day 80, in all four plots. One further observation is that for a 4 or 5 day period ending on day 120, house 2 (Fig. 4B) exhibits a marked lack of accumulated radiation, and it was noted that this problem was due to the actual quantum sensor falling from its platform and being shaded by the plants. It can be seen, then, from this example, that proper care and maintenance of sensors and control equipment are of ultimate importance for maintaining the performance of these scheduling methods. Figure 5 shows the recorded VPD values; this parameter appears to be quite variable from day to day (even from hour to hour), but this may be attributed to the amount of variability in the parameters that are used to calculate VPD. Appendix B describes how VPD was calculated; it is dependent mainly on temperature and relative humidity. However, when variably humid outside air is used both for the heating and cooling cycles, cooling pads are activated, etc., the variation in VPD results. As a note, Fig. 5B shows that there is a depression in the accumulated VPD around day 40; once again this was noted to be caused by human error as the capacitance probe was accidentally removed from its aspirator box and was laying on the surface of a bench, where relative humidity is much higher, causing the deficit to be low. This reinforces that persistent care and maintenance of sensors is essential for these scheduling methods to perform well. Another note from these plots is that there is a concomitant depression in VPD around day 100 (as in the above plots); a depression in VPD is associated with an increase in relative humidity (RH), and as these days were cloudy and cool with associated precipitation, this would explain the increase in RH and decrease in VPD. Although the combination value is also highly variable from day to day (Fig. 6), there are no prolonged depressions as found in the other plots (excepting the day 100 depression). This illustrates one of the powers of this scheduling method: with two measured parameters going into the equation, one can act as a buffer if the other is not functioning correctly. It is true that with two measurements in the equation, two sensors are needed which increases complexity and cost, but both radiation and relative humidity are commonly measured parameters in most greenhouses, and implementation may not be complex or costly.

Irrigation Numbers

Figures 7 and 8 show the total numbers of irrigations per week by treatment for the seven week Valentine's Day harvest period and the 9.5 week Mother's Day harvest periods, respectively. It should be noted here that at week 3, the VPD threshold level was adjusted due to a problem with the IRRMOD simulation used to acquire the threshold value. The threshold value was adjusted up from 350 kPa to 750 kPa after that time, and the associated number of irrigations decreased accordingly. Table 2 gives the weekly mean number of irrigations per bench for the entire period of the study, the Valentine's Day harvest period, and the Mother's Day harvest period. For the given threshold levels, then, VPD always applied the least amount of water, TC or COMB applied the most, and PPF applied an intermediate amount. A discussion of the implications of the total daily numbers of irrigations effect on rose quality and quantity measures follows.

Comparisons of measured parameters and numbers of daily irrigations are shown in Figures 9 through 22. Figures 9 and 10 exhibit the effect of daylength on the TC method, as the number of irrigations increases gradually as the number of three hour periods per day increases. Figures 11-14 show the comparison of daily accumulated radiation and number of irrigations. These plots demonstrate the ability of the PPF method to track irradiance level and its effect on the plant's need for water. In general, as the irradiance levels increase over the course of the year, there is an increase in number of daily irrigations; however, when light levels were reduced (cloudy days) and plants required less water to account for ET, this method called for fewer irrigations. As VPD was important to the Penman equation because it influenced transpiration by the plant and the VPD method used accumulated vapor pressure deficit to initiate irrigations, Figures 15-18 show how the VPD method responded to changing vapor pressure conditions (and thus to evapotranspiration). Again, as accumulated VPD values varied by day we can see the associated change in number of daily irrigations. Finally, Figures 19-22 show how the number of daily irrigations called for by the COMB method tracked the daily accumulated combination values.

Treatment Effect on Quality and Quantity Measures

Table 3 shows stem length means and statistics for the three cultivars over two harvest periods. 'Royalty' showed significant differences between treatments for the Valentine's Day harvest, with the time clock (TC) method having significantly shorter stems than the VPD method. For the Mother's Day harvest, both 'Emblem' and 'Samantha' exhibited significant differences in stem length, with the TC treatment having shorter stems than any of the other three treatments for both cultivars. Table 4 shows that there were significant differences in fresh weight of 'Emblem' and 'Samantha' stems produced for

Mother's Day. For both cultivars, TC resulted in the least fresh weights per stem, although the differences were statistically significant at P=0.05 only between PPF and TC for 'Emblem', and between COMB and TC for 'Samantha'. Likewise, Table 5 shows significant differences in dry weight, but only in cultivar 'Emblem', with PPF having greater dry weight than TC. These results demonstrate that the trend in the three bloom quality measures (length, fresh weight, dry weight) for Valentine's Day and Mother's Day harvests was towards TC having the smallest means, with statistical significance only exhibited as stated above. The treatment means of the other three scheduling methods appeared not to differ in any specific pattern.

Table 6 gives the means for total numbers of blooms (grade A only) produced from treatment benches. Analysis of total production numbers provided no reliable measure of the effect of treatment on production numbers. SAS analysis showed that the variation in the samples was too great within treatments, and we have no good explanation for this problem at this time. One possible complication of this data is that two of the benches in the study had experienced unintended water stresses. Bench 2D (in PPF treatment) and bench 4E (in COMB treatment) both dried to wilting point at one point in time, but before treatments were applied in January. Some plants aborted buds, dropped leaves and/or lost stems. Although plants were given ample time to recover from the extreme stress and were subsequently pinched, the effect of the stress on the plants may have had some impact on the production for future crop cycles. The quality measurements did not appear to be affected by the stress, however, as neither the PPF or the COMB methods showed diminished quality as compared to the other treatments. Future irrigation studies will need to insure that there was no influence of previous stresses on current research, and the elimination of this complicating factor may make it possible to elucidate the treatment effect on production numbers.

Quantity of Irrigation vs. Timing of Irrigation

Based on these findings, over- or under-application of water could explain the differences in bloom quality measures. However, analysis of the number of irrigations data as described above does not support either case. When the data are analyzed over the whole time period of January through May (Table 2), there seems to be no relationship between number of irrigations and quality, because TC does not have either the greatest or the least number irrigations. This is also the case when the data is analyzed for the Mother's Day crop time period by itself. The number of irrigations data does support this theory for the Valentine's Day, as TC has the most number of irrigations, but only 'Royalty' showed significant differences in length (while it showed no differences in any other quality measure at any other time), and TC showed an intermediate response in that quality measure for that harvest period. TC never produced the highest quality roses when there was statistical significance shown; it produced either the lowest quality or blooms intermediate in quality response.

I hypothesize that it is not the number of irrigations that is most important, but the timing of irrigations. Because the time clock has no relationship with actual greenhouse conditions, and thus plant water needs, it may provide as much water as other methods but not provide it at the right *time*. For example, on high evapotranspiration days when plants are using water at a high rate, the PPF, VPD, and COMB methods may increase the number of irrigations by one or two times over the amount on an average day, while the time clock method may irrigate its usual 4 or 5 times possibly leaving plants in a water deficit situation. Likewise, on cloudy, cool days, plants aren't transpiring heavily and may get overwatered by using time clock control, increasing the amount of waste water produced. Hanan (1972) and Halevy (1972) did comprehensive reviews of water stress literature, and related the findings in these publications to horticulturally and floriculturally significant crops such as tobacco, spinach, rose, and carnation. Both reviews indicated that water requirements of plants are obviously directly correlated with environmental conditions (i.e. radiation, temperature, relative humidity, etc.) because plants' need for water in bioprocesses (photosynthesis, CO_2 exchange, uptake of nutrients, translocation of mass flow solutes, temperature maintenance, etc.) is directly correlated with these conditions. Applying water at appropriate times eliminates the restriction on the supply of water to the plant, and reduces problems of decreased growth caused by the restriction of water. This, then, explains why the TC method was not the best method of irrigation scheduling in this study; plants in the TC treatment were not given water at the right time.

Although this study wasn't set up to gather and analyze the data, we also suggest that the timing of irrigations is not only important on a diurnal basis, but also on a *seasonal* basis, with water stress on plants at different developmental stages also being a critical determinant of quality. Hanan (1972) and Halevy (1972) both also point to the importance of adequate water supply during certain critical stages of growth in many plants, and this seasonal timing is correlated with the daily timing of irrigations. Many researchers have determined that there are critical periods in many crops, i.e. silking and seed fill in corn, or bulb development in onion and gladiolus. These critical periods are most closely related to the ultimate product of the plant: seed corn, potato tuber, or rose bloom, and when these organs are being formed. For floriculture crops, the critical period is most likely during floral initiation and bud development, but some crops, i.e. carnation, do not respond well to water stress at any stage of development (Hanan and Jasper, 1969). The implication is that development of future irrigation scheduling methods should include research into a developmental stage parameter or coefficient in a model that determines when and how much to irrigate, such as the crop age parameter in the snap bean irrigation model of Smittle et al. (1990).

Water Use

While the PPF, VPD and COMB methods did not differ greatly with regard to their influence on quality characteristics, they did differ in the amount of water applied. Table 2 shows that in all three analyses of number of irrigations data, VPD applied much less water than either PPF or COMB. For the Valentine's Day crop, VPD applied 10 irrigations per week, as compared to 13 and 16 times per week for PPF and COMB respectively. Over the course of the time period then, PPF and COMB called for 30% and 60% more water, respectively, than VPD, without demonstrating significant differences in quality. For the Mother's Day crop, the differences were even more dramatic: PPF called for 2.5 times more water, while COMB called for 5 times more water. Again, this resulted in no significant difference in quality between the three treatments. These results are similar to those of Lieth and Burger (1989) study who found that two methods of scheduling based on tensiometers used 8 to 24% less water than the time-based treatment without a significant reduction in quality. Plants in their study under higher moisture tensions had smaller fresh and dry weights and shorter stems, but the bloom diameter and crop timing, two important economically-related factors, were not effected.

Through the use of the IRRMOD model, the threshold levels for PPF and COMB could be simulated and modified so that they did not apply as much water, and thus applied much less water like VPD. The TC method could be analyzed with the IRRMOD program as well, and also be reset to reduce the amount of water applied, but irrigation with a time clock control still cannot provide water at the variably optimal time.

How Much to Irrigate

The major question not answered by this study is the determination of the amount of water to irrigate at each irrigation. For this study, the duration of each irrigation event was maintained at a constant two minutes, independent of moisture currently in the media. The Penman and other equations do allow for the actual estimation of the amount of water used by the plant in the form of ET, but because the methods used in this study were derived forms of the combination and radiation methods, no determination of the correlation between certain levels of variables and actual ET by the rose plants was performed. The concepts of Lieth and Burger (1989), using tensiometers to measure when to start an irrigation event and when to stop an event, could be used in conjunction with one of the methods in this study. For example, tensiometers could be set at the lower media level, and when the PPF, VPD or COMB method called for an irrigation, the tensiometer would be used to determine when to terminate the event. This would involve some calibration between tensiometers and threshold levels (such as the double-tensiometer calibration procedure in Tjosvold and Schulbach, 1991). One problem, as mentioned above, may be that the media being used may not be suitable for tensiometers because of poor media-tensiometer contact. In that case, a calibration with tensiometers in a suitable media in the same house, or something such as the Bellani atmometer (Broner and Law, 1991), could provide the correct length of time to irrigate for the specific media conditions being used by the grower.

Economics

The results given above may appear beneficial to a researcher, but oftentimes the grower is left wondering how to practically implement an irrigation scheduling method for a crop. It is our belief that these methods of irrigation scheduling may not be prohibitively expensive to implement, if the grower currently measures temperature, radiation, and relative humidity as most growers do. The major expense may be the purchase of electronically controlled solenoid valves, and some microprocessor, either a full greenhouse range controller or a datalogger. These mathematical equations and accumulations could be done on the simple datalogger, and the grower could monitor on a semi-hourly basis the levels of the accumulation values, and irrigate when the threshold levels are reached, resetting the accumulators to zero by hand. Or, the grower could implement the equations and accumulations within an existent greenhouse environmental control system, and allow the control system to initiate the irrigations, as was done in this experiment. Overall, though, the return on investment should be the ultimate deciding factor for the grower. Return on investment is an difficultly quantified number, but the grower should consider time and material saving factors such as: labor savings over hand watering; increased quality of blooms; less waste of water through reduced leaching; and lower fertilizer use through reduced number of irrigations.

CONCLUSIONS

In conclusion, this irrigation scheduling study provided the following results:

1) These data suggests that the time clock method of irrigation scheduling is not the best irrigation scheduling method for commercial rose production. This method appears not to provide water optimally, since the other three methods performed better in the three quality measures for 'Royalty' on Valentine's Day and for 'Emblem' and 'Samantha' on Mother's Day. I believe that this reduction in quality is be due to the poor *timing* of irrigations (diurnally and/or seasonally) by the time clock method, due to its lack of responsiveness to actual environmental conditions and crop age. The other three methods were based on environmental conditions that are directly related to plant photosynthesis and evapotranspiration, and so these methods are better at predicting the best time to irrigate. However, future models should probably include crop developmental stage as a coefficient for both timing and quantity of irrigations.
2) I found that while there were no great differences in quality between the roses produced under the PPF, VPD, and COMB methods, there were great differences in the amount of water applied by each of these treatments. The VPD method applied as much as 60% less water during the Valentine's Day

crop, and as much as 80% less water during the Mother's Day crop without reducing quality. This, however, is due mainly to the irrigation threshold levels set at the beginning of the experiment. The VPD method at the beginning of the experiment was irrigating much more often than the others, but after resetting the values to a higher level, the VPD method ended up putting on the least amount of water, while still maintaining a level of quality equal to the PPF and COMB methods. Experimentation with IRRMOD and conclusions gathered from this study could be used to develop much higher threshold values for the PPF and COMB methods, thereby reducing the amount of water used without reducing quality.

3) Future studies need to focus on elucidating the treatment effect on production numbers. The effect of previous stress on plants may have been a complicating factor in this analysis and could be eliminated in future studies. Future studies should also focus on the amount of water to apply at each irrigation, based on calibration with tensiometers or atmometers.

4) It is known that growers here in the state of Colorado, as well as in most other areas of the country, will have to become much more conscious of their water use and waste water production. This study showed that irrigation scheduling based on the PPF, VPD, or COMB methods can reduce the amount of water applied without reducing quality. By reducing waste in any greenhouse situation, growers are able to improve their efficiency. Irrigation scheduling not only serves to reduce water wastes, but also labor and flower quality wastes associated with the labor-intensive and often non-uniform hand watering techniques commonly used in many greenhouses today, and poor timing of irrigations caused by the time clock method.

5) Implementation of these scheduling techniques may not be prohibitively expensive, as current sensors used to measure radiation, temperature, and/or relative humidity can be used in conjunction with a microprocessor and readily available, electronically-controlled solenoid valves to achieve similar irrigation control in their greenhouses. When considering implementation of an irrigation scheduling plan and return on investment, growers should consider factors such as labor savings, flower quality and production efficiency improvements, and reduced costs for both water and fertilizer.

6) Sensors must be maintained in good condition if these scheduling methods are to be used to their fullest benefits. Physical checking and cleaning of sensors should be performed at least twice per week; actual calibration checks should be performed every 4 to 6 weeks.

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Table 1. Threshold levels for each treatment.

Treatment[z]	Threshold level	Units
TC	180	minutes
PPF	100,000	µmol m^{-2}
VPD	750	kPa
COMB	4500	**

[z] Treatments were: TC - time clock, PPF - accumulated PPF, VPD - accumulated VPD, COMB - combination of accumulated PPF and VPD.

**Units for this combination method are not meaningful.

Table 2. Mean number of irrigations per week for four treatments over three time periods.

Treatment[y]	No. of irrigations per week[z] Entire Period[x]	Valentine's Day	Mother's Day
TC	20.4 b	17.6a	22.4 b
PPF	14.3 c	13.0 c	15.4 c
VPD	7.7 d	10.3 d	6.0 d
COMB	23.7a	15.9 b	30.0a

[z] Mean separation in columns using Student-Neuman-Keuls multiple range test, $P<0.05$.

[y] Treatments were: TC - time clock, PPF - accumulated PPF, VPD - accumulated VPD, COMB - combination of accumulated PPF and VPD.

[x] Entire period is total time period of study, from 2 January 1992 to 15 May 1992.

Table 3. Mean bloom length for three cultivars and four treatments over three harvest periods.

Cultivar	Treatment[y]	Length (cm)[z]		
		Pre-treatment	Valentine's Day	Mother's Day
Royalty	TC	54.9	57.5 b	77.0
	PPF	56.9	64.4ab	75.6
	VPD	55.7	69.2a	76.1
	COMB	53.4	62.5ab	78.6
Emblem	TC	52.9	58.6	62.6 b
	PPF	50.2	56.2	70.7a
	VPD	48.0	57.8	69.5a
	COMB	50.2	62.3	69.8a
Samantha	TC	66.2a	68.6	70.1 b
	PPF	58.3 b	66.9	75.7a
	VPD	59.8ab	62.4	79.2a
	COMB	62.5ab	66.9	80.7a

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[z] Mean separation in columns by individual cultivars using Student-Neuman-Keuls multiple range test, $P \leq 0.05$.

[y] Treatments were: TC - time clock, PPF - accumulated PPF, VPD - accumulated VPD, COMB - combination of accumulated PPF and VPD

Table 4. Mean bloom fresh weight for three cultivars and four treatments over three harvest periods.

		Fresh weight (g)[z]		
Cultivar	Treatment[y]	Pre-treatment	Valentine's Day	Mother's Day
Royalty	TC	26.2	27.6	33.2
	PPF	25.6	31.6	33.6
	VPD	25.2	36.3	33.4
	COMB	24.9	32.9	36.0
Emblem	TC	23.6	31.2	32.0 b
	PPF	23.2	32.7	40.0a
	VPD	20.3	30.7	36.8ab
	COMB	24.5	33.2	39.0ab
Samantha	TC	29.2	34.5	33.8 b
	PPF	23.5	33.6	39.4ab
	VPD	23.9	28.9	40.6ab
	COMB	27.0	33.9	42.6a

[z] Mean separation in columns by individual cultivars using Student-Neuman-Keuls multiple range test, $P \leq 0.05$.

[y] Treatments were: TC - time clock, PPF - accumulated PPF, VPD - accumulated VPD, COMB - combination of accumulated PPF and VPD

Table 5. Mean bloom dry weight for three cultivars and four treatments over three harvest periods.

		Dry weight (g)[z]		
Cultivar	Treatment[y]	Pre-treatment	Valentine's Day	Mother's Day
Royalty	TC	7.1	8.0	10.0
	PPF	7.1	9.6	10.1
	VPD	6.6	10.1	9.7
	COMB	6.4	9.6	10.2
Emblem	TC	5.5	8.0	7.9 b
	PPF	5.2	8.2	9.8a
	VPD	4.8	7.3	8.7ab
	COMB	5.1	8.0	8.6ab
Samantha	TC	8.1	10.9	9.8
	PPF	6.6	10.5	11.4
	VPD	6.4	8.3	14.6
	COMB	7.1	10.2	11.3

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[z] Mean separation in columns by individual cultivars using Student-Neuman-Keuls multiple range test, $P \leq 0.05$.

[y] Treatments were: TC - time clock, PPF - accumulated PPF, VPD - accumulated VPD, COMB - combination of accumulated PPF and VPD

Table 6. Total mean numbers of blooms produced for three cultivars and four treatments over three harvest periods (grade A only).

Cultivar	Treatment[y]	Mean no. of blooms[z] Pre-treatment	Mean no. of blooms[z] Valentine's Day	Mean no. of blooms[z] Mother's Day
Royalty	TC	45.0	22.5	87.5
	PPF	48.0	31.0	83.0
	VPD	44.0	24.0	72.5
	COMB	50.0	29.0	92.0
Emblem	TC	66.0	26.0	69.5
	PPF	87.0	37.5	84.5
	VPD	67.5	31.0	78.0
	COMB	69.0	35.0	85.0
Samantha	TC	66.5	35.5	55.0
	PPF	73.5	35.5	63.0
	VPD	63.5	24.5	48.5
	COMB	61.0	31.5	59.0

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[z] Mean separation in columns by individual cultivars using Student-Neuman-Keuls multiple range test, $P \leq 0.05$.

[y] Treatments were: TC - time clock, PPF - accumulated PPF, VPD - accumulated VPD, COMB - combination of accumulated PPF and VPD

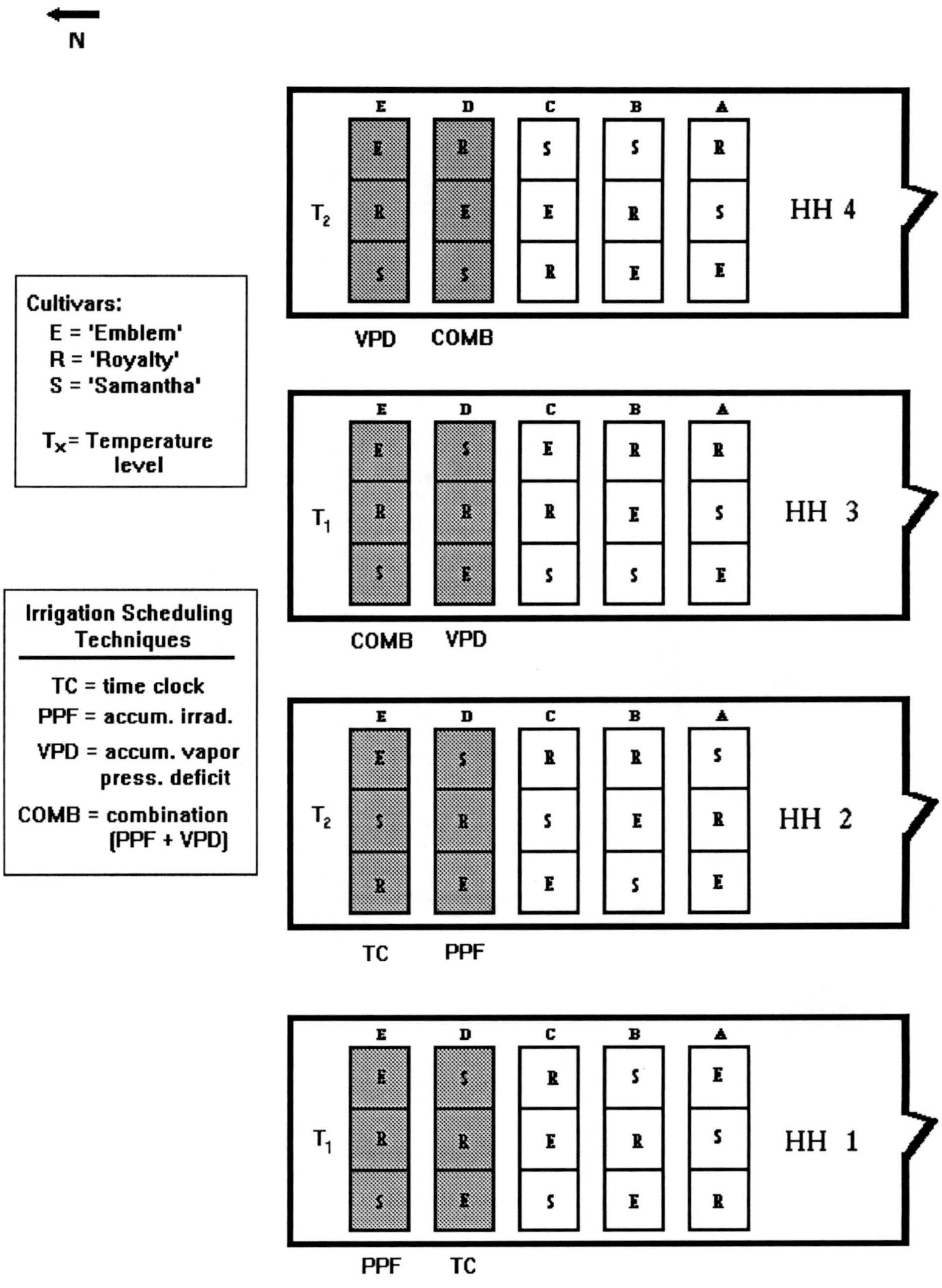


Figure 1. House and bench layout for the irrigation scheduling study.

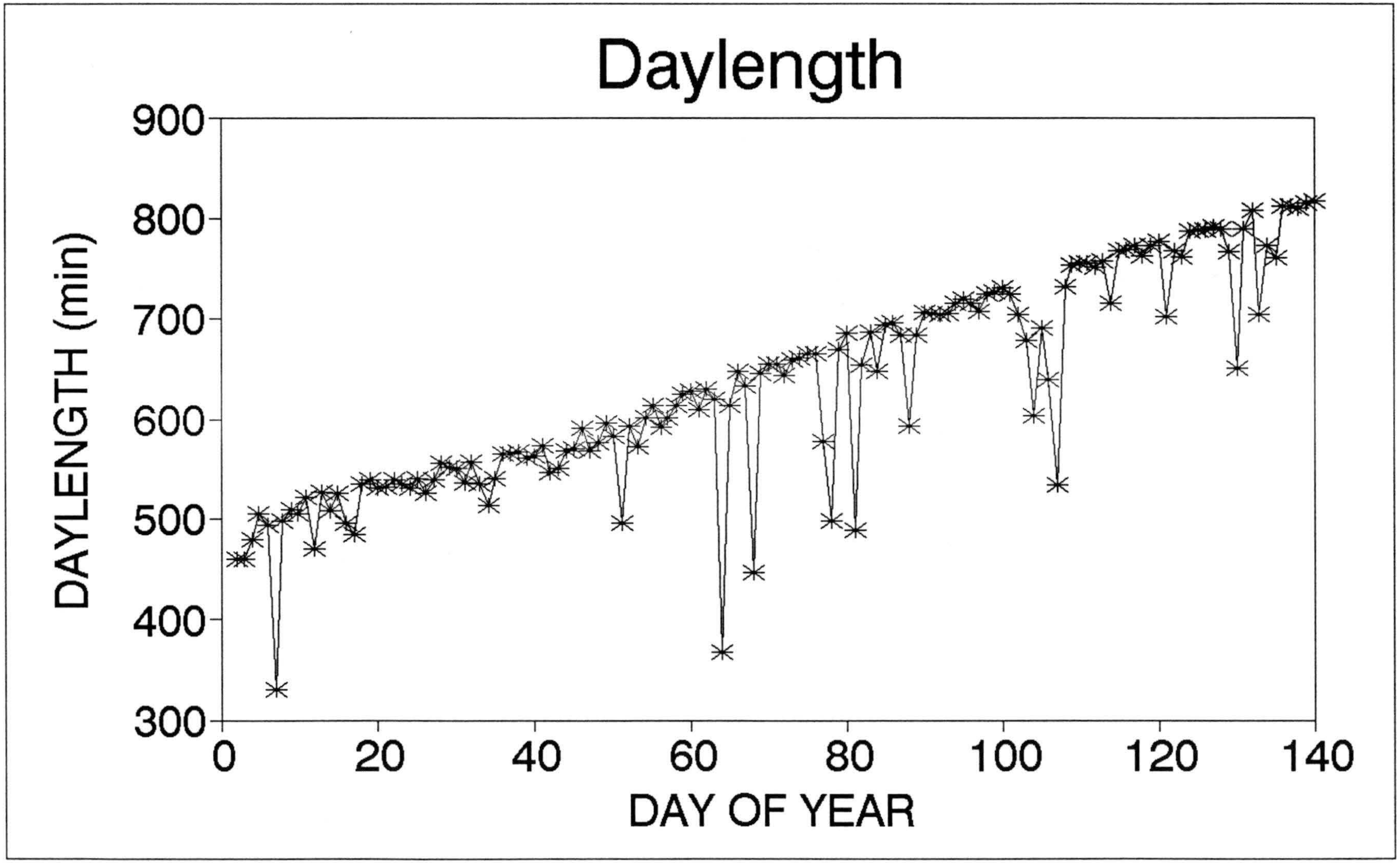


Fig. 2. Daily recorded daylengths measured during the entire study period.

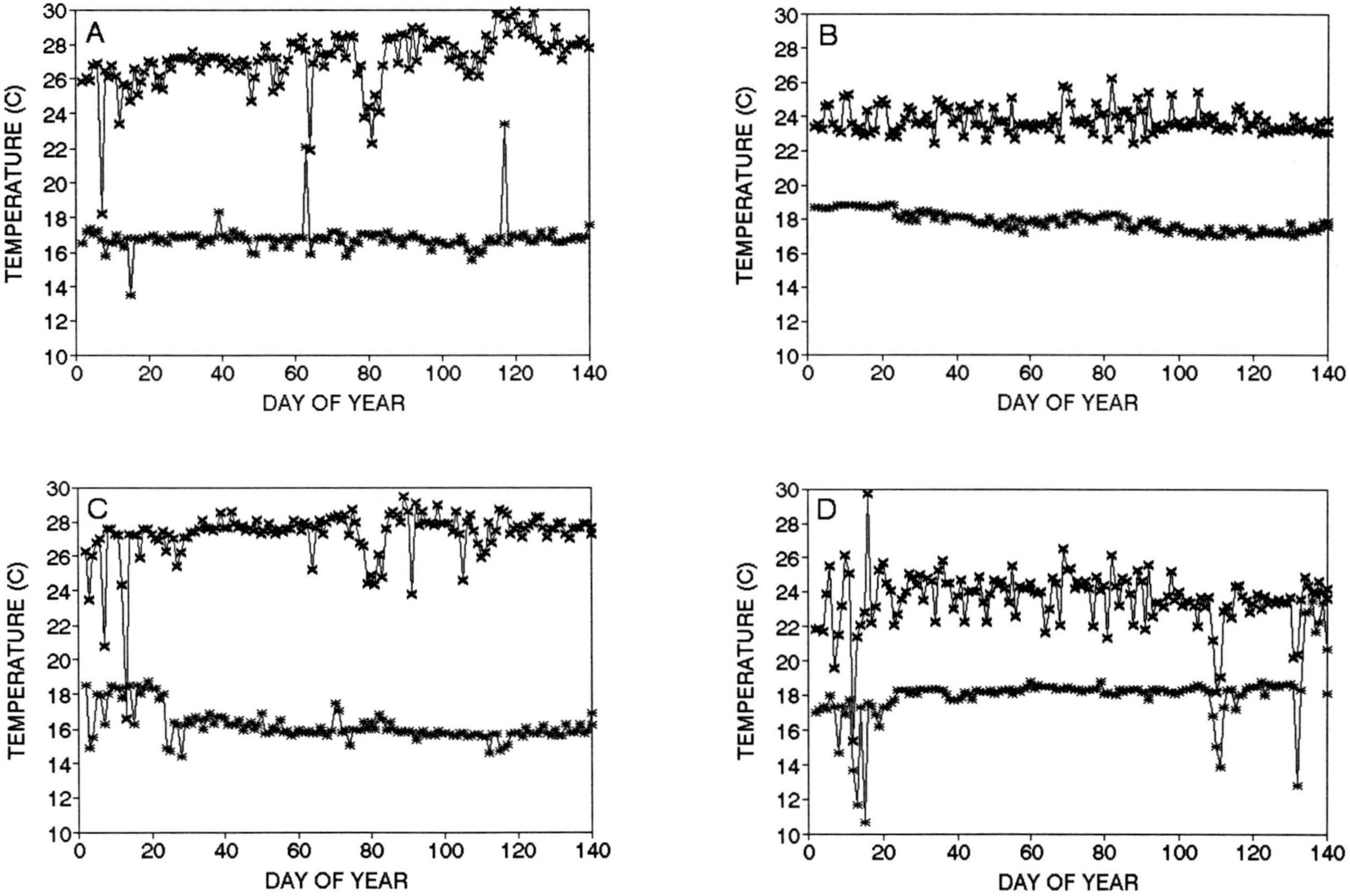


Fig. 3. Mean day (x) and night (*) tempertures measured at the center of each for the entire study period for: A - House 1; B - House 2; C - House 3; and D - House 4.

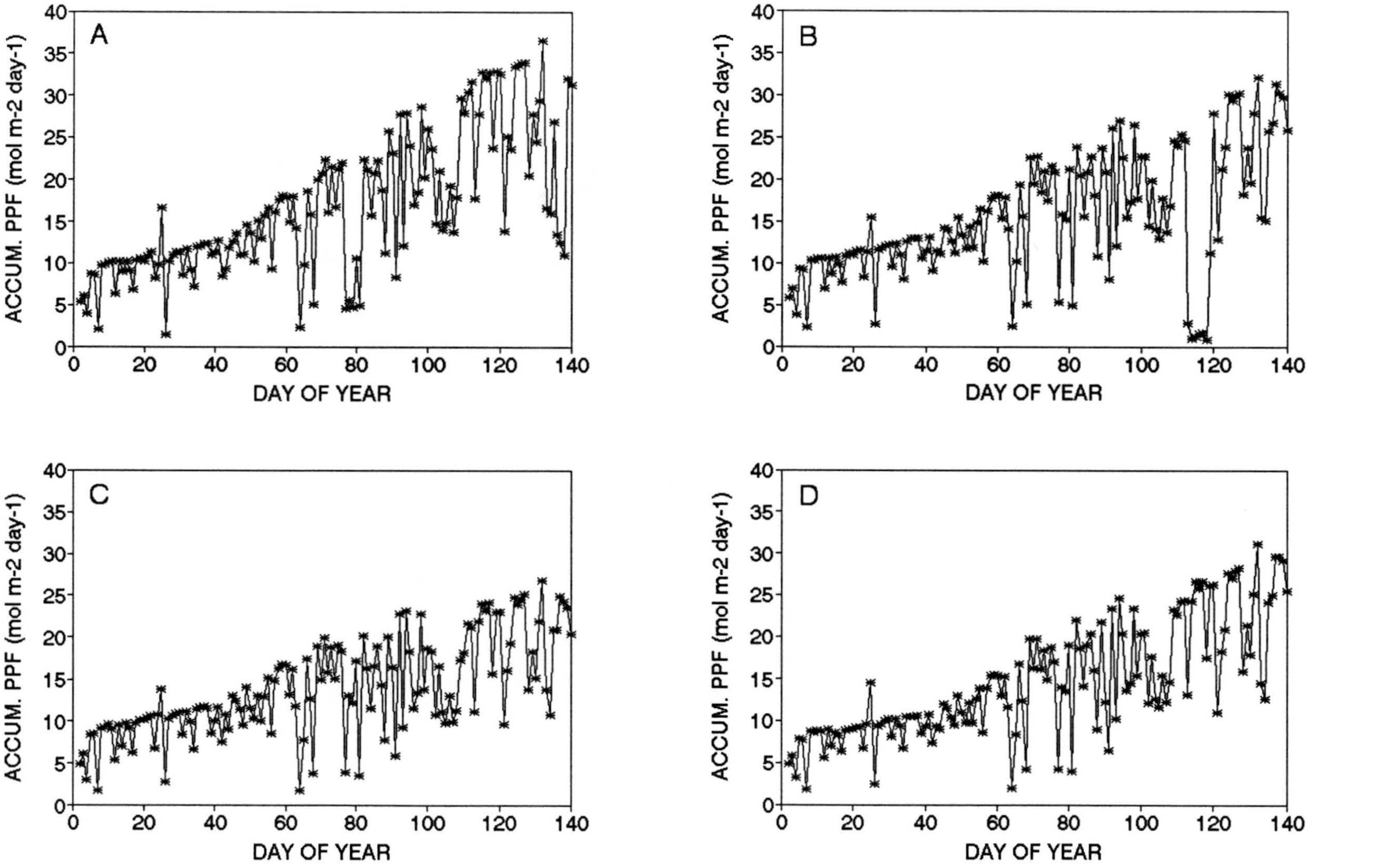


Fig. 4. Daily accumulated photosynthetic photon flux (PPF) measured at the center of each for the entire study period for: A - House 1; B - House 2; C - House 3; and D - House 4.

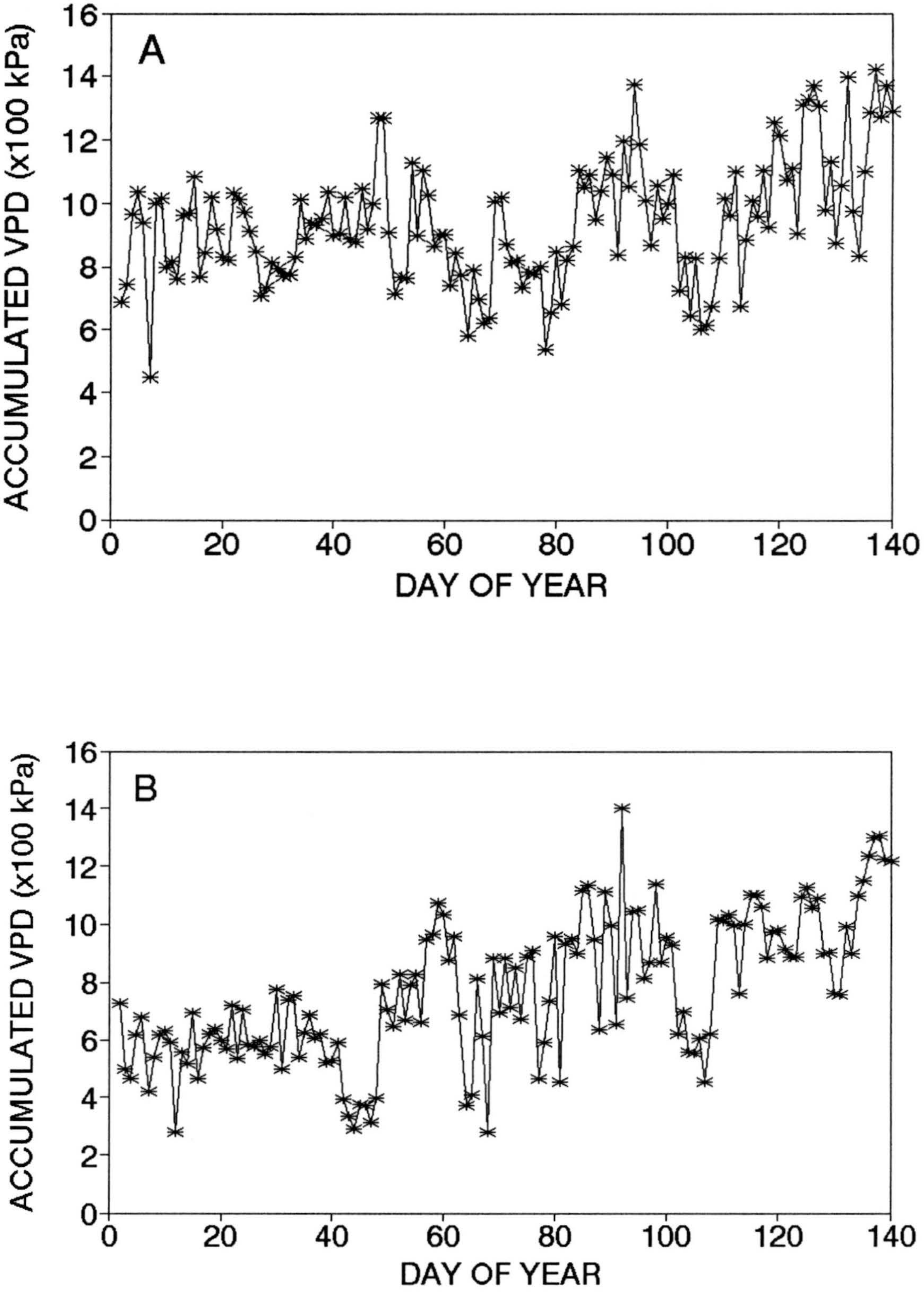
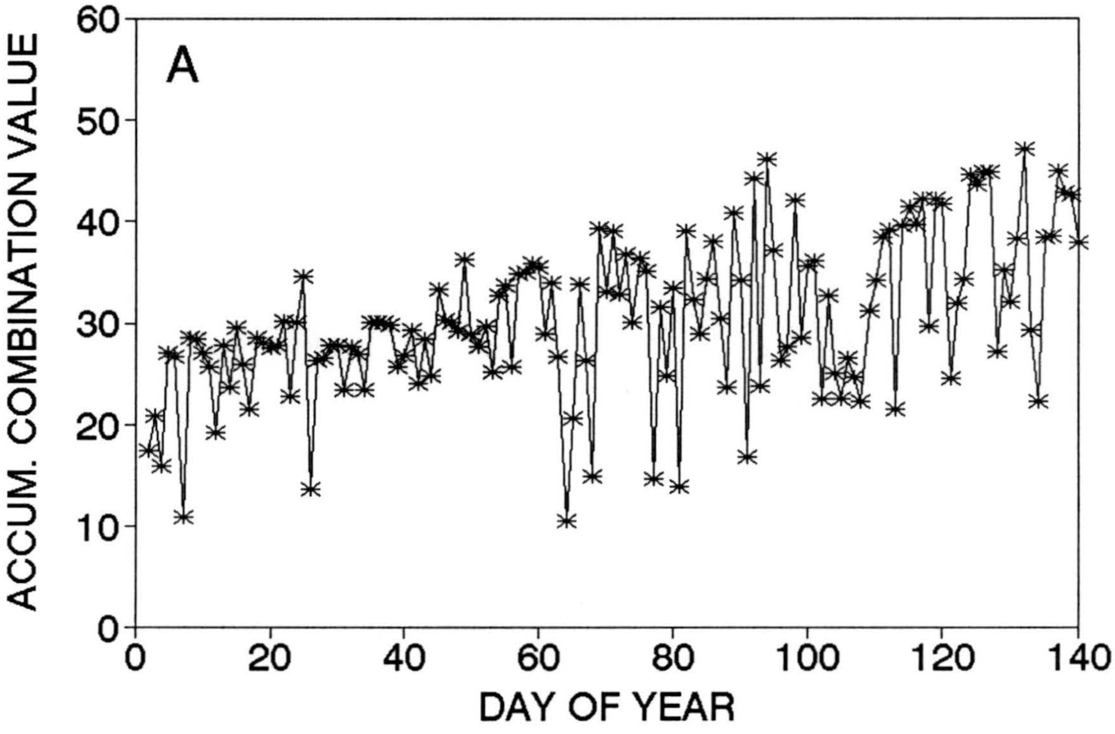


Fig 5. Daily accumulated vapor pressure deficit (VPD) values measured at the center of each house for the entire study period for: A - House 3; and B - House 4.



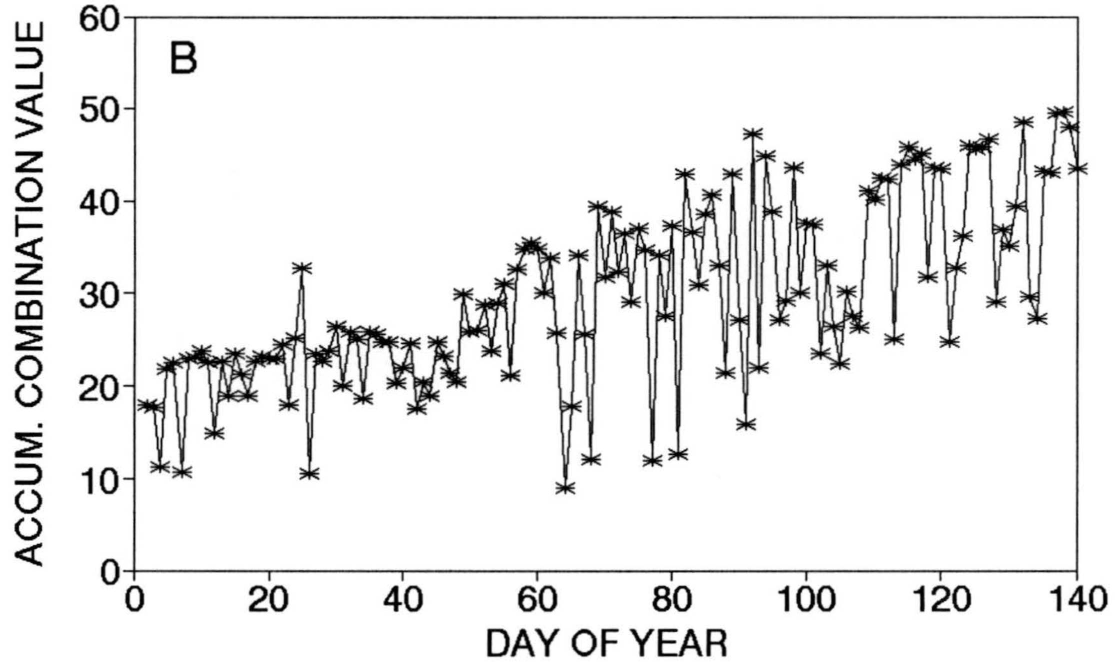


Fig. 6. Daily accumulated combination values, PPF and VPD measured at the center of each house for the entire study period for: A - House 3; and B - House 4.

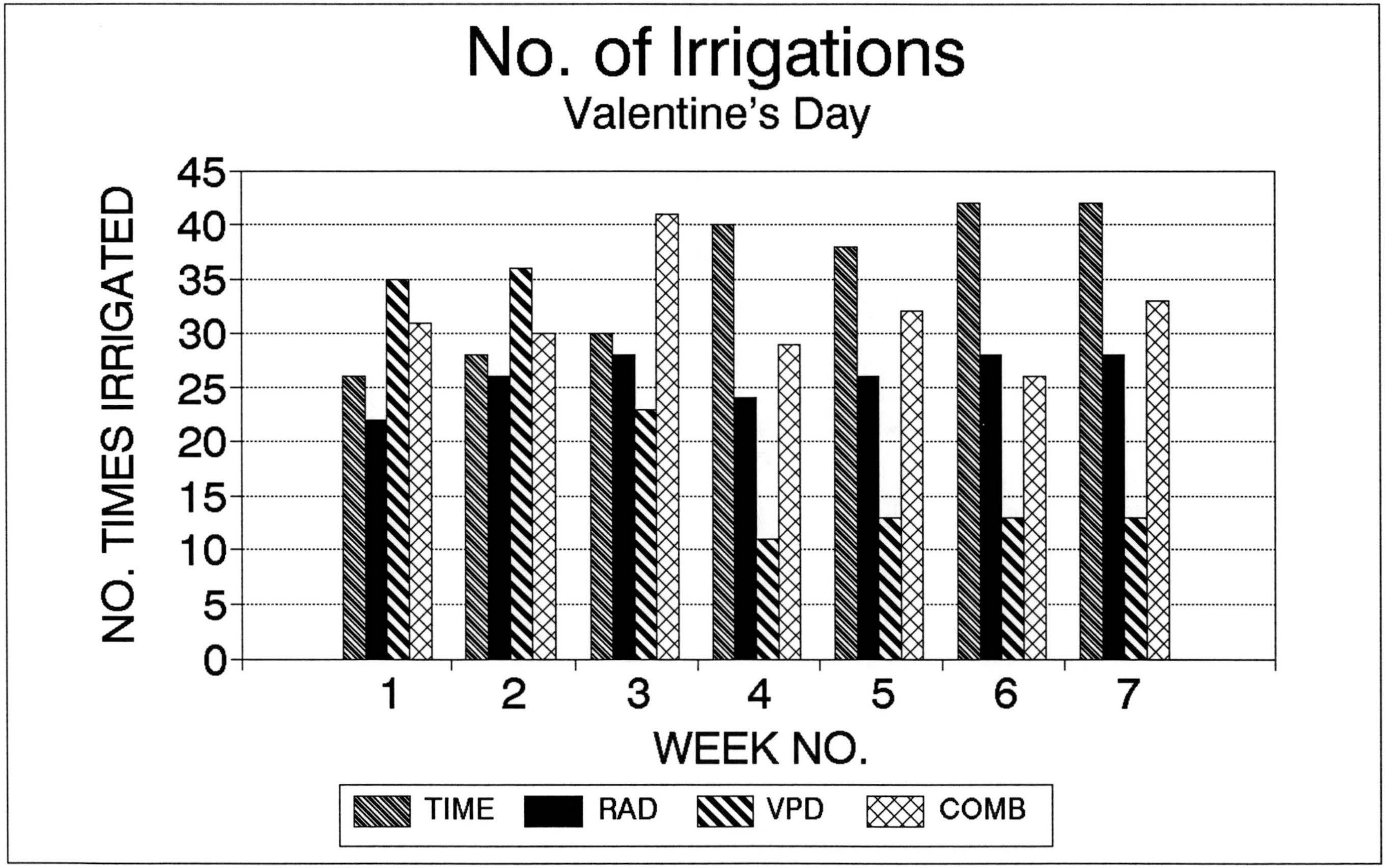


Fig. 7. Total number of irrigations per week by treatment during the Valentine's Day harvest period.

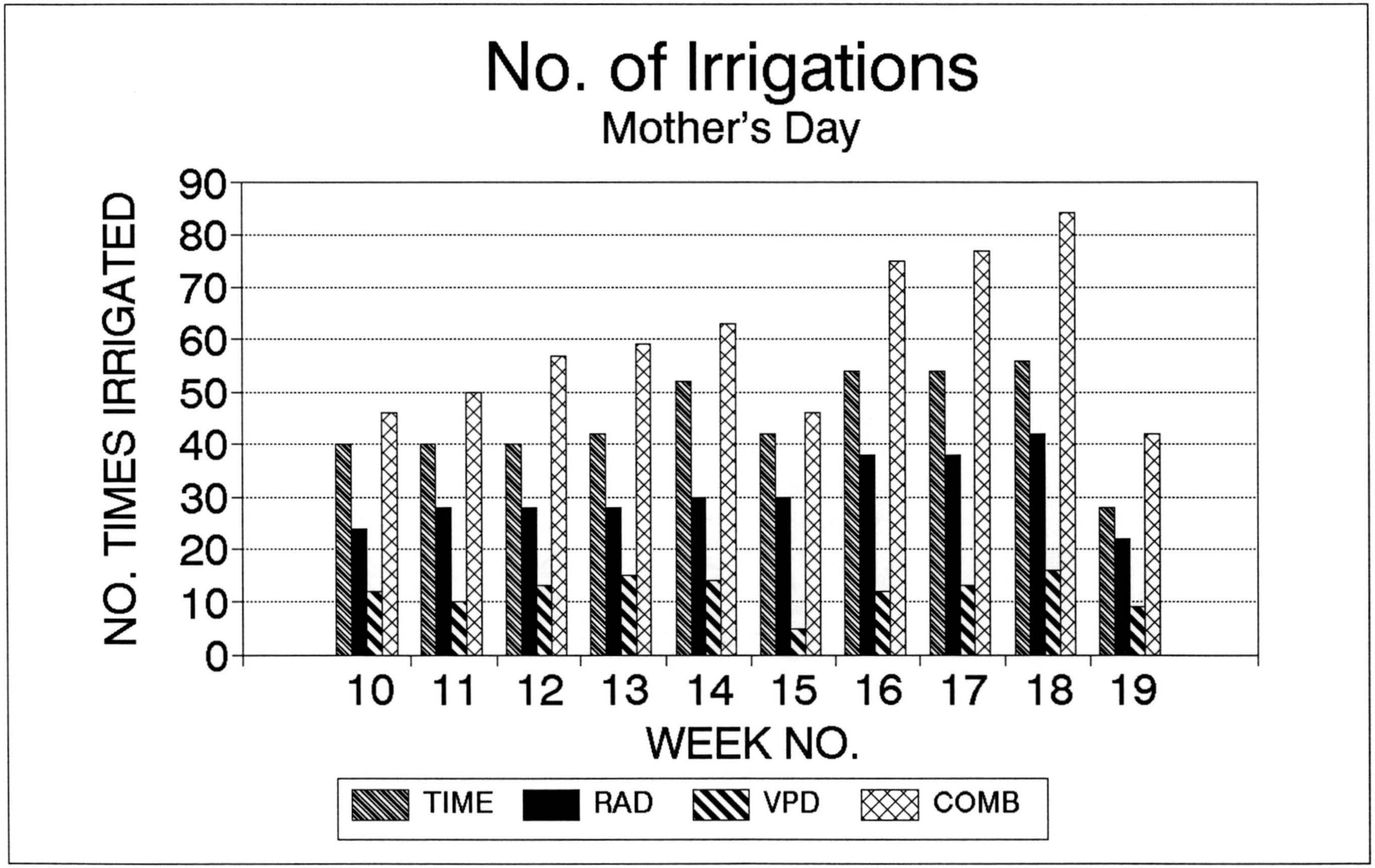


Fig. 8. Total number of irrigations per week by treatment for the Mother's Day harvest period.

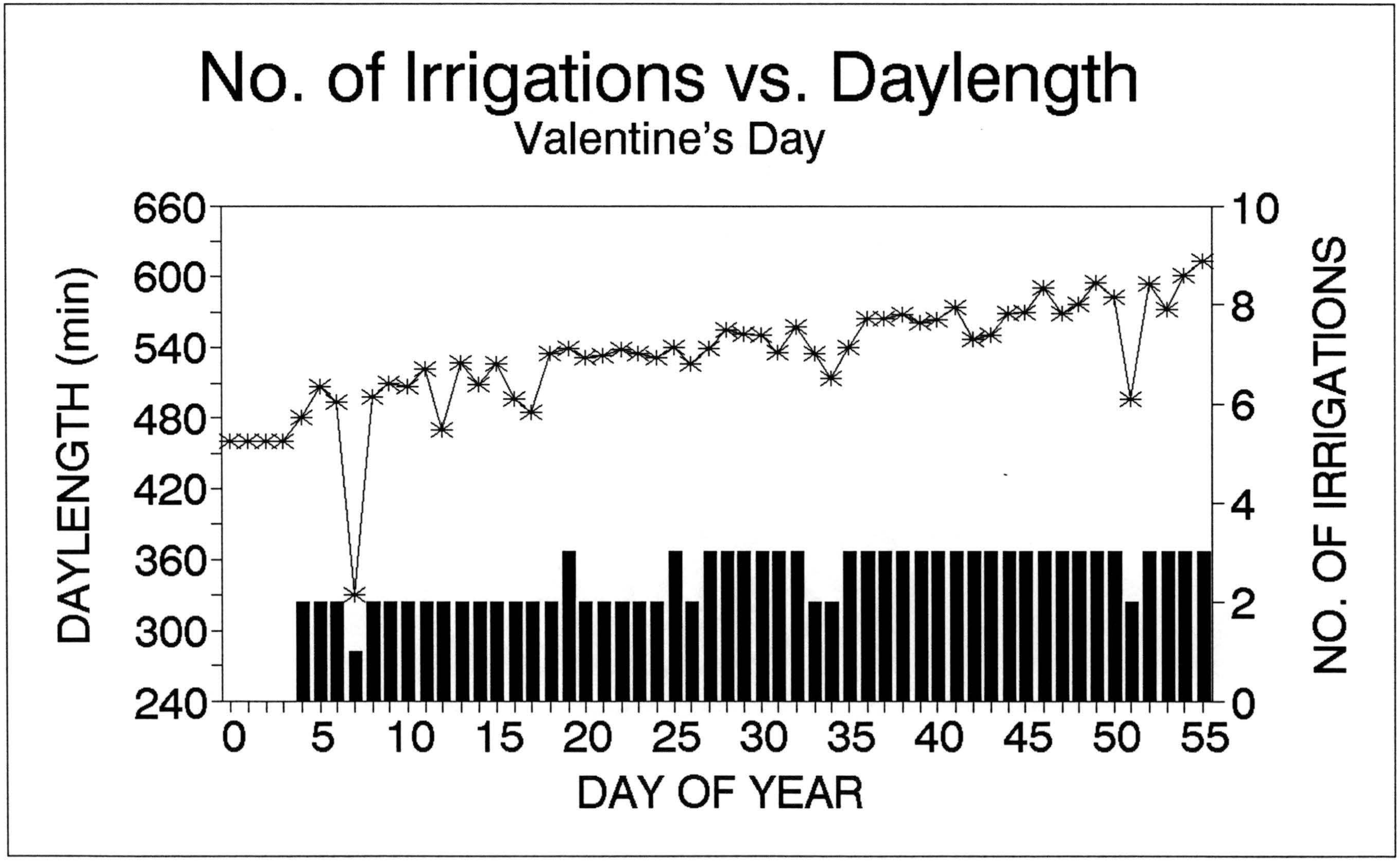


Fig. 9. Comparison of daily number of irrigations and daylength (accumulated time) for the Valentine's Day harvest period.

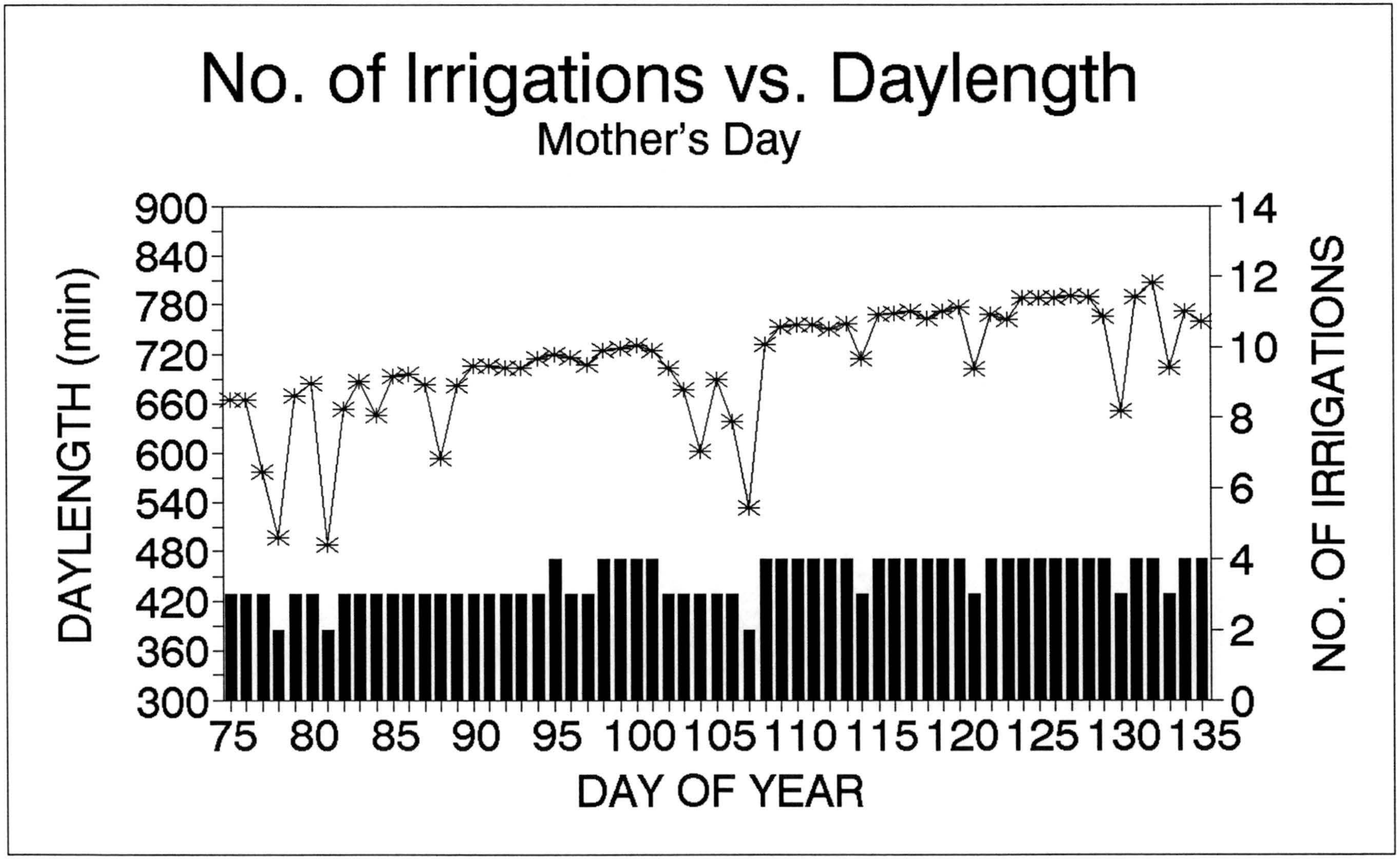


Fig. 10. Comparison of daily number of irrigations and daylength (accumulated time) for the Mother's Day harvest period.

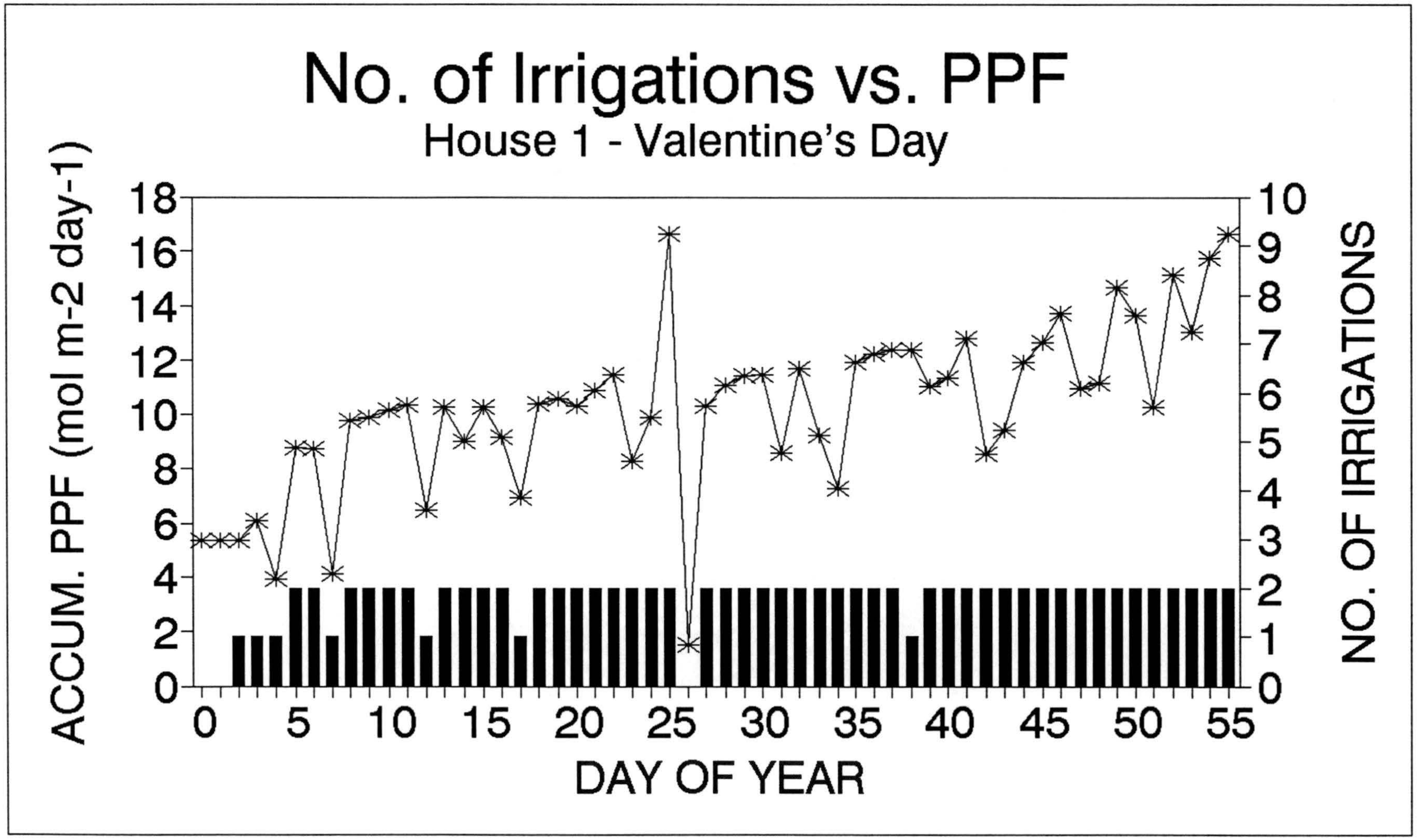


Fig. 11. Comparison of daily number of irrigations and daily accumulated rediation for house 1 during the Valentine's Day harvest period.

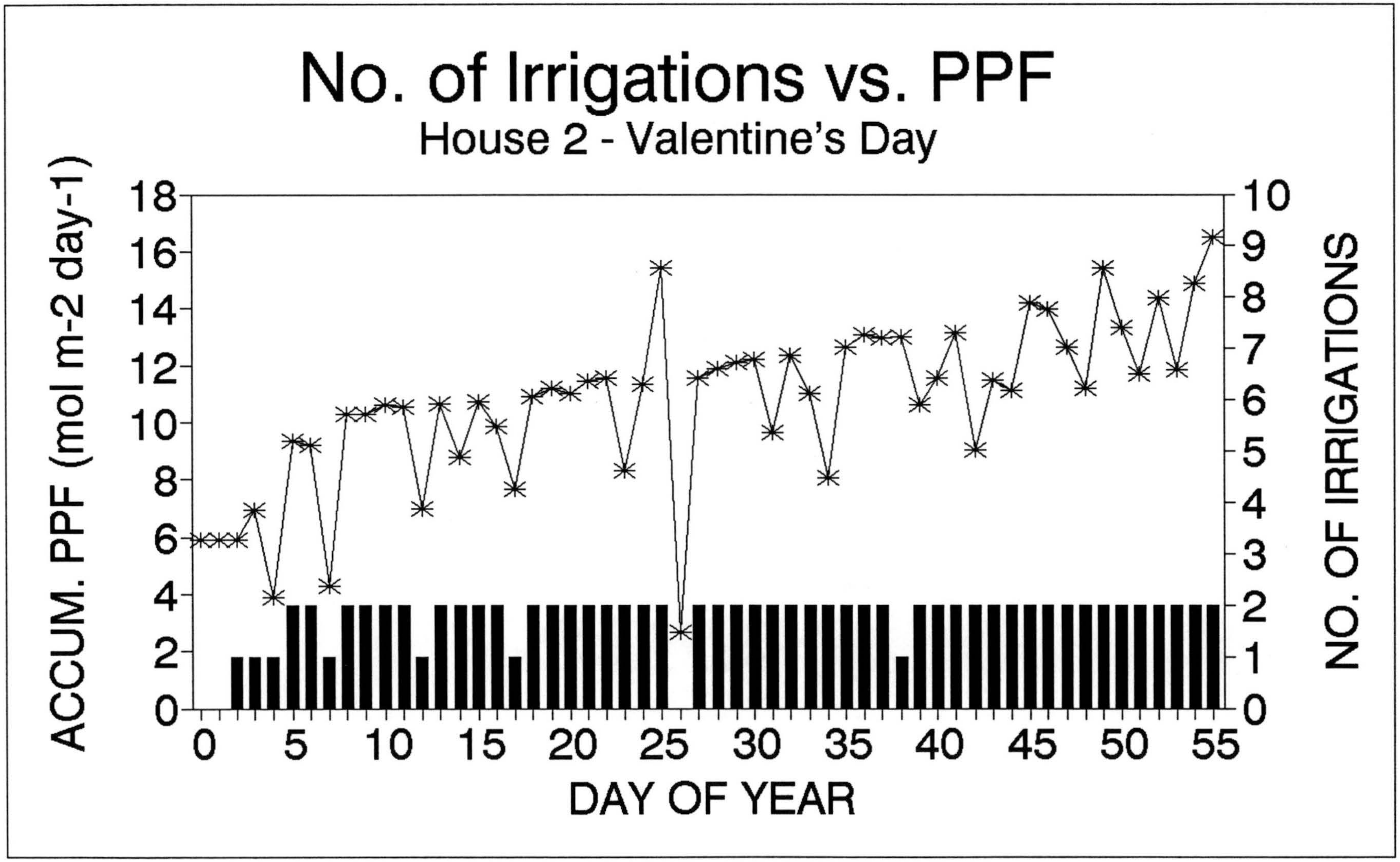


Fig. 12. Comparison of daily number of irrigations and daily accumulated radiation for house 2 during the Valentine's Day harvest period.

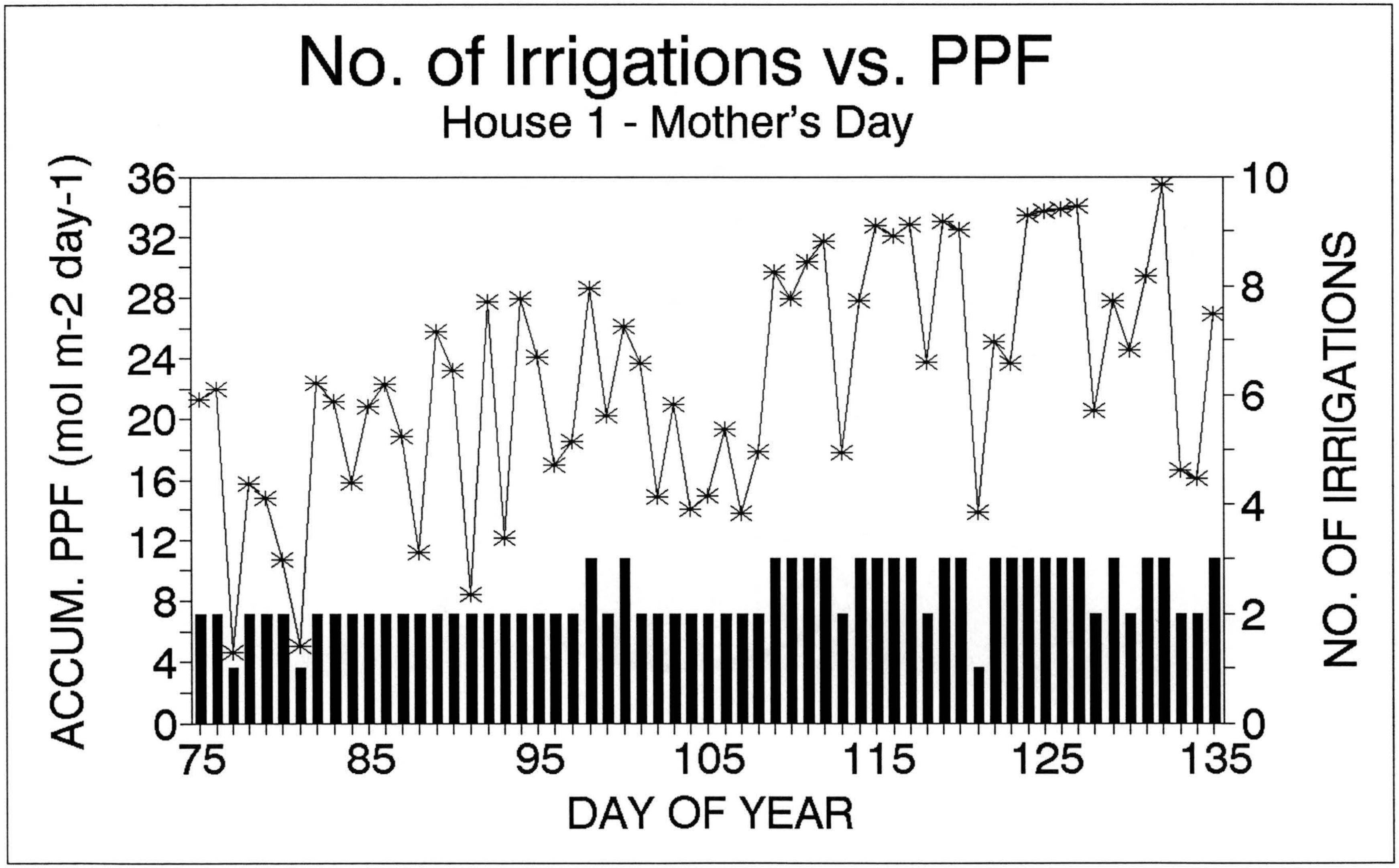


Fig. 13. Comparison of daily number of irrigations and daily accumulated radiation for house 1 during the Mother's Day harvest period.

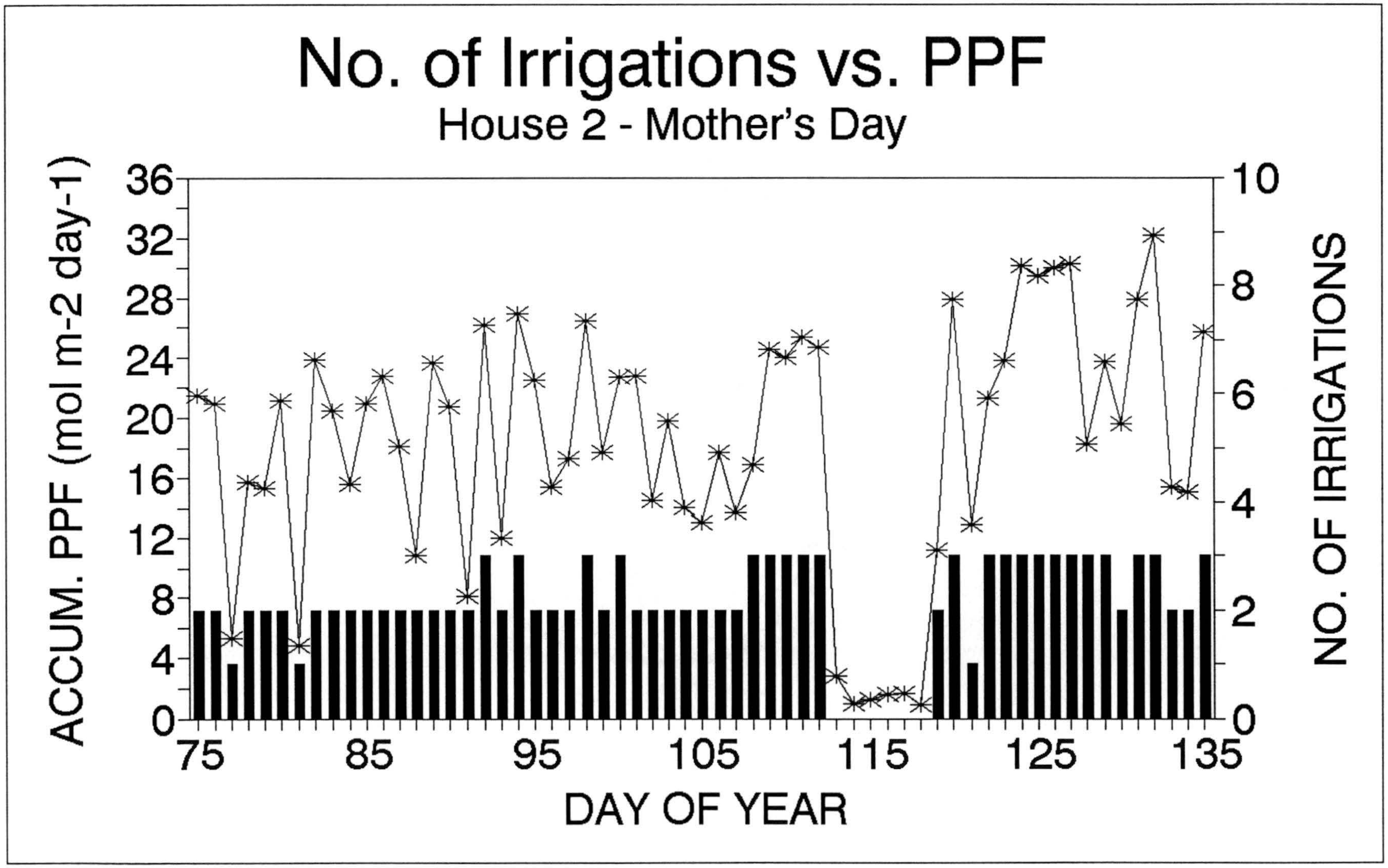


Fig. 14. Comparison of daily number of irrigations and daily accumulated radiation for house 2 during the Mother's Day harvest period.

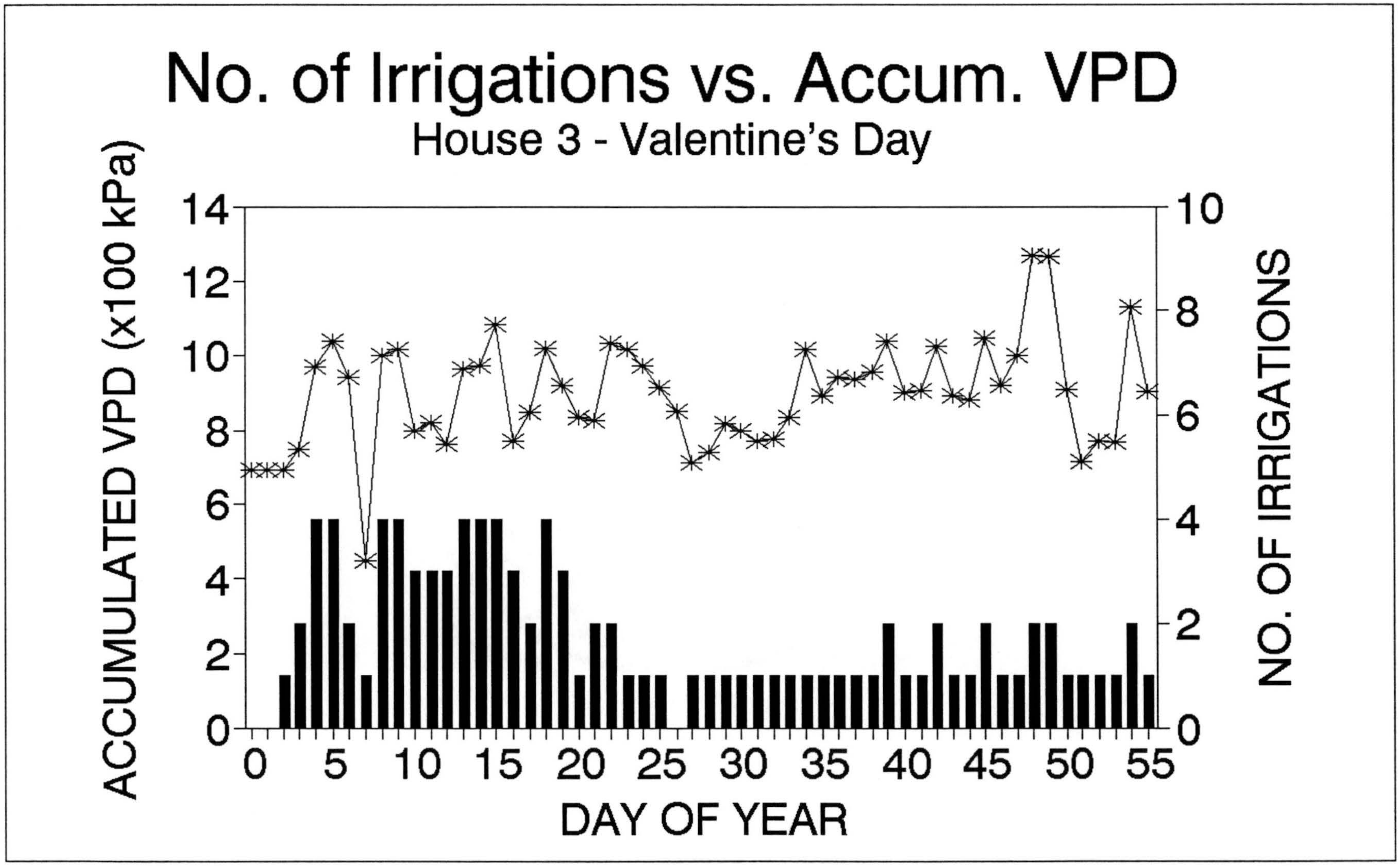


Fig. 15. Comparison of daily number of irrigations and daily accumulated VPD for house 3 during the Valentine's Day harvest period.

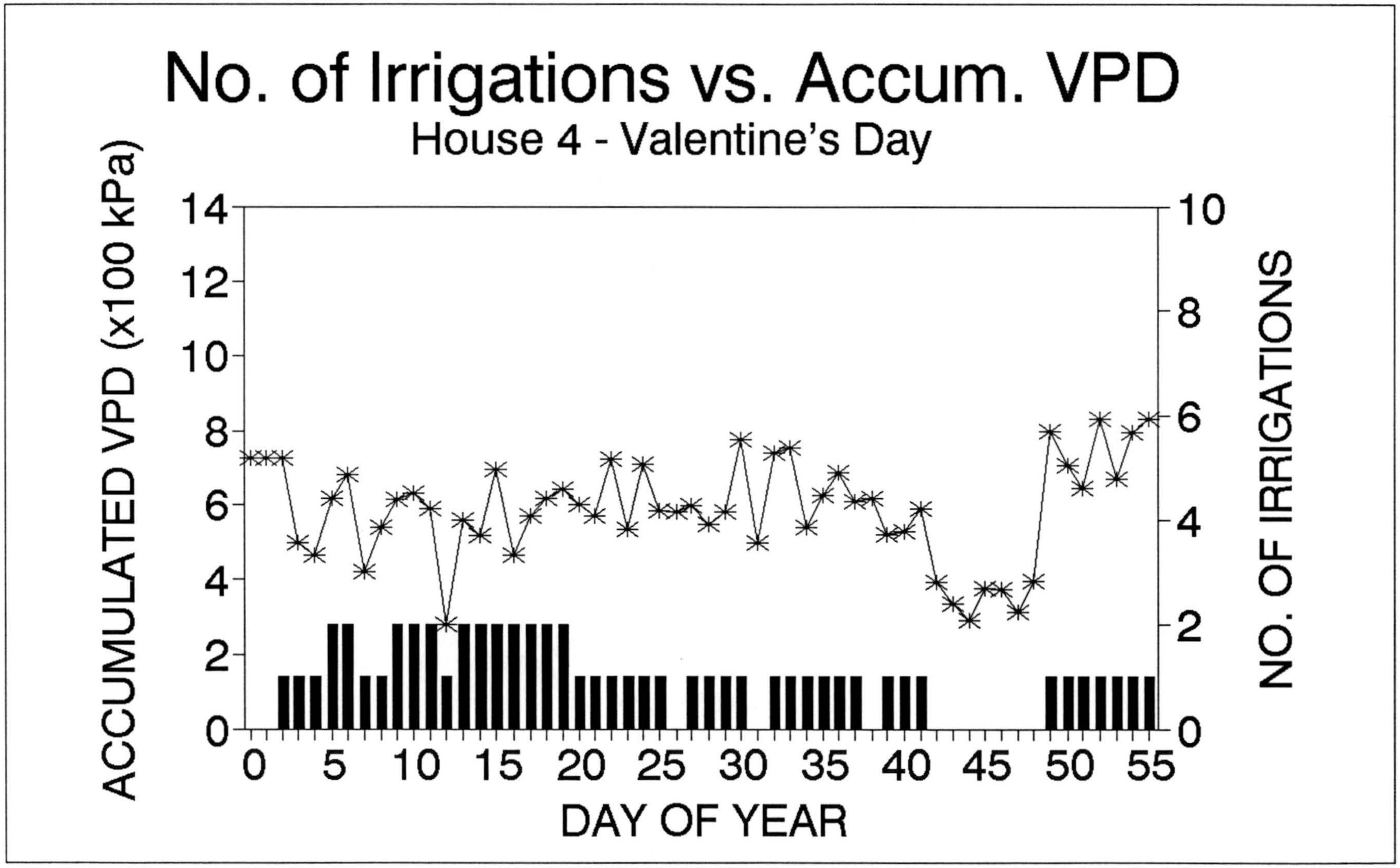


Fig. 16. Comparison of daily number of irrigations and daily accumulated VPD for house 4 during the Valentine's Day harvest period.

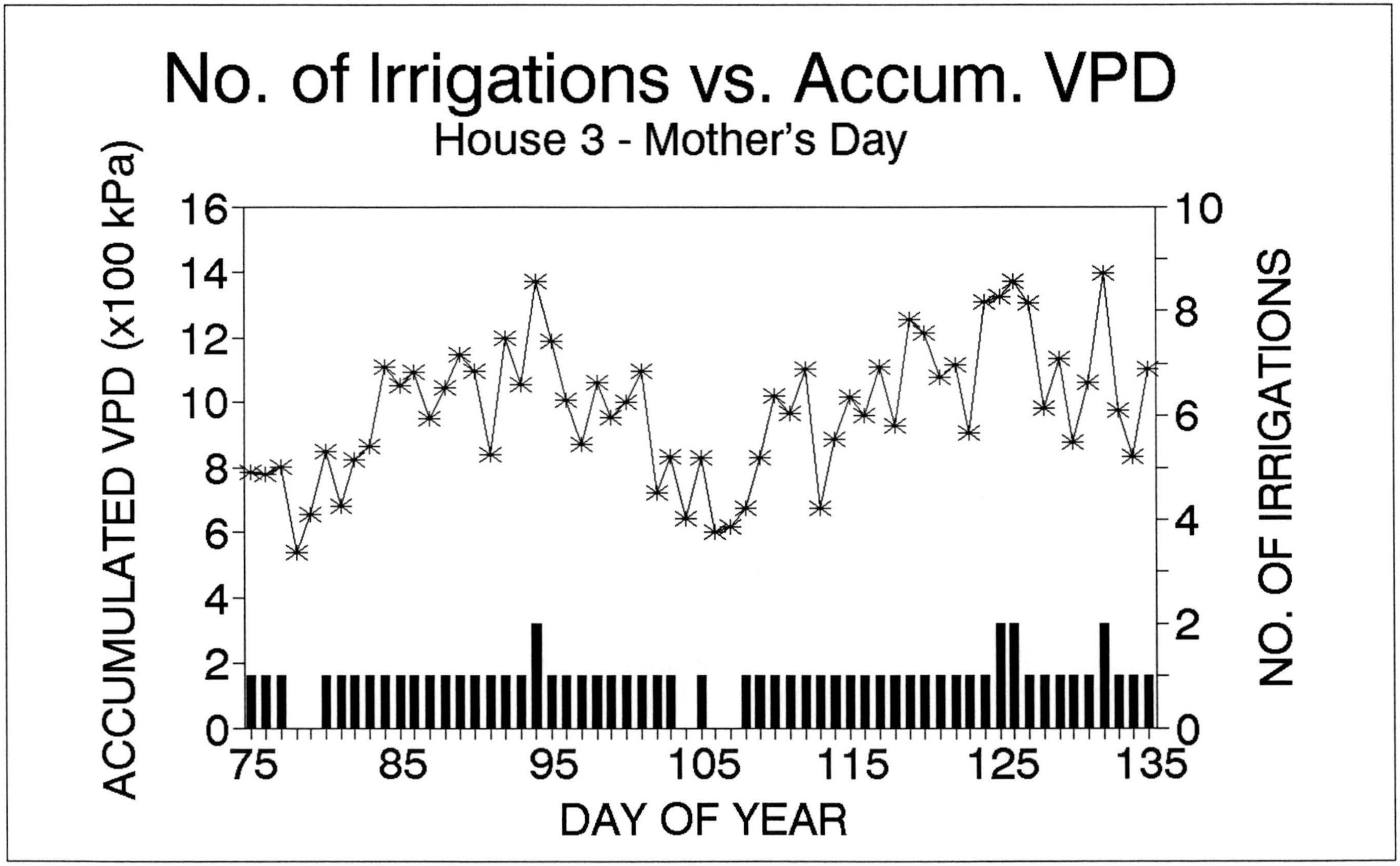


Fig. 17. Comparison of daily number of irrigations and daily accumulated VPD for house 3 during the Mother's Day harvest period.

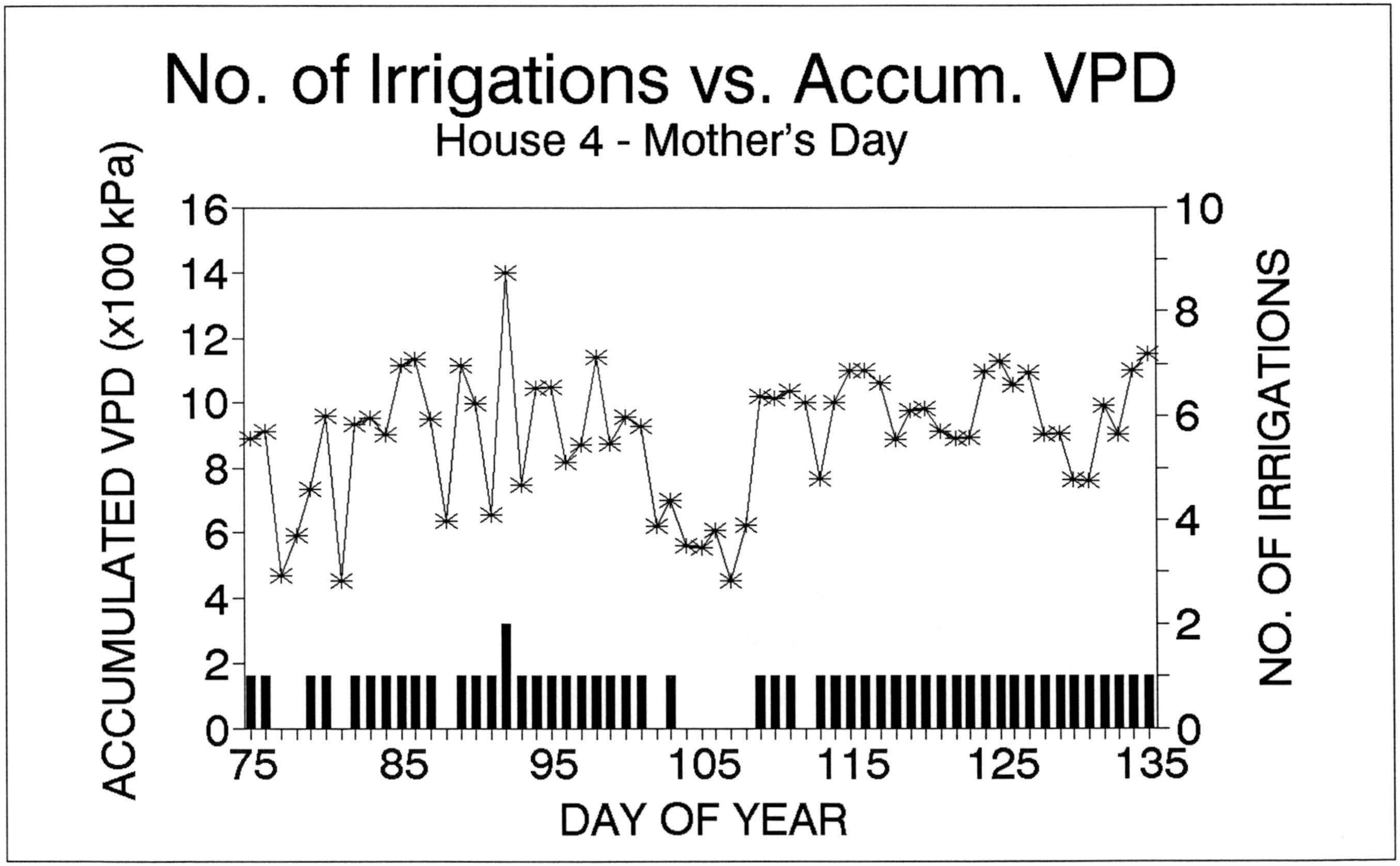


Fig. 18. Comparison of daily number of irrigations and daily accumulated VPD for house 4 during the Mother's Day harvest period.

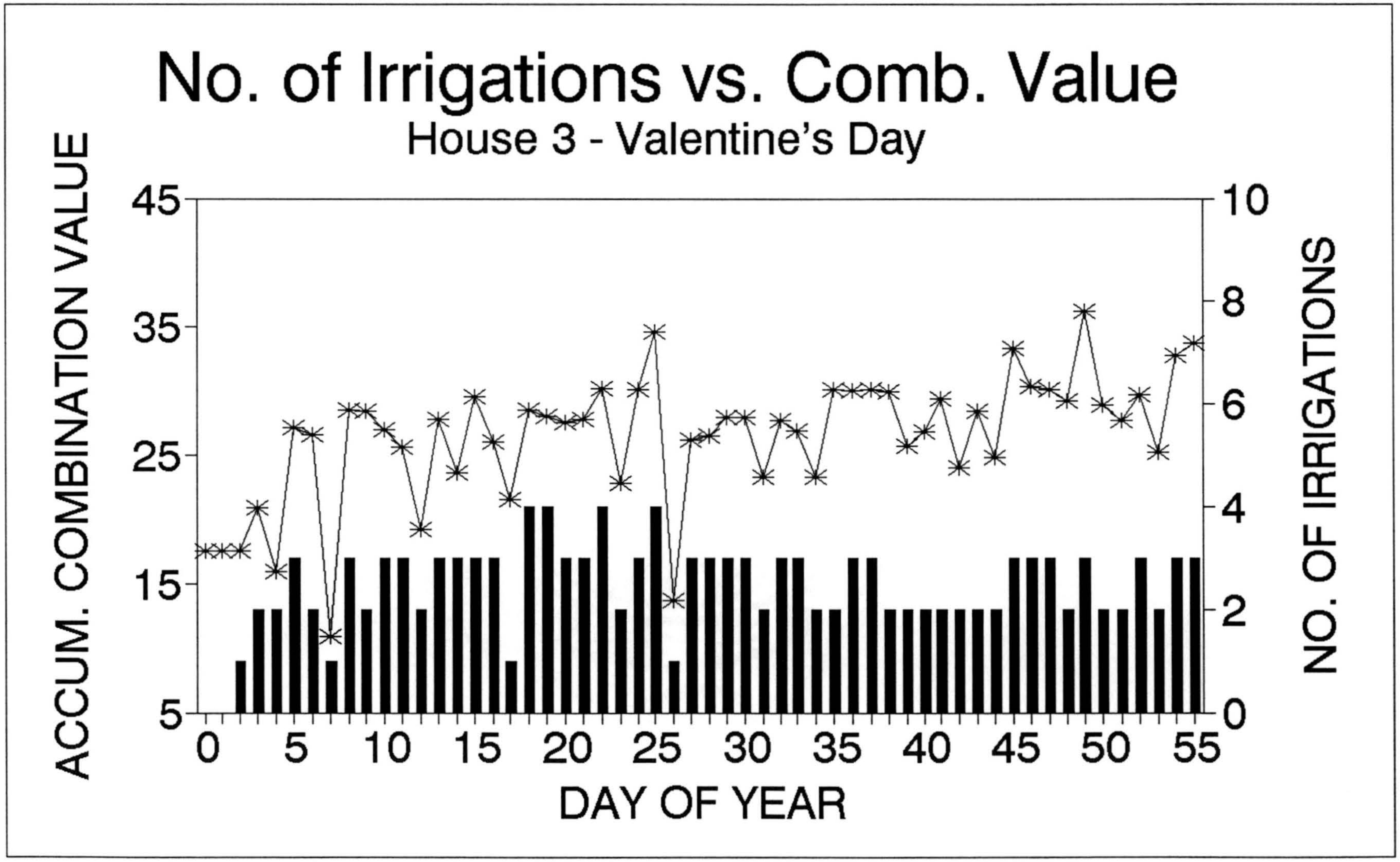


Fig. 19. Comparison of daily number of irrigations and daily accumulated combination values for house 3 during the Valentine's Day harvest period.

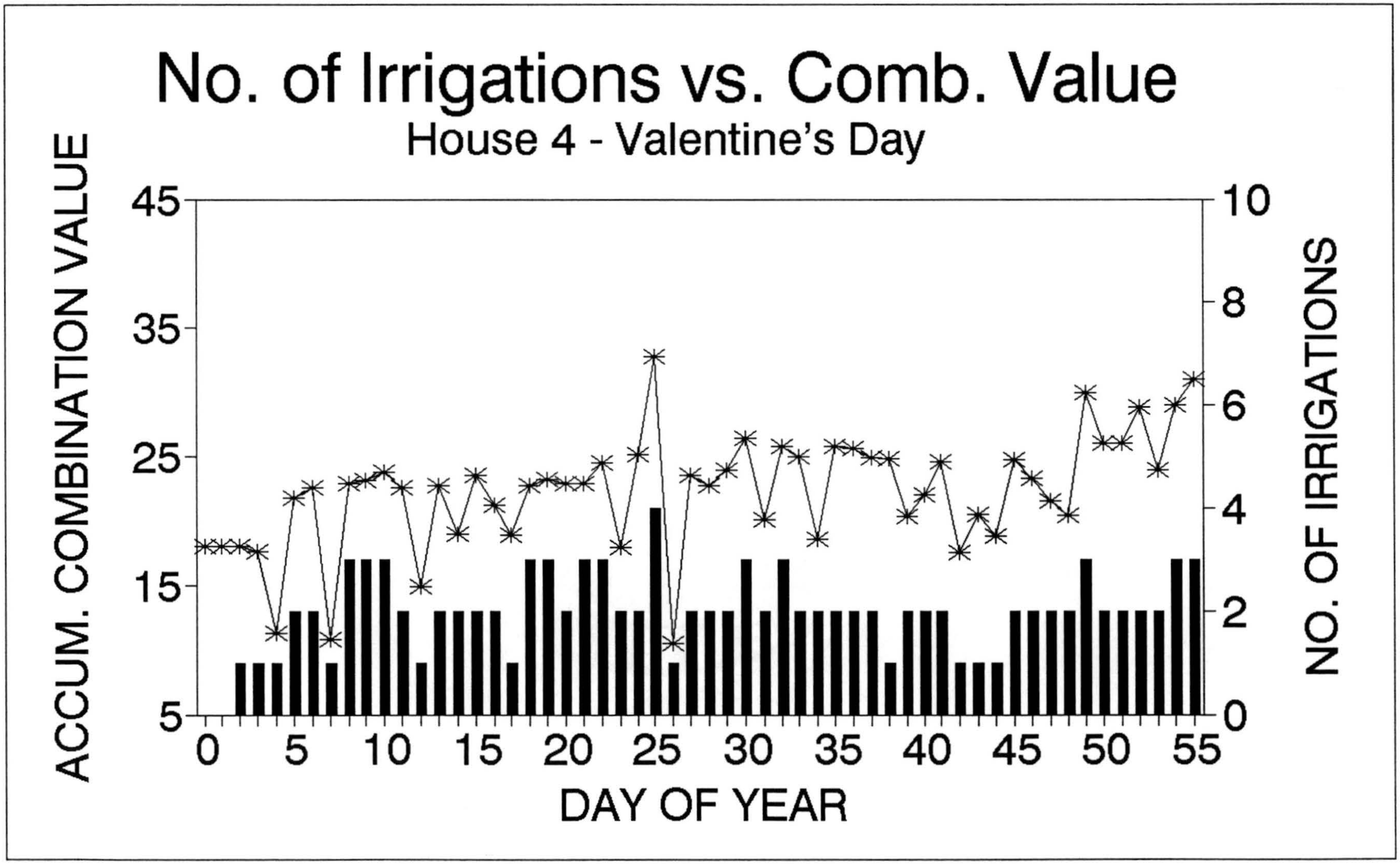


Fig. 20. Comparison of daily number of irrigations and daily accumulated combination values for house 4 during the Valentine's Day harvest period.

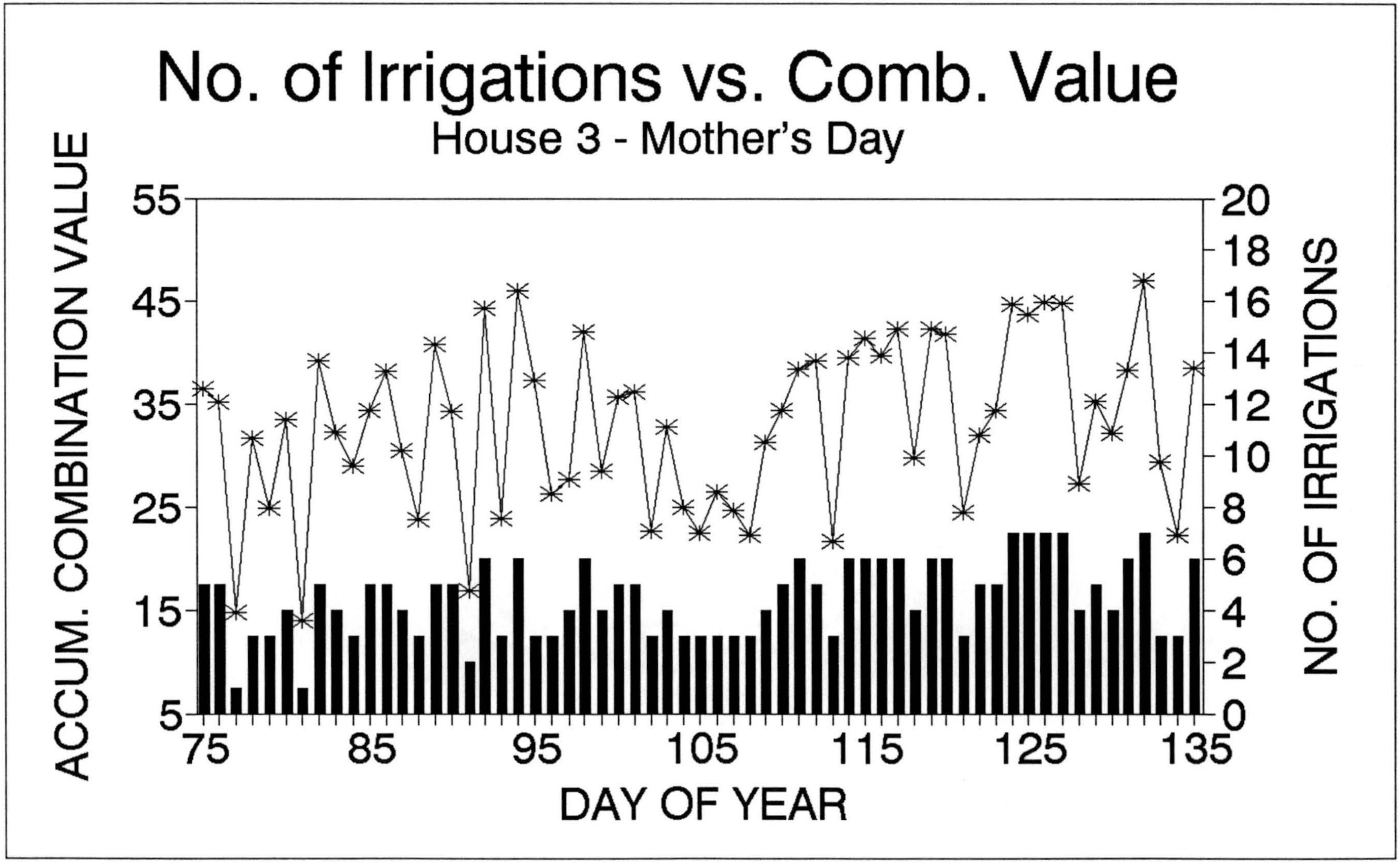


Fig. 21. Comparison of daily number of irrigations and daily accumulated combination values for house 3 during the Mother's Day harvest period.

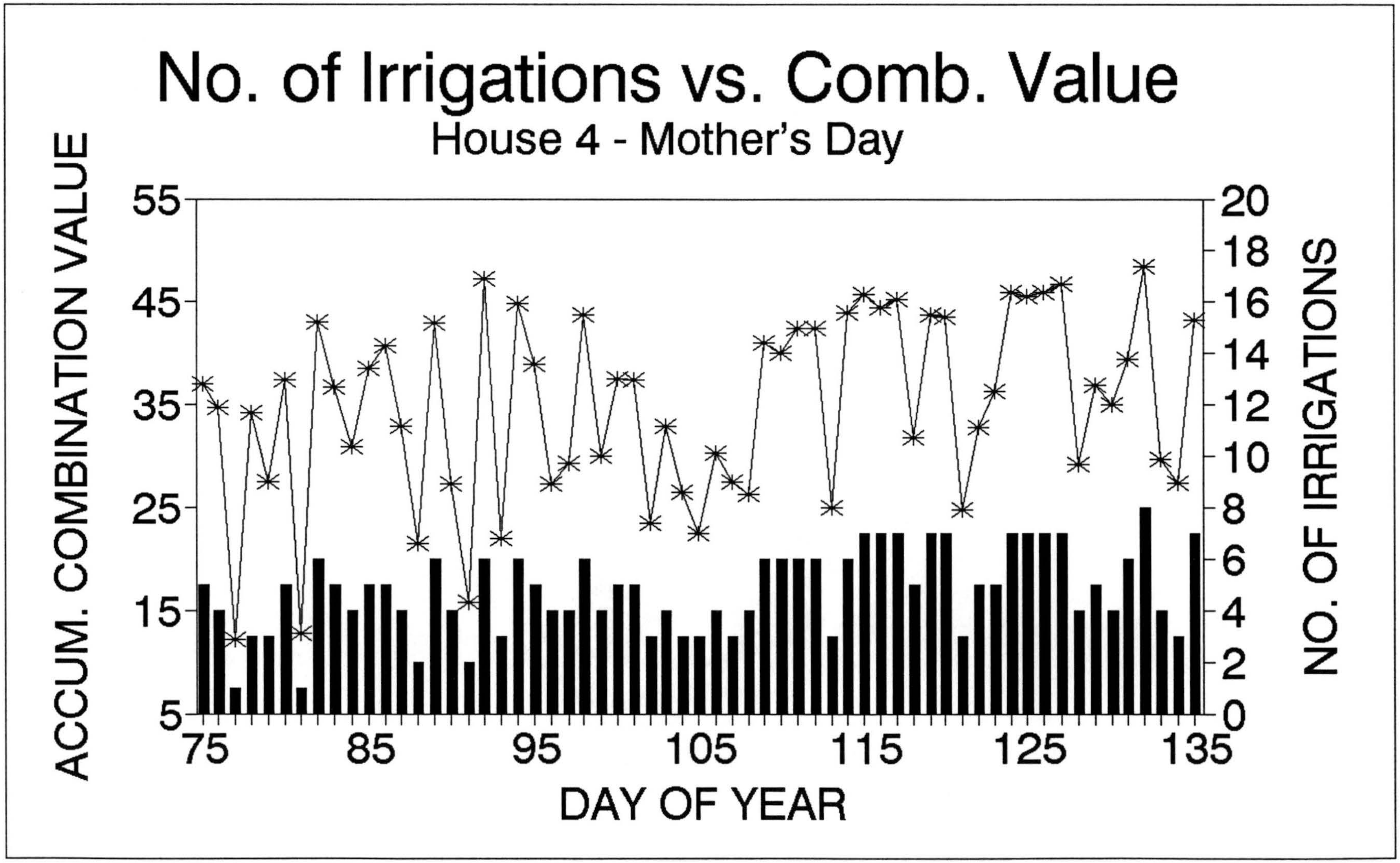


Fig. 22. Comparison of daily number of irrigations and daily accumulated combination values for house 4 during the Mother's Day harvest period.

Appendix A. Colorado State University Plant Environmental Research Center (PERC) Nutrient Solution

Nutrient Source	Amount/Liter
Potassium Nitrate (KNO_3)	121.0 g
Ammonium Nitrate (NH_4NO_3)	32.0 g
Magnesium Sulfate ($MgSO_4{\cdot}H_2O$)	33.0 g
Phosphoric Acid (K_3PO_4 - 80%)	11.0 mℓ
Boric Acid (H_3BO_3)	1.0 g
Zinc Sulfate [$Zn(SO_4)_2$]	158.0 mg
Manganous Sulfate ($MnSO_4{\cdot}H_2O$)	840.0 mg
Calcium Nitrate [$Ca(NO_3)_2.4H_2O$]	87.0 g
Iron Chelate (DTPA)	332.0 mg

Appendix B. Discussion of vapor pressure deficit and calculations in the VPD and COMB methods.

Saturated vapor pressure is defined as the partial pressure exerted by water vapor when moist air is saturated. Saturation of air is considered to be the point at which air and pure water are at equilibrium and the flow of water molecules between the two masses is equal. The derivation of the quantity vapor pressure, e, follows.

Mixing ratio, r, is the ratio of the mass of water vapor to a unit mass of dry air:

$$\mathrm{r} = \mathrm{m_v} / \mathrm{m_a} \qquad [B.1]$$

The saturation vapor pressure of moist air at pressure P and temperature T is

$$e^{\circ} = [\mathrm{r}^{\circ} / \mathrm{r}^{\circ} + 0.622] * P \qquad [B.2]$$

where r° is the saturation mixing ratio.

The vapor pressure of ambient air, e, then, is given as

$$e \;=\; e_w^{\circ} - [\,(P \cdot c_p) / (0.622 \cdot \lambda)\,] * (T - T_w) \qquad [B.3]$$

$$=\; e_w^{\circ} - \gamma\,(T - T_w) \qquad [B.4]$$

where T_w is the wet-bulb temperature (°C), e_w° is the saturation vapor pressure at T_w (kPa) , P is the amtospheric pressure (kPa), c_p is the specific heat of moist air at constant pressure ($\mathrm{MJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}}$), λ is the latent heat of vaporization ($\mathrm{MJ \cdot kg^{-1}}$), T is the ambient air temperature (°C) and γ is referred to as the psychometric constant. At sea level, normal values are: P = (101.3 kPa), c_p = (1.003×10^{-3} $\mathrm{MJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}}$), and λ = (2.453 $\mathrm{MJ \cdot kg^{-1}}$ at 20 °C).

The capacitance probes used in this study contained resistance temperature detectors (RTDs) which measured the actual temperature and performed the calculation of e°. From this then, e can be determined, as well as the vapor pressure deficit (VPD) by

$$\mathrm{VPD} = e^{\circ} - e \text{ [kPa]} \qquad [B.5].$$

This is the value that was passed into the irrigation scheduling subroutine (Appendix C) of the control program, accumulated, and used to initiate irrigation events.

The combination value was determined by scaling the instantaneous PPF value and adding that to the instantaneous VPD value. Scaling simply involved multiplying the instantaneous VPD value by 100, and dividing the total by 10. As a sample calculation:

PPF = 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$

VPD = 1.2 kPa

COMB = (150 $\mu mol \cdot m^{-2} \cdot s^{-1}$ + (1.2 kPa * 100)) / 10 = 27 units [B.6].

At higher PPF levels, the combination value appeared to be dominated by the PPF value, but when averaged over the day and the year, it appears that this scaling is appropriate. Future development of this scheduling factor may assess the appropriateness of using a variable scaling factor.

Appendix C. Irrigation scheduling subroutine, SUB Irr_dec, of the HP BASIC control program "Control_a".

The irrigation scheduling subroutine, SUB Irr_dec, was written for the irrigation scheduling study in HP BASIC to be used in the overall greenhouse environmental control program "Control_a" written by J.J. Hanan and described in Hanan et al. (1987). Actual greenhouse conditions as monitored by the HP9920S system were accumulated in this subroutine by passing the data from the main program into the subroutine, and at each execution (one minute) during daylight hours, accumulating them. To simulate a hardware time clock, time was accumulated as well. The combination value accumulation equation included the scaling factor, as described in Appendix B.

The IF statements following the accumulation equations allow the SUB to check each accumulated value to see if it has exceeded the threshold value specified. When a threshold value is exceeded, the SUB closes the relay that activates the 24V solenoid for that particular set of benches, and irrigation is "ON" for two minutes as time by the "Control_a" program. At the same time, a message is sent to the printer, the accumulation value is reset to zero to restart the accumulation process, and the irrigation event counter is incremented. Following is the HP BASIC code for the subroutine; Acc_time refers to the time clock method; Quant_trig refers to the PPF method; Vpd_trig refers to the VPD method; and Pen_trig refers to the COMB method:

```
13185 !********** SUB Irrigation Decision **********
13186 !
13187 SUB Irr_dec
13188 !
13189 COM /Flags/ INTEGER Flag(*),Tag, Tag$[20]
13190 COM/Ind_var1/Heat_res(*),Cool_res(*),Co2_resmax(*),T_act(*),Co2_act(*),Dif_set1,Dif_set2
,Dif_set3,Rad_out,T_def(*),Co2_del(*)
13191 COM/Ind_var4/INTEGER  Acc_time,  REAL  Quant_trig(*),REAL  Vpd_trig(*),  REAL
Pen_trig(*), INTEGER Irr_on(*), INTEGER Water_no(*), INTEGER Acc_time_prn
```

```
13192 COM /Store/Store_array(*), Store_out(*)
13193 COM /House/ Hse$(*)
13194 COM /Hse_set/ REAL Ind_set(*)
13195 !
13196 INTEGER I
13197 !
13198 IF Flag(11)=1 THEN                !If night is set, set triggers to zero
13199 Acc_time=0
13200 Quant_trig(1,1)=0
13201 Quant_trig(1,2)=0
13202 Quant_trig(1,3)=0
13203 Quant_trig(1,4)=0
13204 Vpd_trig(1,1)=0
13205 Vpd_trig(1,2)=0
13206 Pen_trig(1,1)=0
13207 Pen_trig(1,2)=0
13208 !
13209 FOR I=1 TO 4                      !Reset Irrigations and control settings to zero
13210 !
13211 FOR J=1 TO 3
13212 Water_no(I,J)=
13213 NEXT J
13214 !
13215 Hse$(I)[13,15]="000"
13216 !
13217 NEXT I
13218 !
13219 END IF
13220 !
13221 IF Flag(11)=0 THEN                !If day is set, start accumulations
13222   Acc_time=Acc_time=1             !time accumulator
13223   Quant_trig(1,1)=Quant_trig(1,1)+Store_array(19,1)      !rad accumulators
13224   Quant_trig(1,2)=Quant_trig(1,2)+Store_array(19,2)
13225   Quant_trig(1,3)=Quant_trig(1,3)+Store_array(19,3)
13226   Quant_trig(1,4)=Quant_trig(1,4)+Store_array(19,4)
13227   Vpd_trig(1,1)=Vpd_trig(1,1)+Store_array(43,3)      !vpd accumulators
13228   Vpd_trig(1,2)=Vpd_trig(1,2)+Store_array(43,4)
13229   Pen_trig(1,1)=Pen_trig(1,1)+((Store_array(19,3)/10)+Store_array(43,3))
13230   Pen_trig(1,2)=Pen_trig(1,2)+((Store_array(19,4)/10)+Store_array(43,4))
13231 !
13232 IF Acc_time>=Ind_set(7,1) THEN                    !Check for time trigger
13233     !OUTPUT 701 USING "60A,2X,13A";"ACCUM. TIME TRIGGER IRRIG. (BENCHES
1E&2D) AT ";TIME$(TIMEDATE)
13234   Hse$(1)[15,15]="1"
13235   Hse$(2)[14,14]="1"
13236   Irr_on(1,3)=0
13237   Irr_on(2,2)=0
13238   Acc_time=0                        !If time accum. triggers, reset to zero
13239   Water_no(1,3)=Water_no(1,3)+1
13240   Water_no(2,2)=Water_no(2,2)+1
13241 END IF
13242 !
13243 IF Quant_trig(1,1)>=Ind_set(7,2)*10 THEN          !Check for rad trigger
```

```
13244 !OUTPUT 701 USING "60A,2X,13A";"ACCUM. RAD TRIGGER IRRIG. (BENCHES 1B, 1C AND 1D) AT ";TIME$(TIMEDATE)
13245 Hse$(1)[13,13]="1"
13246 Irr_on(1,1)=0
13247 Quant_trig(1,1)=0                        !If rad accum triggers, reset to zero
13248 Water_no(1,1)=Water_no(1,1)+1
13249 END IF
13250 !
13251 IF Quant_trig(1,2)>=Ind_set(7,2)*10 THEN      !Check for rad trigger
13252 !OUTPUT 701 USING "60A,2X,13A";"ACCUM. RAD TRIGGER IRRIG. (BENCHES 2B, 2C AND 2E) AT ";TIME$(TIMEDATE)
13253 Hse$(2)[13,13]="1"
13254 Irr_on(2,1)=0
13255 Quant_trig(1,2)=0                        !If rad accum triggers, reset to zero
13256 Water_no(2,1)=Water_no(2,1)+1
13257 END IF
13258 !
13259 IF Quant_trig(1,3)>=Ind_set(7,2)*10 THEN      !Check for rad trigger
13260 !OUTPUT 701 USING "60A,2X,13A";"ACCUM. RAD TRIGGER IRRIG. (BENCHES 3B AND 3C) AT ";TIME$(TIMEDATE)
13261 Hse$(3)[13,13]="1"
13262 Irr_on(3,1)=0
13263 Quant_trig(1,3)=0                        !If rad accum triggers, reset to zero
13264 Water_no(3,1)=Water_no(3,1)+1
13265 END IF
13266 !
13267 IF Quant_trig(1,4)>=Ind_set(7,2)*10 THEN      !Check for rad trigger
13268 !OUTPUT 701 USING "60A,2X,13A";"ACCUM. RAD TRIGGER IRRIG. (BENCHES 4B AND 4C) AT ";TIME$(TIMEDATE)
13269 Hse$(4)[13,13]="1"
13270 Irr_on(4,1)=0
13271 Quant_trig(1,4)=0                        !If rad accum triggers, reset to zero
13272 Water_no(4,1)=Water_no(4,1)+1
13273 END IF
13274 !
13275 IF Vpd_trig(1,1)>=Ind_set(7,3)*10 THEN        !Check for vpd trigger
13276 !OUTPUT 701 USING "60A,2X,13A";"ACCUM. VPD TRIGGER IRRIG. (BENCH 3D) AT ";TIME$(TIMEDATE)
13277 Hse$(3)[14,14]="1"
13278 Irr_on(3,2)=0
13279 Vpd_trig(1,1)=0                          !If vpd accum triggers, reset to zero
13280 Water_no(3,2)=Water_no(3,2)+1
13281 END IF
13282 !
13283 IF Vpd_trig(1,2)>=Ind_set(7,3)*10 THEN        !Check for vpd trigger
13284 !OUTPUT 701 USING "60A,2X,13A";"ACCUM. VPD TRIGGER IRRIG. (BENCH 4E) AT ";TIME$(TIMEDATE)
13285 Hse$(4)[15,15]="1"
13286 Irr_on(4,3)=0
13287 Vpd_trig(1,2)=0                          !If vpd accum triggers, reset to zero
13288 Water_no(4,3)=Water_no(4,3)+1
13289 END IF
13290 !
13291 IF Pen_trig(1,1)>=Ind_set(7,4)*10 THEN        !Check for pen trigger
```

```
13292 !OUTPUT 701 USING "60A,2X,13A";"ACCUM. PEN TRIGGER IRRIG. (BENCH 3E) AT
";TIME$(TIMEDATE)
13293  Hse$(3)[15,15]="1"
13294  Irr_on(3,3)=0
13295  Pen_trig(1,1)=0                    !If pen accum triggers, reset to zero
13296  Water_no(3,3)=Water_no(3,3)+1
13297  END IF
13298  !
13299  IF Pen_trig(1,1)>=Ind_set(7,4)*10 THEN          !Check for pen trigger
13300  !OUTPUT 701 USING "60A,2X,13A";"ACCUM. PEN TRIGGER IRRIG. (BENCH 4D) AT
";TIME$(TIMEDATE)
13301  Hse$(4)[14,14]="1"
13302  Irr_on(4,2)=0
13303  Pen_trig(1,2)=0                    !If pen accum triggers, reset to zero
13304  Water_no(4,2)=Water_no(4,2)+1
13305  END IF
13306  !
13307  END IF
13308  SUBEND
```

Appendix D. Explanation, ANSI C code, and example files for IRRMOD - IRRigation Scheduling MODeler.

IRRMOD was developed by the author to simulate greenhouse conditions and show how different irrigation scheduling techniques respond to differing levels of parameters. IRRMOD was written in ANSI C using Borland's C++ compiler for compilation and execution. The main bulk of IRRMOD is used to simulate greenhouse conditions; currently, IRRMOD simulates variable daylength, air temperature, relative humidity, and photosynthetic photon flux (PPF). The input portion of the program asks for input from the user (if defaults are not used), including minimum and maximum daylength over the year, minimum and maximum instantaneous PPF, minimum and maximum day temperatures, minimum and maximum relative humidity, a ramp time (in hours) for moving from minimum to maximum temperature and relative humidity values, number of minutes to run the simulation, day of year to start the simulation, and individual threshold values for initiating simulated irrigation events for the individual scheduling techniques included in the model. During the environmental simulation, IRRMOD calculates a yearly PPF curve, using a sine curve as a model, from the inputed yearly PPF data. From this sine curve and the day of the year, the model selects a minimum and maximum PPF for that day, and creates a sine curve of hourly PPF values. Temperatures and relative humidity are assumed to ramp from a minimum to maximum value over the specified ramp time assigned during the input phase.

For each iteration of one minute, instantaneous PPF, vapor pressure deficit, and combination values (as described in Appendix B) are calculated and accumulated. Time was accumulated by incrementing a variable each time the loop was entered. These accumulated values are checked against the threshold values specified at the beginning of the simulation. When the accumulated value exceeds the threshold value, an irrigation event was simulated and counted. The final printout details the inputed values, as well as the number of times over the course of the simulation that each scheduling technique called for irrigation events.

Multiple simulations can be run at different times of the year to gather performance information over time. Threshold values can also be varied to check the response of the scheduling method as related to the threshold value specified. The main benefit of this model is that one can obtain estimates of appropriate threshold levels for their specific conditions, and the program is flexible enough to allow different irrigation scheduling methods to be included into the simulation. Following is the ANSI C code for IRRMOD and an example output file:

ANSI C code for IRRMOD:

```
==================================================

/*****************************************************************************
 *****          This is the ANSI C code for IRRMOD, the IRRigation scheduling        *****
 ****           MODeler. Simulated greenhouse conditions are based on hourly,         ****
 ***            monthly, and yearly data from Fort Collins, CO weather and             ***
 **             environmental parameters (with the option of specifying other           **
 *              conditions in the setup fxn.). The main purpose of IRRMOD is             *
 *              to "test" different irrigation scheduling techniques. IRRMOD can         *
 *              also provide valuable information about proper levels for event          *
 **             thresholds.                                                             **
***                                                                                    ***
****            Written by Steven E. Woerner                                          ****
 *****             First Edition: Jan. 1992                                           *****
 *****************************************************************************/


#include <stdlib.h>
#include <stdio.h>
#include <time.h>
#include <dos.h>
#include <math.h>
#include <conio.h>
#include "b:\irrmod\struct.h"
#include "b:\irrmod\model1.def"


void PaintIntro(void);
void PaintScreen(void);
void GetInfo(struct Input_vars *In_vars);
void GetTrig(struct Input_vars *In-vars);
void FileHead(struct Input_vars *In_vars);
```

```
void CalcTrig(struct Input_vars *In_vars,struct Calc_vars *calc_vars);


long run_len;

void main(void)
{
struct Input_vars In_vars;
struct Calc_vars calc_vars;

PaintIntro();
GetInfo(&In_vars);
GetTrig(&In-vars);
FileHead(&In_vars);
CalcTrig(&In_vars,&calc_vars);
/*PrintTotal();*/
exit(0);
}

void PaintIntro(void)
{
   clrscr();
   gotoxy(1,2);
     printf("******************************************************************************");
     gotoxy(12,4);
     printf("Welcome to IRRMOD - IRRigation scheduling MODeler");
     gotoxy(1,6);
     printf("______________________________________________________________________________");
     gotoxy(13,10);
   printf("Developed by Steven E. Woerner and Douglas A. Hopper");
   gotoxy(8,11);
     printf("of the Department of Horticulture at Colorado State University");
   gotoxy(18,13);
   printf("Version 1.0 alpha.  Pilot version only.");
   gotoxy(29,17);
     printf("***Please Wait***");
   delay(5000);
   clrscr();
   return;
}

void PaintScreen(void)
{
     clrscr();
     gotoxy(1,1);

printf("******************************************************************************");
     gotoxy(10,2);
     printf("This is the input screen.  You will be prompted for specific");
     gotoxy(20,3);
   printf("inputs for each of the parameters.");
   gotoxy(1,4);
   printf("______________________________________________________________________________
_");
```

```
    gotoxy(10,6);
    printf("Maximum light intensity at solar noon");
    gotoxy(20,7);
    printf("on Dec. 20 (microeinsteins):");
    gotoxy(10,8);
    printf("Maximum light intensity at solar noon");
    gotoxy(20,9);
    printf("on June 21 (microeinsteins):");
    gotoxy(10,11);
    printf("Percent of days that are cloudy (yearly average):");
    gotoxy(10,13);
    printf("Maximum RH (%):");
    gotoxy(10,14);
    printf("Minimum RH (%):");
    gotoxy(10,16);
    printf("Maximum Day Temp. (DT) in C:");
    gotoxy(10,17);
    printf("Minimum Day Temp. (DT) in C:");
    gotoxy(10,19);
    printf("Maximum day length on Dec. 20 (hours):");
    gotoxy(10,20);
    printf("Maximum day length on June 21 (hours):");
    gotoxy(10,21);
    printf("Day starts at (i.e. 8:00=8) on June 20:");
    gotoxy(10,22);
    printf("Day starts at (i.e. 8:00=8) on Dec. 20:");
    gotoxy(10,23);
    printf("Number of days to run:");
    gotoxy(10,24);
    printf("Start with julian day:");
    return;
}

void GetInfo(struct Input_vars *In_vars)
{
 int done;
 double dummy1;
 int dummy2;
 int cor_inp;

 done=FALSE;
 while(!done)
   {
   PaintScreen();
   gotoxy(50,7);
   scanf("%lf",&dummy1);
   In_vars->dec_max_lit=dummy1;
   gotoxy(50,9);
   scanf("%lf",&dummy1);
   In_vars->jun_max_lit=dummy1;
   gotoxy(60,11);
   scanf("%lf",&dummy1);
   In_vars->cloud_per=dummy1;
   gotoxy(27,13);
```

```
scanf("%lf",&dummy1);
In_vars->max_rh=dummy1;
gotoxy(27,14);
scanf("%lf",&dummy1);
In_vars->min_rh=dummy1;
gotoxy(40,16);
scanf("%lf",&dummy1);
In_vars->max_dt=dummy1;
gotoxy(40,17);
scanf("%lf",&dummy1);
In_vars->min_dt=dummy1;
gotoxy(50,19);
scanf("%lf",&dummy1);
In_vars->max_dlen_dec=dummy1;
gotoxy(50,20);
scanf("%lf",&dummy1);
In_vars->max_dlen_jun=dummy1;
gotoxy(55,21);
scanf("%lf",&dummy1);
In_vars->jun_day_start=dummy1;
gotoxy(55,22);
scanf("%lf",&dummy1);
In_vars->dec_day_start=dummy1;
gotoxy(35,23);
scanf("%d",&dummy2);
In_vars->run_days=dummy2;
gotoxy(35,24);
scanf("%d",&dummy2);
In_vars->start_day=dummy2;
clrscr();
gotoxy(10,2);
printf("You have inputted the following:");
gotoxy(5,4);
printf("Max. Light - Dec.: %f",In_vars->dec_max_lit);
gotoxy(5,5);
printf("Max. Light - June: %f",In_vars->jun_max_lit);
gotoxy(5,6);
printf("Percent of cloudy days: %f",In_vars->cloud_per);
gotoxy(5,7);
printf("Maximum RH: %f",In_vars->max_rh);
gotoxy(5,8);
printf("Minimum RH: %f",In_vars->min_rh);
gotoxy(5,9);
printf("Maximum DT: %f",In_vars->max_dt);
gotoxy(5,10);
printf("Minimum DT: %f",In_vars->min_dt);
gotoxy(5,11);
printf("Max. Daylength - Dec.: %f",In_vars->max_dlen_dec);
gotoxy(5,12);
printf("Max. Daylength - June: %f",In_vars->max_dlen_jun);
gotoxy(5,13);
printf("Day starts at - June: %f",In_vars->jun_day_start);
gotoxy(5,14);
printf("Day starts at - Dec.: %f",In_vars->dec_day_start);
```

```
  gotoxy(5,15);
  printf("Number of days to run: %4d",In_vars->run_days);
  gotoxy(5,16);
  printf("Starting with day: %3d",In_vars->start_day);
  gotoxy(5,17);
  printf("Are these values correct? 1=yes, 0=no");
  gotoxy(45,18);
  scanf("%d",&cor_inp);
  if(!cor_inp)
  {
    done=FALSE;
    printf("Please reenter the values.");
    delay(1000);
    clrscr();
  }
  else
  {
    done=TRUE;
    printf("IRRMOD will now begin simulation.");
    clrscr();
  }
 }
return;
}

void GetTrig(struct Input_vars *In_vars)
{
  int done;
  double dummy1;
  int def_inp;

  clrscr();
   printf("Do you want to use default values? 1=yes, 0=no")
   scanf("%d",&def_inp);
   if(!def_inp)
   {
    done=FALSE;
   }
   else
   {
    done=TRUE;
   }

  if(!done)
  {
   gotoxy(10,5);
   printf("Please input the following parameters and thresholds:");
   gotoxy(10,7);
   printf("Day/night ramp time (min.):");
   gotoxy(10,9);
   printf("Time threshold (min.):");
   gotoxy(10,10);
   printf("Radiation threshold (microeinsteins):");
   gotoxy(10,11);
```

```
   printf("Vapor pressure deficit threshold (kPa):");
   gotoxy(10,12);
   printf("Combination method threshold (no units):");
   gotoxy(40,7);
   scanf("%lf",&dummy1);
   In_vars->ramp_time=dummy1;
   gotoxy(32,9);
   scanf("%lf",&dummy1);
   In_vars->time_trig=dummy1;
   gotoxy(46,10);
   scanf("%lf",&dummy1);
   In_vars->rad_trig=dummy1;
   gotoxy(50,11);
   scanf("%lf",&dummy1);
   In_vars->vpd_trig=dummy1;
   gotoxy(50,12);
   scanf("%lf",&dummy1);
   In_vars->comb_trig=dummy1;
  }
  else
  {
   In_vars->ramp_time=60.0;
   In_vars->time_trig=120.0
   In_vars->rad_trig=100000.0;
   In_vars->vpd_trig=2500.0;
   In_vars->comb_trig=9500.0;
  }
}

void FileHead(struct Input_vars *In_vars)
{

  FILE *irrig1;
  irrig1 = fopen("b:\irrmod\Irr_out.dat", "w+");
  fprintf(irrig1,"You have inputted the following:\n");
  fprintf(irrig1,"Max. Light - Dec.: %f\n",In_vars->dec_max_lit);
  fprintf(irrig1,"Max. Light - June: %f\n",In_vars->jun_max_lit);
  fprintf(irrig1,"Percent of cloudy days: %f\n",In_vars->cloud_per);
  fprintf(irrig1,"Maximum RH: %f\n",In_vars->max_rh);
  fprintf(irrig1,"Minimum RH: %f\n",In_vars->min_rh);
  fprintf(irrig1,"Maximum DT: %f\n",In_vars->max_dt);
  fprintf(irrig1,"Minimum DT: %f\n",In_vars->min_dt);
  fprintf(irrig1,"Max. Daylength - Dec.: %f\n",In_vars->max_dlen_dec);
  fprintf(irrig1,"Max. Daylength - June: %f\n",In_vars->max_dlen_jun);
  fprintf(irrig1,"Number of days to run: %d\n",In_vars->run_days);
  fprintf(irrig1,"Starting with day: %d\n",In_vars->start_day);
  fprintf(irrig1,"Time threshold = %5d\n",TIME_TRIG);
  fprintf(irrig1,"Rad. threshold = %8ld\n",RAD_TRIG);
  fprintf(irrig1,"VPD threshold  = %5d\n",VPD_TRIG);
  fprintf(irrig1,"Combination method threshold  = %5d\n",COMB_TRIG);
  fclose(irrig1);
  return;
}
```

```
void CalcTrig(struct Input_vars *In_vars,struct Calc_vars *calc_vars)
 {
  FILE *irrig3;
  calc_vars->jday=In_vars->start_day;
  run_len = In_vars->run_days + In_vars->start_day;
  printf("Starting day is: %3ld\n",In_vars->start_day);
  printf("Number of days to run is: %3ld\n",In_vars->run_days);

  calc_vars->time_trig=0;
  calc_vars->rad_acc=0;
  calc_vars->vp_def_acc=0;
  calc_vars->comb_acc=0;

  calc_vars->day_start_hr=0;
  calc_vars->day_start_min=0;
  calc_vars->dlength_hr=0;
  calc_vars->dlength_min=0;
  calc_vars->max_dint=0;
  calc_vars->temp_act_air=0;
  calc_vars->rh_act=0;

  for (calc_vars->jday=In_vars->start_day;calc_vars->jday<=(run_len-1);calc_vars->jday++)
  {
    int it=0;
    /*double prn_time=0;*/
    long jd;long min_d;
    double t=0;double m=0;

    calc_vars->time_cnt=0;
    calc_vars->rad_cnt=0;
    calc_vars->vp_def_cnt=0;
    calc_vars->comb_cnt=0;
    calc_vars->min=0;

    printf("jday=%ld\n",calc_vars->jday);
    jd=calc_vars->jday;
    t=(double)jd/365;

    calc_vars->max_dlen_dif = (In_vars->max_dlen_jun - In_vars->max_dlen_dec)/2;
    calc_vars->max_dlen_ave = (In_vars->max_dlen_jun + In_vars->max_dlen_dec)/2;
    calc_vars->dlength_hr = (calc_vars->max_dlen_dif * sin(6.2832*(t) - (1.5708))) + calc_vars-
>max_dlen_ave;
    calc_vars->dlength_min = calc_vars->dlength_hr*60;


    calc_vars->max_int_dif = (In_vars->jun_max_lit - In_vars->dec_max_lit)/2;
    calc_vars->max_int_ave = (In_vars->jun_max_lit + In_vars->dec_max_lit)/2;
    calc_vars->max_dint = (calc_vars->max_int_dif * sin(6.2832*(t) - (1.5708))) + calc_vars-
>max_int_ave;

    calc_vars->day_start_dif = (In_vars->dec_day_start - In_vars->jun_day_start)/2;
    calc_vars->day_start_ave = (In_vars->jun_day_start + In_vars->dec_day_start)/2;
    calc_vars->day_start_hr = calc_vars->day_start_ave - (calc_vars->day_start_dif * sin(6.2832*(t) -
(1.5708)));
```

```
   calc_vars->day_start_min = calc_vars->day_start_hr*60;

       printf("Day start is: %6.2f\n",calc_vars->day_start_min);
       printf("Daylength is: %6.2f\n",calc_vars->dlength_min);
       printf("Max daily int is: %6.2f\n",calc_vars->max_dint);

       /*delay(500);*/

   for (calc_vars->min=calc_vars->day_start_min;calc_vars->min<=calc_vars-
>day_start_min+calc_vars->dlength_min;calc_vars->min++)
   {

    m=(calc_vars->min-calc_vars->day_start_min)/calc_vars->dlength_min;
    calc_vars->max_dint_ave = calc_vars->max_dint/2;
    calc_vars->rad_act_unadj = (calc_vars->max_dint_ave * sin(6.2832*(m) - (1.5708))) +
calc_vars->max_dint_ave;

    if(calc_vars->min<=(calc_vars->day_start_min+RAMP)||calc_vars->min>=(calc_vars-
>day_start_min+calc_vars->dlength_min-RAMP))
    {
       calc_vars->temp_act_air = In_vars->min_dt;
       calc_vars->rh_act = In_vars->max_rh;
    }
    else
    {
       calc_vars->temp_act_air = In_vars->max_dt;
       calc_vars->rh_act = In_vars->min_rh;
    }

       /*printf("Act. air temp is: %6.2f\n",calc_vars->temp_act_air);
       printf("Act. rh is: %6.2f\n",calc_vars->rh_act);*/

       it++;
       calc_vars->time_trg++;
       calc_vars->rad_acc += calc_vars->rad_act_unadj;
         calc_vars->vp_sat_lf = (0.61780 * ((17.269*calc_vars->temp_act_air)/(calc_vars-
>temp_act_air+237.30)));
        calc_vars->vp_sat_air = (0.61780 * ((17.269*calc_vars->temp_act_air)/(calc_vars-
>temp_act_air+237.30)));
        calc_vars->vp_act_air = calc_vars->rh_act * calc_vars->vp_sat_air;
         calc_vars->vp_act_lf = 100.0 * calc_vars->vp_sat_air;
        calc_vars->vp_def = calc_vars->vp_act_lf - calc_vars->vp_act_air;
       calc_vars->vp_def_acc += calc_vars->vp_def;
                calc_vars->comb = (calc_vars->vp_def/100) + (calc_vars->rad_act_unadj/10);
         calc_vars->comb_acc += calc_vars->comb;

       /*prn_time = (double)it + calc_vars->day_start_min;*/

       printf("*");
       /*printf("Actuals: %4.0f %6.2f %6.2f %6.2f\n",prn_time,calc_vars->rad_act_unadj,calc_vars-
>vp_def,calc_vars->comb);
       delay(1000);
       printf("Accum.'s: %4.0f %4ld %8.2f %6.2f %6.2f \n",prn_time,calc_vars-
>time_trig,calc_vars->rad_acc,calc_vars->vp_def_acc,calc_vars->comb_acc);
```

```
        delay (500);*/

      calc_vars->rad_act_unadj = 0;
        calc_vars->temp_act_air = 0;
          calc_vars->vp_sat_lf = 0;
         calc_vars->vp_sat_air = 0;
         calc_vars->vp_act_air = 0;
          calc_vars->vp_act_lf = 0;
                  calc_vars->vp_def = 0;
                 calc_vars->comb = 0;

        if (calc_vars->time_trg >= TIME_TRIG)
        {
        /*printf("Time Threshold Irrigation at %f \n",prn_time);*/
        calc_vars->time_trig = 0;
        calc_vars->time_cnt++;
        calc_vars->time_cnt_tot++;
        }

        if (calc_vars->rad_acc >= RAD_TRIG)
        {
        /*printf("Radiation Threshold Irrigation at %f \n",prn_time);*/
        calc_vars->rad_acc = 0;
        calc_vars->rad_cnt++;
        calc_vars->rad_cnt_tot++;
        }

        if (calc_vars->vp_def_acc >= VPD_TRIG)
        {
        /*printf("VPD Threshold Irrigation at %f \n",prn_time);*/
        calc_vars->vp_def_acc = 0;
        calc_vars->vp_def_cnt++;
        calc_vars->vp_def_cnt_tot++;
        }

        if (calc_vars->comb_acc >= COMB_TRIG)
        {
        /*printf("Combined Threshold Irrigation at %f \n",prn_time);*/
        calc_vars->comb_acc = 0;
        calc_vars->comb_cnt++;
        calc_vars->comb_cnt_tot++;
        }
      }

        printf("\n+++++++++++++++++++++++++++++++ jday %ld
+++++++++++++++++++++++++++++++++++++++\n",calc_vars-
>jday);
        irrig3 = fopen("b:\irrmod\Irr_out.dat","a+");
        printf("\n");
        printf("TIME irrigated %ld TOTAL times on jday %ld\n",calc_vars->time_cnt,calc_vars-
>jday);
        printf("RAD  irrigated %ld TOTAL times on jday %ld\n",calc_vars->rad_cnt,calc_vars-
>jday);
```

```
        printf("VPD  irrigated %ld TOTAL times on jday %ld\n",calc_vars->vp_def_cnt,calc_vars-
>jday);
        printf("COMB irrigated %ld TOTAL times on jday %ld\n",calc_vars->comb_cnt,calc_vars-
>jday);
        printf("\n");
        fprintf(irrig3,"\n");
        fprintf(irrig3,"TIME irrigated %ld TOTAL times on jday %ld\n",calc_vars-
>time_cnt,calc_vars->jday);
        fprintf(irrig3,"RAD  irrigated %ld TOTAL times on jday %ld\n",calc_vars->rad_cnt,calc_vars-
>jday);
        fprintf(irrig3,"VPD  irrigated %ld TOTAL times on jday %ld\n",calc_vars-
>vp_def_cnt,calc_vars->jday);
        fprintf(irrig3,"COMB irrigated %ld TOTAL times on jday %ld\n",calc_vars-
>comb_cnt,calc_vars->jday);
        fprintf(irrig3,"\n");
        fclose(irrig3);
 }
 return;
}

==================================================
```

Example output file:

```
==================================================

You have inputted the following:
Max. Light - Dec.: 1000.000000
Max. Light - June: 2000.000000
Percent of cloudy days: 10.000000
Maximum RH: 95.000000
Minimum RH: 75.000000
Maximum DT: 25.000000
Minimum DT: 21.000000
Max. Daylength - Dec.: 10.000000
Max. Daylength - June: 14.000000
Number of days to run: 3
Starting with day: 181
Time threshold =   120
Rad. threshold =   100000
VPD threshold  =  1500
Combination method threshold  =  9500

TIME irrigated 7 TOTAL times on jday 181
RAD  irrigated 8 TOTAL times on jday 181
VPD  irrigated 12 TOTAL times on jday 181
COMB irrigated 8 TOTAL times on jday 181

TIME irrigated 7 TOTAL times on jday 182
RAD  irrigated 9 TOTAL times on jday 182
VPD  irrigated 13 TOTAL times on jday 182
COMB irrigated 8 TOTAL times on jday 182

TIME irrigated 7 TOTAL times on jday 183
RAD  irrigated 9 TOTAL times on jday 183
VPD  irrigated 11 TOTAL times on jday 183
COMB irrigated 9 TOTAL times on jday 183
```