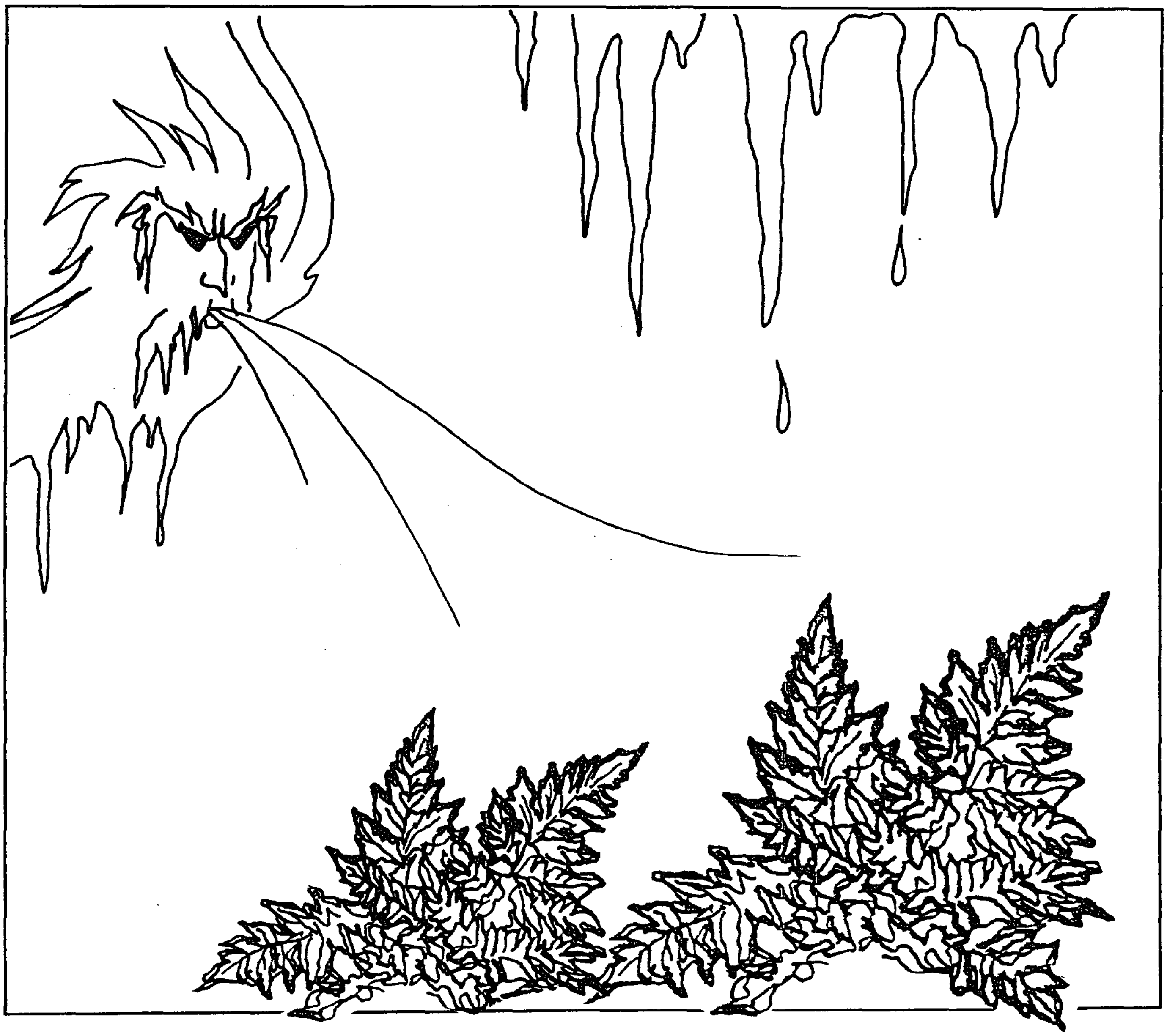
Special Publication SJ 91-SP 15

Cold Protection of Leatherleaf Fern in Lake, Putnam, and Volusia Counties, Florida



St. Johns River Water Management District

Special Publication SJ 91-SP15

COLD PROTECTION OF LEATHERLEAF FERN IN LAKE, PUTNAM, AND VOLUSIA COUNTIES, FLORIDA

by

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EXECUTIVE SUMMARY

Since the 1960's, water — applied using overhead (over-the-crop) irrigation systems — has been used to protect leatherleaf fern [*Rumohra adiantiformis* (Forst.) Ching] from cold damage in Florida. This cold protection technique has been a critical factor in enabling Florida's cut foliage industry to furnish product on a year-round basis. This, in turn, has enabled leatherleaf fern to become the most used cut foliage (florists' green) in the world and the most valuable floriculture crop produced in Florida. Almost all leatherleaf fern production in Florida occurs on land under the jurisdiction of the St. Johns River Water Management District (SJRWMD).

The two "freezes-of-the-century" in December 1983 and January 1985 emphasized the need for more information about using water to cold protect leatherleaf fern. In fact, at that time there was little data relating water application rates to cold damage of leatherleaf fern. The following studies were undertaken to enable the SJRWMD to make more informed decisions about irrigation water application rates and methods of application necessary to cold protect leatherleaf fern. The research objectives were: (1) to determine the effectiveness of different water application rates for cold protection of leatherleaf fern growing under 73 percent polypropylene shade fabric when used in combination with icing of the shade fabric roof and wrapping of the sidewalls with nonporous fabric; (2) to ascertain whether icing of the shade fabric roof of ferneries is effective in reducing heat loss; (3) to test crop covers for their effectiveness in holding heat under the covers when used in combination with irrigation; and (4) to determine the meteorological conditions under which each of the above cold protection techniques is most effective.

Starting in 1985, University of Florida/Institute of Food and Agricultural Sciences (UF/IFAS) faculty and staff worked with individual cut foliage growers, allied supply companies, trade associations, base manufacturers, extension agents and government agencies to get enough equipment, labor, materials and money donated to build a "state-of-the-art" shadehouse research/education facility in Pierson, Florida. This facility was to include a

weather station, nine shadehouses arranged in a 3 × 3 pattern, and a well, diesel engine and pump. In May 1987, the Board of Volusia County Schools gave their approval for use of the Taylor Jr.-Sr. High School (presently the Taylor Middle-High School) agricultural farm for this site. In September 1987, the Governing Board of the SJRWMD voted to fund the data acquisition component of the cold protection research studies to be conducted by UF/IFAS. Additional funding was supplied by cost sharing from UF/IFAS.

The following are the some of the significant findings of these studies:

1) During radiation freezes, application rates as low as 0.12 inch/hr [0.30 $cm \cdot hr^{-1}$] using frost protection sprinklers were effective in maintaining fern temperatures above freezing in iced shadehouses with nonporous sidewalls.

2) Even when shadehouse icing, nonporous sidewalls, frost protection sprinklers and water application rates of up to 0.30 inch/hr [0.76 $cm \cdot hr^{-1}$] were used together, there was damage to immature fern fronds during advective (windy) freezes.

3) At the water application rates tested (0.12-0.30 inch/hr [0.30-0.76 $cm \cdot hr^{-1}$]), the only system that provided good protection to immature fronds during advective freezes was the combination of nonporous sidewalls, frost protection sprinklers, and crop covers.

4) When over-the-crop and over-the-shadehouse irrigation are used with crop covers, temperatures under the covers were significantly warmer than outside the covers and no ice formed on the covers. Temperatures under lighter-weight covers were generally higher and this may have been because more water could penetrate the lighter covers and thereby supply more heat. However, previous research indicates that heavier weight covers would probably provide greater protection from cold damage if the irrigation system were to fail.

5) Icing of shadehouses was beneficial and increased temperatures in shadehouses (when using equivalent water application rates) and reduced cold damage to the crop.

6) Cold protection water application rates had no effect on frond color but did affect vase life at one of four harvests. At that harvest, vase life increased with increasing cold protection water application rate.

7) Yield differences due to water application treatments were not detected even though damage varied with water application rate. This may be due to a number of factors. First, damage to immature fronds occurred in all shadehouses so there was no undamaged control for comparison. For example, during the severe advective freeze of 1989, over three-quarters of all immature fronds were damaged, regardless of water application rate. Second, mature leatherleaf fern fronds, which made up the majority of the fronds in the shadehouses when freezes occurred, were not damaged in any of the treatments tested. Third, in each shadehouse about 10 percent of the immature fronds that might have been cold damaged when irrigation was used alone were protected by crop covers that were being evaluated during the winter of 1990-91.

Additional research is needed to evaluate and develop economical and effective crop cover materials and deployment methods. Research is also needed on ways, such as using genetic engineering or cryoprotectants, to increase the cold hardiness of leatherleaf fern.

ACKNOWLEDGEMENTS

The authors wish to thank Cindy Connery Boone, Danny Burch, Sheila Motley, B. J. Osteen, Mike Register, Diane Rock, Loretta Satterthwaite, Derek Sorzano and Curtis Weldon for their technical support during the course of this project. Their help with the installation and maintenance of the data collection instrumentation made this project possible. Additional help maintaining the site and preparing the shadehouses for cold weather was also contributed by Jana Register and her students at Taylor Middle-Senior High School Vocational Agriculture Department and is gratefully acknowledged.

The authors also wish to thank Mr. Richard Hagstrom and Richard Hagstrom Ferneries, of Pierson, Florida, for caring for and harvesting the leatherleaf fern crop at the research site. Thanks are also extended to the myriad individuals and companies in Florida's cut foliage industry (Appendix A) that contributed to the construction of the research facility itself. Finally, the authors wish to thank the St. Johns River Water Management District for providing funding that allowed the data acquisition component of this project to be carried out.

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ABSTRACT

Nine 29.3 m × 29.3 m × 2.5 m post and cable shadehouses spaced 9.8 m apart were constructed in a 3 × 3 Latin square design in Pierson, Florida for use in experiments testing irrigation rates, shadehouse icing, and crop covers for cold protecting leatherleaf fern [*Rumohra adiantiformis* (Forst) Ching]. The structures were covered with 73% woven polypropylene shade fabric and the sidewalls had an additional covering of nonporous poultry fabric. Each shadehouse was equipped with two irrigation systems — one over-the-crop to supply heat inside the structure and one over-the-shadehouse to supply water for sealing the openings in the shade fabric with ice (icing). The over-the-crop irrigation system consisted of frost protection wedge-drive impact sprinklers spaced 9.8 m apart on risers that extended 1 m above the soil. Each individual shadehouse was equipped with nozzles having one of three different size orifices (2.4, 2.8, and 3.2 mm) which, in conjunction with pressure regulators, provided water application rates of 0.38, 0.54, and 0.71 $cm \cdot hr^{-1}$ or 0.30, 0.56, and 0.76 $cm \cdot hr^{-1}$ during the winters of 1989-90 and 1990-91, respectively. The over-the-shadehouse irrigation systems consisted of impact sprinklers with 4 mm nozzles and were operated only long enough for ice to seal the shade fabric. In 1990-91, one shadehouse in each water application treatment was not iced using the over-the-shadehouse irrigation system. In addition, 6 m × 9 m spunbonded polypropylene crop covers weighing 20 and 51 $g \cdot m^{-2}$ were tested during the winter of 1990-91. During radiation freezes, all water application rates protected immature fronds from damage. Damage during advective freezes decreased with increasing water application rate, but even when crop covers were used in conjunction with irrigation some damage still occurred. Temperatures under the lighter-weight cover were higher than under the heavier-weight one, probably because more water passed through the lighter cover to the crop. Comparison of shadehouses receiving the same water application rates showed that icing of shadehouses increased inside temperatures. Cold protection water application rates had no effect on frond color or yield, but vase life of fronds harvested at one of four harvests may have been affected by application rate.

INTRODUCTION

Research Objectives

Irrigation systems have been used to apply water to protect leatherleaf fern [*Rumohra adiantiformis* (Forst) Ching] from cold damage in Florida for about three decades. Almost all leatherleaf fern production occurs on land under the jurisdiction of the St. Johns River Water Management District (SJRWMD). The following studies were undertaken to enable the SJRWMD to make more informed decisions about the parameters of irrigation water application rates and methods of application necessary to cold protect leatherleaf fern in production areas. The research objectives were: (1) to determine the effectiveness of different water application rates for cold protection of leatherleaf fern growing under 73 percent polypropylene shade fabric when used in combination with icing of the shade fabric roof and wrapping of the sidewalls with nonporous fabric; (2) to ascertain whether icing of the shade fabric roof of ferneries is effective in reducing heat loss; (3) to test crop covers for their effectiveness in holding heat under the covers when used in combination with irrigation; and (4) to determine the meteorological conditions under which each system is most effective.

Background Information

Leatherleaf Fern Production

Although Florida's cut foliage industry started in the late 1800's, there were only 42 acres of leatherleaf fern [*Rumohra adiantiformis* (Forst.) Ching] production in the state in 1956 (Chiang, 1958). By 1990 there were at least 4,846 acres devoted to leatherleaf fern production in Florida (USDA, 1991). The majority of that acreage is located in Lake, Putnam and Volusia counties (Cunningham and Sheehan, 1991). Today, leatherleaf fern is the predominant cut foliage crop in the world and the most valuable floricultural crop produced in Florida (USDA, 1991). The value of Florida sales at wholesale for the crop was conservatively estimated to be $70.5 million in 1990 (Fla. Agr. Statistics Serv., 1991).

Leatherleaf fern is a tropical plant that has a primarily circum-austral distribution (Tryon and Tryon, 1982). This herbaceous perennial plant is grown under shade on well-drained, sandy soils that have low water holding capacities (Henley et al., 1980). Immature leatherleaf fern fronds are not cold tolerant and sustain injury after exposure to temperatures below 30°F [-1°C] (Henley et al., 1980). Unfortunately, the probability that temperatures in the major fern producing counties will go below freezing during the winter are almost 100 percent (Bradley, 1983). The immature fronds produced during the winter months are especially important economically since they normally are ready for sale during the months from March through June when demand and prices are highest (Cunningham and Sheehan, 1991). In addition, the ability to consistently supply product on a year-round basis is critical if growers are to keep their customers (Stamps, 1991).

Since the 1960's, leatherleaf fern has been cold protected in Florida using irrigation water (Stamps and Conover, 1986). Published recommendations for minimum water application rates to use for cold protection of leatherleaf fern range from 0.3 to 0.35 inch/hr [0.8 to 0.9 $cm \cdot hr^{-1}$] (Harrison and Conover, 1970; Henley et al., 1980), equivalent to 139 to 158 gallons of water per minute (gpm) per acre [1,300 to 1,478 liters per min per hectare (ha)], respectively. The St. Johns River Water Management District (SJRWMD) has listed a maximum lower sprinkler system water application rate of 0.22 inch/hr [0.6 $cm \cdot hr^{-1}$], equal to 100 gpm/acre [935 $liter \cdot min^{-1} \cdot ha^{-1}$], as one of the approved water conservation methods for use when growing leatherleaf fern under artificial shade (SJRWMD, 1985). Mature fronds are more cold tolerant and, even though they form a canopy above the immature fronds, they are rarely damaged when irrigation is used for cold protection. However, immature leatherleaf fern fronds are damaged even when being cold protected using currently employed irrigation water application rates (Korosec, 1990).

Heat Transfer Principles

Heat is energy that flows from one place to another due to a difference in temperature. There are three main ways in which heat transfer ordinarily takes place: (1) conduction, the flow of heat through a material or from one body to another cooler body in contact with it; (2) convection, heat transfer caused by the circulation of gases or liquids; and (3) radiation heat loss due to radiant heat emission from the surface of bodies across space, such as from objects on earth into space (Lehrman and Swartz, 1965).

Considering a leaf as analogous to a flat metal plate, the nocturnal heat balance of the leaf is the algebraic sum of all three types of the heat transfers and may be written as follows (Harrison et al., 1974):

$$0 = C(dT/dt) + R_N + H_l + H_S$$

Where:

0 = zero

C is the heat capacity of the leaf per unit cross-sectional area

T is temperature

t is time

R_N is radiation

H_l is latent heat

H_S is convective heat

During calm freezes with clear skies, radiation (R_N) would be the major source of heat loss from the leaf and this type of freeze is called radiational. During windy (advective) freezes which result from large-scale mass movements of cold air, H_l and H_S would be the greater sources of heat loss.

Methods of Cold Protection

Cold Protection Using Plastic Sheeting and Heaters. Cold injury can be prevented by reducing heat loss and adding heat. Structures and heaters have long been used to cold protect high value ornamental crops, including some cut foliages. Conover et al. (1978) outlined procedures for attaching plastic to wooden-framed shadehouses and heating with various types of heaters. The plastic is used to reduce convectional heat loss but has relatively little effect on radiational heat loss except when the plastic is covered with condensate water (Kon et al., 1985; Seginer et al., 1988). It is reported that winter yield increases of up to 25 percent are possible using plastic sheeting and heaters (Conover et al., 1978). However, the costs of building shadehouses so that plastic can be attached to the frame; of buying, putting up, and disposing of the plastic sheeting; and of purchasing, fueling, maintaining and storing heaters are now too high to be economically feasible for use during leatherleaf fern production. In fact, simple comparisons of stack heaters used without wrapping shadehouses in plastic versus using overhead irrigation show that using heaters is eight times more expensive than using water (Castaldi, 1990). Therefore, leatherleaf fern in Florida is almost universally cold protected using overhead irrigation (Portier, 1988). The cut foliage industry is the second largest user of agricultural water in the St. Johns River Water Management District (Portier, 1988) and 60 percent or more of the water pumped may be used to protect the crops from cold (Leary, 1982).

Cold Protection Using Crop Covers. A newer cold protection method utilizes spunbonded polypropylene or polyester crop covers ("blankets") that are draped over the crop to trap heat rising from the soil. At the present time, the use of crop covers is expensive — the material alone costs from $750 to $2,000 per acre [$1,850 to $5,000$\cdot$ha^{-1}]. Covers vary in durability and have to be replaced when they wear out. Some materials may last a couple of years while heavier weight covers may last longer. While crop covers share the same storage and disposal problems as plastic sheeting, deployment of covers is more labor intensive because the covers have to be spread out over the crop before and rolled back up after each potential freeze event. In addition, large scale deployment of covers in shadehouses or oak hammocks would be difficult due to the numerous sprinklers and posts/trees that would be in the way. Furthermore, these impediments would necessitate the use of more and narrower pieces of crop cover materials than are used for field crops, thereby increasing the amount of cover perimeter that must be secured to the ground. Securing the perimeters causes mechanical damage to the fern and it is at these perimeter locations that much of the cold damage may occur. This technique works best on low growing crops like strawberries, but even then temperatures under the covers may drop below freezing even if drip irrigation is used under the covers (Hochmuth et al., 1986). Another problem associated with using crop covers in cut foliage production is that the rolled up covers would be in the way of the cutters that harvest the crops. Finally, the logistics of applying these covers to large acreages in a timely fashion before each potential freeze event are formidable. Finding a willing labor force capable of deploying the covers over thousands of acres of leatherleaf fern before each freeze may not be possible. Cheaper materials and new deployment technology are being studied; however, there is little information available at this time about the economics of using this technology on relatively low value crops like leatherleaf fern. Further research is needed to develop economical and effective materials and deployment methods.

Cold Protection Using Water. Water gives off heat, called sensible heat, as it cools after it is applied. For example, as 72°F [22°C] well water cools to 32°F [0°C] it gives off 332 British thermal units (Btu's) of heat per gallon of water. However, far greater amounts of heat gains (and losses) occur when water undergoes phase changes as from liquid to solid or liquid to gas (Table 1). For example, a much greater amount of heat is released (1,200 Btu's) as a gallon of water is converted from a liquid to a solid. However, loss of heat due to evaporation or sublimation can be 7-10 times greater than the amount of heat produced when water freezes. Table 1 lists the amounts of heat gains and losses associated with using water to cold protect crops.

Table 1. Approximate specific heating (or cooling) values for water (Harrison et al., 1974; Nobel, 1983).

	Phase change	Energy units*		
		British thermal units (Btu)	Calorie (cal)	Joule (J)
Heat capacity (mass basis)	no	8.3 Btu's/gallon/°F	1.00 cal • g^{-1} • $°C^{-1}$	4,187 J • kg^{-1} • $°C^{-1}$
Heat of fusion	yes (liquid|solid)	1,200 Btu's/gallon	78 cal • g^{-1}	0.325 MJ • kg^{-1}
Heat of vaporization at 32°F [0°C]	yes (liquid|gas)	8,100 Btu's/gallon	597 cal • g^{-1}	2.501 MJ • kg^{-1}
Heat of sublimation at 32°F [0°]	yes (solid|gas)	9,300 Btu's/gallon	675 cal • g^{-1}	2.826 MJ • kg^{-1}

*1 Btu = the heat required to raise the temperature of 1 pound of water 1°F (from 63 to 64°F), or raise 816 grams of water 1°C; 1 J = 0.239 cal = the amount of energy necessary to raise the temperature of 1 gram of water 1°C; 1 Btu = 1,055 J = 252.0 cal; 1 cal = 0.004 Btu = 4.186 J; 1 J = 0.0009 Btu = 0.239 cal.

When overhead irrigation is used for cold protection, the water must be applied more or less continuously (Harrison and Conover, 1970). If the interval between wetting of the foliage of the crop is too long, the temperature could drop low enough for the crop to be damaged (Harrison et al., 1974; Wheaton and Kidder, 1965). Indeed, the temperature that wet foliage would drop to during a given period of time is greater than that of a dry leaf under the same environmental conditions, unless the air around the leaf is saturated with water vapor. This is due to the relatively high heat loss from evaporation that was mentioned above. The drier the air, the greater will be the depression of the temperature. Table 2 illustrates the relationship between wet leaf and dry leaf temperatures under different temperature and relative humidity conditions.

Table 2. Approximate lowering of wet leaf temperature compared to dry leaf temperature for selected air temperatures and relative humidities when the barometric pressure is 30 inches of mercury [101 kPa] (Marvin, 1937).

Air temperature (°F)	Approximate relative humidity (percent)											
	95	90	85	80	75	70	65	60	55	50	45	40
36	0.5	1.0	1.5	2.2	2.8	3.2	4.0	4.5	5.0	5.6	6.1	6.8
32	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
28	0.5	0.8	1.4	1.7	2.1	2.5	3.0	3.5	4.0	4.4	4.8	5.3
24	0.4	0.8	1.3	1.5	1.8	2.3	2.7	3.0	3.5	3.8	4.2	4.5
20	0.4	0.7	1.0	1.3	1.6	2.0	2.4	2.6	3.0	3.4	3.7	4.0
16	0.2	0.6	0.8	1.2	1.4	1.8	2.0	2.3	2.6	2.8	3.2	3.4
14	0.2	0.5	0.8	1.0	1.4	1.6	1.8	2.3	2.4	2.6	3.0	3.2
Air temperature (°C)	Approximate relative humidity (percent)											
	95	90	85	80	75	70	65	60	55	50	45	40
2.2	0.3	0.6	0.8	1.2	1.6	1.8	2.2	2.5	2.8	3.1	3.4	3.8
0	0.3	0.6	0.8	1.1	1.4	1.7	1.9	2.2	2.5	2.8	3.1	3.3
-2.2	0.3	0.4	0.8	0.9	1.2	1.4	1.7	1.9	2.2	2.4	2.7	2.9
-4.4	0.2	0.4	0.7	0.8	1.0	1.3	1.5	1.7	1.9	2.1	2.3	2.5
-6.7	0.2	0.4	0.6	0.7	0.9	1.1	1.3	1.4	1.7	1.9	2.1	2.2
-8.9	0.1	0.3	0.4	0.7	0.8	1.0	1.1	1.3	1.4	1.6	1.8	1.9
-10.0	0.1	0.3	0.4	0.6	0.8	0.9	1.0	1.3	1.3	1.4	1.7	1.8

Adequate irrigation water application rates are necessary to offset conductive, convectional, and radiant heat losses. Uniformity of application is important to maximize the efficiency of this cold protection technique. Application of too little water, as noted above, results in damage to the crop (Harrison et al., 1974). Conversely, application of too much water leads to water runoff from the foliage that contributes little heat energy and may cause erosion or other problems (see next section).

- Disadvantages of Using Water for Cold Protection — Using sprinkler irrigation to cold protect cut foliage crops requires large quantities of water — up to 200 gpm/acre [1,870 liter$\cdot$min$^{-1}\cdot$ha^{-1}] (Leary, 1982; Ross, 1980), using application rates of 0.35 to 0.44 inch/hr [0.9 to 1.1 cm$\cdot$hr^{-1}] (Harrison et al., 1974; Stamps and Mathur, 1982). [Note: an acre-inch of water is the amount of water it would take to cover an acre to a depth of one inch and is equivalent to 27,152 gallons.] Large applications of water can leach fertilizers and pesticides past the root zone of the crop (Harrison and Conover, 1970; Henley et al., 1980; Norcini, 1987), cause considerable temporary declines in water levels in the aquifer (Ross, 1980) and cause saturation of the crop root zone with the resulting potential for disease development (Harrison and Conover, 1970). Furthermore, using irrigation water to cold protect leatherleaf fern may not provide protection for immature fronds (Korosec, 1990) and the weight of the ice formed during cold protection can crush both immature and mature fronds. This latter problem is usually not too severe unless the fern is tall and/or sparse or the freeze is long in duration.

  Another problem associated with the use of water for cold protection is that if there is an interruption of water application for any reason — e.g., power failure, pump breakdown, line bursting — cold damage to the crop may be greater than if water were not applied at all (Rosenberg et al., 1983). Since a continuous supply of electricity cannot be assured during freeze events, most growers (80 percent) power their pumps using diesel engines (Boggess et al., 1991).

- Advantages of Using Water for Cold Protection — Despite the above disadvantages of using water to protect crops from cold damage, the use of water to supply heat to prevent cold damage to crops remains the method of choice for cut foliage growers because of economics and logistics as mentioned previously. In addition, growers now routinely also use their irrigation systems for other purposes such as applying fertilizers and pesticides (Boggess et al., 1991; Stamps, 1990a), thereby further reducing production costs.

Previous Cut Foliage Cold Protection Research Using Water Over-the-Crop

Early research by personnel of the University of Florida's Institute of Food and Agricultural Sciences (IFAS) and the U.S. Weather Bureau (now the National Weather Service) showed that various water application rates can be used with some success in controlling temperatures and protecting cut foliage crops (Dean, 1965; Dean, 1966; Harrison and Conover, 1970). Dean (1966) reported protection of plumosus fern (*Asparagus plumosus*) with water application rates of 0.29 inch/hr [7.4 $mm \cdot hr^{-1}$], equal to 131 gpm [497 $liter \cdot min^{-1}$] using conventional, 1 revolution/minute (rpm), low-angle impact sprinklers under minimum air temperature of 20°F [-6.7°C] and 1 to 3 miles/hour [1.6 to 4.8 $km \cdot hr^{-1}$] wind speeds. However, 10 to 15 percent of the crop was damaged when temperatures were warmer (low of 25°F [-3.9°C]) but wind speeds higher (15 to 25 mph [24 to 40 $km \cdot hr^{-1}$]). The above research failed to quantify the precise application rates necessary under varying cold conditions and did not deal with crops growing under polypropylene shade fabric — where over 65 percent of leatherleaf fern production occurs (Stamps and Conover, 1986).

Research in the early 1980's showed that leatherleaf fern could be successfully cold protected during a radiation freeze with only 0.20 inch/hr [5.2 $mm \cdot hr^{-1}$] of water by using frost protection impact sprinklers with rotation rates of 6 rpm (Stamps and Chase, 1981). The minimum (dry bulb) temperature was 11°F [-12°C] and wind speeds were calm during this study.

Stamps and Mathur (1982) reported that water application rates of 0.18 inch/hr [4.6 $mm \cdot hr^{-1}$] using frost protection wedge-drive sprinklers making 2.9 rpm were as effective as applying 0.34 inch/hr [8.6 $mm \cdot hr^{-1}$] using conventional 1.1 rpm impact sprinklers when wind speeds were low (Figure 1). However, both irrigation systems proved to be inadequate when wind speeds were high (Figure 2).

Previous Cut Foliage Cold Protection Research Using Water Over-the-Shadehouse

The first study to use ice to seal the openings of a porous covering attached to a structure covering a cold sensitive crop was conducted in Idaho (Cary, 1974). Water was applied to an aluminum window screen-covered enclosure. The screen and ice cover reduced heat loss from the enclosure.

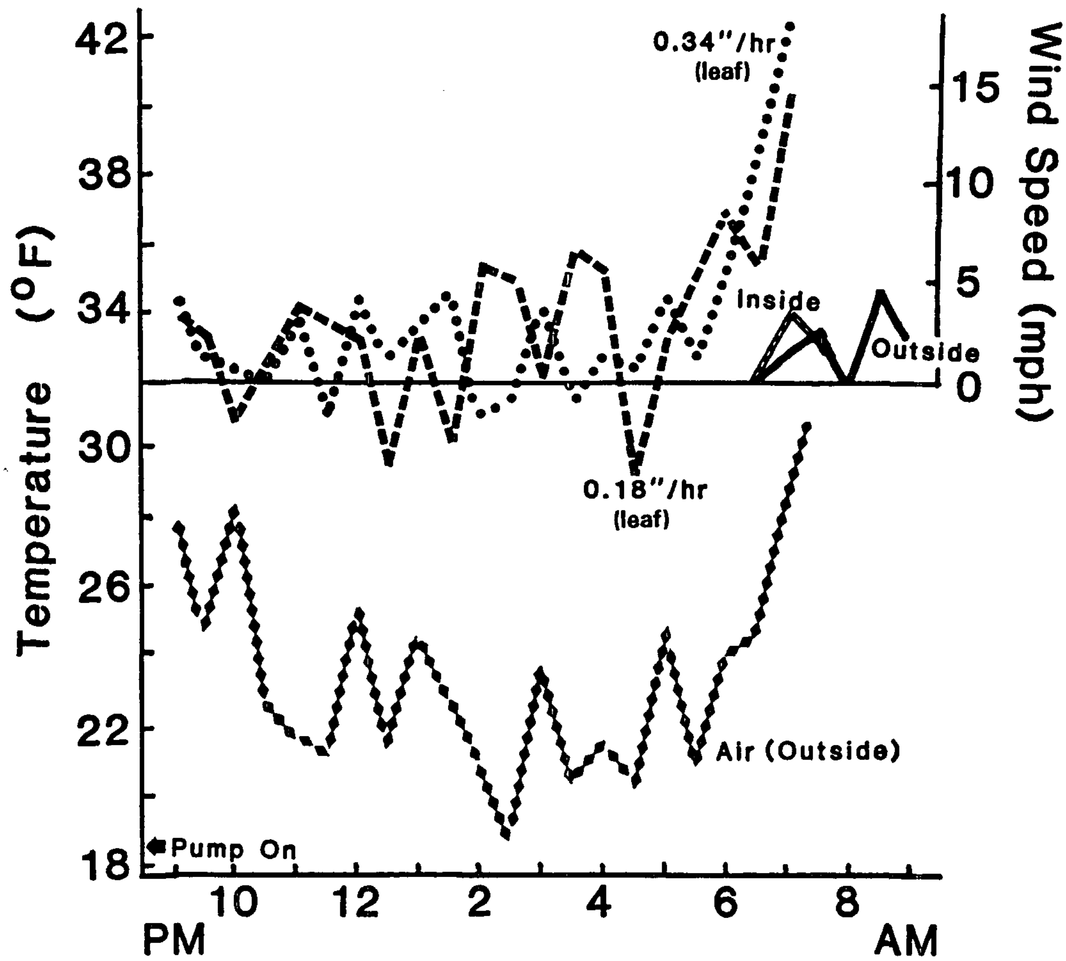

Figure 1. Comparison of leaf (---, ····) and air (-◆-) temperatures when using conventional irrigation sprinklers (1.1 rpm, 0.34 inch/hr [8.6 mm·hr^{-1}]) and frost protection sprinklers (2.9 rpm, 0.18 inch/hr [4.6 mm·hr^{-1}]) during a radiation freeze (Stamps and Mathur, 1982). The wind was calm until sunrise both inside and outside the shadehouse.

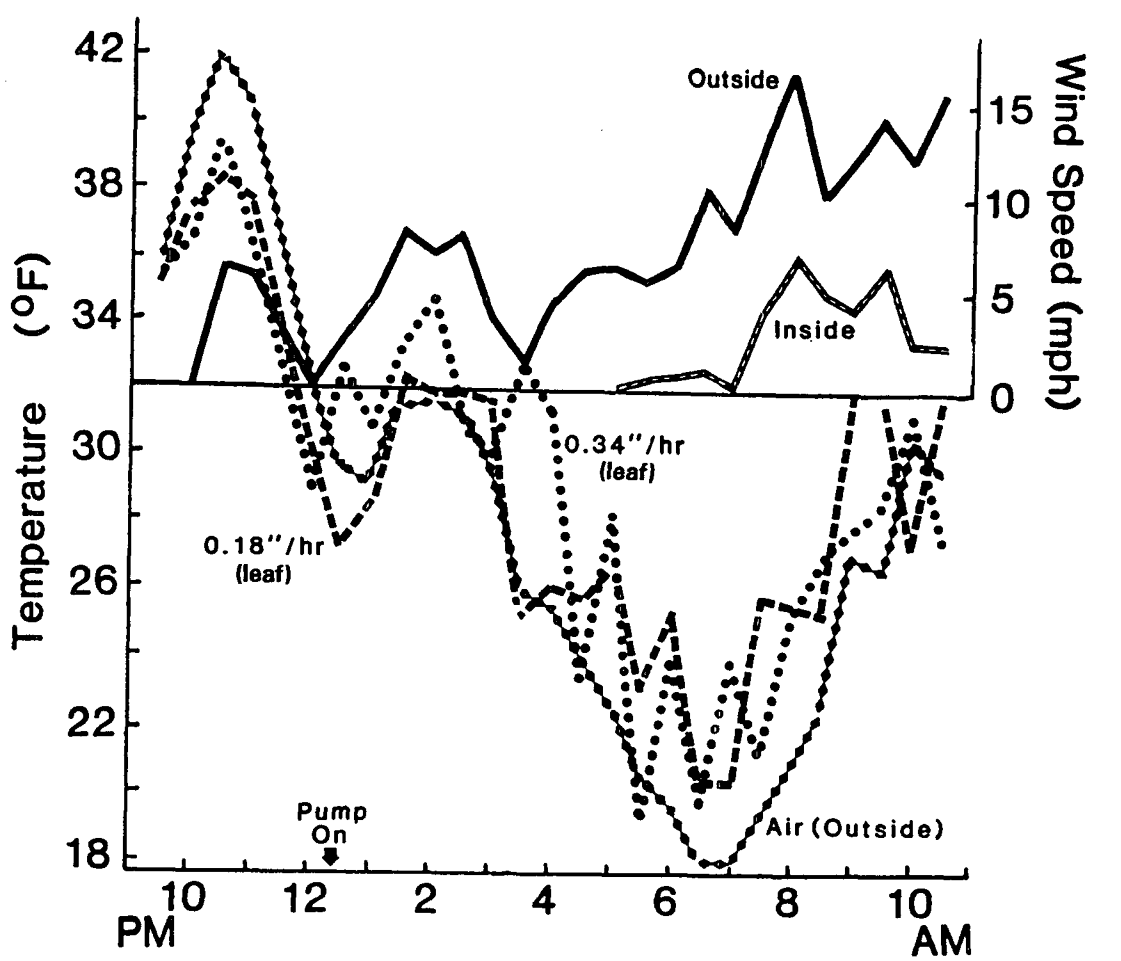

Figure 2. Comparison of leaf (---- , ••••) and air (-•-•-) temperatures when using conventional irrigation sprinklers (1.1 rpm, 0.34 inch/hr [8.6 mm•hr^{-1}]) and frost protection sprinklers (2.9 rpm, 0.18 inch/hr [4.6 mm•hr^{-1}]) for cold protection during an advective freeze (Stamps and Mathur, 1982). The highest wind speed recorded inside the fernery was 6.8 mph [10.9 km•hr^{-1}].

Studies conducted in Florida in iced shadehouses during the winter of 1985-86 suggested that the technique of using ice to seal polypropylene shade fabric-covered shadehouses might reduce irrigation system water application rates required inside the structures for cold protection of crops (Stamps, 1987). Temperatures were consistently higher two feet [0.6 m] below the shadehouse roof than at crop level (two feet above the soil surface), indicating that much of the heat from the irrigation water was not useful for protecting the crop. These preliminary studies were not conducted with replication of the shadehouse treatments and could not provide information regarding under what conditions and to what extent icing of shadehouses is beneficial during cold protection. However, these studies did suggest that icing may require the concurrent use of windbreaks and/or shelterbelts during advective freezes.

Subsequent research showed that the use of the now patented technique of sealing the shade fabric using over-the-shadehouse irrigation that formed ice to seal the openings (U.S. Patent and Trademark Office, 1988) in conjunction with frost protection nozzles can increase temperatures in shadehouses using equivalent amounts of irrigation water and/or reduce the amount of water necessary to maintain temperatures at a given level during radiation freezes (Stamps, 1989). Figure 3 illustrates the ability to maintain higher temperatures in iced versus uniced shadehouses when applying the same amount of water inside the structures.

Previous Cut Foliage Cold Protection Research Using Crop Covers

Light-weight (0.6 oz/yd^2 [20 g$\cdot$m^{-2}]) covers have been reported to offer 2.5°-5.5°F [1.5°-3°C] of cold protection for low-growing crops produced in the open (Hochmuth et al., 1986; Loy and Wells, 1982; Wells and Loy, 1985), and more expensive, heavier-weight covers have been shown to offer somewhat greater cold protection when used on strawberries (Hochmuth et al., 1986). Stamps (1990b) demonstrated that temperatures under 0.6 oz/yd^2 [20 g$\cdot$m^{-2}] row covers were 5°-6°F [2.7°-3.5°C] higher than where covers were not used (Figure 4). Temperatures were 7°-9°F [3.9°-5.1°C] higher than ambient under heavier 1.5 oz/yd^2 [51 g$\cdot$m^{-2}] covers. It should be noted that temperatures during these studies were only in the mid-20°s [-3° to -4°C] and wind speeds were low (typical radiation freeze events). The temperature differential between outside the covers and under the covers would, of course, be reduced under colder and/or windier conditions.

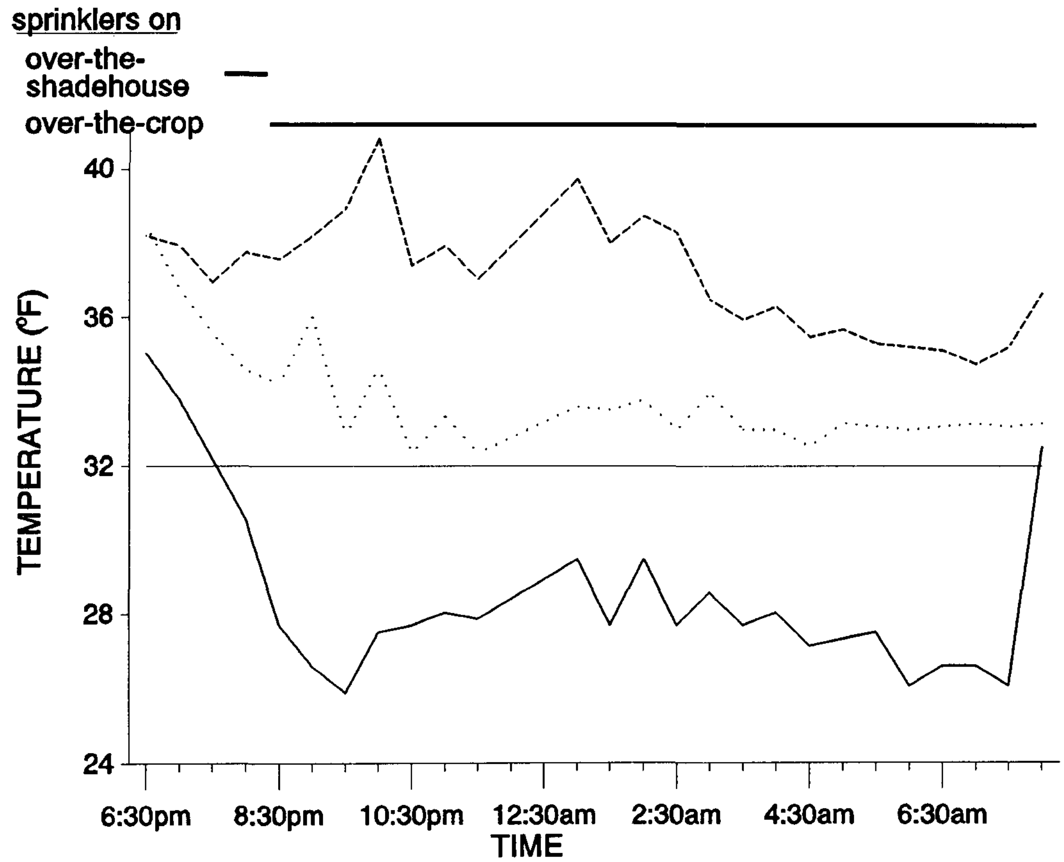

Figure 3. Ambient air temperatures outside shadehouses (—) and inside uniced (·····) and iced (- - -) shadehouses. The irrigation rate inside both shadehouses was 0.25 inch/hr [6.4 mm·hr^{-1}] (Stamps, 1989).

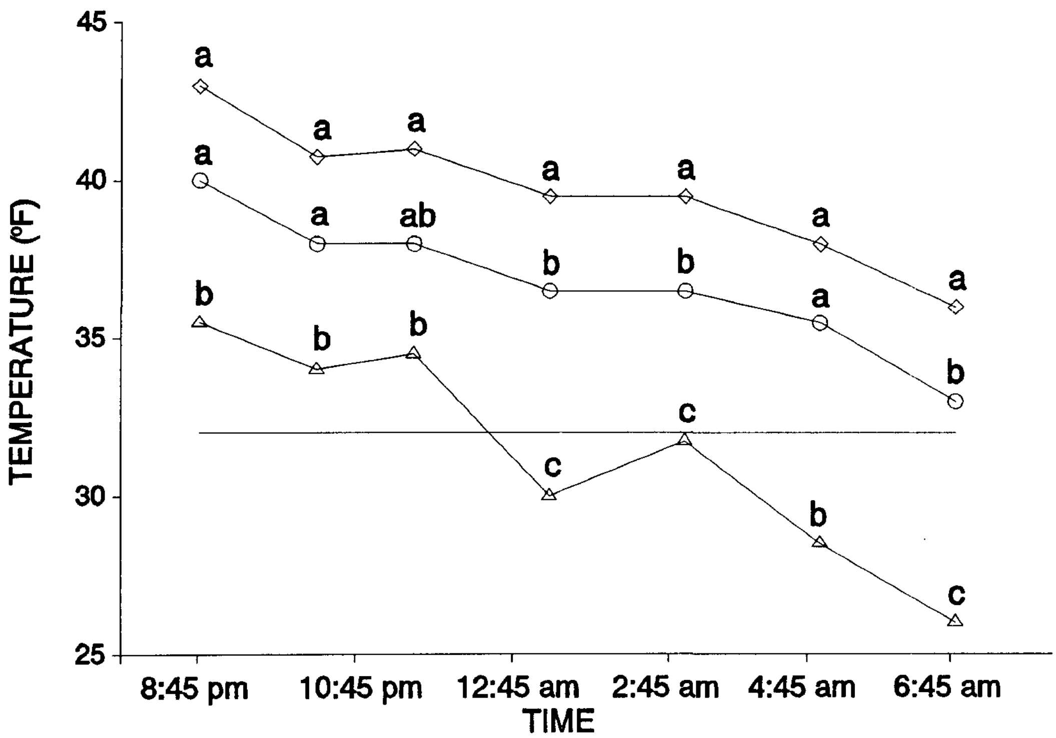

Figure 4. Temperatures 9 inches [23 cm] above the soil surface under 0.6 oz/yd^2 [20 g·m^{-2}] (··○··) or 1.5 oz/yd^2 [51 g·m^{-2}] (---◇---) spunbonded polypropylene crop covers or no cover (—▵—) (Stamps, 1990b). For a given time, temperatures marked with the same letter are not statistically different (Duncan's new multiple range test, P=0.05).

Previous Cut Foliage Cold Protection Research Using Crop Covers and Over-the-Crop Irrigation

Only one study has ever been conducted using the combination of crop covers and overhead irrigation to cold protect leatherleaf fern (Stamps, 1991) and that study was limited to one irrigation application rate (0.25 inch/hr [6.4 $mm \cdot hr^{-1}$]). As was shown previously, heavier and less porous covers provided the most protection when used without over-the-crop irrigation (Figure 5). However, differences in cover weight and porosity did not affect temperatures under covers when over-the-crop irrigation was applied (Figure 6).

Finally, damage to immature fronds was decreased by 75 to 99 percent when covers were used alone and by 98 to 99 percent when covers were used in combination with over-the-crop irrigation (Figure 7).

MATERIALS AND METHODS

Shadehouse design

Nine 96 ft by 96 ft [29.3 m × 29.3 m] post and cable shadehouses spaced 32 ft [9.8 m] apart were constructed in a 3 × 3 Latin square design (Denes and Keedwell, 1974) in Pierson, FL (Figure 8). The structures, located on Volusia County Schools' property, were 8.5 ft [2.5 m] tall and covered with 73 percent woven polypropylene shade fabric. The individuals, organizations and institutions that contributed to this research project are listed in Appendix A. Since the ratio of exposed surface area to the volume of these experimental shadehouses is higher than that of a larger shadehouse (see Appendix B), the results obtained in these experiments should be considered worst case — i.e., all things being equal except shadehouse size, less crop damage would occur in larger structures. During the winter, all ferneries had their sidewalls wrapped with nonporous poultry fabric.

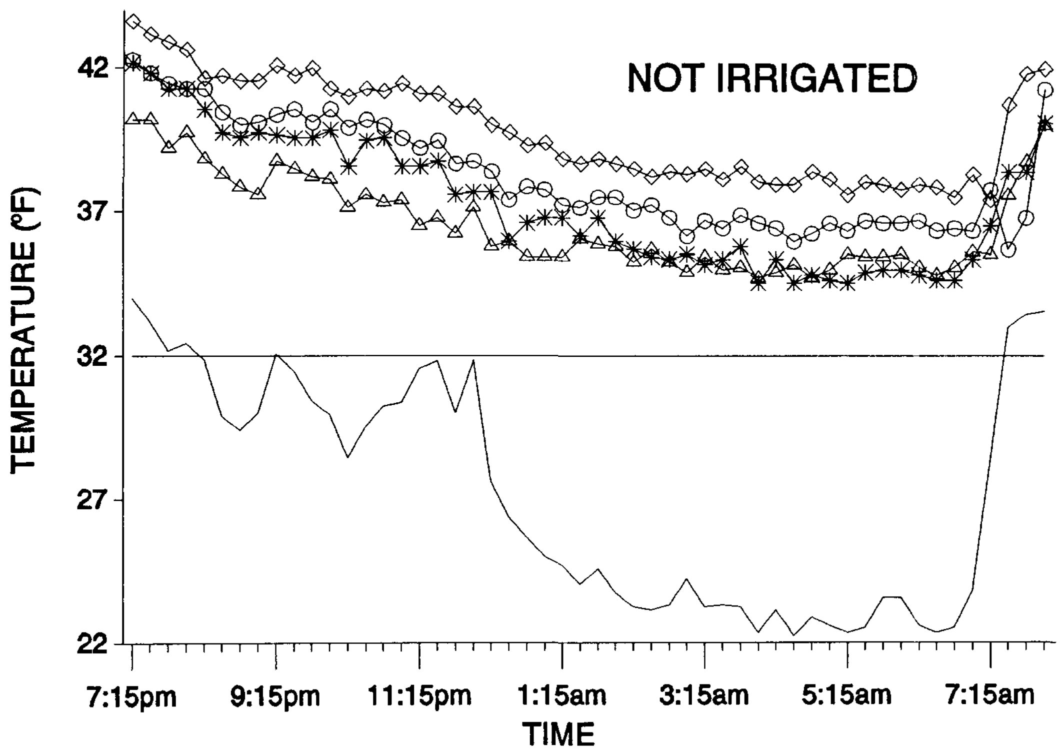

Figure 5. Air temperatures inside a shadehouse (—) and under crop covers of 0.62 oz/yd^2 [21 g·m^{-2}] polyester (△) and 0.6 oz/yd^2 [20 g·m^{-2}] (*), 1.5 oz/yd^2 [51 g·m^{-2}] (◇), and 1.9 oz/yd^2 [64 g·m^{-2}] (○) polypropylene (Stamps, 1991).

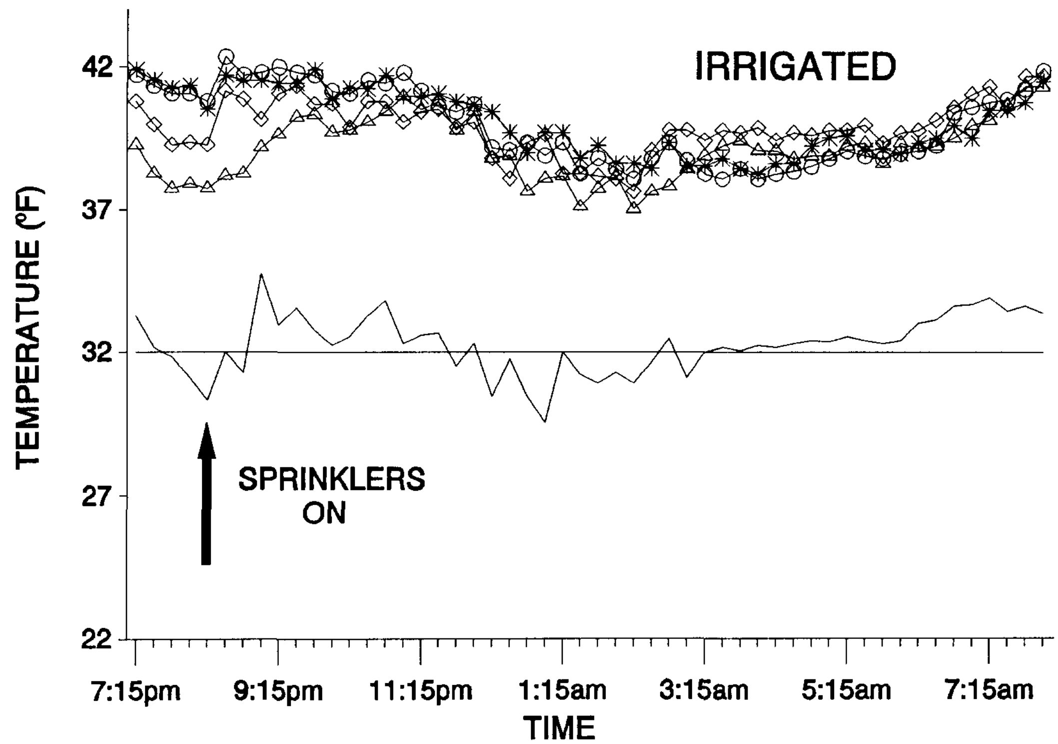

Figure 6. Air temperatures inside a shadehouse (—) and under crop covers of 0.62 oz/yd^2 [21 g·m^{-2}] polyester (△) and 0.6 oz/yd^2 [20 g·m^{-2}] (*), 1.5 oz/yd^2 [51 g·m^{-2}] (◇), and 1.9 oz/yd^2 [64 g·m^{-2}] (○) polypropylene (Stamps, 1991).

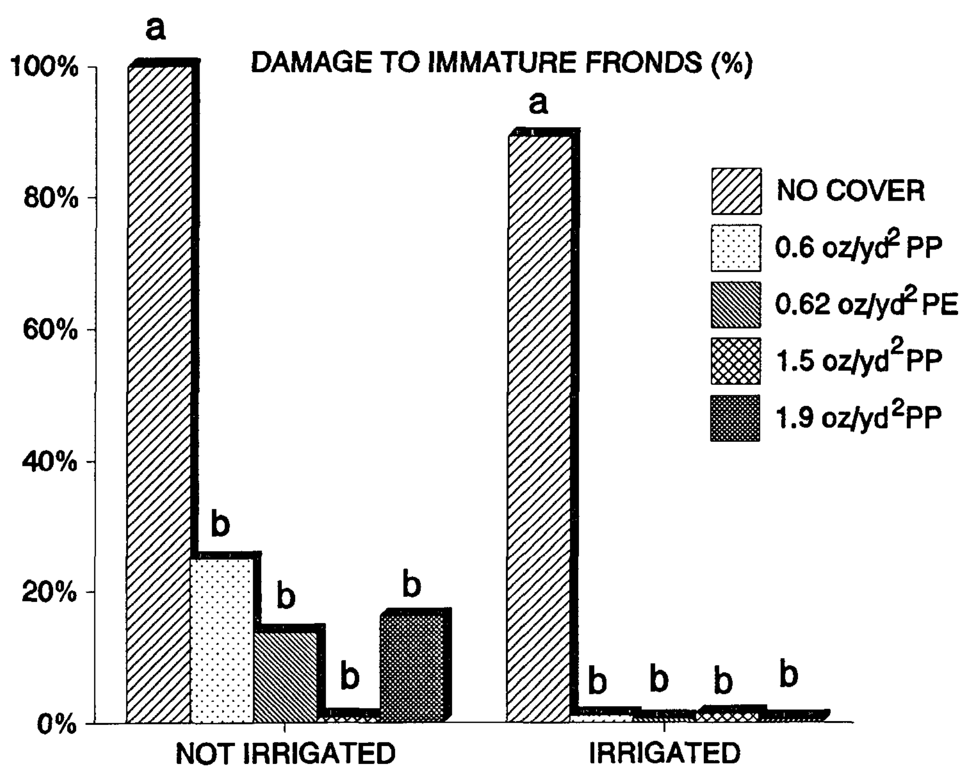

Figure 7. Frond damage under 0.6, 0.62, 1.5, or 1.9 oz/yd^2 [20, 21, 51, or 64 g·m^{-2}] spunbonded polyester (PE) or polypropylene (PP) crop covers compared with no crop cover, with and without over-the-crop irrigation (Stamps, 1991).

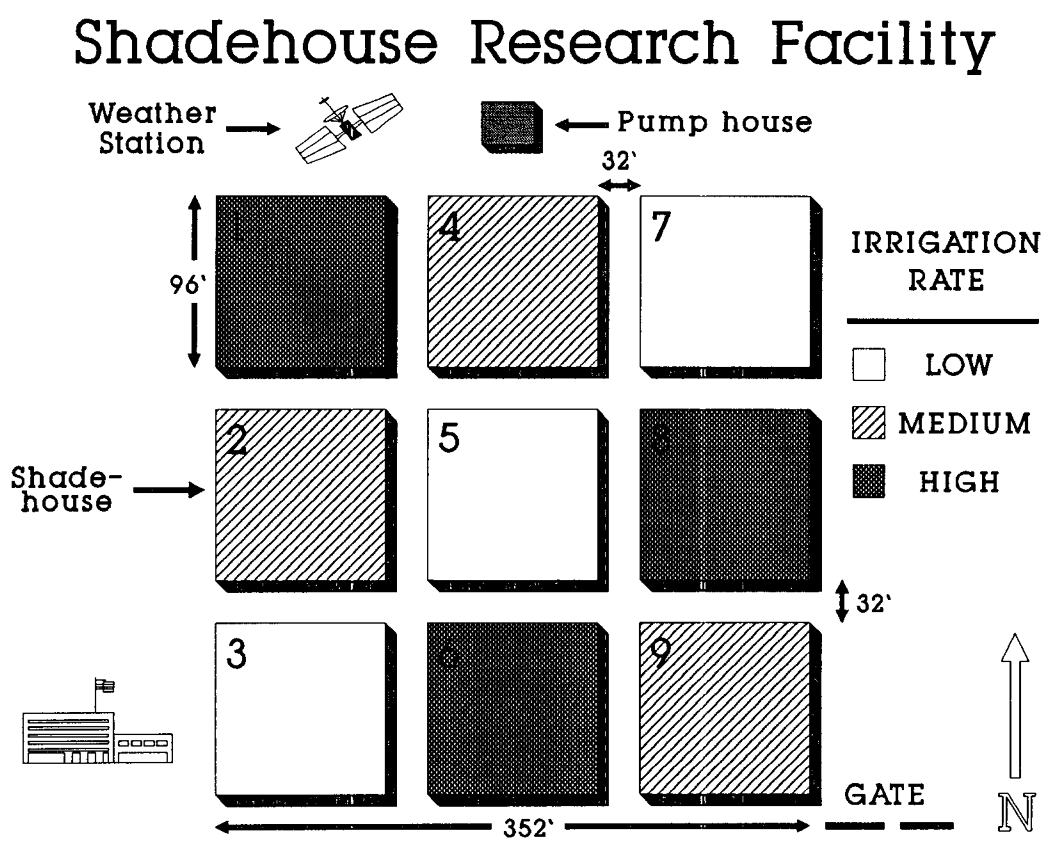

Figure 8. Latin-square design of irrigation water application rate treatments at shadehouse research facility in Pierson, Florida.

Irrigation systems

Each shadehouse was equipped with two irrigation systems (Figure 9) — one over-the-crop to supply heat inside the structure and one over-the-top of the shadehouse to supply water for sealing the openings in the shade fabric with ice to help retain the heat. When there was no threat of cold weather, the over-the-crop irrigation system consisted of frost protection wedge-drive impact sprinklers (L20VH, Rain Bird, Glendora, Calif. 91740) with 1/8 inch [3.2 mm] orifices. Sprinklers were spaced 32 ft [9.8 m] apart on risers that extended 3 ft [1 m] above the soil. Prior to each freeze, the sprinklers in a given shadehouse were changed and the same type of sprinkler, equipped with either 3/32, 7/64 or 1/8 inch [2.4, 2.8 or 3.2 mm] orifice nozzles with square openings (LP-1, Rain Bird), were installed. Three shadehouses were equipped with each of the three different orifice size sprinklers in the Latin square design illustrated previously. In addition to changing the sprinklers before a freeze, pressure regulators for the over-the-crop irrigation system for each house were changed so that the desired water application rates could be obtained. The rates tested during the winter of 1989-90 are listed in Tables 3 and 4 and those for 1990-91 are listed in Tables 5 and 6. The over-the-crop irrigation systems were turned on when wet-bulb temperatures dropped below 34°F [1 °C] and irrigation was stopped when wet-bulb temperatures went above that same temperature.

Water applied by each irrigation system in each shadehouse was monitored using totalizing flowmeters. After each freeze event the first set of sprinklers, all with 1/8 inch [3.2 mm] orifice nozzles, were reinstalled as were the standard pressure regulators. This use of two sets of sprinklers eliminated the problem of incorrect nozzle alignment in the sprinklers (the orifices in LP-1 nozzles are asymmetrical) and assured that all frost protection sprinklers would have the same number of hours of operation. The use of uniform nozzles, sprinklers and pressure regulators in all houses during all periods, except when actually cold protecting the crop, also assured that there would be no bias in the yield or vase life results due to non-uniform chemigation, fertigation or irrigation application among shadehouses.

The over-the-shadehouse irrigation systems consisted of impact sprinklers (3023, Senninger, Orlando, FL 32811) with 5/32 inch [4 mm] nozzles. Sprinklers were spaced 60 ft [18.3 m] apart on 10 ft-tall [3.1 m-tall] risers that extended about 1.6 ft [0.5 m] above the top of the shadehouse. The over-the-shadehouse systems were operated at 40 psi [276 kPa] to deliver water at approximately 0.12 inch/hr [0.3 $cm \cdot hr^{-1}$]. When temperatures were

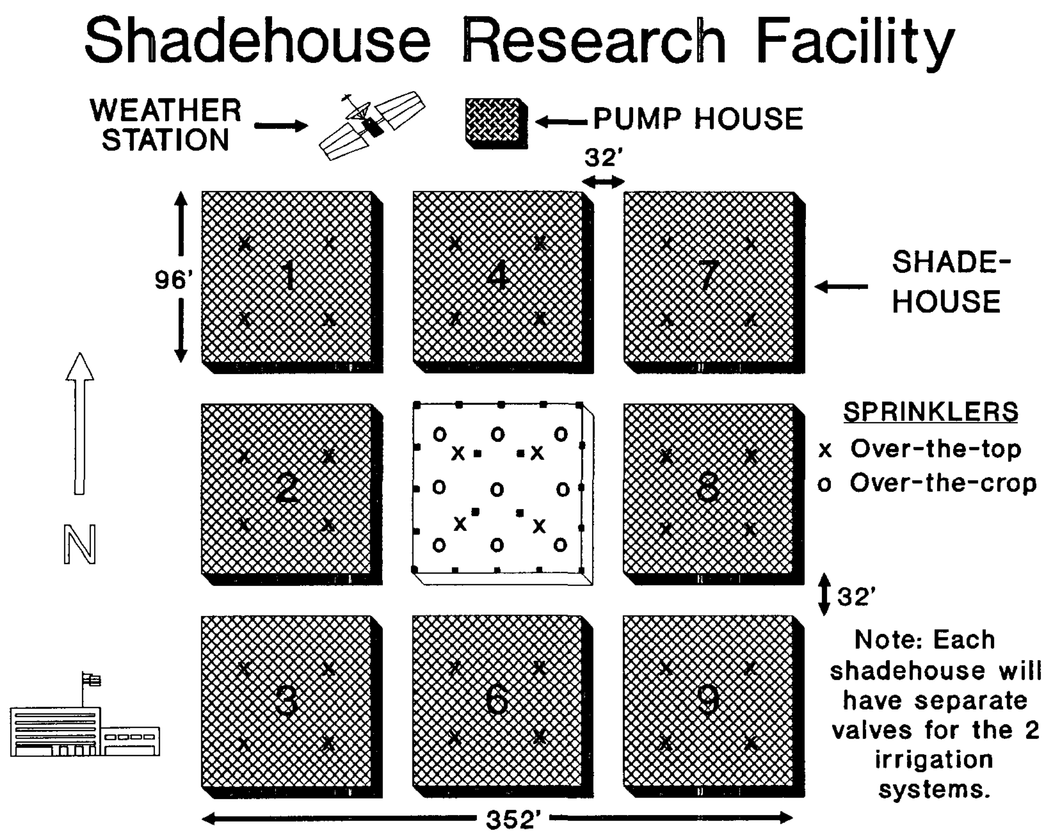

Figure 9. Schematic of shadehouse research facility in Pierson, Florida. Note that the shade fabric has been removed from the center shadehouse to reveal the layout of the over-the-crop irrigation systems. Each shadehouse was equipped with both over-the-shadehouse (over-the-top) and over-the-crop irrigation systems.

low enough for ice to form, the over-the-shadehouse irrigation systems were operated just long enough to seal the shade fabric with ice using 15- to 60-minute applications. Once the shadehouses were sealed, no further overhead irrigation was applied during the night. In 1990-91, one shadehouse in each water application treatment was not iced using the over-the-shadehouse irrigation system during each freeze event to determine the effects of icing.

Crop covers

Spunbonded polypropylene crop covers (Kimberly-Clark, Roswell, GA 30076) weighing 0.6 oz/yd^2 [20 g$\cdot$m^{-2}] and 1.5 oz/yd^2 [51 g$\cdot$m^{-2}] were used during the winter of 1990-91 to determine the interactive effects of crop cover weight and irrigation water application rate for cold protection of leatherleaf fern. Twenty ft $\times$ 30 ft [6 m $\times$ 9 m] covers were rolled lengthwise and pinned to the ground along one edge using wire. The covers were located in the center of the shadehouse so that they would extend over two beds of fern and be pinned in the aisles (Figure 10).

Temperature measurement

Temperatures in each shadehouse were monitored with nine thermocouples (AWG 24, Omega Engineering, Stamford, CT 06907) attached to a datalogger (CR10, Campbell Scientific, Logan, UT 85321) via multiplexers (AM32, Campbell Scientific). One thermocouple measured the temperature of the shadehouse roof, two were located at the top of the fern canopy, and four others measured air temperatures in the shadehouse. Two thermocouples were located in an aspirated box placed inside a weather enclosure. One of these thermocouples measured dry-bulb temperatures and the other measured wet-bulb temperatures. Fans in the enclosures were turned on three minutes before readings were made. The wet-bulb temperatures were used to determine when to turn on the irrigation systems. During the crop cover studies (1990-91), four additional thermocouples in each shadehouse (two for each row cover) monitored temperatures under the covers. One measured temperatures in the middle of the fern bed at a location 9 inches [23 cm] above the soil surface and one measured temperatures near the top of the fern canopy on the underside of the crop cover.

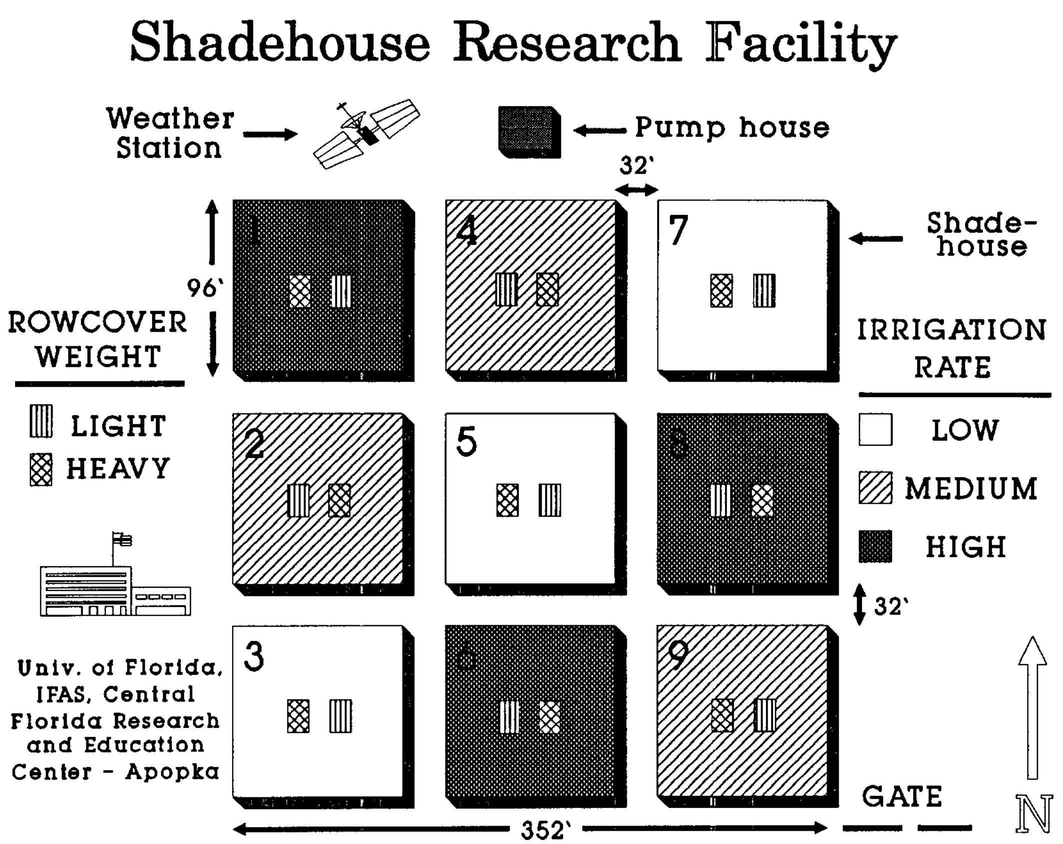

Figure 10. Location of crop covers in shadehouses at the shadehouse research facility in Pierson, Florida.

Wind speed measurement

Anemometers outside the shadehouses and inside the center shadehouse monitored wind speeds. The outputs from the anemometers were measured and converted to wind speed by the datalogger.

Cold damage assessments

Cold damage to leatherleaf fern fronds was determined by counting damaged and undamaged fronds in two randomly selected 11 ft^2 [1 m^2] subplots near the center of each shadehouse (1989-90), and both in and outside each row cover plot (1990-91). In addition, overall cold damage in the center (34 ft × 34 ft [10.4 m × 10.4 m]) of each shadehouse (but outside the row cover plots) was visually assessed and rated on a scale from 0-3 (0 = none, no damage; 1 = slight, minimal damage to individual fronds, fronds still salable; 2 = moderate, >10 percent of fronds unsalable; and 3 = severe, most of the fronds unsalable) during the winter of 1990-91.

Frond color determinations

Frond color was measured after freezes using a color meter (CR-100, Minolta, Ramsey, NJ 07446). An opaque black card was held behind a central pinna of newly matured fronds on which readings were being taken. Chromaticity was expressed numerically using the $L^{\star}a^{\star}b^{\star}$ color notation system where $L^{\star}$ indicates value (lightness or darkness), $a^{\star}$ indicates hue (color), and $b^{\star}$ indicates chroma (saturation). Chroma $C^{\star}$ was calculated as:

$$C^{*} = \sqrt{a^{*2} + b^{*2}}$$

A larger $L^{\star}$ value indicates a lighter color, a larger negative $a^{\star}$ indicates a stronger green color and a larger $b^{\star}$ indicates a brighter yellow color.

Vase life determinations

Vase life of mature fronds harvested after freeze events was determined under simulated home/office conditions. Periodically, mature, dark-green fronds were harvested at random from the center of each shadehouse in the area delineated by the four interior posts. Fronds were harvested using clippers, bunched in groups of twenty, placed inside polyethylene bags and transported to CFREC-Apopka where water was added to the bags before they were placed in waxed corrugated fiberboard boxes and stored at 40°F [4.4°C] for 7 days. After storage, frond stipe bases were recut using razor blades and fronds were held in deionized water in rooms that were maintained at 73° ± 2°F [23° ± 1°C] and lighted using cool white fluorescent lamps supplying 115 ft-c (15 $\mu mol \cdot s^{-1} \cdot m^{-2}$) of photosynthetically active radiation for 12 hours per day.

Yield

Commercial fern cutters harvested fronds from the research shadehouses throughout 1990 and 1991. Yield was determined by counting the number of bunches of fern (25 stems/bunch) harvested from each shadehouse. In addition, researchers carefully harvested bunches that had exactly the same number of stems of similar physiological maturity — determined by the developmental stage of sori on the fronds. These latter bunches were used to determine if treatments had any effect on frond size.

Statistical analysis

Data were analyzed using analysis of variance (qualitative treatments) and regression analysis (quantitative treatments). Percentage data were transformed when appropriate using arcsine transformation prior to statistical analysis. All comparisons were made at $P = 0.05$.

RESULTS

Temperatures

Radiation Freezes

December 3-4, 1989. This radiation freeze had low temperatures of 23°F [-5°C]. The over-the-shadehouse irrigation systems were turned on at 7:25 p.m. [1925 HR] when the wet-bulb temperatures inside the shadehouses dropped below 34°F [1°C] and were run for 30 minutes until a thin layer of ice had formed on the shadecloth. The over-the-crop irrigation systems were started at 8:20 p.m. [2020 HR] when the wet-bulb temperatures inside the shadehouses once again dropped below 34°F [1°C]. At 12:35 a.m. [0035 HR] the over-the-crop irrigation was stopped and the over-the-shadehouse system restarted since the heat from the lower irrigation system was melting holes in the ice covering the shadecloth. At 1:10 a.m. [0110 HR] the shadecloth was thoroughly wet and ice was forming again so the over-the-shadehouse irrigation systems were turned off. Thirty minutes later wet-bulb temperatures inside the shadehouses dropped below 34°F [1°C] so the over-the-crop irrigation system was turned on and run until 8:25 a.m. [0825 HR] when temperatures rose above 34°F [1°C]. Table 3 lists the amounts of water applied during this radiation freeze.

Table 3. Cold protection water application rates for the December 3-4, 1989 freeze event.

Rate	gpm/acre	inches/hr	$cm \cdot hr^{-1}$	Total gallons	*Percent difference compared* to 100 gal/min/acre criteria
High	123	0.27	0.71	42,077	+ 23
Medium	99	0.22	0.53	33,987	- 1
Low	67	0.15	0.38	22,850	- 33
An average of 1,347 gallons of water was applied to each shadehouse by the over-the-shadehouse irrigation systems.					

Temperatures were higher in the shadehouses than outside the shadehouses throughout the irrigated period and were highest in the houses with the high and medium over-the-crop water application rates (Figure 11). During the period when the over-the-crop irrigation system was in operation and ambient temperatures were below freezing (1:45-7:30 a.m. [0145-0730 HR]), overall leaf temperatures averaged 11°F [6°C] higher in the iced and wrapped shadehouses than outside and remained above 34°F [1°C]. During that period, leaf temperatures averaged 10°, 13° and 12°F [5.5°, 7° and 6.6°C] higher in the low, medium and high water application rate shadehouses, respectively, than outside (ambient).

December 24-25, 1989. During this radiation freeze, ambient temperatures dropped to 19°F [-7.8°C]. Table 4 lists irrigation water application rates used during this freeze event. Increased water application rates provided higher temperatures (Figure 12); however, all application rates maintained temperatures above 33°F (0.6°C). From 5:30 p.m. - 8:30 a.m. (1730-0830 HR), temperatures were 10°, 12° and 13°F [6°, 7° and 7.3°C] higher in the low, medium and high water application rate houses, respectively, than outside (ambient). During this time period, ambient temperatures were below freezing and the over-the-crop irrigation system was running. Overall,

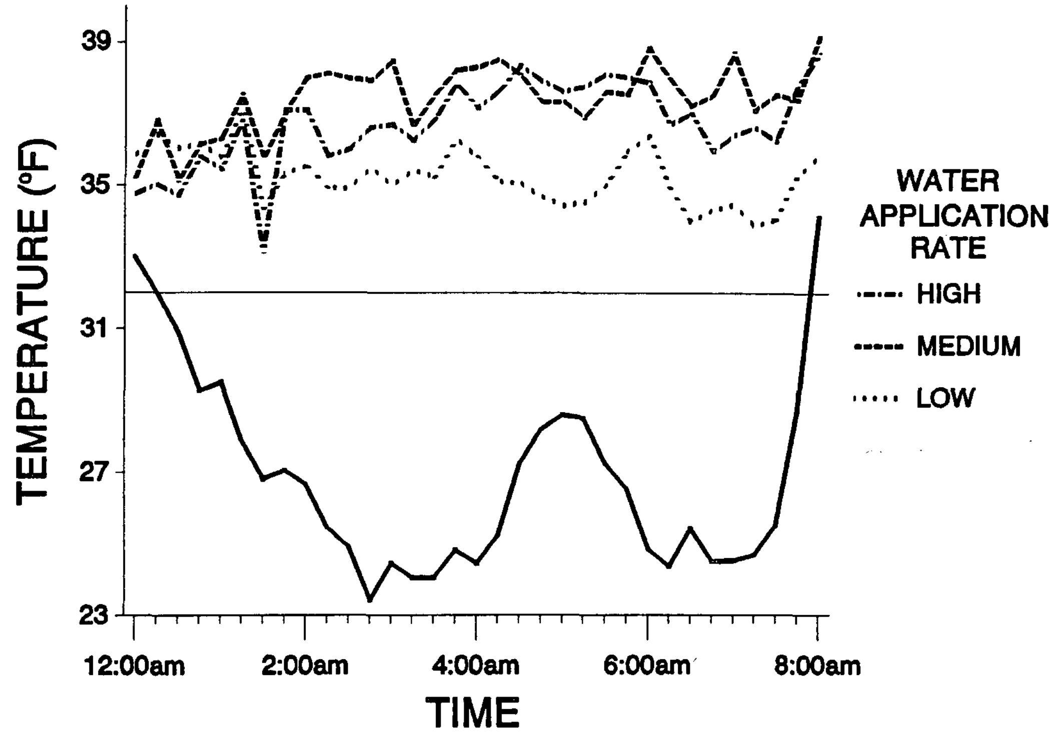

Figure 11. Outside ambient air temperatures (solid line) and leaf temperatures inside iced shadehouses equipped with side curtains and cold protected using three different irrigation water application rates (Table 3) on December 3-4, 1989.

irrigation raised temperatures by an average of 12°F (6.6°C) in the iced shadehouses equipped with side curtains.

Table 4. Water application rates for the December 24-25, 1989 freeze event.

Rate	gpm/acre	inches/hr	$cm \cdot hr^{-1}$	Total gallons	Percent difference compared to 100 gal/min/acre criteria
High	127	0.28	0.71	201,482	+ 27
Medium	97	0.21	0.54	160,385	- 3
Low	67	0.15	0.38	104,867	- 33

An average of 817 gallons of water was applied to each shadehouse by the over-the-shadehouse irrigation systems.

February 16-17, 1991 — without crop covers. Table 5 lists water application rates for this radiation freeze. The over-the-shadehouse irrigation system was run from 6:49 p.m. to 7:49 p.m. [1849-1949 HR] and from 10:10 p.m. to 10:40 p.m. [2210-2240 HR]. Ambient temperatures reached a minimum of about 26.6°F [-3°C]. During the period from 2:45 a.m. to 7:15 a.m. [0245-0715 HR] when ambient temperatures stayed below freezing, temperatures in iced shadehouses receiving the low (0.10 inch/hr, [0.26 $cm \cdot hr^{-1}$]), medium (0.18 inch/hr [0.46 $cm \cdot hr^{-1}$]), and high (0.25 inch/hr [0.64 $cm \cdot hr^{-1}$]) water application rates averaged 6.2°F [3.4°C], 7.6°F [4.2°C], and 7.8°F [4.3°C] higher than ambient, respectively (Figure 13). Overall, temperatures in iced and wrapped shadehouses averaged 7.2°F [4°C] higher than outside during that time period. Comparing iced with uniced shadehouses receiving the same over-the-crop water application rates, leaf temperatures were 3.1°F [1.7°C], 2.9°F [1.6°C], and 3.5°F [2°C] higher in iced

Table 5. Water application rates for the February 16-17, 1991 freeze event.

Rate	gpm/acre	inches/hr	$cm \cdot hr^{-1}$	Total gallons	Percent difference compared to 100 gal/min/acre criteria
High	137	0.30	0.76	24,542	+ 37
Medium	100	0.22	0.56	17,953	0
Low	54	0.12	0.30	9,717	- 46

An average of 1023 gallons of water was applied to each shadehouse by the over-the-shadehouse irrigation systems.

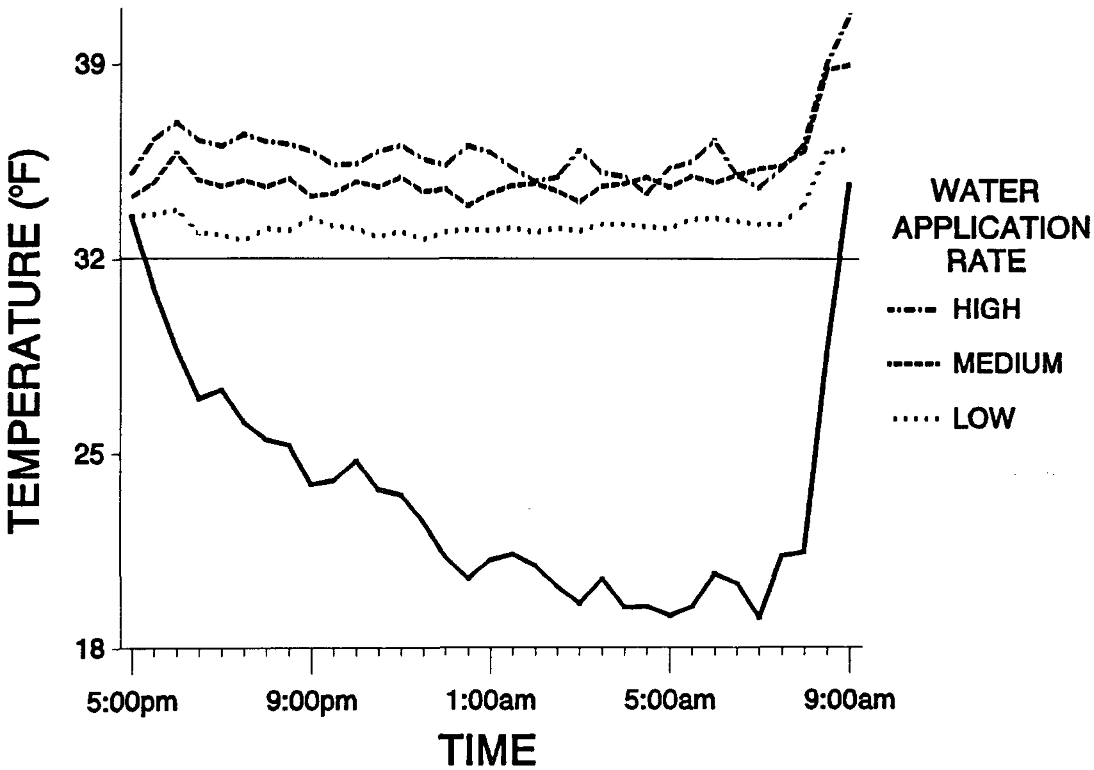

Figure 12. Outside ambient air temperatures (solid line) and leaf temperatures inside iced shadehouses equipped with side curtains and cold protected using three different irrigation water application rates (Table 4) on December 24-25, 1989.

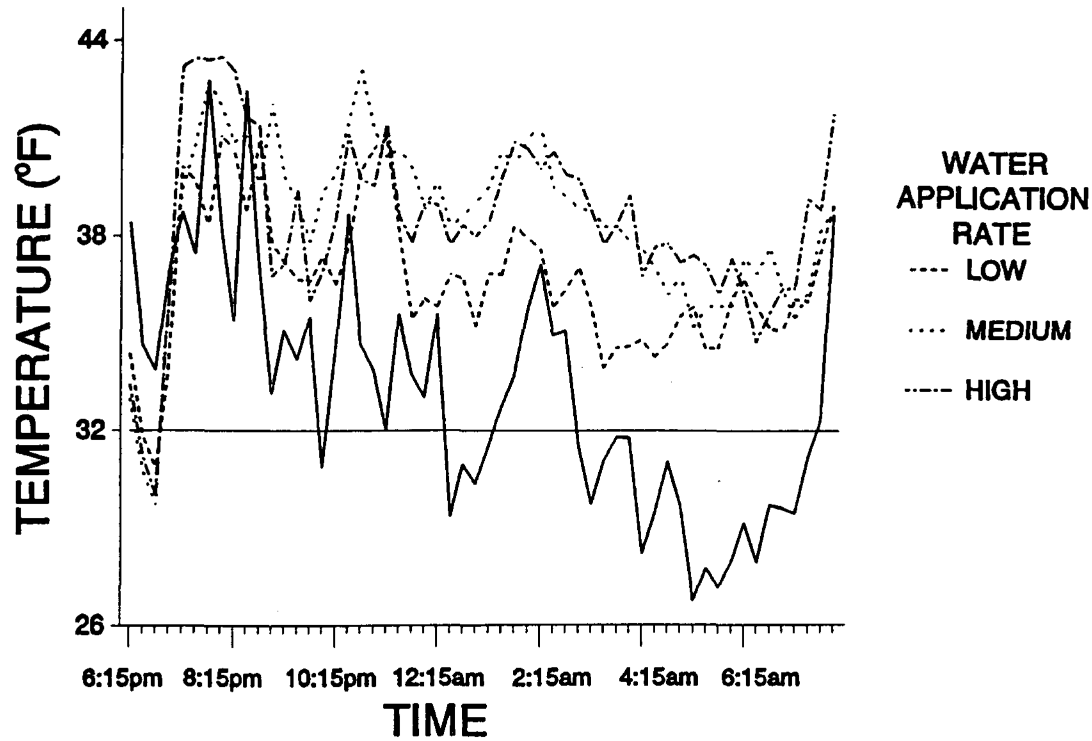

Figure 13. Outside ambient air temperatures (solid line) and leaf temperatures inside iced shadehouses equipped with side curtains and cold protected using three different irrigation rates (Table 5) on February 16-17, 1991.

shadehouses receiving the low, medium and high water application rates, respectively, than leaf temperatures in uniced shadehouses (Figure 14). Overall, leaf temperatures averaged 3.2°F [1.8°C] higher when shadehouses were iced.

February 16-17, 1991 — with crop covers. Figure 15 illustrates the temperatures at the high (18 inch above the soil surface) thermocouple location, both under and outside the crop covers, in iced shadehouses. Temperatures under crop covers were significantly higher than outside the covers whenever the ambient temperatures inside the shadehouses were below about 38°F [3.5°C]. For most of the evening, temperatures were generally warmer under the lighter-weight cover than under the heavier cover, i.e., in the regression analysis the sum of squares for the quadratic term was greater than that for the linear term in almost every case. In addition, the quadratic term was significant at eight time periods when the linear term was not. Therefore, the temperature response to crop cover weight when overhead irrigation was applied was predominantly quadratic and may have been due to less water passing through the heavier cover than through the lighter-weight one. However, from about 5:45 a.m. [0545 HR] until sunrise there was little difference between the temperatures under the covers.

Temperatures were generally higher when measured closer to the soil surface (Figure 16), but followed the same patterns mentioned above — temperatures were higher under the covers than outside the covers and were higher under the lighter-weight cover than the heavier-weight ones. Further evidence that the crop covers were trapping heat is provided by the observation that no ice formed on the covers while the fern outside the covers was encased with ice.

Advective Freezes

December 22-24, 1989. The water application rates used during this advective freeze were the same as listed in Table 4. Ambient temperatures during this "freeze-of-the-century" reached a low of 18°F [-7.8°C] and wind speeds of up to 22 mph [35 km•hr^{-1}] were recorded. The over-the-shadehouse irrigation system was run from 10:10 p.m. to 10:45 p.m. [2210-2245 HR] on the 22nd, and from 7:20 a.m. to 8:50 a.m. [0720-0850 HR] and 10:50 a.m. to 11:40 a.m. [1050-1140 HR] on the 23rd. The over-the-crop system was run from 4:45 p.m. [1645 HR] on the 23rd until 3:30 p.m. [1530 HR] on the 24th. All irrigation water application rates maintained fern temperatures around

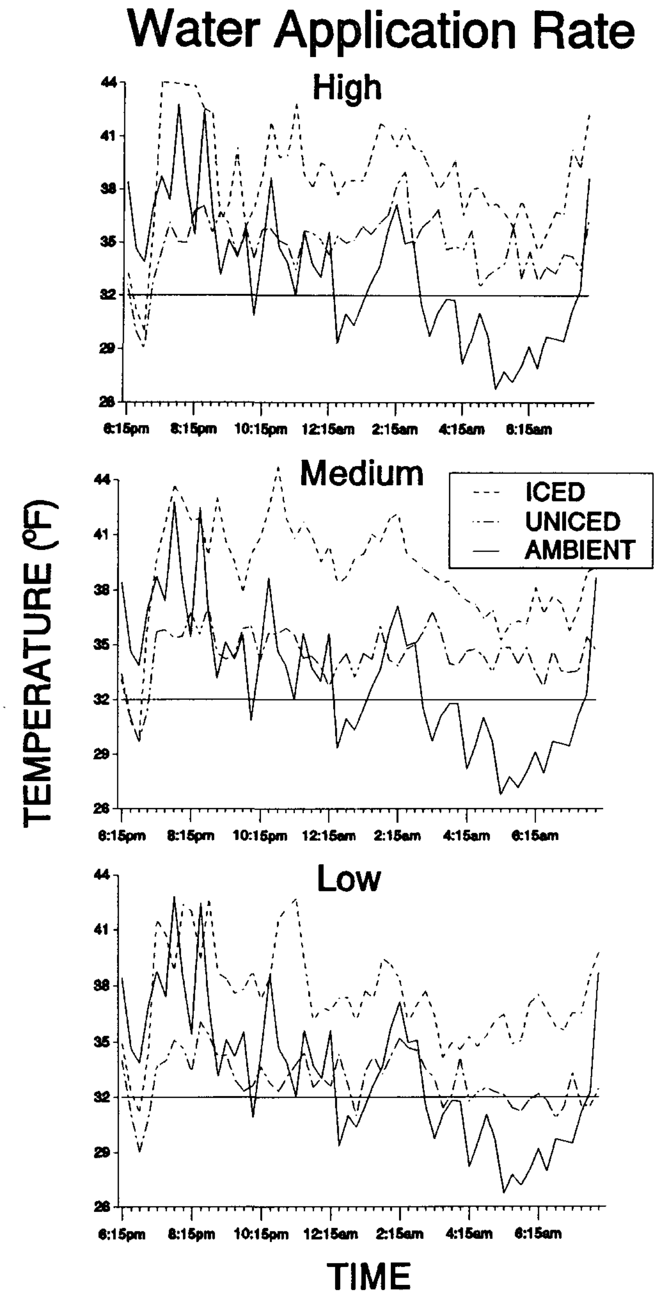

Figure 14. Comparison of leaf temperatures in iced and uniced shadehouses receiving 0.12 inch/hr [0.30 cm$\cdot$hr^{-1}] (low), 0.22 inch/hr [0.56 cm$\cdot$hr^{-1}] (medium), or 0.30 inch/hr [0.76 cm$\cdot$hr^{-1}] (high) water application rates on February 16-17, 1991.

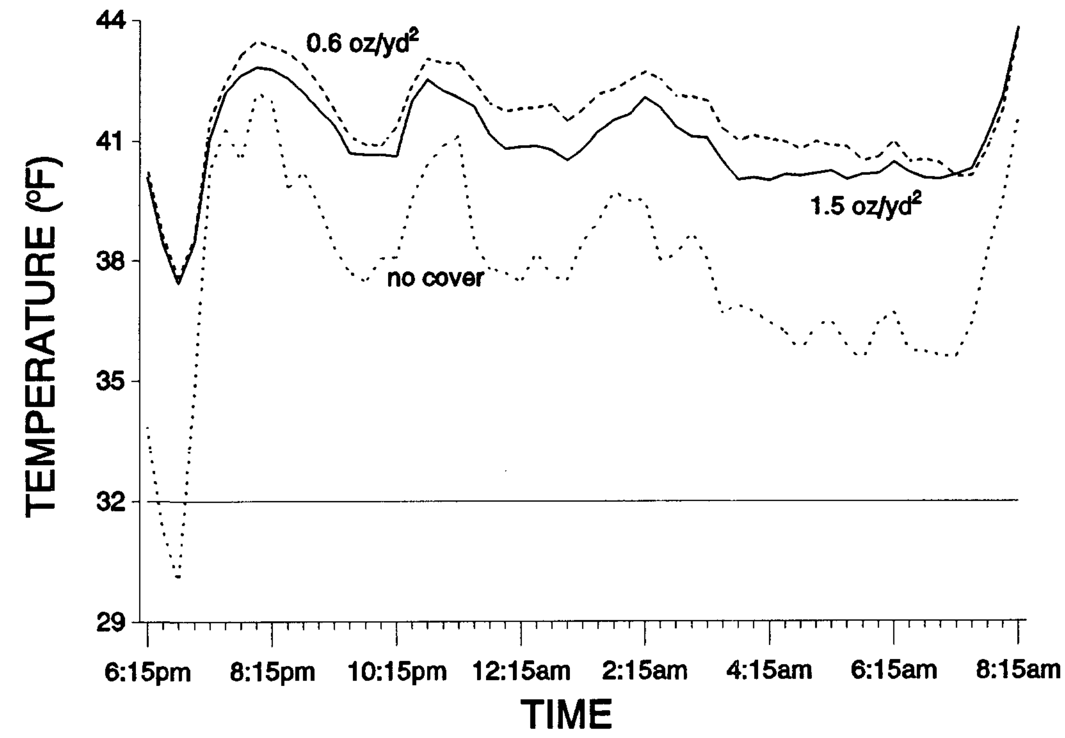

Figure 15. Temperatures measured approximately 18 inches [46 cm] above the soil surface outside crop covers and at the underside of the crop covers in iced shadehouses receiving overhead irrigation on February 16-17, 1991.

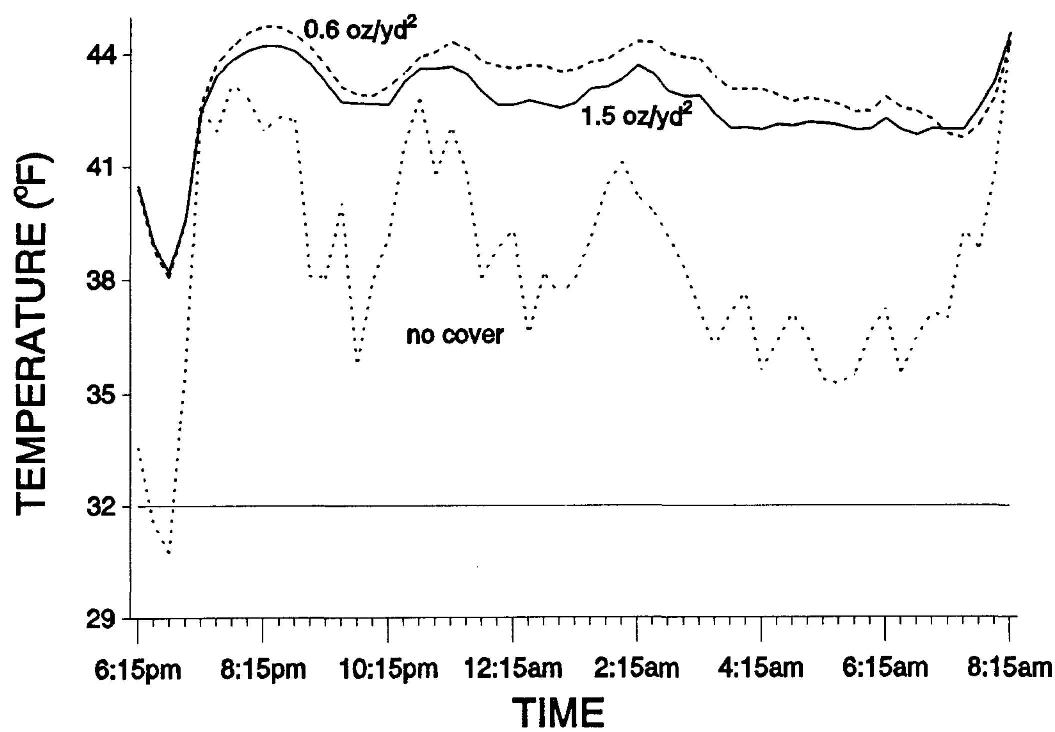

Figure 16. Temperatures measured 9 inches [24 cm] above the soil surface outside and under crop covers in iced shadehouses receiving overhead irrigation on February 16-17, 1991.

freezing and there were no temperature differences due to water application rate during this freeze (Figure 17).

February 15-16, 1991 — without crop covers. Table 6 lists the water application rates used during this freeze. Maximum wind speeds recorded inside and outside the shadehouses were 1.9 mph [3.1 km$\cdot$hr^{-1}] and 5.4 mph [8.7 km$\cdot$hr^{-1}], respectively. During the period from 3:30-7:45 a.m. [0330-0745 HR] when ambient temperatures stayed below freezing, temperatures in iced shadehouses receiving the low (0.10 inch/hr [0.26 cm$\cdot$hr^{-1}]), medium (0.18 inch/hr [0.46 cm$\cdot$hr^{-1}]), and high (0.25 inch/hr [0.64 cm$\cdot$hr^{-1}]) water application rates averaged 2.5°F [1.4°C], 3.3°F [1.9°C], and 1.6°F [0.9°C] higher than ambient, respectively (Figure 18). Overall, temperatures in iced and wrapped shadehouses averaged 2.5°F [1.4°C] higher than ambient — considerably less of a difference than during radiation freezes.

Table 6. Water application rates for the February 15-16, 1991 freeze event.

Rate	gpm/acre	inches/hr	cm$\cdot$hr^{-1}	Total gallons	Percent difference compared to 100 gal/min/acre criteria
High	133	0.29	0.74	24,877	+ 33
Medium	95	0.21	0.53	17,754	- 5
Low	52	0.12	0.30	9,792	- 48

An average of 588 gallons of water was applied to each shadehouse by the over-the-shadehouse irrigation systems.

Comparison of leaf temperatures in iced versus uniced shadehouses during this advective freeze show that icing increased temperatures in shadehouses receiving the medium and low water application rates (Figure 19). The data from the high irrigation application rate was not used due to technical reasons. Leaf temperatures were considerably below freezing in uniced houses receiving the low and medium irrigation water application rates. These results illustrate the necessity of sealing shadehouses during advective freezes, especially when applying lower amounts of water. They also show why higher water application rates must be used in hammocks where protection from convectional heat loss is impractical. The consequences of this lack of ability to maintain temperatures near freezing is obvious from the crop damage assessments following this freeze (see next section).

February 15-16, 1991 — with crop covers. Irrigation water application rate had no effect on temperatures and there was no interaction between

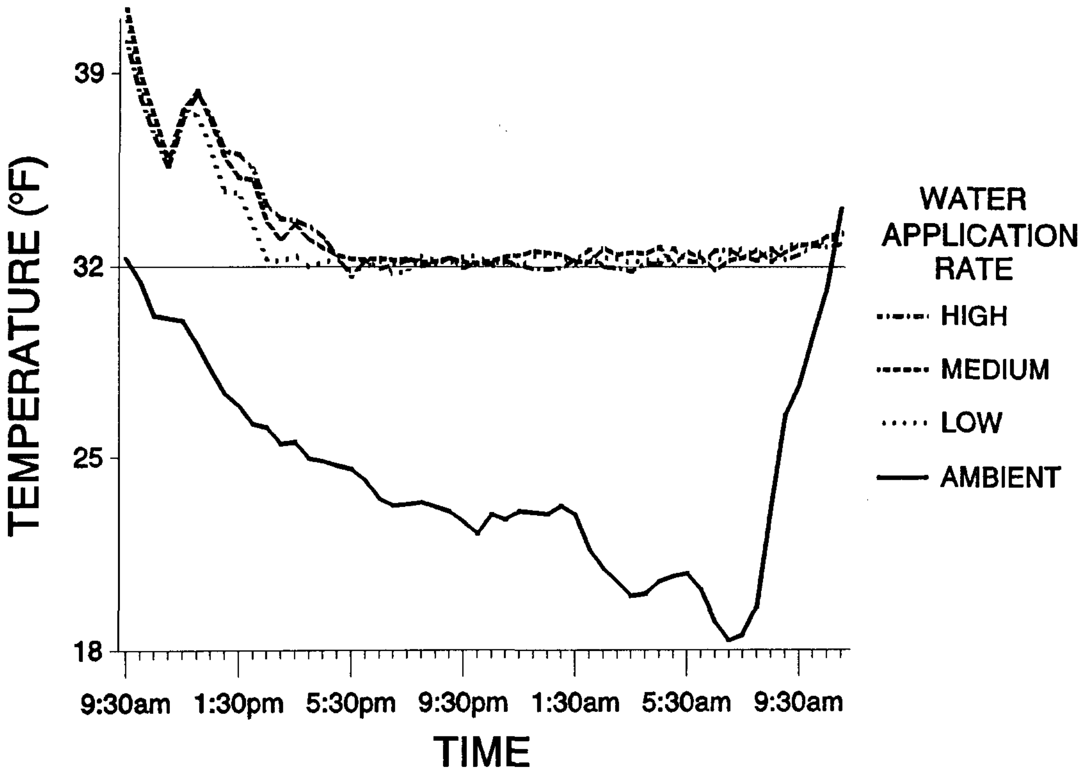

Figure 17. Outside ambient air temperatures (solid line) and leaf temperatures inside iced shadehouses equipped with side curtains and cold protected using low, medium and high water application rates (Table 5) on December 23-24, 1989.

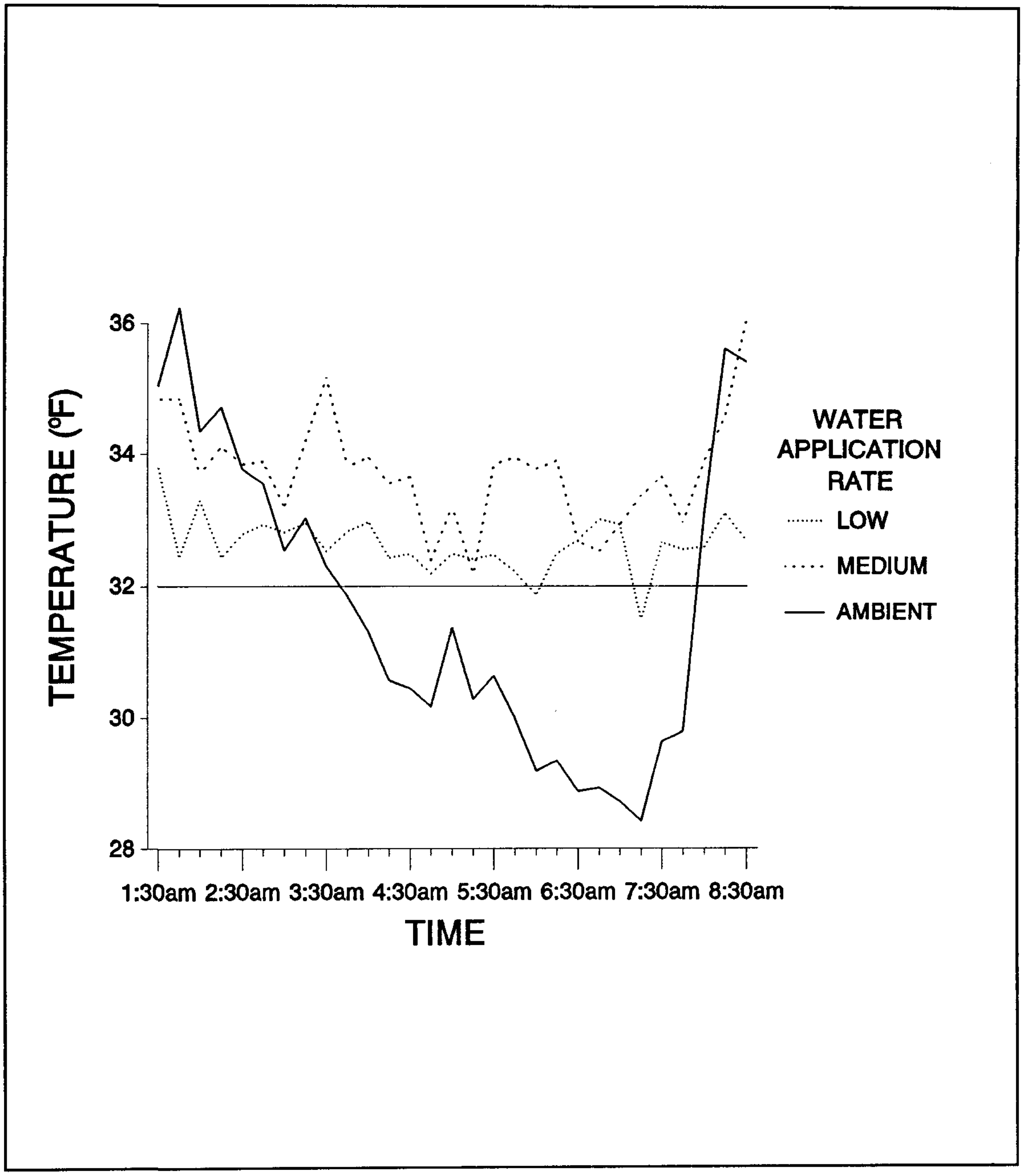

Figure 18. Outside ambient air temperatures and leaf temperatures inside iced shadehouses equipped with side curtains and cold protected using low and medium water application rates (Table 6) on February 15-16, 1991. Data from the high irrigation application rate houses was not considered reliable and, therefore, is not reported.

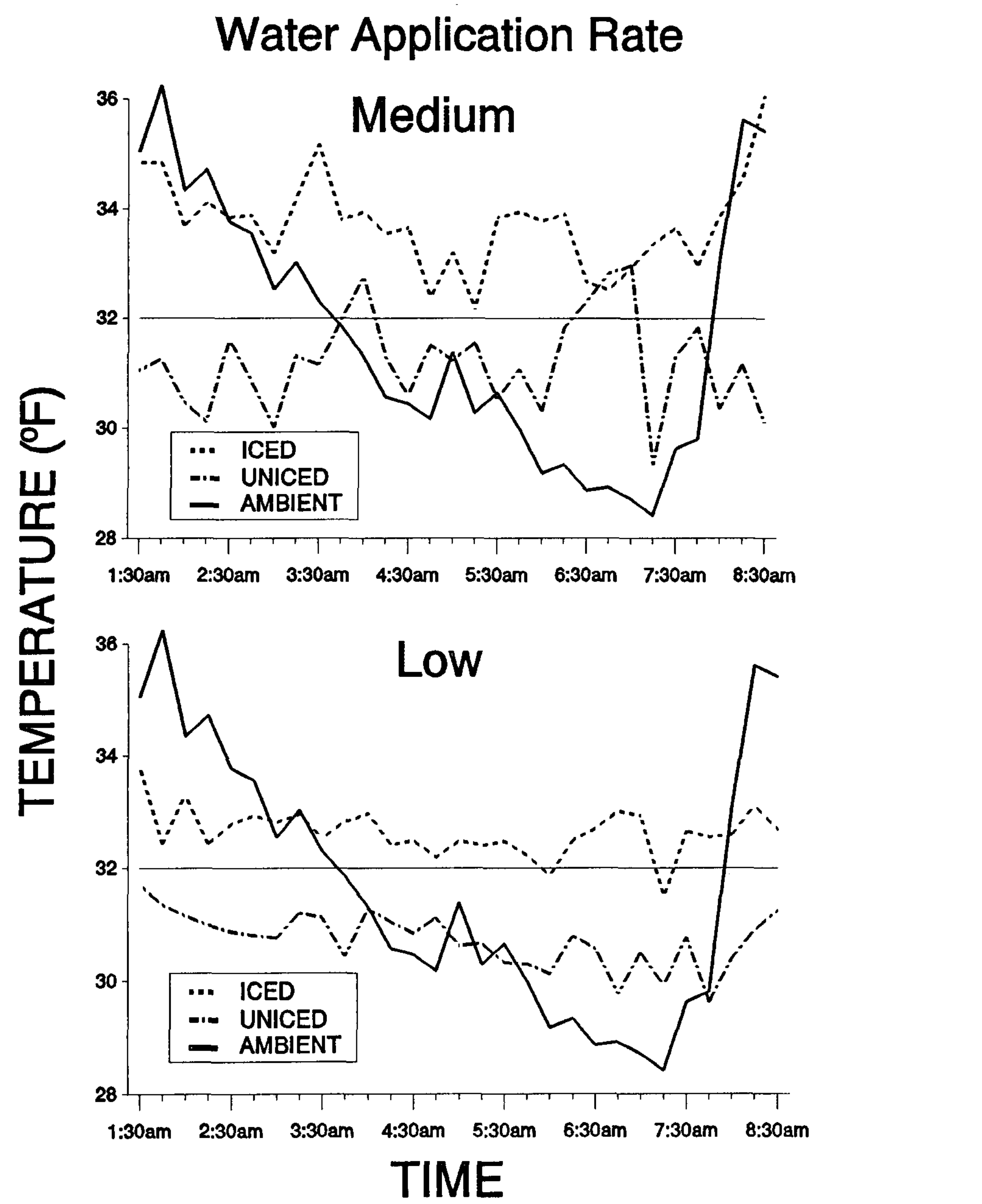

Figure 19. Comparison of temperatures in iced versus uniced shadehouses irrigated at low and medium application rates (Table 6) during an advective freeze on February 15-16, 1991. Data from the high irrigation application rate houses was not considered reliable and, therefore, is not reported.

application rate and row cover weight. Temperatures measured at the high (18 inch [46 cm]) location were significantly higher under the covers than outside the covers (Figure 20). Temperatures under the light-weight cover were consistently higher than under the heavier cover. Temperatures measured closer to the ground (9 inches [23 cm]) in the middle of the fern canopy were higher and exhibited the same patterns noted above (Figure 21).

Crop Cold Damage

Radiation freezes

No cold damage occurred during any radiation freeze that occurred independent of advective freeze. Temperature data recorded during radiation freezes that followed directly behind advective freezes also suggest that all irrigation water application rates tested were capable of maintaining crop temperatures above those that would result in cold damage (Figures 11, 12, 13, 14).

Advective freezes

Generally, cold damage to immature leatherleaf fern fronds increased with decreasing water application rates. For example, 23, 62, and 81 percent of immature fronds not covered with crop covers in the high, medium and low water application rate iced shadehouses, respectively, were damaged during the February 1991 freeze (Figure 22). The linear regressions of water application rate versus damage ratings and percent damage were extrapolated to get an estimate of the water application rate that would have been necessary to prevent any damage to the fern fronds. Both regressions resulted in a water application rate of about 0.37 inch/hr [0.96 $cm \cdot hr^{-1}$] being required to prevent all damage; interestingly, this value is in the middle of water application rates that have traditionally been used by the industry (Dean, 1966; Harrison and Conover, 1970).

During the severe December 23-25, 1989 freeze, none of the irrigation water application rates provided significant protection and 78 to 89 percent of the immature fronds were damaged (Figure 23).

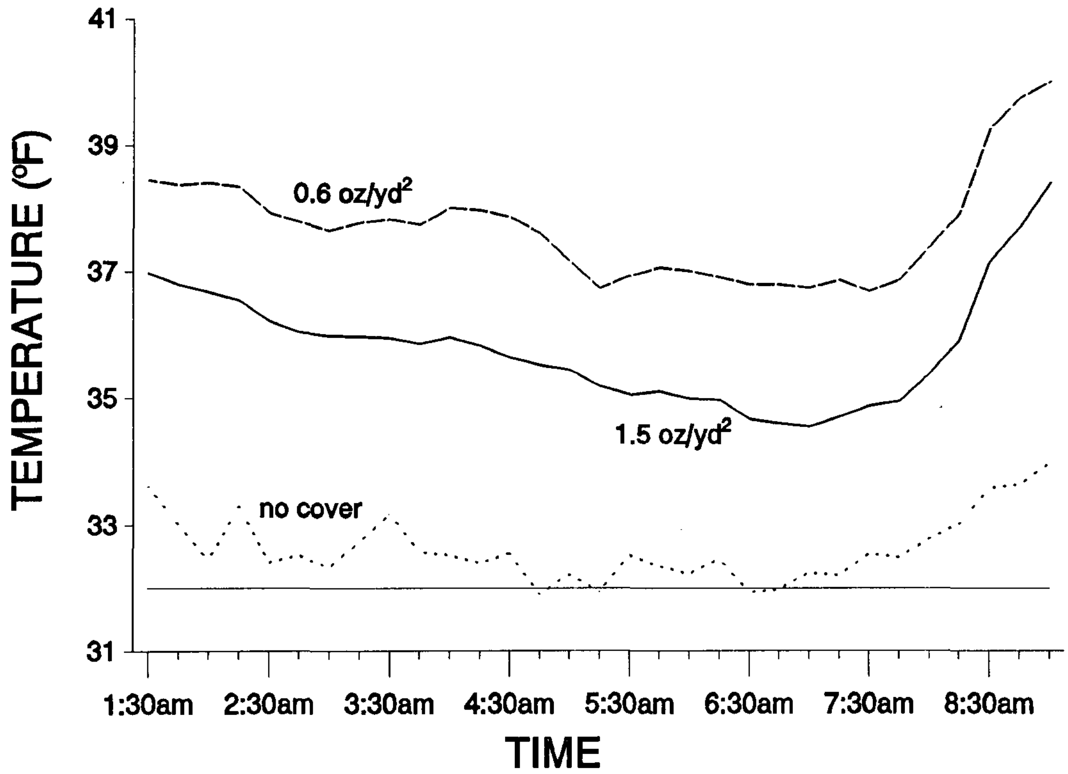

Figure 20. Temperatures measured approximately 18 inches [46 cm] above the soil surface outside crop covers and at the underside of the crop covers in iced shadehouses receiving overhead irrigation on February 15-16, 1991.

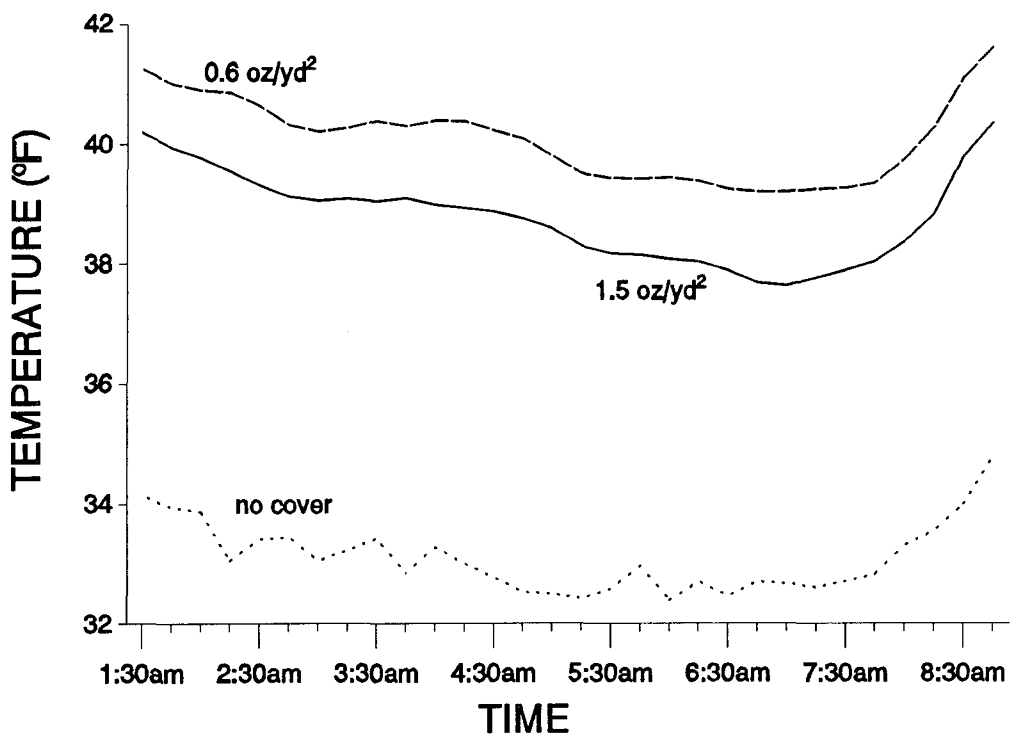

Figure 21. Temperatures measured 9 inches [23 cm] above the soil surface outside crop covers and under crop covers in iced shadehouses receiving overhead irrigation on February 15-16, 1991.

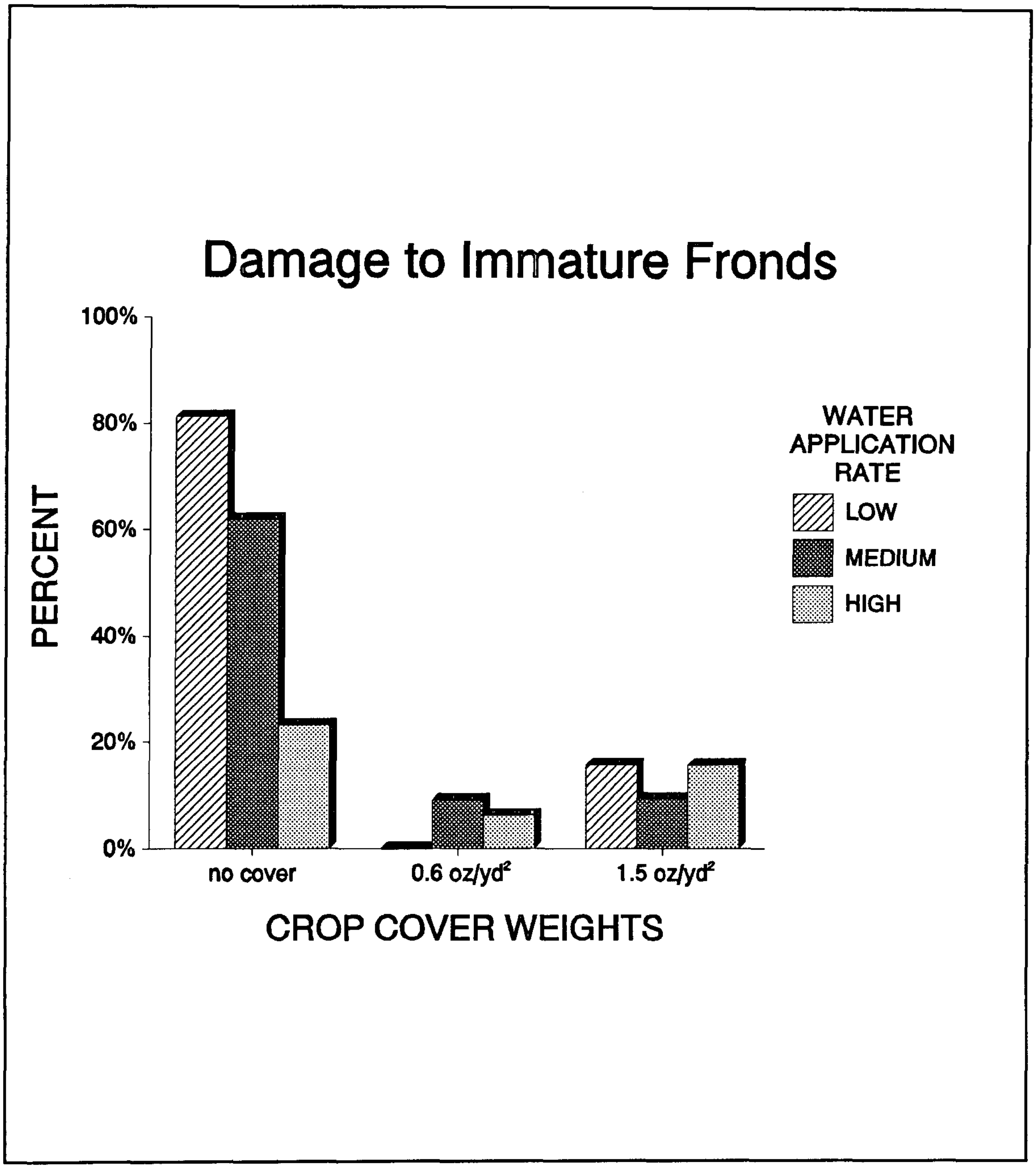

Figure 22. Percentage of immature fronds with cold damage following the February 1991 freeze. Treatments included three water application rates (0.12, 0.22 or 0.30 inch/hr [0.3 cm, 0.56 or 0.76 $cm \cdot hr^{-1}$]), two spunbonded polypropylene crop cover weights (0.6 or 1.5 oz/yd^2 [20 or 51 $g \cdot m^{-2}$]), and a control with no crop cover.

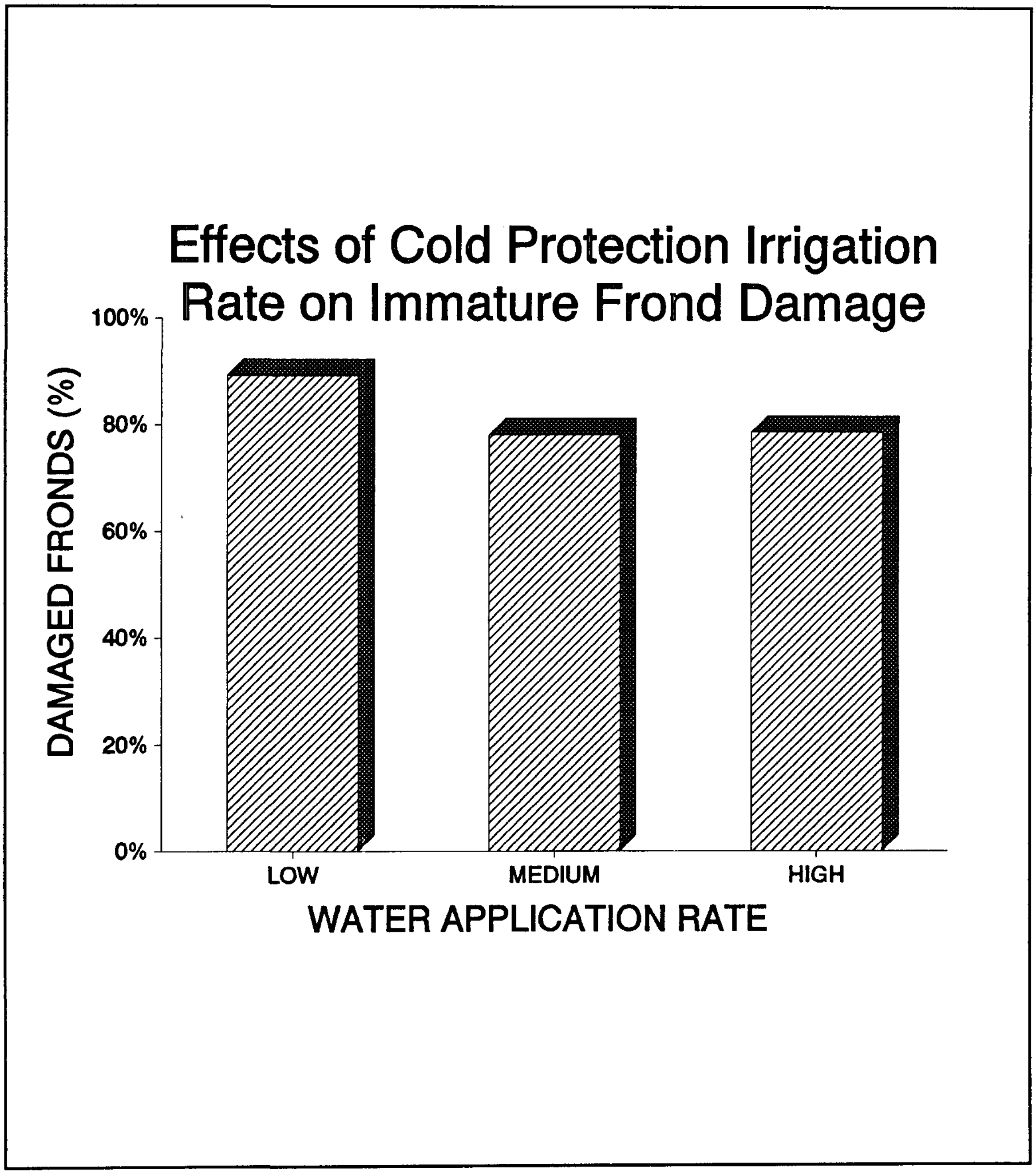

Figure 23. Percent cold damage to immature leatherleaf fern fronds following a severe advective (windy) freeze in December 1989.

Advective freezes - with crop covers

The use of crop covers significantly reduced damage to immature fronds in iced shadehouses (Figure 22). Damage under the light-weight and heavy-weight covers averaged about 5 and 15 percent, respectively. Not only was the percentage of damage reduced by the covers, but the severity of damage to individual fronds under the covers was much less than to fronds outside the covers. In fact, some of the damage to fronds under the covers was so slight that the fronds would have been commercially acceptable for harvesting.

Advective freezes - icing versus no icing

Even though some immature fronds were damaged in iced shadehouses during the February 1991 freeze, all (100 percent) of the immature fronds were damaged in the uniced shadehouses regardless of water application rate. This demonstrates the importance of sealing shadehouses that are used to cold protect leatherleaf fern during advective freezes.

Yield

1990

There were no differences in yield due to cold protection irrigation water application rate for any individual harvest or for total yield following the freezes that occurred during December 22-25, 1989 (Figure 24). The lack of yield differences is consistent with the lack of differences in cold protection efficacy described under crop cold damage — all three water application rates were inadequate to protect immature fronds from damage during this severe freeze. Frond size (fresh weight) was also not affected by cold protection water application rate (data not shown).

1991

Yield differences were also not detected following the February 1991 freeze (Figure 25). This was probably due, in part, to the fact that all houses sustained some damage, crop covers prevented damage to part of the fern in all shadehouses, and the data from the uniced shadehouses were excluded

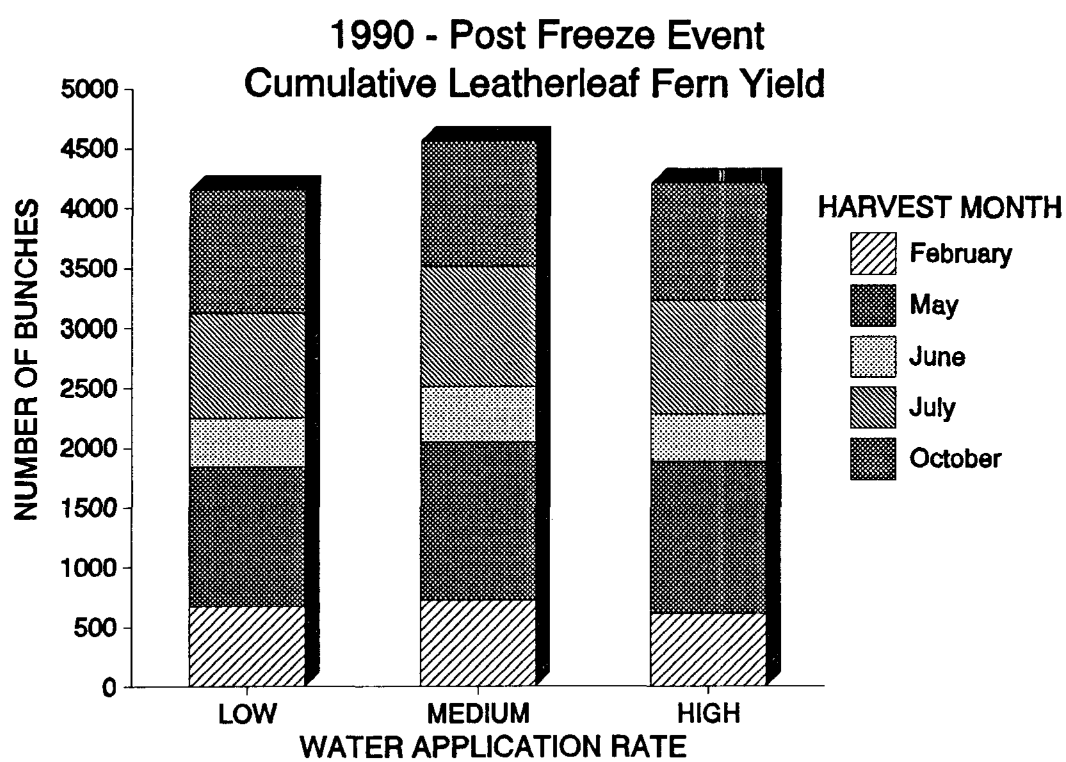

Figure 24. Average number of bunches of leatherleaf fern (25 fronds/bunch) harvested by commercial fern cutters in 1990 from research shadehouses cold protected using three water application rates (Tables 3 and 4).

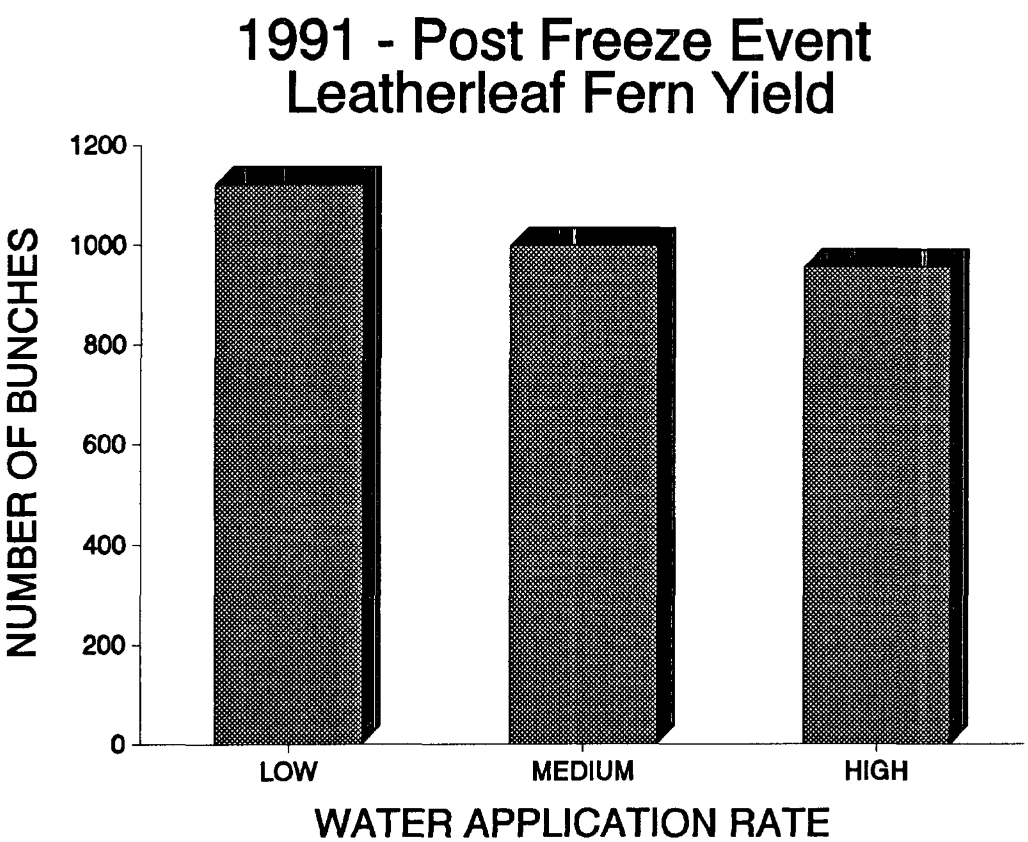

Figure 25. Yield of fern fronds harvested by commercial fern cutters in April 1991 following the February 1991 freeze was not affected by irrigation water application rate used for cold protection. See text for details.

from the analysis thereby reducing the number of replications in iced houses to two. Any damaged fern left in the field can be a continuing source of future problems because that fern slows harvesting and can serve as a source of disease inoculum.

Frond Color

Frond color ($L^\star a^\star b^\star$ and chroma $C^\star$) was not affected by irrigation treatments (Table 7).

Table 7. Leatherleaf fern frond color from shadehouses that were treated with three different water application rates to protect the crop from cold damage.

Rate	gpm/acre	inches/hr	$cm \cdot hr^{-1}$	Frond color			
				L★	a★	b★	C★
High	123	0.27	0.71	34.0	-8.8	10.1	13.4
Medium	99	0.22	0.53	34.4	-9.0	10.9	14.1
Low	67	0.15	0.38	34.7	-9.1	10.6	13.9
Significance[z]							
Linear				ns	ns	ns	ns
Quadratic				ns	ns	ns	ns

[z]ns = not significant.

Vase Life

Although overall frond vase life exhibited normal seasonal declines as the weather warmed up, there were no differences in vase life due to the cold protection irrigation treatments until the April 26, 1990 harvest (Figure 26). Vase life of fronds harvested on that date, four months after the December 1989 freezes, increased linearly with increasing cold protection water application rates. The difference between vase life of fronds from the low and high water application rate treatments averaged 1.6 days, or a 28 percent difference.

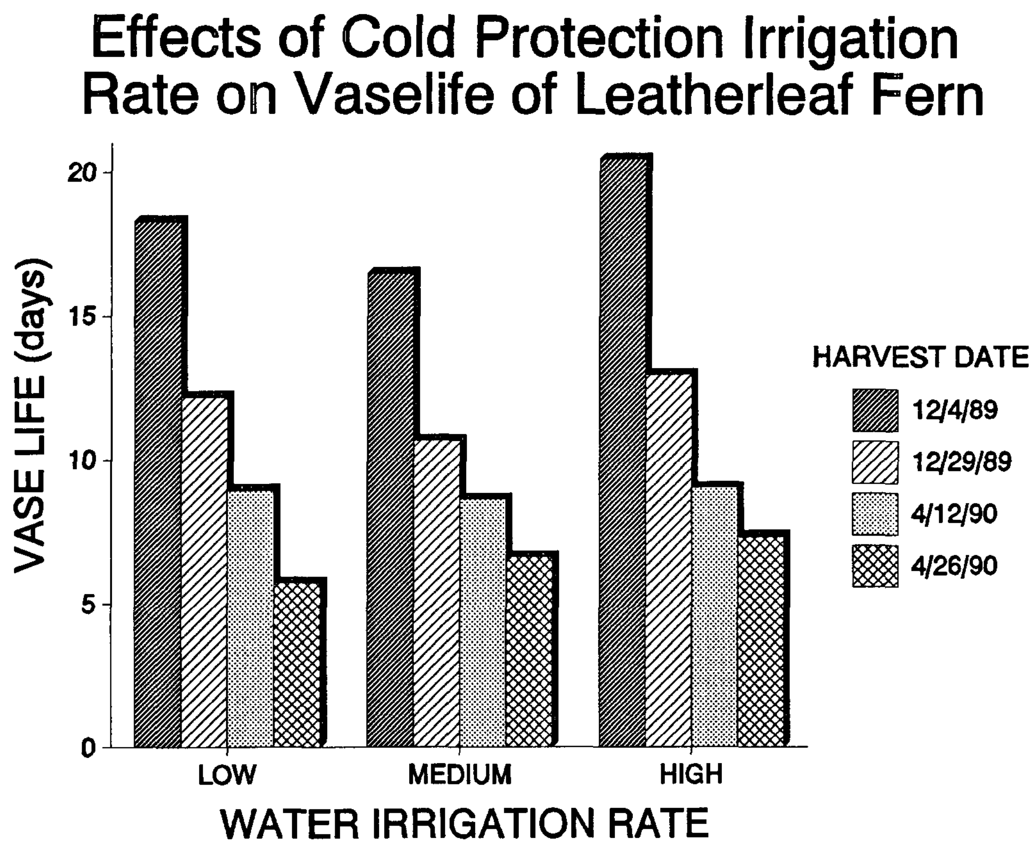

Figure 26. Vase life of leatherleaf fern fronds harvested after freezes in 1989. Vase life was not associated with cold protection irrigation rate except at the April 26, 1990 harvest when vase life increased linearly with water application rate.

CONCLUSIONS

Objective 1 - to determine the effectiveness of different water application rates for cold protection of leatherleaf fern growing under 73 percent polypropylene shade fabric when used in combination with icing of the shade fabric roof and wrapping of the sidewalls with nonporous fabric - All water application rates were high enough to protect immature leatherleaf fern fronds in iced shadehouses that had nonporous sidewalls during the radiation freezes encountered during these studies. Leaf temperatures under those conditions remained above 32°F [0°C]. However, the tested water application rates were inadequate to prevent damage during advective freezes and the lower the water application rate the greater the damage to the crop. Water application rates greater than the high rate tested in these studes, 0.30 inch/hr [0.76 cm$\cdot$hr^{-1}], would be necessary to prevent all damage to immature fronds during advective freezes like those occurring during these studies.

Damage to mature fronds was never detected regardless of water application rate. In addition, color, size and vase life of mature fronds were not generally affected by cold protection water application rates. Yield differences due to cold protection water application rates were also not detected. This was mostly due to the fact that mature fronds were not damaged by the cold and they made up the majority of the fern in the shadehouses. In addition, immature fronds were damaged by cold in most of the shadehouses during each advective freeze, thereby making comparisons with shadehouses without damage impossible.

Objective 2 - to ascertain whether icing of the shade fabric roof of ferneries is effective in reducing heat loss - In all cases, temperatures were higher in iced shadehouses than shadehouses that had not been iced. In fact, leaf temperatures during the advective freeze in 1991 went below freezing in uniced houses being irrigated at the low and medium water application rates and all immature fronds were damaged in those houses.

Objective 3 - to test crop covers for their effectiveness in holding heat under the covers - Temperatures under crop covers show potential for reducing crop damage and the need for traditionally high water application rates. If the problems of economics and logistics can be overcome they may prove useful, at least on low-growing, high value crops. Further cold protection research using crop covers is needed.

Objective 4 - to determine the meteorological conditions under which each system is most effective. - All the systems tested are most effective when wind speeds are low. These results agree with those Dean (1966) reported for plumosus fern growing in oak hammocks. At the water application rates tested, the combination of nonporous sidewalls, frost protection sprinklers, and row covers was the only system tested that provided good protection to immature fronds during advective freezes.

GLOSSARY

Advective freeze. A weather event in which temperatures drop to or below the freezing point (32°F [0°C]) resulting from large-scale mass movements of cold air (windy conditions).

Anemometer. An instrument for measuring wind speed.

Chemigation. The use of an irrigation system to apply chemicals.

Chromaticity. The quality of color determined by combining its three elements — hue, brightness and saturation.

Circum-austral. Occurring around the southern part of the earth.

Conduction. The flow of heat through a material or from one body to a cooler body in contact with it.

Convection. Heat transfer caused by the circulation of gases or liquids.

Crop cover. A cold protection device that is draped over a crop to trap heat from the soil.

Cryoprotectant. Any agent added to living tissue that reduces susceptibility to cold injury.

Cut foliage. Crops and the industry which supply harvested plant materials to be used as decorative "greenery" in floral arrangements.

Dry-bulb temperature. Temperature measured using a thermometer with an unmoistened bulb.

Evaporation. The physical process by which a liquid or solid is transferred to the gaseous state.

Fertigation. The use of an irrigation system to apply fertilizer.

Fiddle head (crosier). Young fern frond that has not unfurled and is still curled up.

Floriculture. The cultivation of ornamental plants (predominantly flowering plants) for use either as potted plants, in floral arrangements or in the landscape.

Frond. Leaf of a fern.

Heat. Energy transferred from one place to another by virtue of a temperature difference.

Heat of fusion. The heat required to melt a solid; conversely, the heat released as a liquid becomes a solid.

Heat of sublimation. The heat required when water changes from solid form to a vapor without passing through a liquid phase, and conversely, the heat released when a vapor changes directly to a solid.

Heat of vaporization. The heat required to change a liquid to a gas, and conversely, the heat required to change a gas to a liquid.

Icing. Technique of using water to form ice that seals the openings of shade fabric.

kPa (kilopascal). The SI unit of pressure equal to 0.295 inch of mercury (Hg).

Latent heat. Heat conducted or convected with the evaporation or condensation of water.

Leatherleaf fern. An herbaceous perennial tropical plant grown for use as a cut green by florists and as a groundcover in landscapes.

Nocturnal. Pertaining to or occurring at night.

Over-the-crop irrigation. Application of water to a crop from above.

Over-the-shadehouse irrigation. Application of water to the shade fabric on top of shadehouses. A technique used to wet the shade fabric during the icing of shadehouses.

Perennial. Continuing to live from year to year.

Photosynthesis. The process, driven by light energy, in which plants convert water and carbon dioxide into useful chemical energy.

Photosynthetically active radiation (PAR). Light of the wavelengths that are used during photosynthesis (400-700 nm).

Radiation. Energy transferred through space as electromagnetic waves.

Radiation freeze. A weather event in which temperatures drop to or below the freezing point (32°F [0°C]) under calm conditions.

Relative humidity. The ratio of actual to saturation vapor pressure (at the same temperature).

Saturation vapor pressure. The maximum pressure possible when equilibrium is reached between water amd water vapor. Saturation vapor pressure increases exponentially with increasing temperature.

Shade fabric. Knitted or woven materials which block part of the sunlight, thus creating artificial shade. (Percent blockage of light is dependent on the opacity of the threads and the tightness of the weave.)

SI. International System of Units.

Thermocouple. Junctions of dissimilar metals which generate an electric current proportional to the temperature of their surroundings.

Vase life. The period of time over which fresh plant materials in floral arrangements maintain an attractive appearance.

Wet-bulb temperature. Temperature measured using a thermometer with a moistened bulb.

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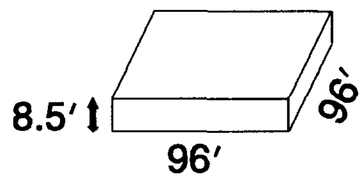
APPENDICES

APPENDIX A: Contributors to the shadehouse research project

Contributors to the shadehouse research project at Taylor Jr.-Sr. High School in Pierson, FL.* (Stamps and Conover, 1989)	
Braddock, Adam	Brown, John
Central Florida Fern Co-op	Ciba-Geigy
David's Irrigation Service	Fern Growers Wholesale Supply
Florida Fern Growers Association	Future Farmers of America, Taylor Jr.-Sr. High School Chapter
Gentry Oil	Gilmore, Bob
Goodin, Larry	Gould Pump Company
Hagstrom, Albin & Son, Inc.	Hagstrom, Richard
J & S Pump Company	James, Greg
Loadholtz, Larry	Matthews, Eric
Modern Power	Monsanto Corporation
Morris, Billy	Nicolon-Baycor, Inc.
Peninsula Petroleum	Peterson, James
Pierson Supply	Pittman, Joe
Rain Bird Sales	Register, Jana
Register, Jimmy	Richardson, Curtis
Pierson Supply	Rain Bird Sales
Rhône-Poulenc	St. Johns River Water Management District
Senninger Irrigation	Stamps, Bob
Stone, Lloyd	Taylor, James O.
University of Florida, IFAS, Agricultural Engineering Department	University of Florida, IFAS, Central Florida Research and Education Center-Apopka
Volusia County Agricultural Extension Office Schools	Volusia County Schools
*The authors apologize if they have inadvertently forgotten to acknowledge any contributor to this project.	

APPENDIX B: **Exposed surface area to volume ratio comparison of a 0.2 acre [.09 ha] research shadehouse and a five acre [2.02 ha] shadehouse.**

RESEARCH SHADEHOUSE

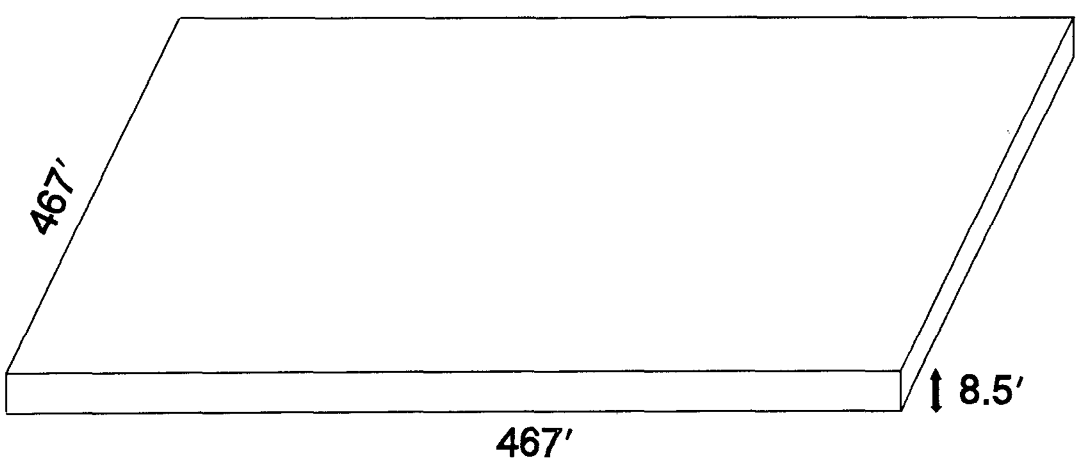


exposed surface area = 12,480 ft^2

volume = 78,336 ft^3

surface:volume ratio = 1:6.3

FIVE ACRE SHADEHOUSE



exposed surface area = 233,967 ft^2

volume = 1,853,756 ft^3

surface:volume ratio = 1:7.9