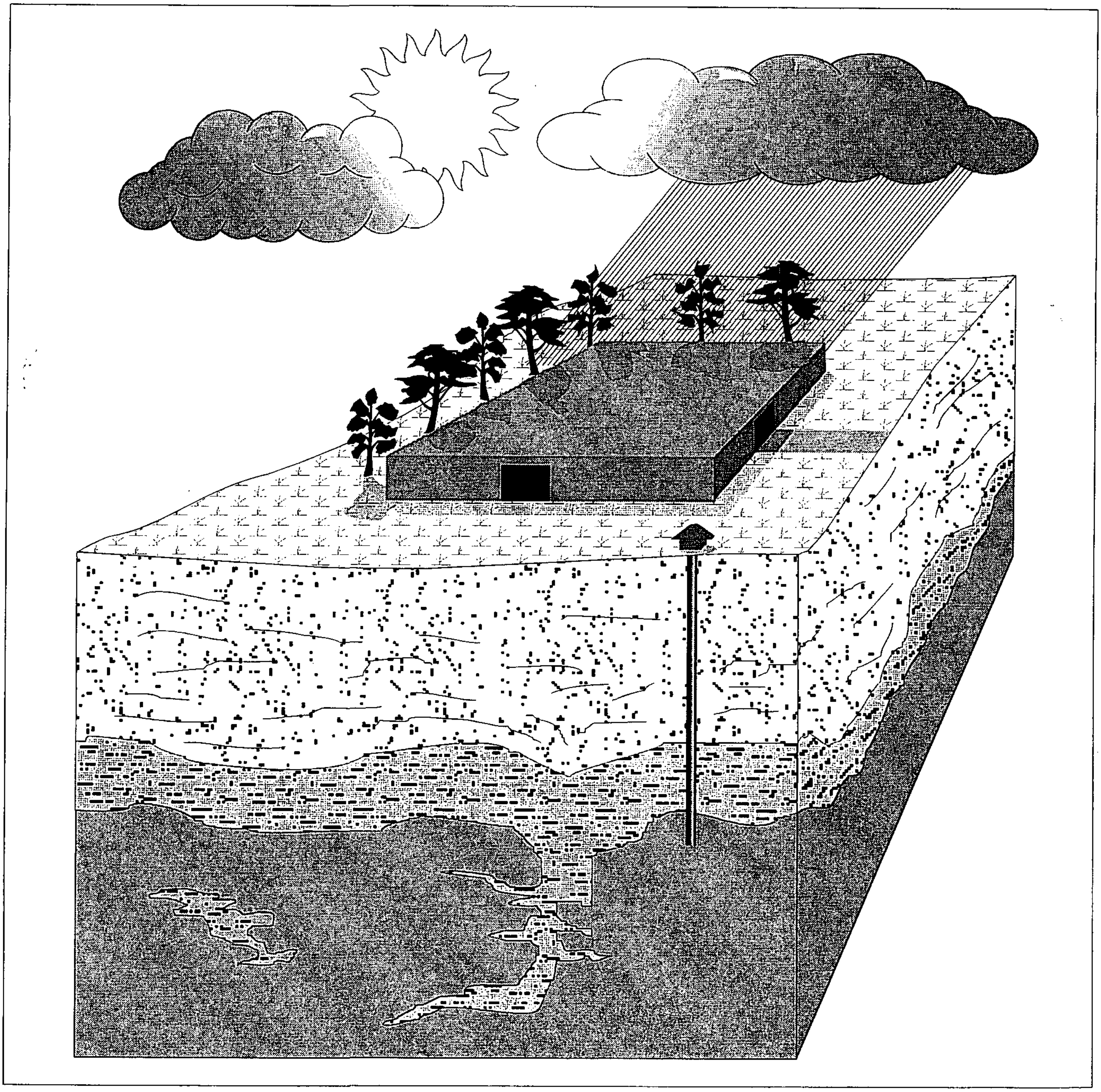
Special Publication SJ94-SP10

Evapotranspiration and Nitrogen Leaching During Leatherleaf Fern Production in Shadehouses



St. Johns River Water Management District

Special Publication SJ94-SP10

EVAPOTRANSPIRATION AND NITROGEN LEACHING DURING LEATHERLEAF FERN PRODUCTION IN SHADEHOUSES

— SOIL AND FERNERY MAPPING, LYSIMETER AND FIELD STUDIES —

by

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Final Report for

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Executive Summary

A geographic information system (GIS) computer database was created containing the locations of each soil type in the main leatherleaf fern producing counties (Lake, Putnam, Volusia) in Florida. Locations of existing leatherleaf ferneries were added to the database by digitizing aerial photographs (shadehouse locations) and ground-truthing (shadehouses and hammock ferneries) to determine the range of water-holding and nitrogen-leaching characteristics for the soils on which leatherleaf fern was being produced.

In addition, experiments were conducted to (1) determine water use by leatherleaf fern growing in a shadehouse, and (2) study the effects of soil moisture irrigation setpoints and nitrogen (N) fertilizer application rates on (2a) N leaching and (2b) leatherleaf fern frond yield (number and weight) and quality (color, transpiration and vase life). Leatherleaf fern was grown in lysimeter tanks to enable all water moving past the root zone of the crop to be collected, measured and analyzed for N content. Fertilization and irrigation setpoint (based on soil moisture potentials) treatments were applied for periods of 6 to 10 months to determine their effects. In addition, leatherleaf fern was grown in the ground in shadehouses in Pierson (established ferneries) and Seville (new fernery), Florida, where water from the surficial aquifers was monitored for NO_3-N.

Mapping of soils and leatherleaf fernery locations. Essentially all leatherleaf fern production was found to occur on soils classified with low to medium available water-holding capacity, very rapid or rapid permeability, and high nitrate nitrogen (NO_3-N) leaching potentials. These are the types of soils on which good NO_3-N leaching management can have the greatest beneficial effect.

Leatherleaf fern water use. Annual water use (actual evapotranspiration, ET_{actual}) by leatherleaf fern during these studies was about 50 cm [20 in]. This water use rate is about 60–85% less than rates reported for turfgrasses and most vegetable and agronomic crops. Similarly, the annual

crop water use coefficient (K_c) for leatherleaf fern, based on pan evaporation outside the shadehouse, was 0.29, or about ¼ to ⅓ that reported for many irrigated agricultural crops. The reason for this relatively low water use is that the shadehouse in which the fern are grown affects those factors that influence plant water use (humidity, radiation, temperature and wind), thereby reducing ET_{actual}.

Nitrogen leaching. Most of the nitrogen in the leachate occurred in the form of nitrate nitrogen (NO_3–N). N leaching decreased with decreasing nitrogen application rates and average NO_3–N concentrations were below the Environmental Protection Agency (EPA) maximum contamination level (MCL) of 10 $mg \cdot liter^{-1}$ [10 ppm] for nitrogen application rates at or below about 335 $kg \cdot ha^{-1} \cdot yr^{-1}$ [300 lb per acre per yr]. N leaching was not significantly affected by the soil moisture irrigation setpoints used.

In a year-long field study using an annual N application rate of 114 $kg \cdot ha^{-1} \cdot yr^{-1}$ [102 lb per acre per yr] in shadehouses with established leatherleaf fern beds, only once did surficial aquifer NO_3–N concentrations exceed the EPA's MCL. However, surficial aquifer NO_3–N concentrations exceeded the MCL by 400% when conventional liquid fertilization rates were used during leatherleaf fern bed establishment (a process which can take over a year).

Leatherleaf fern frond quantity and quality. Nitrogen fertilization rates, applied for the periods of time and under the conditions of these experiments, had no effect on yield or quality of leatherleaf fern fronds. All fern in these studies was of commercially acceptable quality, and fern from the field studies was harvested by commercial fern cutters and sold commercially. However, because there are no established grades for this product, yield was measured only in terms of numbers and fresh weights of fronds.

CONCLUSIONS

Leatherleaf fern production occurs on soils with high NO_3-N leaching and ground water recharge potentials. Leatherleaf fern growing in shadehouses used much less water than it was previously thought was used and, therefore, grower practices (as determined from an on-farm survey conducted concurrently with the beginning of the lysimeter studies) and old irrigation recommendations can be changed to better reflect actual crop water use. Reducing the amount of irrigation water applied to leatherleaf fern would decrease costs associated with running and maintaining irrigation systems. Additionally, reduced water applications would result in decreased nitrogen leaching which would allow nitrogen fertilizer application rates to be reduced — further reducing production costs and the potential for ground water contamination.

The results from these studies suggest that commercially acceptable leatherleaf fern can be produced, at least for a period of about a year's duration, using nitrogen application rates $^1/_2$ to $^1/_6$ those currently used if irrigation and cold protection water is managed properly. At the same time, surficial aquifer NO_3-N concentrations can, on the average, be maintained below the MCL using these reduced nitrogen application rates on established leatherleaf fern beds. However, high NO_3-N concentrations in the surficial aquifer resulted when multiple weekly fertilizer applications were applied all at the same time in order to "catch-up" for weeks when irrigation water was not needed and, therefore, fertigation did not occur. Field results indicate that by using the lowest nitrogen application rate tested (114 $kg \cdot ha^{-1} \cdot yr^{-1}$ [102 lb per acre per yr]), ground water NO_3-N concentrations below established ferneries might remain below the NO_3-N MCL all or almost all of the time. These findings will be used as the basis for new irrigation and nutrient management practices designed to protect water quality during the production of established leatherleaf fern. A bulletin will be published reflecting appropriate improved management practices.

The results at the newly planted fernery site show that NO_3-N contamination of the surficial aquifer can readily occur when there is no well-established mass of fern roots to intercept and utilize the nitrogen applied (even when the nitrogen application rate is less than $^2/_3$ the rate currently used for commercial production of established fern). These results indicate a need for further research dealing with nutrient and water management during the establishment phase of leatherleaf ferneries.

ACKNOWLEDGEMENTS

As with any project of this scope and duration, the final result is based on the contributions of many individuals. The author wishes to thank Sheila Motley, Cindy Connery Boone, Susan Smallwood-Wild, Loretta Satterthwaite, Diane Rock, Mark Dubberly, Rick Breed and Bob Kratzer for technical support during the course of this project. Their help with equipment set up and maintenance, application of treatments, and data collection and analysis made this project possible. Additional help with lysimeter installation and moving of soil and plants from Pierson, Florida, to Apopka, Florida, was provided by Steve Eshom and Donald and Larry Cox. Thanks also to Mark Ward and Dan Steele for installing field sampling wells. Advice from Dr. Allen Smajstrla, Agricultural Engineering Department, University of Florida, was given freely and is greatly appreciated. Thanks are also extended to Dr. Art Hornsby, Soils and Water Science Department, University of Florida, for providing much of the county-specific information on soil properties used in the geographic information system database (Appendix A). The author is also grateful to Joe Clark for running computer simulations of nitrogen leaching (Appendix F), and to Adam and Lori Braddock and the Taylor Middle-Senior High School Vocational Agriculture Department for their cooperation in the field studies.

Funding for this project was provided by Florida's Department of Environmental Protection, the St. Johns River Water Management District and the University of Florida. Without their cooperation and financial assistance these studies could not have been conducted.

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ABSTRACT

A geograpic information system database was used to store and layer digitized information about the location of soils and leatherleaf ferneries in Lake, Putnam and Volusia counties, Florida. Soil characteristics information was added to the database and it was determined that virtually all leatherleaf fern production occurred on soils with low water-holding and high nitrate nitrogen-leaching characteristics [available water holding capacity <0.13 $cm \cdot cm^{-1}$, 0.01 MPa water content (% by weight) $<20\%$, water transmission rate >15 $cm \cdot hr^{-1}$].

Leatherleaf fern (*Rumohra adiantiformis*) was grown in lysimeter tanks in a shadehouse covered with polypropylene shade fabric designed to reduce incoming radiation by 70%. Microenvironmental conditions inside and outside the shadehouse were monitored. A series of factorial experiments was conducted to determine the effects of soil moisture irrigation setpoint and fertilization rate on nitrogen (N) leaching, and crop growth and quality. Volume and N (NO_x–N, NH_4–N and TKN) concentrations in the leachate from the tanks were measured to determine crop water use and N leaching. Frond color, transpiration, yield (numbers and weights) and vase life were measured periodically. A field study was also conducted to measure the effects of N application method to established fern beds on N concentrations in the surficial aquifer and on frond yield and quality. The 2 application methods were commercial practice (CP, fertilizer injected at beginning of irrigation cycle) and constant feed (CF, fertilizer applied throughout the irrigation cycle). Surficial aquifer N concentrations below established ferneries fertilized with controlled-release fertilizer (CRF) and a newly planted fernery fertilized using conventional liquid fertilization and rates were also monitored.

On an annual basis, incoming, net and photosynthetically active radiation were reduced 79%, 73% and 74%, respectively, inside the shadehouse compared to outside. Wind speeds and wind run were greatly reduced, and relative humidities were higher, inside compared to outside the

shadehouse. Evaporatory pan water losses (E_{pan})were 75% less inside than outside the shadehouse. Leatherleaf fern water use (ET_{actual}) averaged 50 cm·yr^{-1} resulting in a crop coefficient (ET_{actual}/E_{pan}) of 0.29.

There were no differences in yield or frond quality in any lysimeter study due to soil moisture irrigation setpoint or N fertilization rate. Leachate NO_x–N leaching was not affected by irrigation setpoints, and NH_4–N and TKN were not affected by fertilizer application rates. NO_x–N accounted for about 96% of the N in the leachate and both the concentration and the percentage of applied nitrogen in the leachate increased linearly with increasing N application rate. Average NO_x–N concentrations were below the EPA maximum drinking water contamination level (MCL) of 10 mg·liter^{-1} when N application rates were at or below about 334 kg·ha^{-1}·yr^{-1}.

In the field study comparing CP and CF application methods where N application rate was 114 kg·ha^{-1}·yr^{-1}, average NO_3–N concentrations in the surficial aquifer were below the EPA MCL for both treatments throughout the year. There were no differences in frond yield or quality due to fertilizer application method. In the CRF study, NO_3–N concentrations in the surficial aquifer exceeded the MCL, predominantly during the warmer months. NO_3–N concentrations in the surficial aquifer below the newly planted fernery rose rapidly to about 40 mg·liter^{-1} and remained there throughout most of the monitoring period.

INTRODUCTION

Leatherleaf fern [*Rumohra adiantiformis* (Forst.) Ching] accounts for 57% of total production area and 60% of the wholesale sales value of United States-produced cultivated cut foliage and over 97% of this production occurs in Florida (USDA, 1993). This herbaceous, perennial crop is grown predominantly in three counties (Lake, Putnam, Volusia) in central and northeastern parts of the state (Cunningham and Sheehan, 1991) where there are about 2,395 hectares [5,900 acres] of production (Stamps, 1994). Water use in leatherleaf fern production areas in all three counties is under the jurisdiction of the St. Johns River Water Management District.

In Florida, leatherleaf fern is grown under shade, with two-thirds of the production in shadehouses and the remainder under evergreen oak trees (Boggess et al., 1991; Figure 1). Plants are grown predominantly on well-drained, mostly sandy soils having low water- and nutrient-holding capacities (Stamps, 1992; Stamps and Conover, 1986). In Volusia county, where leatherleaf fern accounts for about 60% of cut foliage production acreage (St. Johns River Water Management District, unpublished), two-thirds of all fresh water used by agriculture is used for irrigating and freeze-protecting cut foliage crops (Marella, 1990; Figure 2).

IRRIGATION OF LEATHERLEAF FERN

Although annual precipitation in cut foliage-producing areas of Florida is around 125 centimeters (cm)$\cdot$yr^{-1} [49 inches (in)/year], it occurs unevenly (NOAA, 1990; Figure 3). Fern growth and productivity are markedly reduced under water stress and, therefore, supplemental irrigation is required for commercial production (Henley et al., 1980). Irrigation water is applied using solid set overhead irrigation impact sprinklers because the crop is

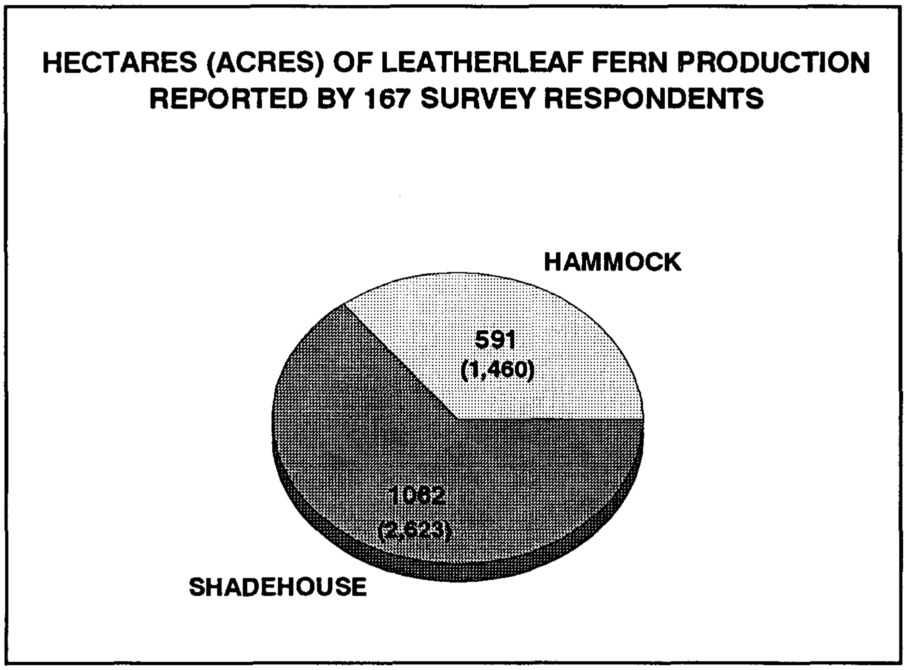

Figure 1. Leatherleaf fern grower survey respondents reported that almost two-thirds of their production occurred in shadehouses (Boggess et al., 1991).

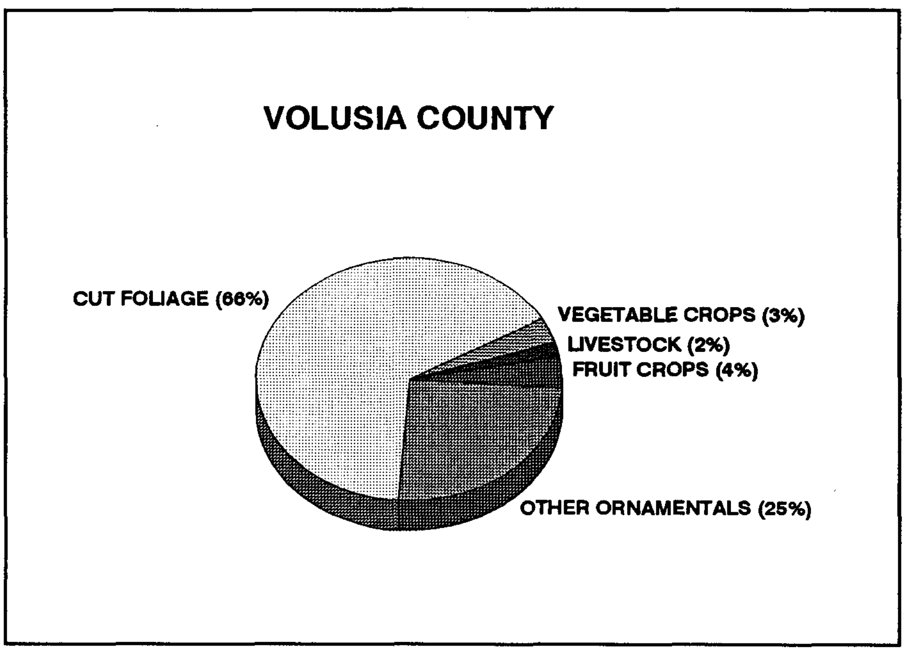

Figure 2. Agricultural water use in Volusia county in 1987 (Marella, 1990).

grown as a continuous canopy and the irrigation system is used for cold protection as well as for fertigation and chemigation (Harrison and Conover, 1970; Henley et al., 1980; Stamps and Haman, 1991; Stamps et al., 1991).

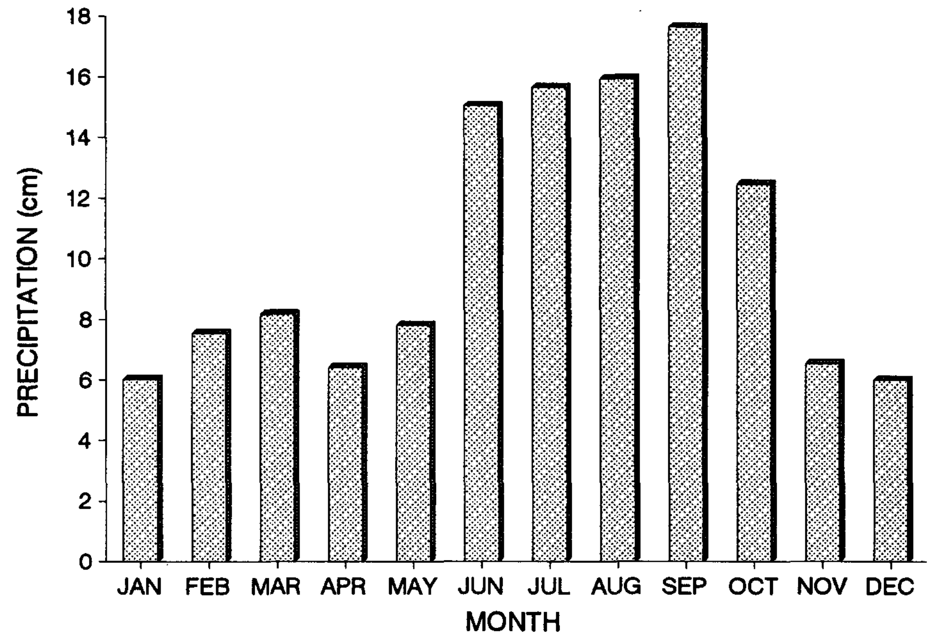

Figure 3. Mean monthly precipitation over 30 years at National Oceanic and Atmospheric Administration weather station in Daytona Beach, Florida (NOAA, 1990).

Early irrigation recommendations stated that ferns generally require 2.5 cm [1 in] of water every three days during the summer months and 1.3 cm (½ in) every four to seven days during winter months (Conover and Loadholtz, 1970; Henley et al., 1980). On a weekly basis, this is about 5.9 cm [2.3 in] of water during the summer and 1.3 to 2.3 cm [0.5 to 0.9 in] during winter months, for a yearly total of from 231 to 245 cm [91 to 96 in] of water. Actual irrigation amounts would be less, due to contributions to soil moisture by precipitation.

Grower irrigation system management practices have been determined during an on-farm survey. Grower responses indicated that shadehouse-grown leatherleaf fern was being irrigated with an average of 1.2 cm [0.46 in] of water every 6.8 days during the summer and with 1.5 cm [0.6 in] of water every 3.9 days during the summer (Stamps et al., 1991). No quantitative methods of irrigation scheduling have been suggested and in the above survey only 1 firm out of 167 used tensiometers to quantify when and how much water to apply (Boggess et al., 1991).

Sensitivity analysis of estimated leatherleaf fern irrigation requirements (IRREQ) done using a numerical simulation model suggests that IRREQ is most sensitive to irrigation efficiency (see following paragraph), time of year, and crop water use coefficients (Smajstrla and Stamps, 1993; Appendix G). Crop water use coefficients have not been developed for leatherleaf fern.

In Florida, irrigation efficiency using overhead irrigation is considered to be about 70% to 75%, that is, 25% to 30% of the water leaving the sprinkler does not increase soil moisture due to losses through evaporation and wind drift off target (Harrison and Conover, 1970). These figures are based on work with field crops and the losses in shadehouses could be less due to reduced wind velocities, lower radiation levels, and higher relative humidities. However, no research has quantified field conditions and fernery conditions at a given site at the same time.

Very little research has been conducted regarding irrigation of leatherleaf fern (see Appendix B) and none to determine water use by this crop.

NITROGEN (N) AND POTASSIUM (K) FERTILIZATION OF LEATHERLEAF FERN

Early fertilization rates for leatherleaf fern were based on experience with other crops and limited grower experience with leatherleaf fern. Rates of application of 6N–2.6P–5K [6N–6P_2O_5–6K_2O] fertilizers ranged from 4,480 to 7,840 kilograms per hectare per year ($kg \cdot ha^{-1} \cdot yr^{-1}$) [4,000 to 7,000 pounds per acre per year (lb/acre/yr)] for north and central Florida, where most leatherleaf fern is grown (Conover, 1966). Using those fertilizer rates, the elemental nitrogen and potassium application rates ranged from 269 to 470 $kg \cdot ha^{-1} \cdot yr^{-1}$ [240 to 420 lb/acre/yr] and 223 to 390 $kg \cdot ha^{-1} \cdot yr^{-1}$ [199 to 349 lb/acre/yr] for N and K, respectively. The lower rates were for use in heavy or amended sandy soils in north Florida and the higher rates for use in non-amended sandy soils in warmer locations where leatherleaf fern grows year-round.

In 1970, new fertilization rates were published with N and K fertilization ranging from 588 to 806 $kg \cdot ha^{-1} \cdot yr^{-1}$ [525 to 720 lb/acre/yr] and 488 to

669 $kg \cdot ha^{-1} \cdot yr^{-1}$ [436 to 598 lb/acre/yr], respectively, for leatherleaf fern grown in Florida under 60 to 70 percent shade (Conover and Loadholtz, 1970). The lower rates were generally recommended for unheated ferneries and the higher rates for heated ferneries. Like previously published rates, these were also based on field observations and experience, and not on experimental data.

Elemental nitrogen and potassium application rates ranging from 412 to 672 $kg \cdot ha^{-1} \cdot yr^{-1}$ [368 to 600 lbs/acre/yr] were suggested in 1980 (Henley et al.). However, the use of rates above 588 $kg \cdot ha^{-1} \cdot yr^{-1}$ [525 lbs/acre/yr] applied only to leatherleaf fern grown in heated structures and heated structures are very rarely used commercially.

Most of the research on the nutritional requirements of leatherleaf fern was conducted in the early 1970s at the University of Florida's Institute of Food and Agricultural Sciences' Agricultural Research Center in Apopka, Florida and is reported in Appendix C. However, that research was conducted using dry fertilizers and irrigation scheduling on a calendar basis and, therefore, does not apply to the current industry standard practice of applying liquid fertilizer using irrigation systems (fertigation) or to irrigation scheduling based on plant water use.

NITROGEN LEACHING

Nitrate concentrations in root zone drainage can be high, even when organic (poultry manure) nitrogen sources are used. For example, NO_3–N concentrations measured in leachate collected below the root zone of vegetable crops growing in podzolized sands low in organic matter in Australia ranged from 71 to 209 $milligrams \cdot liter^{-1}$ ($mg \cdot l^{-1}$) [71 to 209 parts per million (ppm)] (Pionke et al., 1990).

Water flow rates through soils depend on soil hydraulic conductivity and the driving force (Kramer, 1983). As mentioned previously, almost all leatherleaf fern production in Florida occurs on sandy soils (see Introduction, page 1). Other factors being constant, hydraulic conductivity increases as pore size increases (Donahue et al., 1977) and the total water flow rate in soil pores is proportional to the fourth power of the radius (Brady, 1990). Therefore, sandy soils generally transmit water rapidly.

Significant water drainage and leaching of solutes generally only occur when soil moisture content is above field capacity (Jackson et al., 1987). This condition can occur during leatherleaf fern production due to (1) rainfall, (2) irrigation for cold protection or (3) water application during chemigation/fertigation/irrigation events. Irrigation management practices can help reduce leaching from all three of the above circumstances.

Several studies have shown direct correlations between leaching of fertilizer nitrogen and irrigation practices (Bingham et al., 1971; Stewart et al., 1968; Ward, 1970). Snyder et al. (1984) showed that tensiometer-controlled irrigation reduced N leaching in turfgrass, regardless of nitrogen source. N leaching was increased during rainy months and decreased during dry months when ET-adjusted irrigation was used compared to ET-fixed (overirrigation) for turfgrass plots (Cisar et al., 1991).

Besides modifying irrigation management practices, fertilization management techniques can also be changed to reduce nitrate nitrogen (NO_3–N) leaching. NO_3–N is water soluble and moves readily through soil dissolved in water (Gardner, 1965; Tisdale and Nelson, 1975). Since most soil solids are negatively charged and so is NO_3–N, significant adsorption generally does not occur (Keeney, 1986) and NO_3–N is readily leached (Hageman, 1984; Jury and Nielsen, 1989). The main route of nitrogen loss from field soils is through leaching, with nearly all of the nitrogen in the form of nitrates (Allison, 1966). Even when nitrogen is applied in other, non-nitrate forms (urea, $CO(NH_2)_2$; ammonium, NH_4^+), it can be rapidly transformed to the nitrate form through the process of nitrification. Nitrification can proceed at rates of 11.2 to 22.4 kg N/ha per day [10 to 20 lb N/acre per day] in warm, moist sandy soil with pHs of 6 to 8 (Jackson et al., 1987).

In recent years, Florida's leatherleaf fern producers have adopted the technique of fertigation (fertilizer application using irrigation systems) as the preferred method of fertilizer application. In fact, 94% of commercial leatherleaf fern growers in Florida reported that they applied fertilizers using irrigation systems (Stamps et al., 1991). Fertigation allows growers to apply small amounts of nutrients on a regular basis so crop growth is optimized. In addition, the quantity of nutrients in the soil at any given time can be kept low (compared to using dry fertilizer) so that leaching is minimized when heavy rainfall or irrigation for cold protection occurs.

Controlled- and slow-release nitrogen sources can be used to reduce N leaching under certain circumstances (see Appendix D). In addition, plant uptake of nitrogen can reduce leaching (see Appendix D). Nitrogen sources can also affect N-leaching. In fact, preliminary computer modeling of alternative management practices for fertilizing leatherleaf fern suggest that selection of N sources can significantly affect N, especially NO_3-N, leaching (Appendix F).

DRINKING WATER AND CONCERNS WITH NITRATES

In 1975, about 86% and 95% of water in Florida for public-supply and rural use, respectively, were obtained from ground water sources (Leach, 1978). In 1987, all public supply and domestic self-supply water used in Lake, Putnam and Volusia Counties came from ground water sources (Marella, 1990).

Concerns about adverse health effects of ingesting nitrate nitrogen, especially relating to the occurrence of methemoglobinemia in infants (blue baby; Walton, 1941), has led to the establishment by the U. S. Environmental Protection Agency (EPA) of a maximum drinking water contamination level (MCL) of 10 mg NO_3–N per liter (45 mg NO_3 per liter) [10 ppm NO_3–N, 45 ppm NO_3]. This standard has recently been reaffirmed by EPA. In Florida, the standard has been adopted as a primary drinking water quality standard, and is applied as an enforceable ground water quality standard. In 1985, NO_3–N concentrations in the surficial aquifer at one commercial leatherleaf fern production site located in Volusia County were determined to be above the established MCL for NO_3–N (Hicks, 1985).

The determination that leatherleaf fern production, at least at one site, could be associated with elevated surficial aquifer nitrate nitrogen levels suggested that there was a need to develop irrigation and fertilization management practices for use when producing leatherleaf fern. These management techniques must be economically sound and minimize the potential for nitrate nitrogen contamination of ground water which serves as a current or potential source of drinking water. This research is part of the effort to develop and test those management practices.

PURPOSE AND SCOPE

The soils and leatherleaf ferneries mapping was done to determine on which soils leatherleaf fern is being produced. In addition, the water-holding and nitrogen-leaching characteristics of these soils were tabulated to ascertain whether or not good nitrogen (N) management would be expected to have a significant effect in reducing N-leaching.

The lysimeter research was conducted to determine the effects of irrigation scheduling and nitrogen application rate on leachate nitrogen content, and crop growth and quality of leatherleaf fern (*Rumohra adiantiformis*) growing under artificial shade. In addition, crop water use was determined using the lysimeters. The field studies provided an opportunity to test, on a larger scale than possible with the lysimeters, the effects of N application rate and application method on fern yield and N leaching. The surficial aquifer monitoring wells at the Taylor Middle-Senior High School site furnished the first opportunity to study N leaching during leatherleaf fern production using controlled release fertilizer and at the new fernery site allowed the monitoring of N concentrations in the surficial aquifer during leatherleaf fern bed establishment.

These results will be used to help determine improved management practices (IMPs) for producing leatherleaf fern in shadehouses on Tavares fine sand or soils with similar characteristics. These results do not necessarily apply directly to leatherleaf fern production under natural shade provided by trees but should reveal trends that could help in determining IMPs for use under those conditions.

MATERIALS AND METHODS

SOILS MAPPING

Parcel and aerial photography maps of Lake, Putnam and Volusia counties were obtained from the tax appraiser's office in each county. Aerial and parcel maps were 1:200 and 1:400 scale maps, respectively. The aerial maps were used to visually locate the shadehouse ferneries. However, hammock ferneries could not be identified by this method due to the tree foliage preventing the determination of which forested areas were in fern production and which were not. Tax offices were able to provide the section, township, and range that contained parcels that were assessed as commercial fern production sites. This information helped to identify locations for ground investigation for fern production. Those locations that were identified as containing fern were thoroughly investigated; primarily looking for hammock ferneries but also for shadehouse ferneries that were added since the photographs were taken.

If a fernery was located during a site visit, its boundaries and well locations were drawn on the parcel maps. While at each site the following were determined: 1) fern variety, 2) type of irrigation system, 3) type of freeze protection system, 4) source of water for irrigation, and 5) well diameter, when possible. In ferneries where more than one variety of cut foliage was being produced, production areas were differentiated by variety. The annotated parcel maps were used to digitize the boundaries of the ferneries and well locations into the geographic information system (GIS) database (ArcInfo for Unix). In addition, site parameters were entered into the database.

Soils information from county soil surveys were also digitized and entered into the database. Database inquiries were then made linking fernery locations with soil types to determine the soil types and area being used for leatherleaf fern production in the three counties.

EXPERIMENTAL DESIGNS

Lysimeter Studies

These randomized complete block design experiments initially had a 3 × 3 factorial design consisting of 3 soil moisture potential irrigation setpoints and 3 nitrogen application rates. Later studies had 3 × 4 factorial designs (see below for details).

Field Studies

A 3 × 3 Latin-square design was used for the experiments at Taylor Middle-Senior High School.

LOCATIONS

Lysimeter Studies

The lysimeter studies were carried out at the University of Florida's Central Florida Research and Education Center - Apopka in a 642 square meter (m^2) [6,912 square feet (ft^2)] leatherleaf fernery that was in close proximity to support facilities required for these types of studies.

Field Studies

Replicated field studies were conducted at the Taylor Middle-Senior High School research shadehouse facility (TMSHS) in Pierson, Florida, which consists of nine 29 m × 29 m [96 ft × 96 ft] shadehouses. (For a detailed layout of the TMSHS shadehouse facility see Stamps and Haman, 1991). Additional field monitoring was conducted at a 5-acre, newly planted (at the time of sampling initiation) commercial fernery in Seville, Florida.

LYSIMETERS

Thirty-six drainage lysimeters similar to those described by Smajstrla (1985) were constructed. Lysimeters were installed lengthwise in the established fern beds (Figure 4).

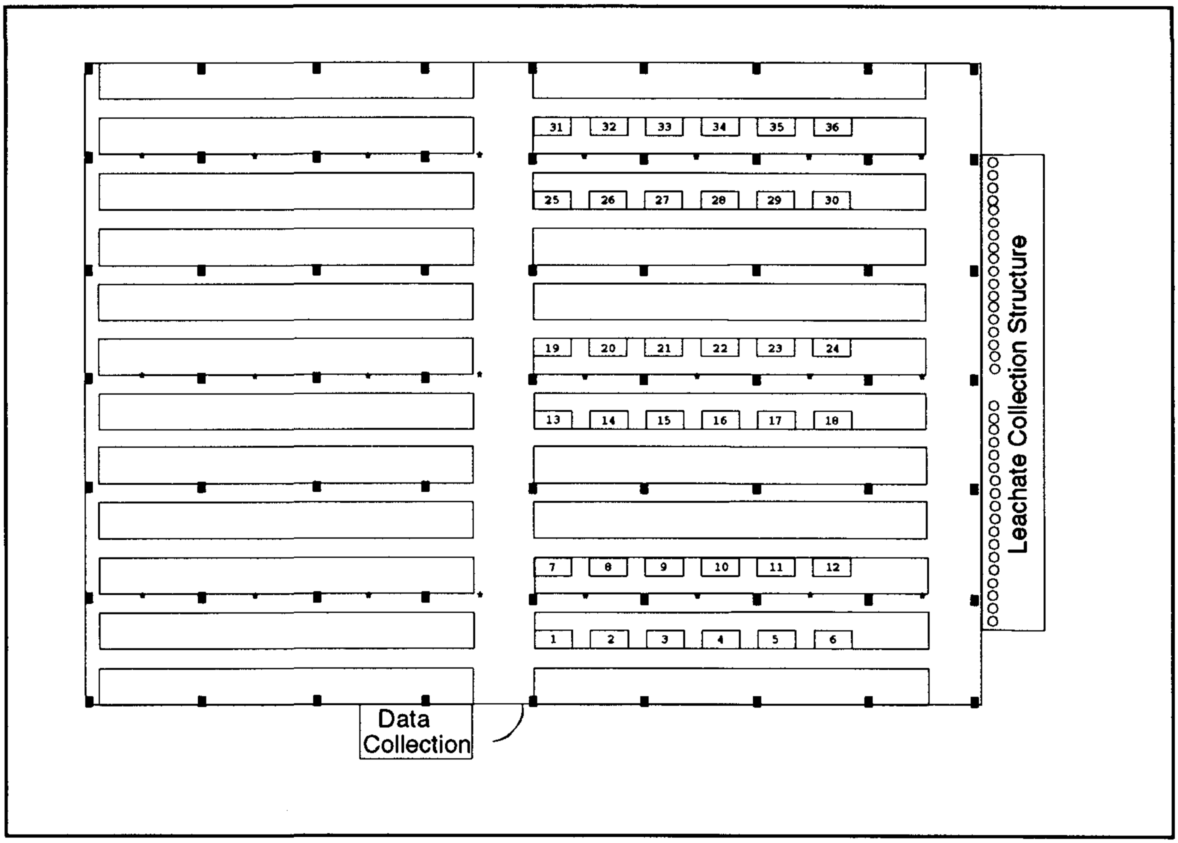

Figure 4. Schematic diagram of research fernery showing location of 36 lysimeter tanks, data collection station, and leachate collection structure.

Lysimeter tanks were constructed of 0.64-centimeter (cm) [0.25-inch (in)] thick fiberglass and measured 1.2 m [4 ft] long, 0.6 m [2 ft] wide, and 0.9 m [3 ft] deep. The molds for the tanks were made so that the smooth surface was on the exterior of the tanks and the rough surface was on the interior. The purpose of this design was to minimize the possibility of water channeling between the soil and the tank wall. Two aluminum oxide filter tubes (Refractron Corporation, Newark, NY 14513) measuring 76-cm [30-in] long with outside diameters of 6 cm [2.4 in] were installed in the bottom of each tank and covered with builders' sand. Tubes had a wall thickness of 1 cm [0.4 in], mean pore size of 10 microns and allowed leachate to be pulled from the bottom of the lysimeters using vacuum. Each filter tube had a surface area of approximately 1,432 cm^2 [222 in^2] and was attached to a separate vacuum line inside the tanks. This redundancy was built into the system so that, in the event of a leak in one of the underground leachate extraction lines, the other system could still be used for leachate extraction and the integrity of the fern rhizome and root system, as well as the soil profile in the tank, would not have to be disturbed. Having two filters in each tank also doubled the leachate collection surface, thereby facilitating extraction of leachate during prolonged rainfalls or periods of cold protection when high flow rates would be necessary. The prevention of saturated soil conditions is important in lysimeter research because denitrification, which occurs under anaerobic conditions, could invalidate nitrate leaching data (Keeney, 1986).

Lysimeter tanks were placed in the ground so that the top rim was approximately 5 cm [2 in] above the surrounding soil surface. Lysimeters were hand-packed to reconstruct the soil profile of Tavares fine sand (hyperthermic, uncoated, Typic Quartzipsamments) from the Pierson, Florida, fernery from which the soil and fern were dug. The soil was dug and planted in 5-cm [2-in] layers. Fern was removed from the source fernery in 30.5 cm [12 in] × 45.7 cm [18 in] slabs with as much of its root system intact as possible. Fern slabs were replanted in the research fernery as soon as the soil profile in a lysimeter was reconstructed. Fern was allowed to become established for 9 months prior to treatment initiation. This was done to allow time for the rhizome and root systems to regenerate, especially into the areas between the slabs, and thereby prevent unrestricted movement of fertilizer and water around the root zone. During this time the fern was fertilized with liquid fertilizer (see FERTILIZATION, page 19) at a minimal maintenance rate of 84 kg N/ha per yr [75 lb N/acre per yr]. This establishment period also allowed time to develop working lysimeter management techniques.

Leachate Extraction

Individual polyvinyl chloride (PVC) leachate extraction systems were connected to the aluminum oxide filter tubes from each lysimeter and connected to separate leachate collection tanks located in the leachate collection structure. Two high-volume vacuum pumps (2567–V108, GAST, Benton Harbor, MI) were connected to the vacuum manifold that was attached to each leachate collection tank. The incoming leachate extraction line had a 30-cm [12-inch] drop pipe connected to it so that water would enter the leachate collection tank well below the point where the vacuum manifold was connected to the tank and, therefore, water would not be drawn into the vacuum manifold system (Figure 5).

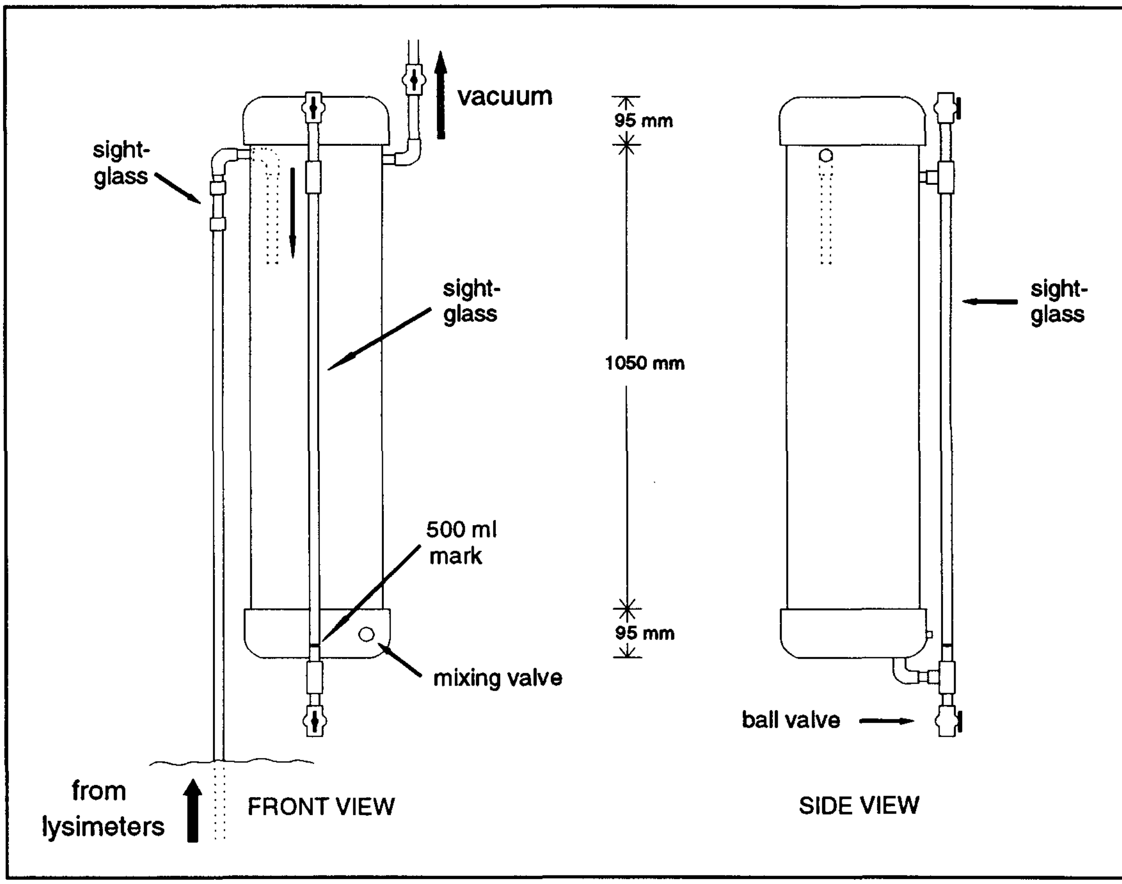

Figure 5. Schematic representation of leachate collection tanks.

Leachate collection tanks were constructed using 20 cm [8 in] PVC pipe and caps (Figure 5). Each leachate collection tank was equipped with a sight-glass in the incoming vacuum extraction line to allow visual determination of when the bubbling pressure of the ceramic filter had been reached. An additional calibrated sight-glass ran vertically from the bottom to the top of the collection tank to allow rapid determination of leachate volume by measuring the height of the water column in the tank. Leachate was mixed just prior to sample collection using three short, high pressure (6 $kg \cdot cm^{-2}$ [85 psi]) air blasts introduced through an air valve located at the bottom of each leachate collection tank. Multiple 25-ml [0.85-fluid ounce] samples from each leachate collection tank were collected into high density polyethylene scintillation vials. Half of the samples were acidified at the time of collection to a pH of 2 using sulfuric acid and all samples were held at 4°C [39°F] during storage and transport.

Leachate was collected every two weeks or more often when necessitated by the need to prevent water-saturated soil conditions from occurring. The unscheduled leachate extractions were due to heavy rainfall or irrigation for cold protection.

MONITORING WELLS

Preliminary investigations of the field sites were performed to determine depths to the water table at various locations and from that information determine the direction of ground water flow across the property. This involved the installation of shallow water level-monitoring wells at the corners of the property boundaries. These wells were constructed with 5.1 cm [2 in] PVC well casing and a 1.5 m [5 ft] length of PVC well screen. The position of the well screen was such that one-half of the section was above the water table and the lower half was below the water table.

Once the direction of ground water flow in the surficial aquifer was determined, water level hydrographs from the SJRWMD Pierson Airport monitoring well cluster, approximately one-quarter mile away from the Taylor Middle-Senior High School site, were examined to get an estimate of the seasonal fluctuation of the water table. This information was used as a basis for the interior nitrate-monitoring well design. As a result of that information it was determined that it would be desirable to account for a minimum 0.3 m [1 ft] fluctuation in the water table over the term of the project.

A pair of nitrate-monitoring wells was installed near the center of each shadehouse at the Taylor Middle-Senior High School site and four pairs were installed in a rectangular pattern at the new fernery site. A 16 cm [6¼ in] hollow stem auger was used to bore the hole for each well. Then the 5 cm [2 in] PVC well casing was placed inside the auger and sand was used to back fill the hole to within 0.3 m [1 ft] of the soil surface. Grout was used to back fill the rest of the way up to the soil surface. The shallower of each pair of wells was constructed using a 0.6 m [2 ft] screen straddling the water table elevation present at the time of installation (Figure 6). This allowed for sampling to be possible as long as the decline or increase in the water table elevation was less than 0.3 m [1 ft]. Because of the prevailing drought condition at the time of installation, the second well was installed with a 0.3 m screen set immediately below the ending point of the shallow well screen. This allowed for an additional 0.3 m decline or an overall 0.6 m decline in the water table at the site. It would also allow for additional water quality samples from a lower horizon which might give some insight into the mobility of nitrates in the ground water system. Depths to the water table at the time the wells were installed ranged from 76 to 122 cm [30 to 48 in] at the Taylor Middle-Senior High School site and 109 to 170 cm [43 to 67 in] at the Seville site.

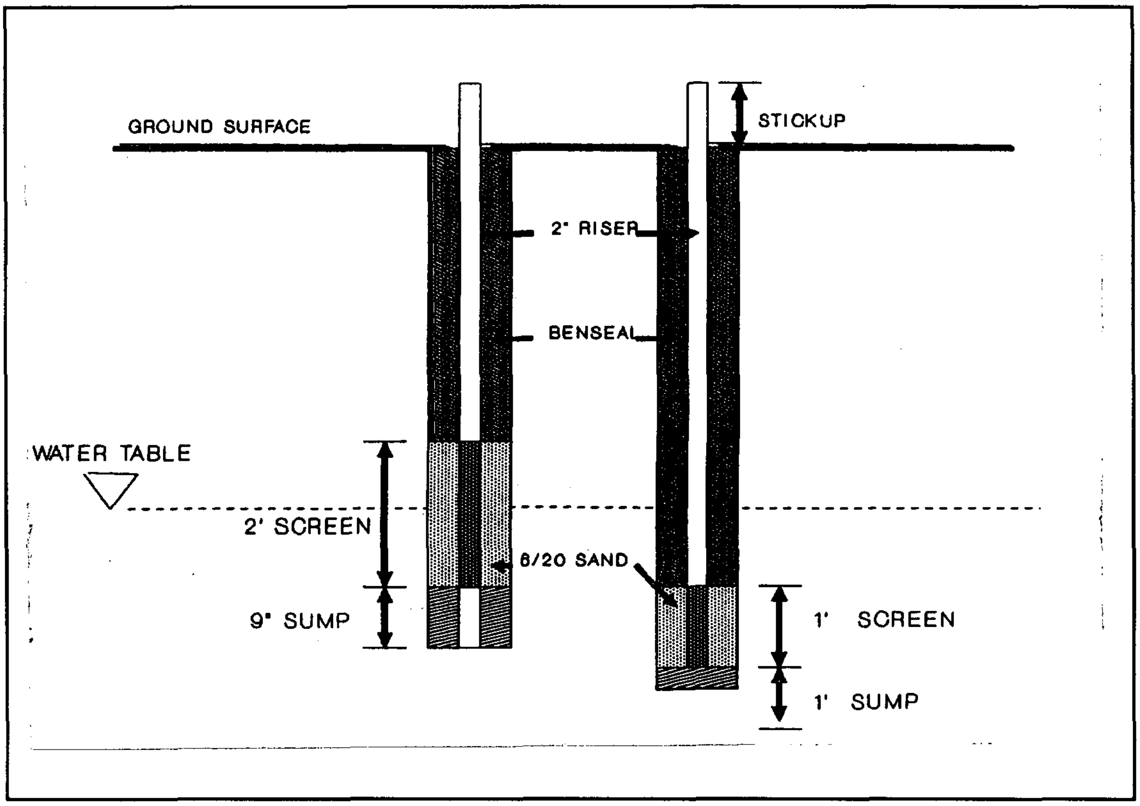

Figure 6. Schematic of monitoring well installation used to sample from the surficial aquifer at the field sites.

Sample Collection

Samples were collected monthly from the field nitrate-monitoring wells. A calibrated meter (YSI 3560) was used to measure conductivity, pH and temperature of samples. A separate piece of polypropylene tubing, one for each well, was inserted into the well and connected to a peristaltic pump on one side and the YSI chamber on the other so that water being purged from the well went into the YSI chamber. The peristaltic pump was started and as soon as the chamber filled initial readings were taken. Pumping was continued for a timed period calculated to allow for 3 well volumes to be purged at the pumping rate of 0.6 liters per min [0.17 gallons per min]. Well volumes varied with well depth and water levels and were determined individually for each well as follows:

$$well\ volume\ (in\ gallons) = (WD - DTW) \times (dia)^2 \times 0.041$$

where WD = well depth
DTW = depth to water
$dia.$ = inside diameter of well casing

Readings were recorded after purging each well volume and, if conductivity, pH and temperature were stabilized within 10% of the first volume reading, samples were collected. If the readings had not stabilized, purging was continued for up to two more well volumes.

Samples were collected into two bottles — one sulfuric acid preservative, chilled (SC) bottle and 1 chilled only (C) bottle. One-half ml [0.015 oz] of sulfuric acid was added to the water in each SC bottle. Both bottles were then placed on ice in a cooler. The tubing was removed from the well to be taken back at the lab for cleaning. The peristaltic pump and YSI chamber were cleaned in the field with deionized water before the next well was sampled.

ANALYSIS OF WATER SAMPLES

Water samples were analyzed according to the following reference analytical methods:

Ammoniacal nitrogen	EPA 350.1
Nitrate/nitrite nitrogen	EPA 353.2
Total Kjeldahl nitrogen (TKN)	EPA 351.2

Ammoniacal and nitrate/nitrite samples were generally analyzed within 48 hours of sampling, and TKN was analyzed within the prescribed 28-day time period. When unscheduled sampling was necessitated by heavy rainfall or cold protection, all samples were acidified and analyzed within 28 days.

SOIL MOISTURE

Each lysimeter was equipped with two horizontally installed remote-sensing tensiometers (RST, Irrometer, Riverside, CA 92503), one at 7.6 cm [3 inches] and the other at 15.2 cm [6 inches], to allow monitoring of soil moisture conditions in the crop root zone using a datalogger (CR10, Campbell Scientific, Logan, UT 84321). Each tensiometer was calibrated prior to installation. Figure 7 shows the linearity of the output from the transducers used in the tensiometers. Available water-holding capacity of the soil was determined gravimetrically from soil cores taken at the site where the fern was dug in Pierson.

Three vertically oriented tensiometers were setup in each field shadehouse so that the porous ceramic tip of each one was centered about 12 cm [5 in] below the soil surface. Soil moisture readings were taken manually in each shadehouse and the three reading per shadehouse averaged.

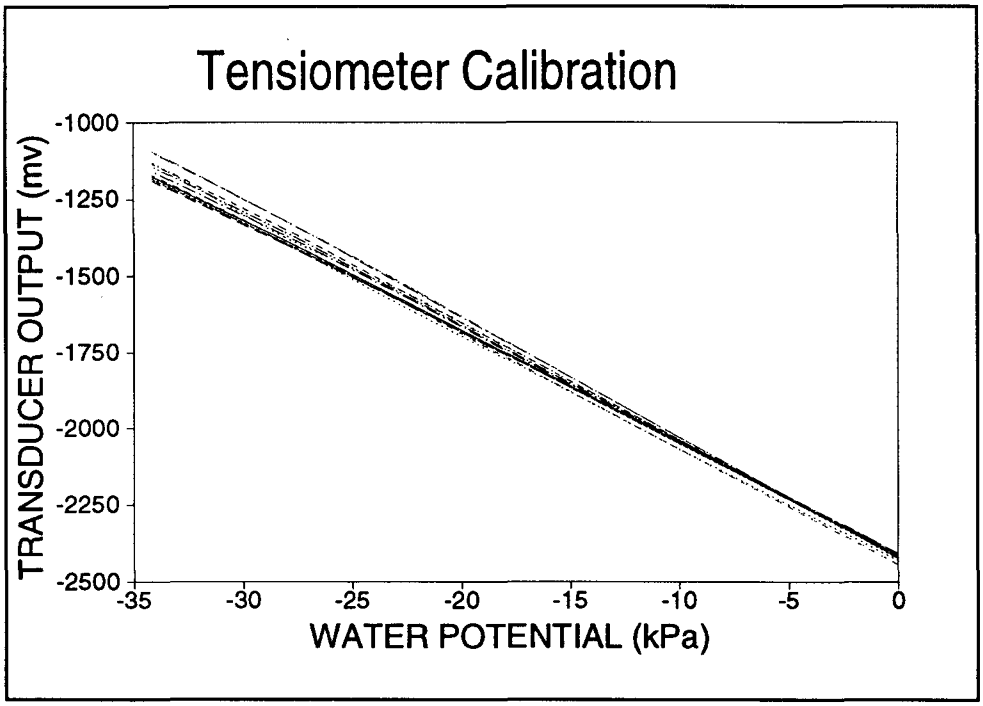

Figure 7. Typical calibration curves for several tensiometers.

IRRIGATION SCHEDULING

The average of the two tensiometer readings in each lysimeter was monitored daily to determine when to irrigate each tank. Soil moisture levels of −6, −12, −18 kiloPascal (kPa) [−6, −12, −18 centibars (cbar)] were initially used as setpoints to trigger irrigation events. Later, setpoints were changed to −8, −12 and −16 kPa [−8, −12 and −16 cbar]. The irrigation setpoint for field shadehouses was −12 kPa [−12 cbar].

IRRIGATION

Lysimeter Studies

Lysimeters were watered individually using water containers with multiperforate spouts. Irrigation amounts were varied according to the soil moisture potential and were designed to replenish available water in the crop root zone. Liquid fertilizer was included in the water if the lysimeter being watered needed to be fertilized for the week. Catch cups located at the ends of each lysimeter tank and polyethylene bins located above selected lysimeters were used to monitor irrigation amounts when the overhead irrigation system was used for cold protection.

Field Studies

Shadehouses were watered using solid set irrigation systems with impact sprinklers mounted on ~1 m [3 ft] risers. Irrigation amounts at the Taylor Middle-Senior High School site varied according to soil moisture potentials and were designed to replenish available water in the crop root zone. Irrigation at the new fernery site was managed by the owner.

PRECIPITATION

Precipitation throughout the fernery where crop water use was to be determined (lysimeter studies) was not uniform due to the interception and channeling effects of the shade fabric covering the fernery. Therefore, the relationship between precipitation and the amount of rain entering the lysimeters had to be determined individually for each lysimeter. During rain events, water was collected in three polyethylene bins placed on wooden supports over individual lysimeter tanks. The combined collection area of the three bins was similar to that of the lysimeter tanks. Rain water volume was measured using graduated cylinders. The rain water volume collected in each set of three bins was then converted to an average rainfall depth using the surface area of the bins. Equations describing the relationship between the amount of precipitation occurring outside the shadehouse and at each lysimeter tank were determined using linear regression analysis. Coefficients of determination (r^2) for the regression lines ranged from 0.875 to 0.999 with most values (97%) greater than 0.92 and two-thirds greater than 0.98 (Appendix E). Regression coefficients (slopes), b, of the fitted lines ranged from 1.03 to 1.63 (Appendix E), indicating that the lysimeter tanks received 3% to 63% more rain water per unit area than areas outside the fernery. This increase was due to the interception and channeling of rain water by the shade fabric as mentioned above.

FERTILIZATION

Lysimeter Studies

Fertilization treatments consisted of more or less weekly applications of liquid fertilizer at various annual nitrogen (N) application rates. Initial nitrogen (Study 1) application rates of 390, 600 and 810 $kg \cdot ha^{-1} \cdot yr^{-1}$ [350, 535 and 723 lb/acre/year] were applied for 6 months. In Study 2 which lasted 10 months, N application rates were then lowered to 281, 373, 455 and 571 $kg \cdot ha^{-1} \cdot yr^{-1}$ [251, 333, 406 and 510 lb/acre/year]. Study 3, which lasted ~6 months, N application rates were lowered further to 265, 334, 417 and 503 $kg \cdot ha^{-1} \cdot yr^{-1}$ [237, 298, 372 and 449 lb/acre/year]. Required fertilizer was applied with the irrigation water as described in the preceding section. The amount of the macronutrient fertilizer containing nitrogen varied with treatment but all lysimeters were fertilized with the same amount of micronutrient fertilizer. Micronutrient fertilizer was applied to deliver B, Cu, Fe, Mg, Mn and Zn at annual rates of 1.2, 0.8, 3.7, 112, 3.1 and 2.1 $kg \cdot ha^{-1}$ [1.1, 0.7, 3.3, 100, 2.8 and 1.9 lb/acre] as recommended by Henley et al. (1980). Tables 1 and 2 give the analyses of the liquid fertilizers used.

Table 1. Analysis of liquid macronutrient fertilizer used in the experiment.	
Element	**Percent by weight**
Nitrogen (N)	
– nitrate	2
– ammoniacal	2
Potassium (K)	4
Derived from ammonium nitrate, potassium chloride, ammonium thiosulfate, calcium nitrate, potassium nitrate.	

Table 2. Analysis of liquid micronutrient fertilizer used in the experiment.	
Element	**Percent by weight**
Boron (B)	0.015
Copper (Cu)	0.0005
Iron (Fe)	0.005
Magnesium (Mg)	0.05
Manganese (Mn)	0.05
Sulphur (S)	0.05
Zinc (Zn)	0.05
Derived from sodium borate, copper sulphate, iron sulphate, magnesium sulphate, manganese sulphate and zinc sulphate.	

Field Studies

Each shadehouse at the Taylor Middle-Senior High School (TMSHS) site was fertilized individually. At the beginning of this experiment (22 March 1993), 3 shadehouses were fertilized with 15N–2.6P–12.4K [15N–6P_2O_5–15K_2O] controlled-release fertilizer (CRF) (CB 86–92, Grace-Sierra, Milpitas, CA 95035) designed to supply nutrients for 1 year from the time of application. The nitrogen application rate in the CRF shadehouses was 396 kg·ha^{-1}·yr^{-1} [354 lb/acre/yr]. The remaining 6 shadehouses were fertilized with commercial 8N–0P–6.6K (8N–0P_2O_5–8K_2O) liquid fertilizer. This fertilizer was measured volumetrically and poured into stock solution tanks in each of the three constant feed shadehouses prior to turning the irrigation systems on. Each constant feed shadehouse was equipped with bypass valving to force the incoming water through a water-driven injector (Model D8R, Dosatron International, Clearwater, FL 34615) that pumped the fertilizer throughout the irrigation cycle. The volume of stock solution was sometimes increased using water to allow longer duration irrigating if soil moisture conditions indicated that additional watering was necessary to replenish available water in the crop root zone. The same volume of liquid fertilizer that was applied to the constant feed shadehouses was injected into the three commercial practice shadehouses using an injection pump connected to an injection fitting on the incoming irrigation line of the each shadehouse. Injection took place at the beginning of the irrigation cycle and lasted about 2 minutes. Liquid fertilizer was applied once every 2 to 4 weeks from March 1993 through February 1994 at an annual N application rate of 114 kg·ha^{-1}·yr^{-1} [102 lb/acre/yr].

Liquid fertilizer was applied at the new fernery site in the same manner as it was applied in the commercial practice plots at TMSHS.

ENVIRONMENTAL MONITORING

An automated weather station monitored air, soil and leaf temperatures, relative humidity, windspeed, wind run, photosynthetically active radiation (PAR) and incoming radiation inside and outside the shadehouse. Table 3 lists the environmental monitoring equipment and locations where the equipment was used.

Saturation vapor pressures were calculated using an approximating polynomial (Lowe, 1977) and temperatures (air and leaf) measured using thermocouples. Wet- and dry-bulb temperatures were used to determine unsaturated vapor pressures using the following equation (Marvin, 1937):

$$e_a = e_s^{wet\text{-}bulb} - 0.000660\,P\,(T_{dry\text{-}bulb} - T_{wet\text{-}bulb}) \times [1 + (0.00115 \times T_{wet\text{-}bulb})]$$

Table 3. Microenvironment monitoring sensors and locations.				
Instrument	Model	Manufacturer or Supplier	Location	
			Shadehouse	Weather station
Anemometer, totalizing	2511	Qualimetrics, Inc., Sacramento, CA 95834	✓	✓
Anemometer, wind speed	014	Met One, Inc., Grants Pass, OR 97526	✓	
Net radiometer	Q6	Radiation and Energy Balance Systems, Seattle, WA 98115	✓	✓
Pan, evaporatory	USWS Class A	Qualimetrics, Inc., Sacramento, CA 95834	✓	✓
Pyranometer	LI200SZ	LI-COR, Inc., Lincoln, NE 68504	✓	✓
Quantum sensor	LI190SZ	LI-COR, Inc., Lincoln, NE 68504	✓	✓
Rain gauge, tipping bucket	TE525	Texas Electronics, Dallas, TX 75209		✓
Relative humidity sensor		U. of Fla., IFAS, Agr. Engineering Dept., Gainesville, FL 32611	✓	✓
Temperature sensor, T-type thermocouples	FF-T-24	Omega Engineering, Stamford, CT 06906	✓	✓
Wind monitor	05103	R. M. Young, Traverse City, MI 49684		✓

where: e_a = actual vapor pressure (kPa)

$e_s^{wet\text{-}bulb}$ = saturation vapor pressure (kPa) at the wet-bulb temperature (°C)

P = air (atmospheric) pressure (kPa)

$T_{dry\text{-}bulb}$ = dry-bulb temperature (°C)

and $T_{wet\text{-}bulb}$ = wet-bulb temperature (°C)

Percent relative humidity was calculated as:

$$RH = \frac{e_a}{e_s} \times 100$$

where: RH = relative humidity

e_a = actual vapor pressure (kPa)

and e_s = saturation vapor pressure (kPa).

Water evaporation from National Weather Service Class A evaporation pans (E_{pan}) located inside and outside the shadehouse was measured manually on a daily basis, as were precipitation and windrun. These latter two measurements were redundant of electronically measured data and served as a check on the electronic data collection. More precise monitoring of rainfall (and irrigation water for cold protection) was provided by placing catch cups at the end of each lysimeter tank and polyethylene bins over selected lysimeter tanks (see PRECIPITATION, page 18). The volume of water collected in the cups and bins was measured for each tank to determine average rain and irrigation water application rate for each lysimeter. This was necessary because of the non-uniformity in rainfall distribution due to the shadehouse structure and shade fabric and also to the non-uniformity of the distribution of water by the irrigation system.

REFERENCE (POTENTIAL) EVAPOTRANSPIRATION (ET_o)

An estimate of reference (potential) evapotranspiration was made using the Penman equation (Penman, 1948):

$$ET_o = \frac{\Delta R_n / \lambda + \gamma E_a}{\Delta + \gamma}$$

where: ET_o = daily potential evapotranspiration, $\mathrm{mm \cdot day^{-1}}$

Δ = slope of saturated vapor pressure curve of air, $\mathrm{mb \cdot {}^\circ C^{-1}}$

R_n = net radiation, $\mathrm{cal \cdot cm^{-2} \cdot day^{-1}}$

λ = latent heat of vaporization of water, 59.59 – 0.055 T_{avg} $\mathrm{cal \cdot cm^{-2} \cdot mm^{-1}}$ or about 58 $\mathrm{cal \cdot cm^{-2} \cdot mm^{-1}}$ at 29°C

$E_a = 0.263\ (e_a - e_d)(0.5 + 0.0062\ u_2)$

e_a = vapor pressure of air = $(e_{max} - e_{min})/2$, mb

e_d = vapor pressure at dewpoint temperature T_d (for practical purposes $e_d = T_{min}$), mb

u_2 = wind speed at a height of 2 meters, km·day^{-1}

γ = psychrometric constant = 0.66 mb·°C^{-1}

$T_{avg} = (T_{max} + T_{min})/2$, °C

e_{max} = maximum vapor pressure of air during a day, mb

e_{min} = minimum vapor pressure of air during a day, mb

T_{max} = maximum daily temperature, °C

and T_{min} = minimum daily temperature, °C.

CROP PHYSIOLOGY

Transpiration rates and water potentials of individual fern fronds were measured using a solid state porometer (LI-1600, LI-COR, Lincoln, NE 68504) and a pressure chamber (3005, Soil Moisture Equipment, Santa Barbara, CA 93105), respectively. Transpiration rate of the abaxial leaf surface of a frond was taken and then the frond was harvested and placed in a plastic bag lined with a moist paper towel. The stipe was recut with a razor blade and the bag was immediately placed in the pressure bomb where the pressure was slowly raised until the leaf sap was forced from the cut end.

CROP YIELD

Lysimeter Studies.

Dark green, mature leatherleaf fern fronds were harvested periodically using clippers as is done commercially. Frond numbers and fresh weights were recorded.

Field Studies

The fern from the Taylor Middle-Senior High School shadehouses, except the small amounts used for vase life studies, was harvested by commercial fern cutters and the number of bunches recorded by shadehouse.

CROP QUALITY

Frond color, one characteristic determining commercial quality, was measured using a colormeter (CR-11, Minolta, Ramsey, NJ 07446). Ten mature dark green fronds were also harvested from each lysimeter, stored for two weeks at 4°C [39°F], and tested for vase life under simulated home/office conditions as previously described by Stamps and Nell (1986).

STATISTICAL ANALYSIS

Data were analyzed using analysis of variance and regression analysis (SAS, SAS Institute, Cary, NC 27511–8000). Percentage data were transformed when appropriate using arcsine or square root transformations prior to statistical analysis (Gomez and Gomez, 1984). All comparisons were made at $P = 0.05$.

RESULTS

SOILS UTILIZED FOR LEATHERLEAF FERN PRODUCTION

Tavares fine sand, Astatula fine sand, and DeLand fine sand were the predominant soil types on which commercial leatherleaf fern production occurred and accounted for 27%, 24% and 13%, respectively, of total production area (Appendix A). Essentially all soils used for commercial leatherleaf fern production are rated by the United States Department of Agriculture/Soil Conservation Service as having very rapid (51 + cm [20 + in]) or rapid (15–51 cm [6–20 in]) permeability (Figure 8). Soils in these permeability classes characteristically are prone to nitrate-nitrogen (NO_3-N) leaching and a beneficial response from initiating good NO_3-N leaching management practices can be expected (Smith and Cassel, 1991).

Similar results occurred when other indices of the NO_3-N leaching potential of soils, such as available water holding capacity and 0.01 MPa [$^1/_{10}$ bar] water content (% by weight) were used. Ninety-seven to 99% of the soils were found to have a high potential for NO_3-N leaching. Maps of Lake, Putnam and Volusia counties indicating NO_3-N leaching potentials of soils (based on 0.01 MPa bar water content) are included in Appendix H at the back of this report.

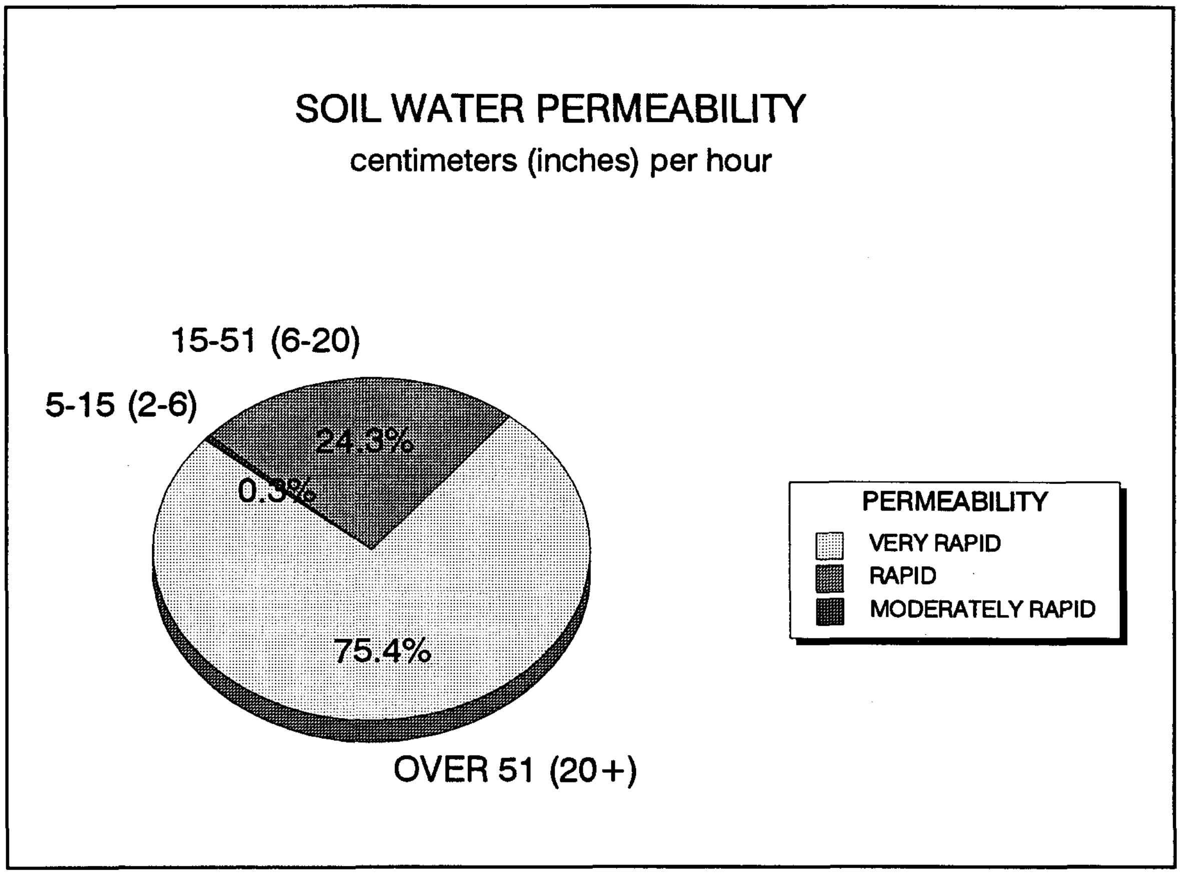

Figure 8. Soil water permeability (infiltration/percolation) rates of soils currently planted with leatherleaf fern in Lake, Putnam and Volusia counties.

MICROENVIRONMENT

Radiation - sunny day

Incoming radiation. Radiant flux density inside and outside the shadehouse on a sunny day in March changed diurnally (Figure 9). Maximum irradiance values were 13.79 and 46.02 $kJ \cdot m^{-2}$, respectively, for inside and outside the shadehouse. This 70% difference in total radiation reflects the fact that the shadehouse was covered with polypropylene shade fabric designed to provide 70% shade.

Net radiation. Net radiation values followed the same pattern as incoming radiation, but the values were lower due to the inclusion of the radiation loss back to the sky (Figure 9). Peak midday values inside were reduced by about 66% compared to values measured outside the shadehouse. Net radiation values were negative from midnight to 0500HR and from 1800HR to 2400HR.

Photosynthetically active radiation (PAR). PAR inside the shadehouse at midday was reduced 52% compared to outside (Figure 9). Total quantum flux over the 24-hour period was reduced by 76% inside compared to outside the shadehouse and is probably due to a greater than 70% reduction in radiation when the sun is at an oblique angle to the shade fabric.

Radiation - cloudy day

Incoming radiation. The presence of clouds greatly influenced total incoming radiation, but the pattern of much lower irradiance inside the shadehouse compared to outside was similar to that of a sunny day (Figure 10).

Net radiation. Radiation losses during the early morning (midnight to 0500HR) were reduced due to the presence of cloud cover, as compared to losses during the night (1700HR to 2400HR) when clouds were not present (Figure 10).

Photosynthetically active radiation. PAR followed the same pattern as incoming and net radiation (Figure 10). Total quantum flux over the 24-hour period was reduced by 80% inside compared to outside the shadehouse.

Radiation - monthly

Incoming radiation. Incoming radiation patterns were typical, with reduced levels in the winter and maximum levels in the summer (Figure 11). The decline in incoming radiation in June was due to the relatively high incidence of cloud cover during that month and is normal. Radiation levels inside the shadehouse were greatly reduced.

Net radiation (R_n). Monthly net radiation values had a distinct seasonal pattern of higher values in the summer and lower ones in the winter (Figure 11). The seasonal trends are smoother than those for incoming radiation because the clouds that reduce incoming radiation also reduce outgoing radiation losses. Monthly R_n values were approximately ½ of those for incoming radiation due to reflection and reradiation. A net radiometer was only available during certain months to measure R_n inside the fernery.

Photosynthetically active radiation (PAR). Monthly PAR values were also seasonal and PAR values inside the shadehouse averaged 26% of PAR values measured outside the shadehouse (Figure 11).

Radiation - yearly

Incoming, net and photosynthetically active radiation were reduced 79%, 73% and 74%, respectively, inside the shadehouse compared to outside on an annual basis.

Temperature - cold weather

Air temperatures. Air temperatures measured in 6-plate gill radiation shields located 2 m [6.5 ft] above the soil surface were generally warmer inside the shadehouse than outside (Figure 12). This was, of course, especially true during the night when the irrigation system inside the shadehouse was used to supply heat to protect the crop from cold damage.

Leaf temperatures. Leaf temperatures were cooler inside the shadehouse than outside except when the irrigation system was on to protect the crop from cold damage (2000HR to 0900HR). The reduced daytime leaf temperatures inside the shadehouse are probably due to the reduced irradiance levels at the leaf surface (Figure 9 and Figure 10).

Soil temperatures. As is typically found, soil temperature fluctuations 10 cm [4 in] below the soil surface were reduced compared to air temperature above the soil. Temperatures in the field outside the shadehouse exhibited the usual diurnal pattern of warming up during the day and cooling down during the night (Figure 12). Soil temperatures inside the shadehouse were affected by the irrigation water that was applied to protect the crop from cold temperature damage.

Temperature - warm weather

Air temperatures. Air temperatures in 6-plate gill radiation shields located 2 m above the soil surface level were generally cooler during the day and warmer during the night inside the shadehouse (Figure 13). This was probably due to the shade fabric intercepting incoming radiation.

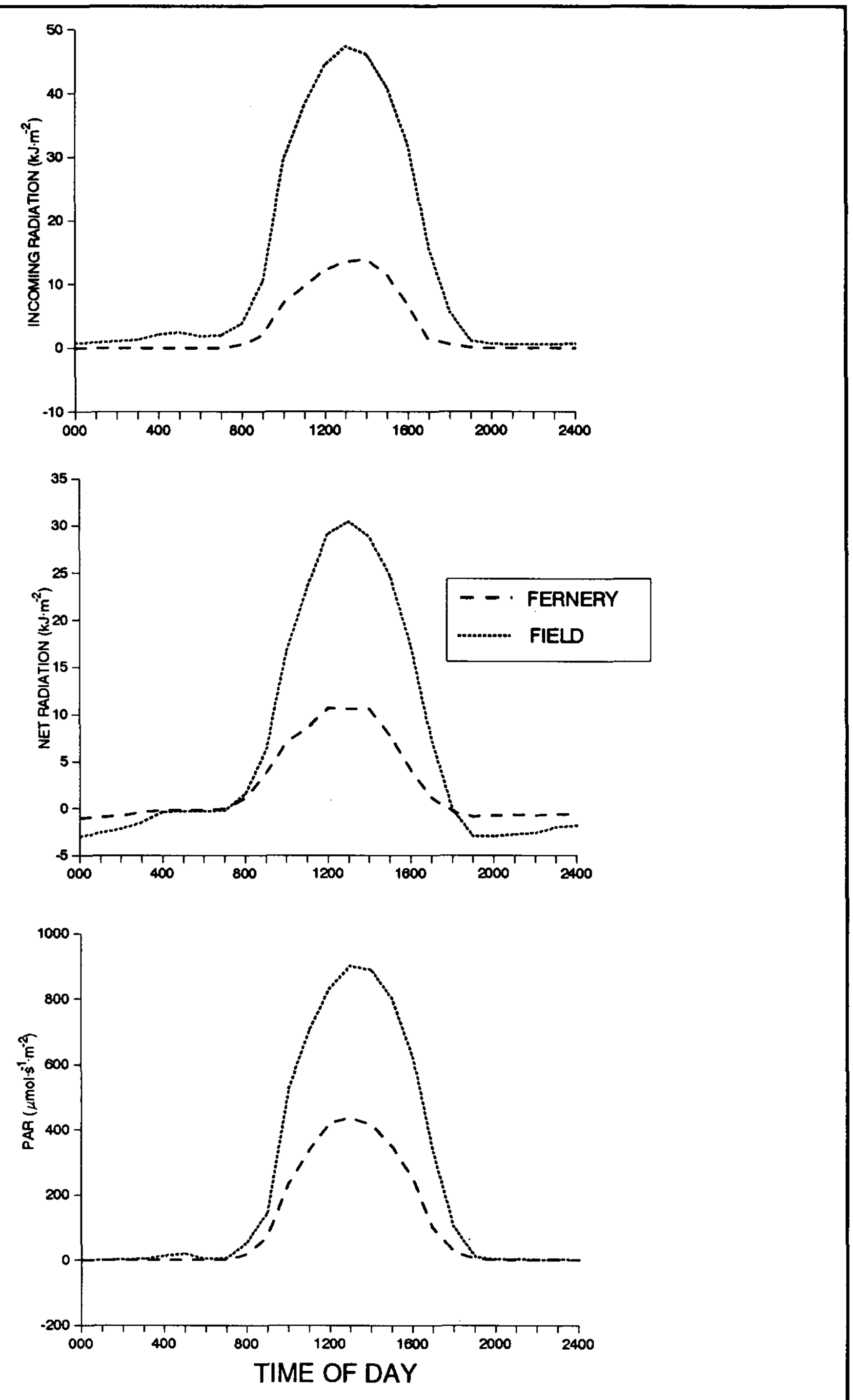

Figure 9. Total incoming radiation, net radiation and photosynthetically active radiation (PAR) measured on a sunny day (6 March 1994) inside and outside a shadehouse covered with polypropylene shade fabric designed to provide 70% shade.

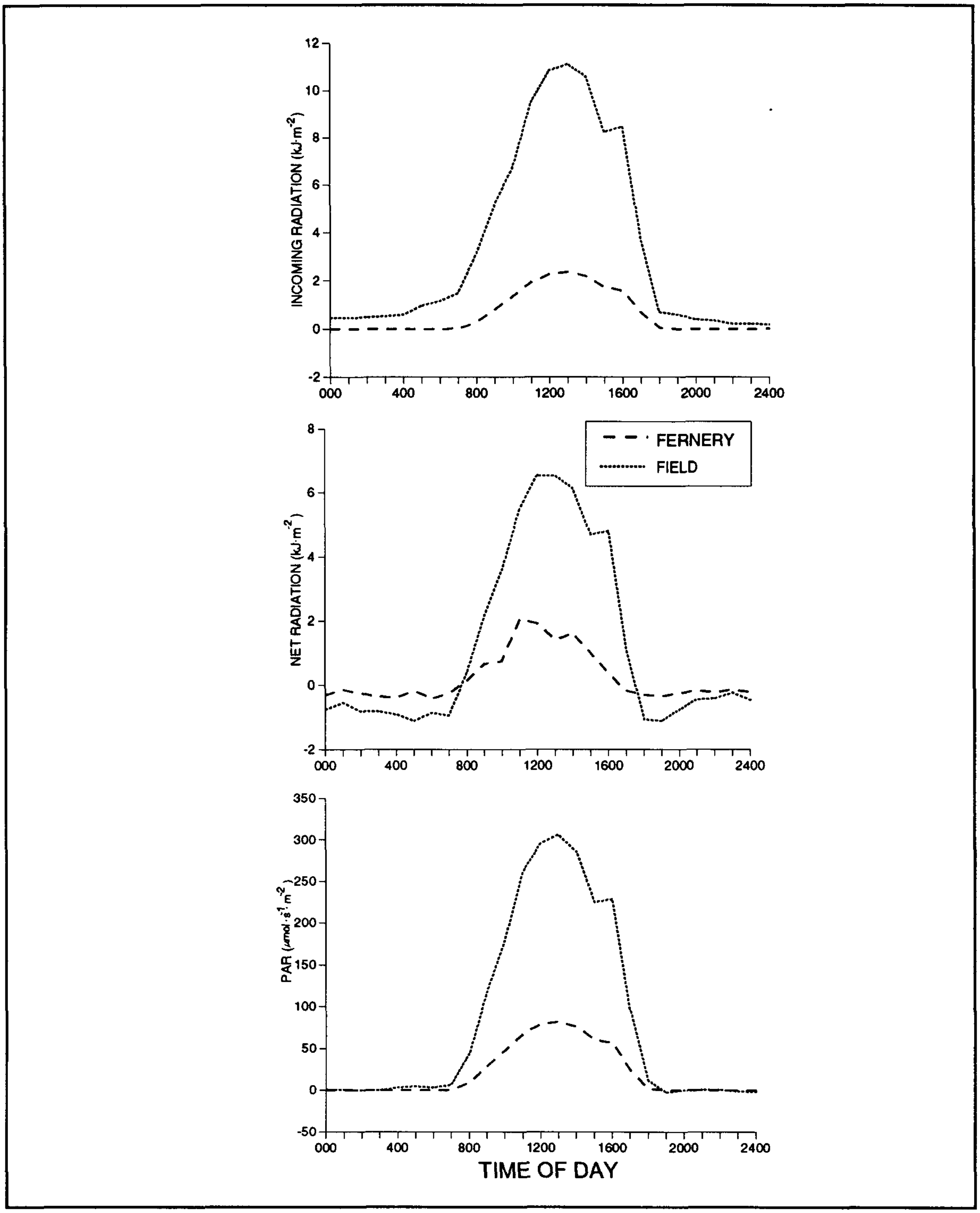

Figure 10. Total incoming, net and photosynthetically active radiation (PAR) measured on a cloudy day (11 November 1993) inside and outside a shadehouse covered with polypropylene shade fabric designed to provide 70% shade.

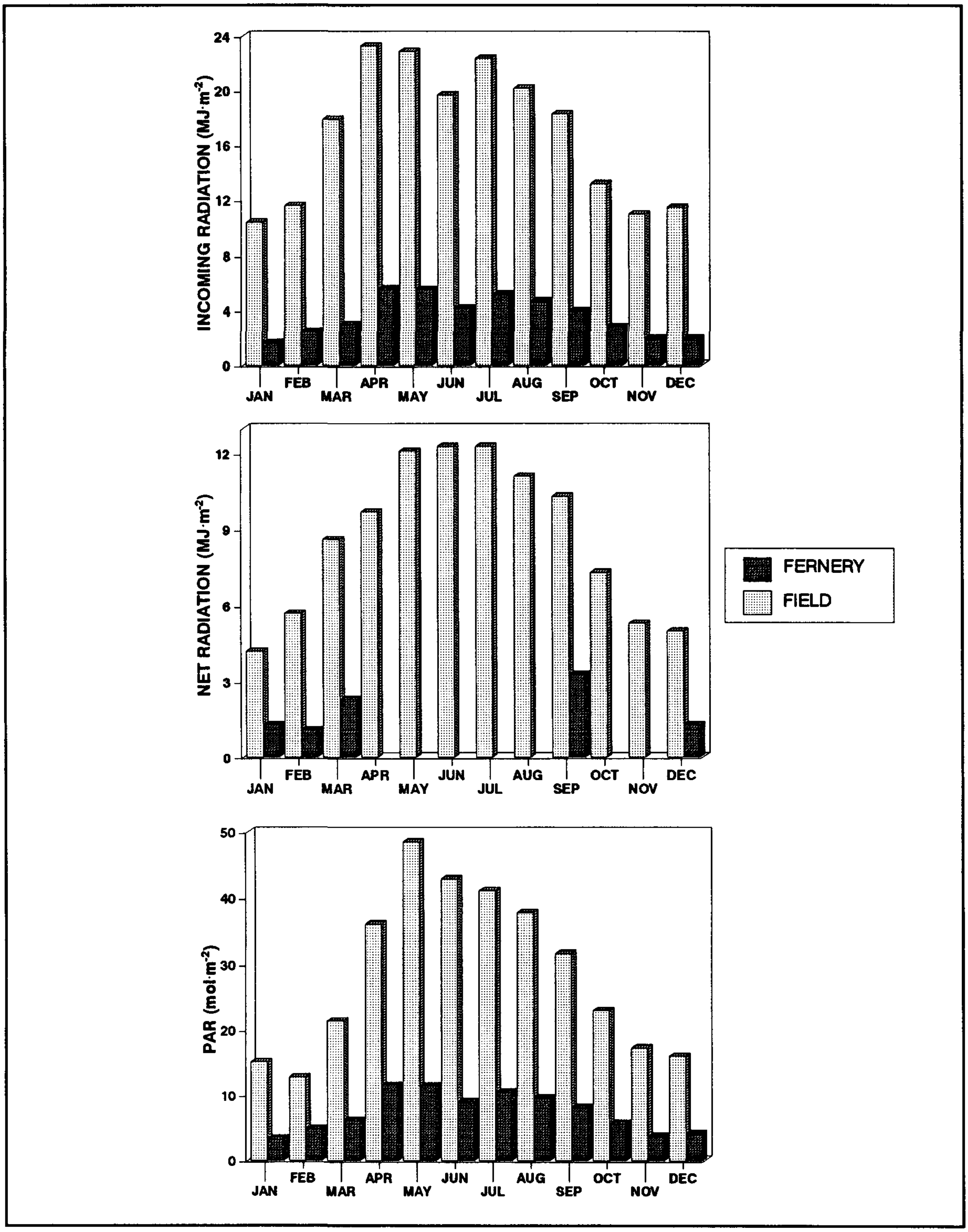

Figure 11. Average daily radiation (incoming, net and photosynthetically active), by month, inside and outside a shadehouse covered with polypropylene shade fabric designed to provide 70% shade.

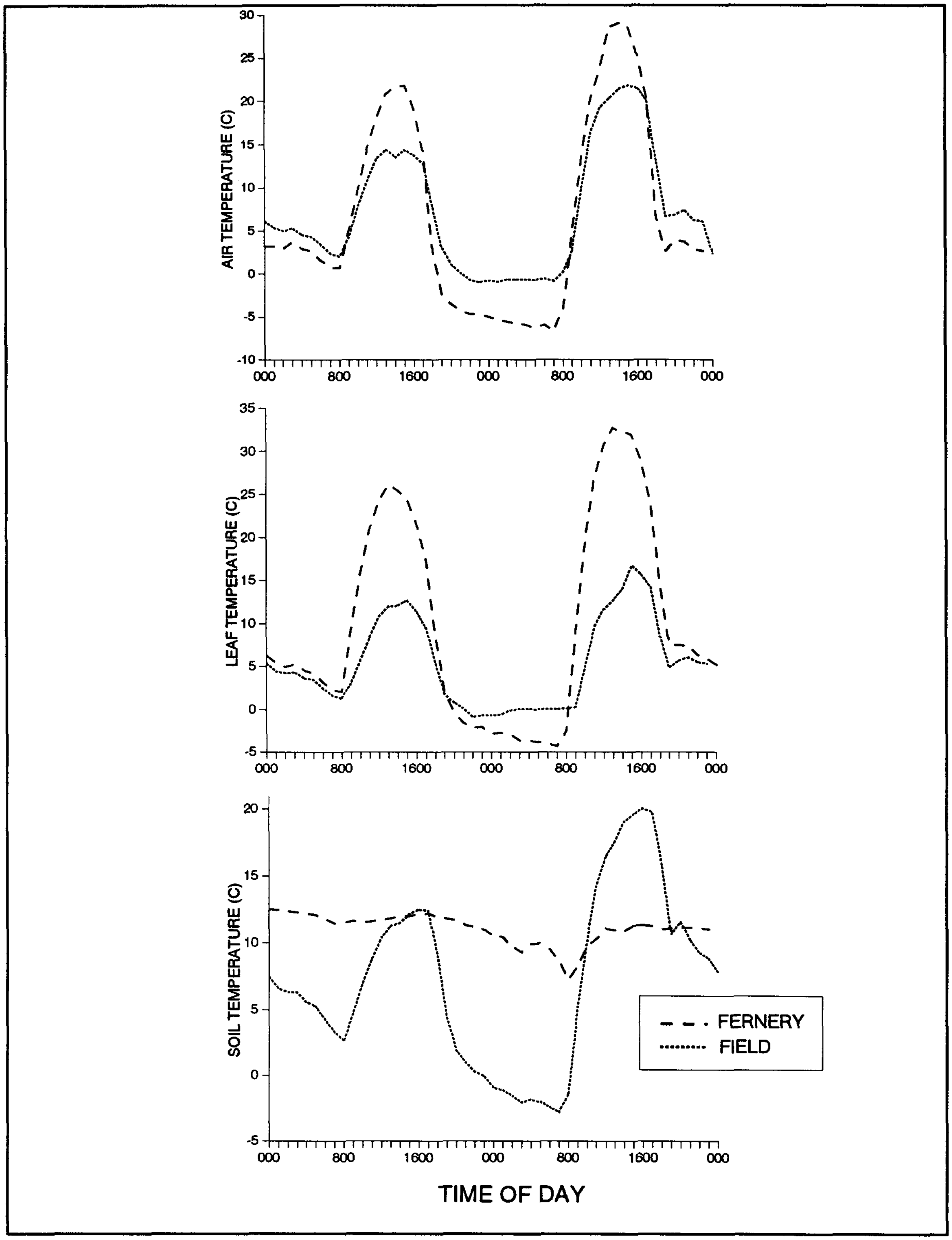

Figure 12. Temperatures inside and outside the shadehouse during a radiation freeze (26-27 December 1993).

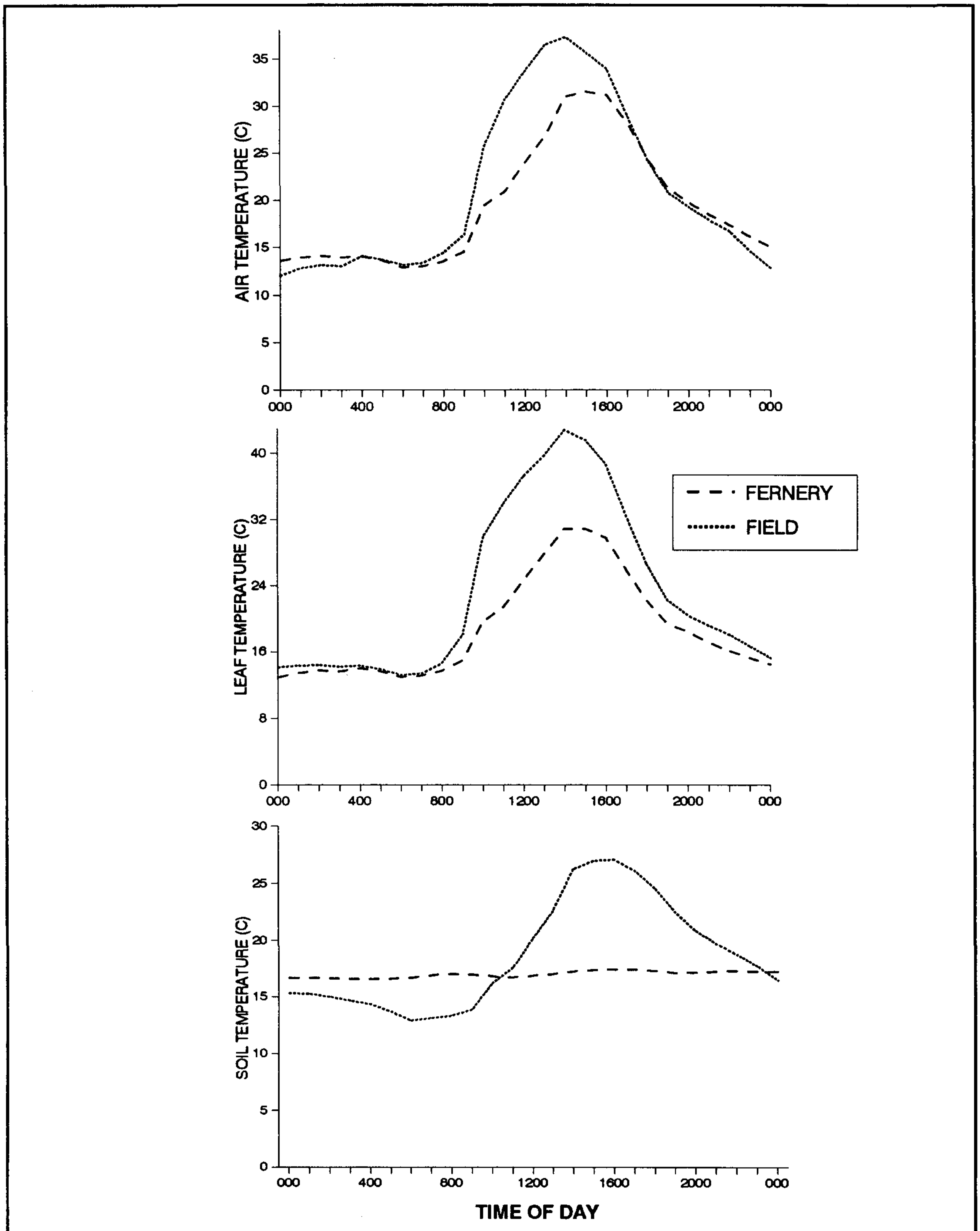

Figure 13. Temperatures inside and outside the shadehouse during a warm day (6 March 1993).

Leaf temperatures. During the daylight hours leaf temperatures were considerably cooler inside the shadehouse than outside (Figure 13). This would be due predominantly to reduced irradiance inside the shadehouse, and also probably to reduced moisture stress of leaves inside the irrigated and humid shadehouse.

Soil temperatures. Soil temperatures outside the shadehouse fluctuated diurnally but were almost constant inside the shadehouse (Figure 13). The reduced soil warming inside compared to outside the shadehouse during the day is due to the shade fabric and especially to the dense fern canopy intercepting radiant energy inside the shadehouse. In the field outside the shadehouse the mowed, sparse bahia grass does not intercept nearly so much radiant energy.

Wind

Wind speeds. Wind speeds, measured at 2 m above the soil surface, were greatly reduced inside the shadehouse compared to outside (Figure 14).

Wind run - cumulative daily. Like wind speeds, wind run measured near the top of the fern canopy (60 cm [2 ft] above the soil surface) was also greatly reduced inside the shadehouse compared to outside (Figure 15).

Wind run - monthly. Wind run varied seasonally with March being the windiest month in 1993 (Figure 16). The shadehouse and fern canopy greatly reduced wind run compared to that occurring outside the fernery.

Relative humidity

Relative humidities were generally higher inside the shadehouse than outside on both sunny and cloudy, rainy days (Figure 17). These higher relative humidities may be due mainly to water vapor being transpired by the dense fern canopy inside the shadehouse and reduced mixing of drier outside air with air inside the fernery because of the shade fabric barrier. Comparisons of relative humidities measured at different temperatures should be made carefully, since saturation vapor pressure (e_s) is temperature dependent and increases exponentially with increasing temperature (Rosenberg et al., 1983). Since air temperatures were higher in the shadehouse during sunny weather (Figure 13) and warmer air can hold more water vapor than cooler air (Smith, 1966), the higher relative humidities

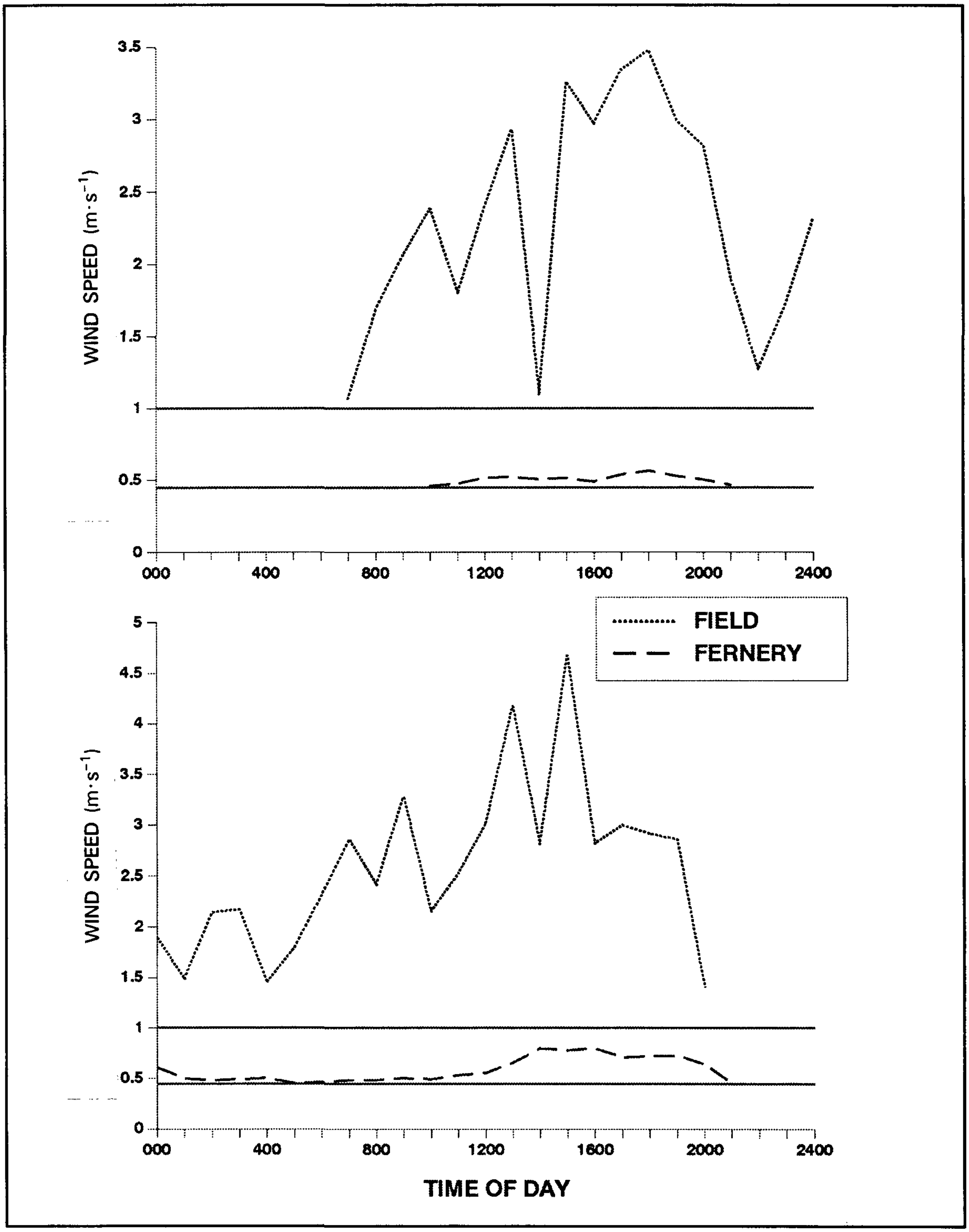

Figure 14. Wind speeds inside and outside the shadehouse on two days (5 and 9 April 1992). The upper and lower horizontal lines in each graph represent the thresholds for the outside and inside anemometers, respectively.

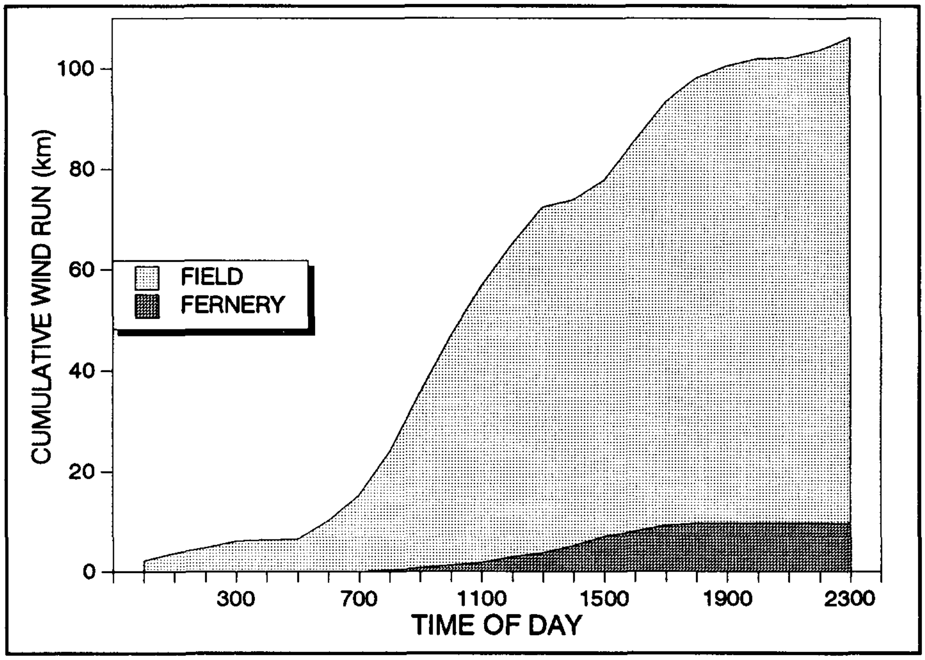

Figure 15. Cumulative wind run inside and outside the shadehouse (20 February 1992).

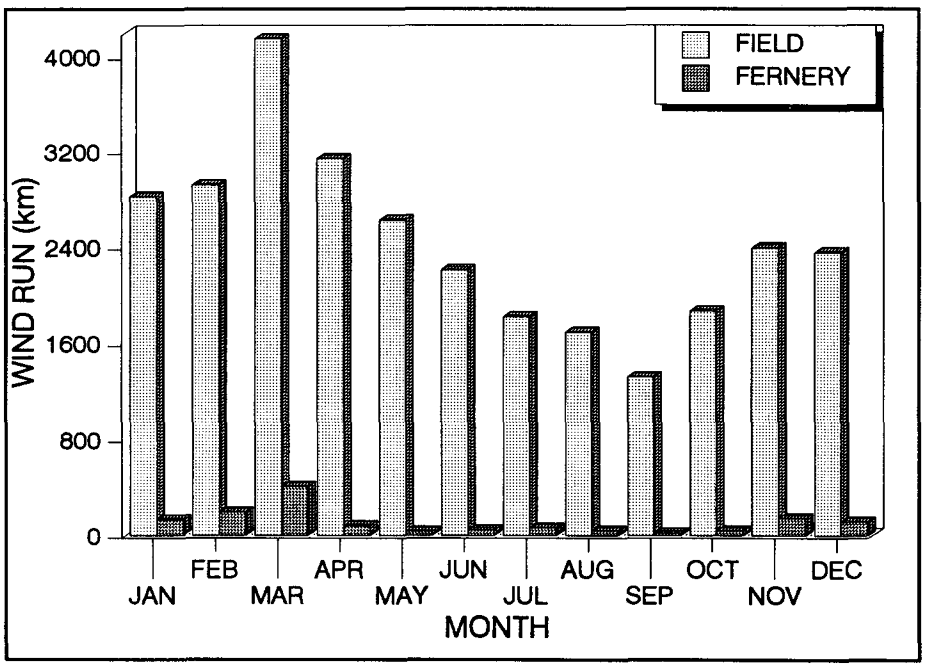

Figure 16. Monthly wind run (km) inside and outside the fernery for 1993.

inside the shadehouse are of increased significance. O'Leary and Knecht (1971) found that water consumption of red kidney bean plants was lowered and the dry weight produced per unit of water consumed was greater in those plants grown at 95–100% relative humidity compared to plants grown at 70–75% or lower relative humidities.

Vapor pressure

Vapor pressures within the crop canopy (leatherleaf fern inside the shadehouse and bahia grass outside the fernery) and above the crop canopy (at 2 m), displayed typical diurnal increases from sunrise to a midafternoon peak and subsequent declines throughout the rest of the afternoon and evening (Rosenberg et al., 1983). Vapor pressures were similar inside and outside the shadehouse at night, but during the day vapor pressures above the crop canopies were nearly two times greater outside the shadehouse as inside (Figure 18).

Vapor pressure gradient (deficit)

The differences in vapor pressures mentioned in the preceding section resulted in significantly greater cumulative leaf-to-air vapor pressure deficit outside the shadehouse than inside it on a sunny day (Figure 19). Since the difference in vapor pressure of water within a leaf and in the air beyond the boundary layer is the driving force for transpiration (Salisbury and Ross, 1978), water loss from a given kind of leaf to the air would be less inside the shadehouse than outside, given that all other factors were the same.

Evaporation

Daily. Evaporation of water from the evaporatory pan was reduced by 40% on a cloudy day and 76% on a sunny day inside the shadehouse compared to outside (Figure 20). The sunny day reduction in evaporation inside the shadehouse was about the same as the reduction in incoming radiation (74%) for that same day.

Monthly. Changes in monthly *Epan* water losses (Figure 21) paralleled changes in monthly radiation levels (Figure 11) and did not reflect changes in wind run (Figure 16).

Yearly. Yearly E_{pan} water losses outside and inside the shadehouse were 169.7 cm [66.8 in] and 41.6 cm [16.4 in], respectively.

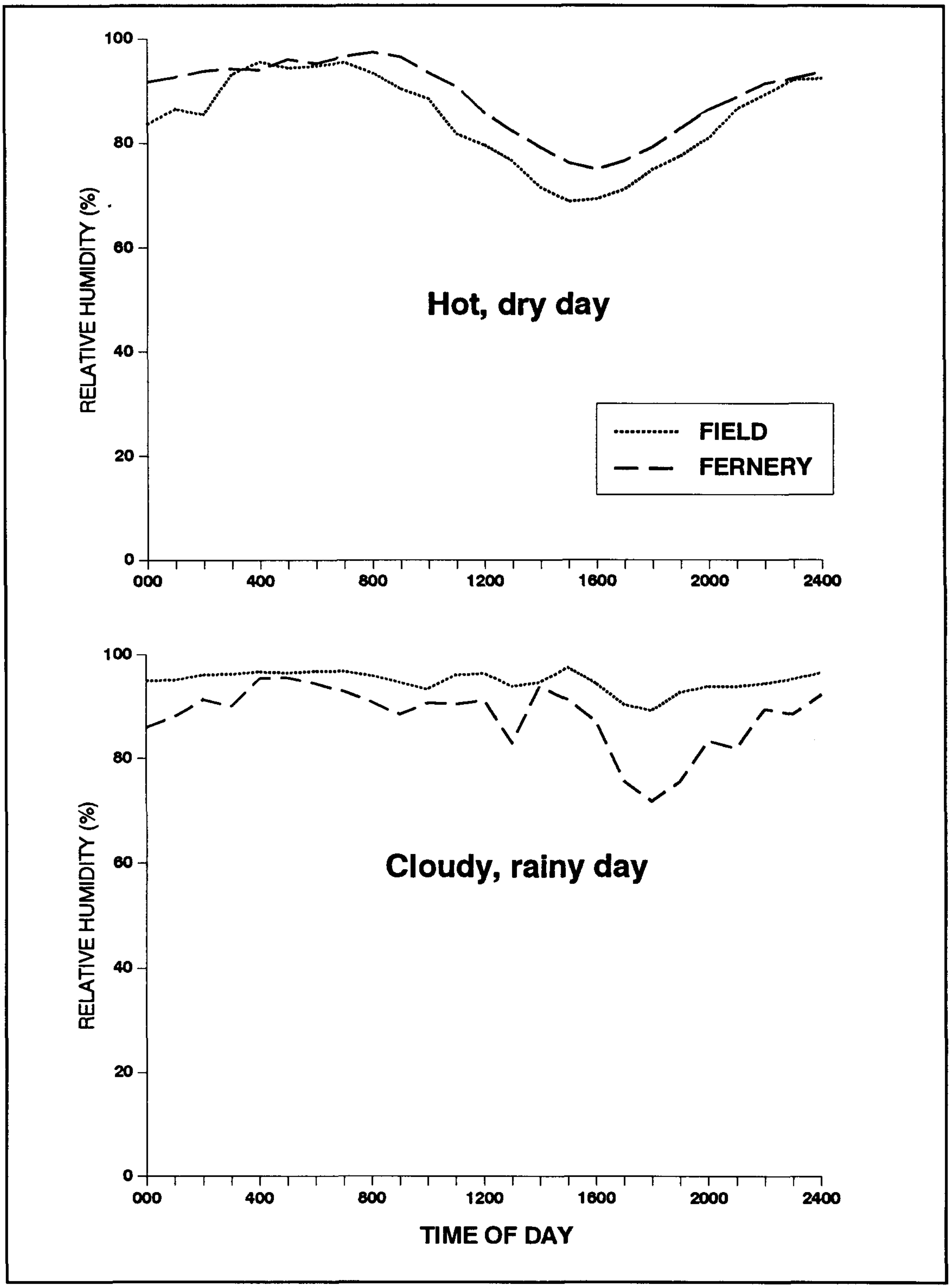

Figure 17. Relative humidities inside and outside the shadehouse on a warm, dry day (2 April 1992) and a cloudy, rainy day (7 March 1992).

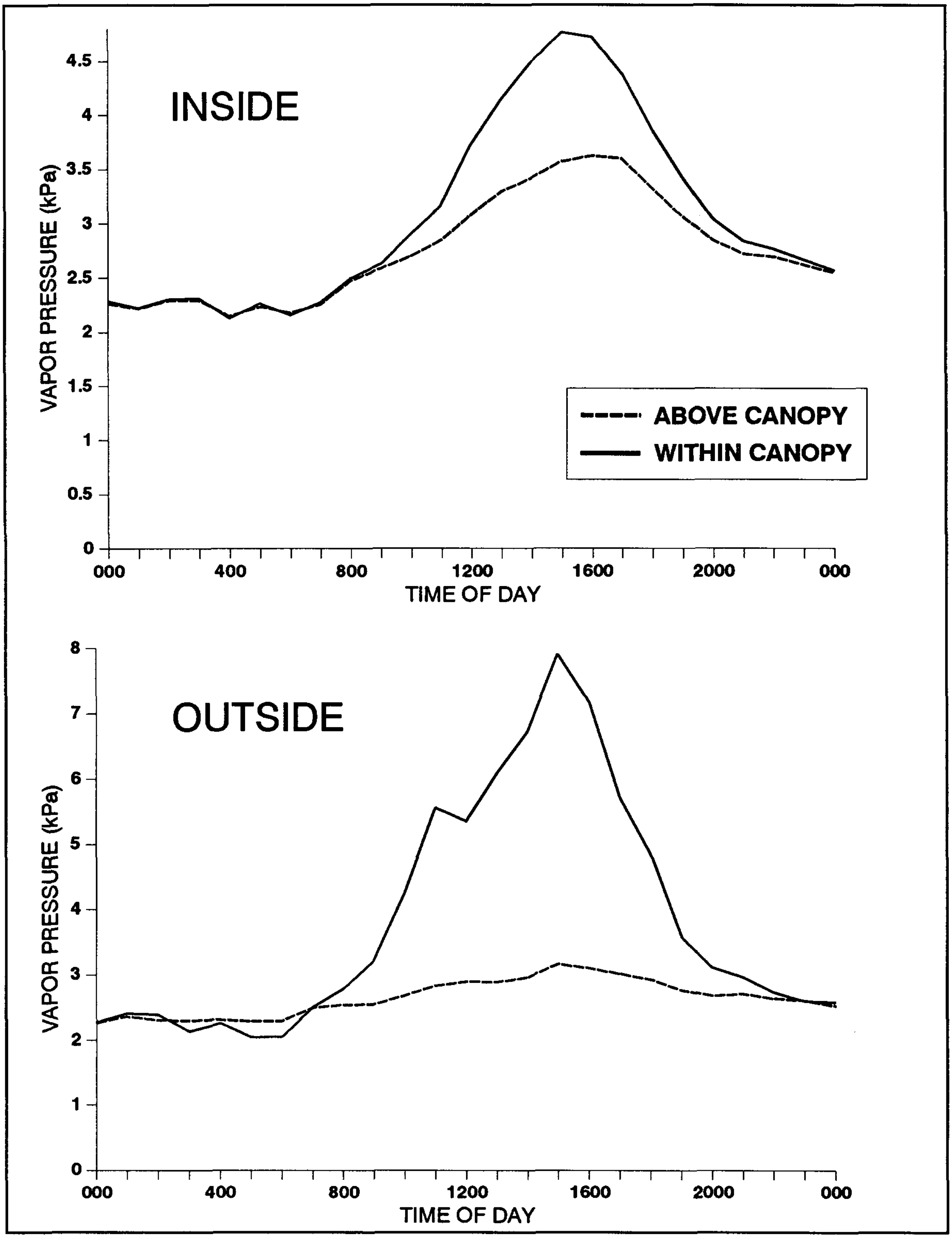

Figure 18. Within and above crop canopy vapor pressures inside and outside the shadehouse on 25 April 1992.

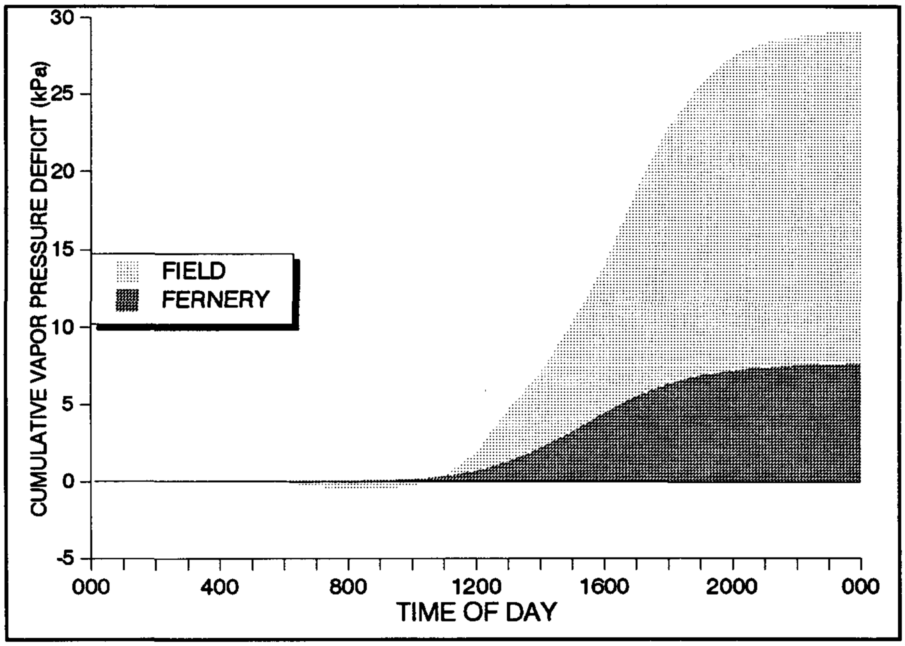

Figure 19. Cumulative vapor pressure deficit inside (fernery) and outside (field) the shadehouse during a warm, sunny day (25 April 1992).

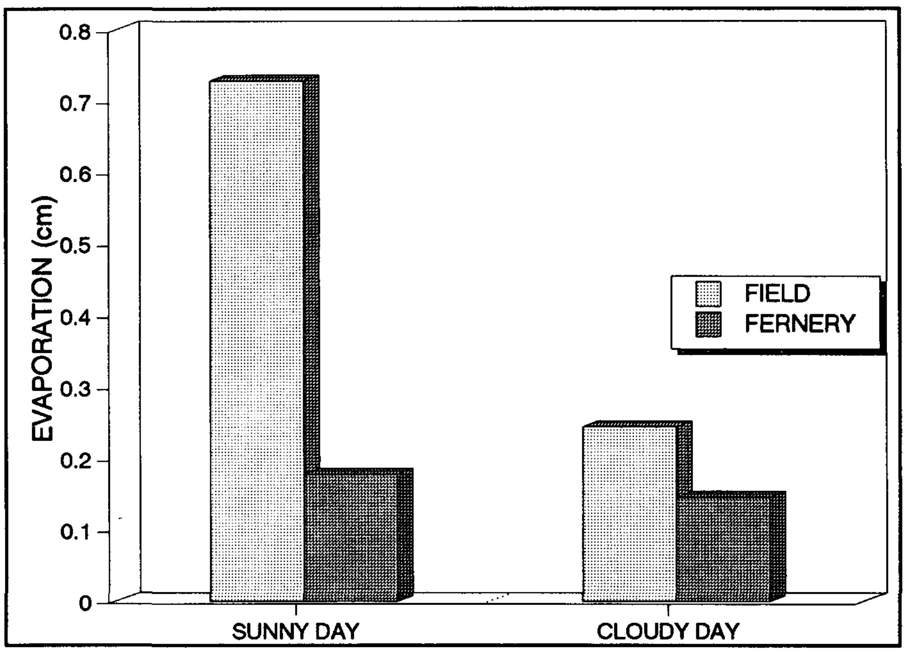

Figure 20. Relative pan evaporation inside (fernery) and outside (field) the shadehouse on a sunny (5 April 1992) and a cloudy (3 April 1992) day.

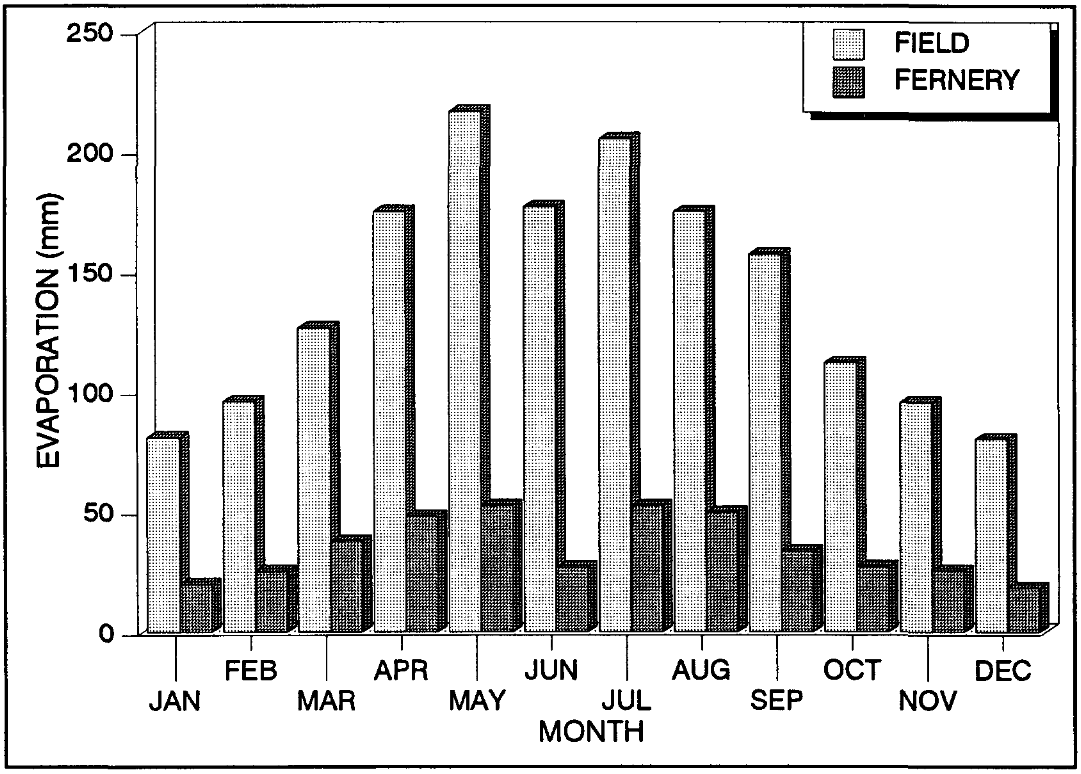

Figure 21. Monthly evaporatory water losses from U.S. Weather Service Class A Evaporatory Pans located inside and outside a shadehouse covered with polypropylene shade fabric designed to provide 70% shade.

PLANT WATER USE

Reference (potential) evapotranspiration (ET_o)

Monthly reference evapotranspiration values (ET_o) calculated using the Penman (1948) equation and an approximation of saturated vapor pressure based on T_{avg} (Bosen, 1960) followed a similar pattern (Figure 22) to that of measured E_{pan} values (Figure 21). ET_o was highest during the summer and lower during the winter months.

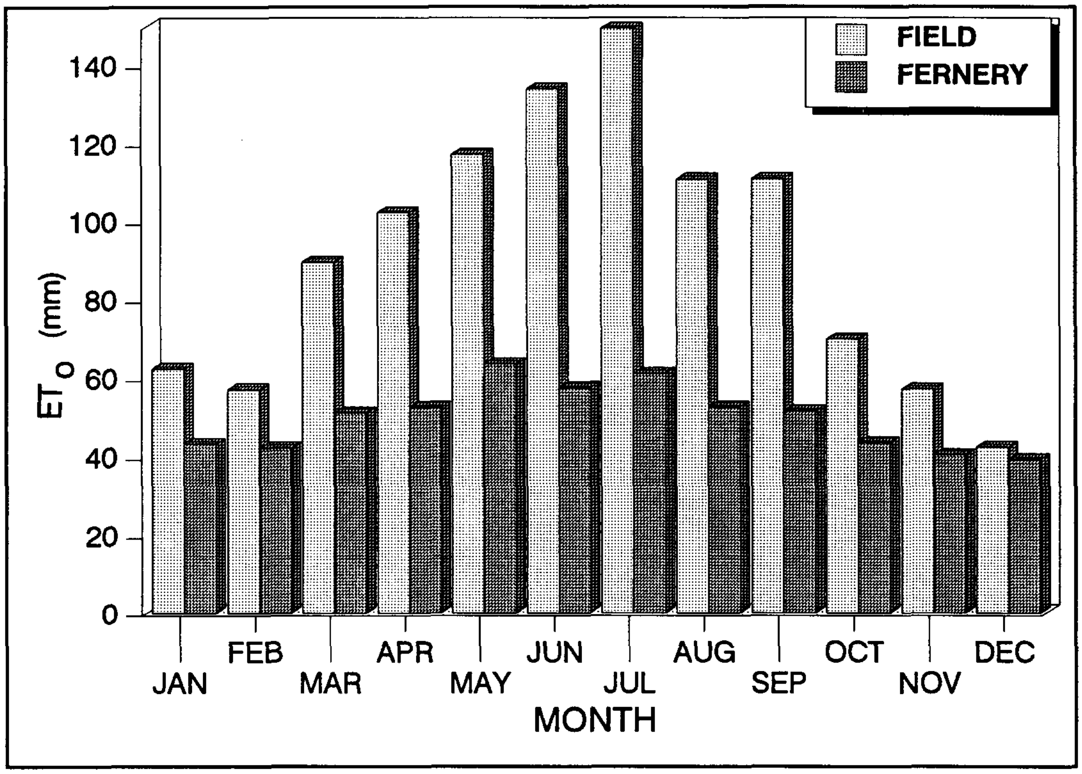

Figure 22. Monthly reference (potential) evapotranspiration (ET_o) inside (fernery) and outside (field) the shadehouse calculated using the Penman equation.

Actual evapotranspiration (ET_{actual})

Seasonal. ET_{actual} of the leatherleaf fern growing in the lysimeter tanks varied seasonally with summer values about twice that of winter values (Table 4).

Table 4. Seasonal monthly ET_{actual} (in cm [in]) for leatherleaf fern growing in a shadehouse covered with polypropylene shade fabric designed to provide 70% shade.

Winter (Nov.-Feb.)	Spring/Fall (March, April, Oct.)	Summer (May-Sept.)
2.7 [1.1]	3.2[1.3]	5.8 [2.3]

Annual. ET_{actual} of the leatherleaf fern growing in the lysimeter tanks averaged 50 cm [19.6 in] annually and was midway between ET_o and E_{pan} (Figure 23). Rosenberg et al. (1983) suggest that pans show less evaporation than ET_{actual} from vegetation because the water surface extracts less sensible heat energy from the passing air due to the smaller aerodynamic roughness of water surfaces relative to vegetation. The closer agreement between ET_o and E_{pan} inside the shadehouse compared to outside is consistent with previous research which has shown evaporation pans to provide realistic estimates of ET_o under humid conditions (Pruitt and Lourence, 1968; Stewart et al., 1977). The slightly greater disparity between ET_p and E_{pan} outside the shadehouse is understandable since the conditions outside were more arid than inside.

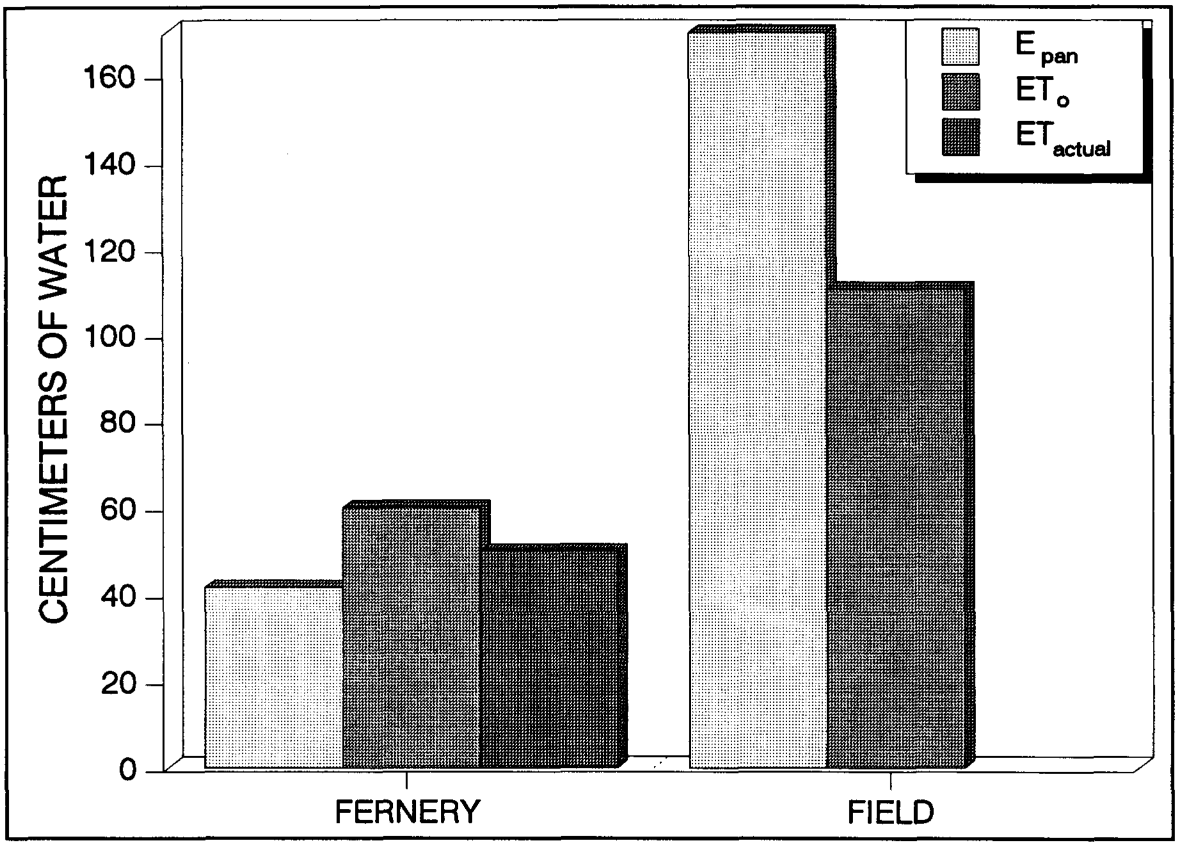

Figure 23. Annual ET_{pan} (measured directly) and ET_o (determined using the Penman equation) inside (fernery) and outside (field) the shadehouse compared to actual water (ET_{actual}) use by the leatherleaf growing in lysimeters in the shadehouse.

Crop coefficient (K_c)

Seasonal. K_c is defined both as the ratio of ET_{actual} to E_{pan} and as the ratio of ET_{actual} to ET_o (Rosenberg et al., 1983). Seasonal K values determined using E_{pan} and ET_o values determined inside the shadehouse ranged from 0.65 to 1.35 and outside the shadehouse ranged from 0.23 to 0.49 (Table 5).

Table 5. Seasonal monthly crop coefficients (K_c) for leatherleaf fern growing in a shadehouse covered with polypropylene shade fabric designed to provide 70% shade. Evaporatory pan water loss (E_{pan}) and reference evapotranspiration (ET_o)[z] were determined inside and outside the shadehouse.

	Winter (Nov.-Feb.)		Spring/Fall (Mar., Apr.,Oct.)		Summer (May-Sep.)	
	Location of E_{pan} or sensors used to determine ET_o					
	Field	Shade-house	Field	Shade-house	Field	Shade-house
$ET_{actural}/E_{pan}$	0.31	1.23	0.23	0.84	0.31	1.35
ET_{actual}/E_o	0.49	0.66	0.37	0.65	0.47	1.02

[z]ET_o determined using the Penman equation.

Annual. Annual K_c values were 0.29 and 0.45 when using the field values for E_{pan} and ET_o, respectively. For comparison, typical K_c determined using the E_{pan} method for established vegetable crops are 0.80–1.15 (Doorenbos and Kassam, 1979) and for turfgrasses in Florida are 0.55–0.8 (McCarty et al., 1993). Fitzpatrick (1980) found that ET_{actual} of *Ficus benjamina* grown under 73% shade from Jan. through Aug. correlated poorly with E_{pan} but correlated well with ET_o calculated by the Thornwaite method (Rogers and Marlowe, Jr., 1977). The resulting K_c of 0.35 for the ficus is similar to the 0.45 determined for leatherleaf fern in this study. The value for ficus may be smaller because the ficus were grown in containers and may have been subjected to lower soil moisture tensions than those maintained in the lysimeters. When using E_{pan} and ET_o values determined inside the shadehouse, K_c values were 1.2 and 0.83, respectively.

NITROGEN LEACHING

Total nitrogen

Lysimeter studies. Study 1— Due to errors in water application the soil moisture tension irrigation setpoint data on nitrogen leaching was considered invalid and is not reported. The amount of nitrogen in leachate increased with increasing fertilizer application rate (Figure 24). This was because the total amount of NO_3-N in leachate increased linearly as fertilization increased ($y = -0.88 + 0.02x$, $P < 0.0003$, $r^2 = 0.33$) with application rate, and NO_3-N accounted for about 96% of the nitrogen in the leachate. Total NH_4-N and TKN did not vary with application rate.

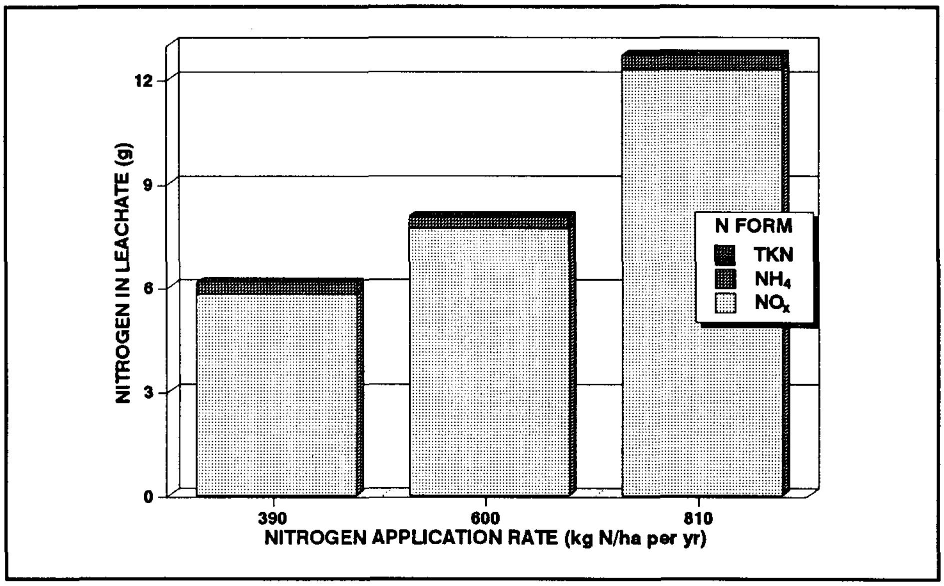

Figure 24. The amount (g) of nitrogen in leachate increased with increasing nitrogen application rate.

Study 2 — There was no interaction between fertilization rate and soil moisture tension irrigation setpoint on nitrogen leaching. The amount of nitrogen in leachate increased linearly with increasing fertilizer application rate (Figure 25). This was because the total amount of NO_3-N in leachate increased as fertilization rate increased ($y = -4.60 + 0.04x$, $P < 0.0001$, $r^2 = 0.79$) with application rate. As in study 1, NO_3-N accounted for almost all of the nitrogen in the leachate. Total NH_4-N and TKN did not vary with

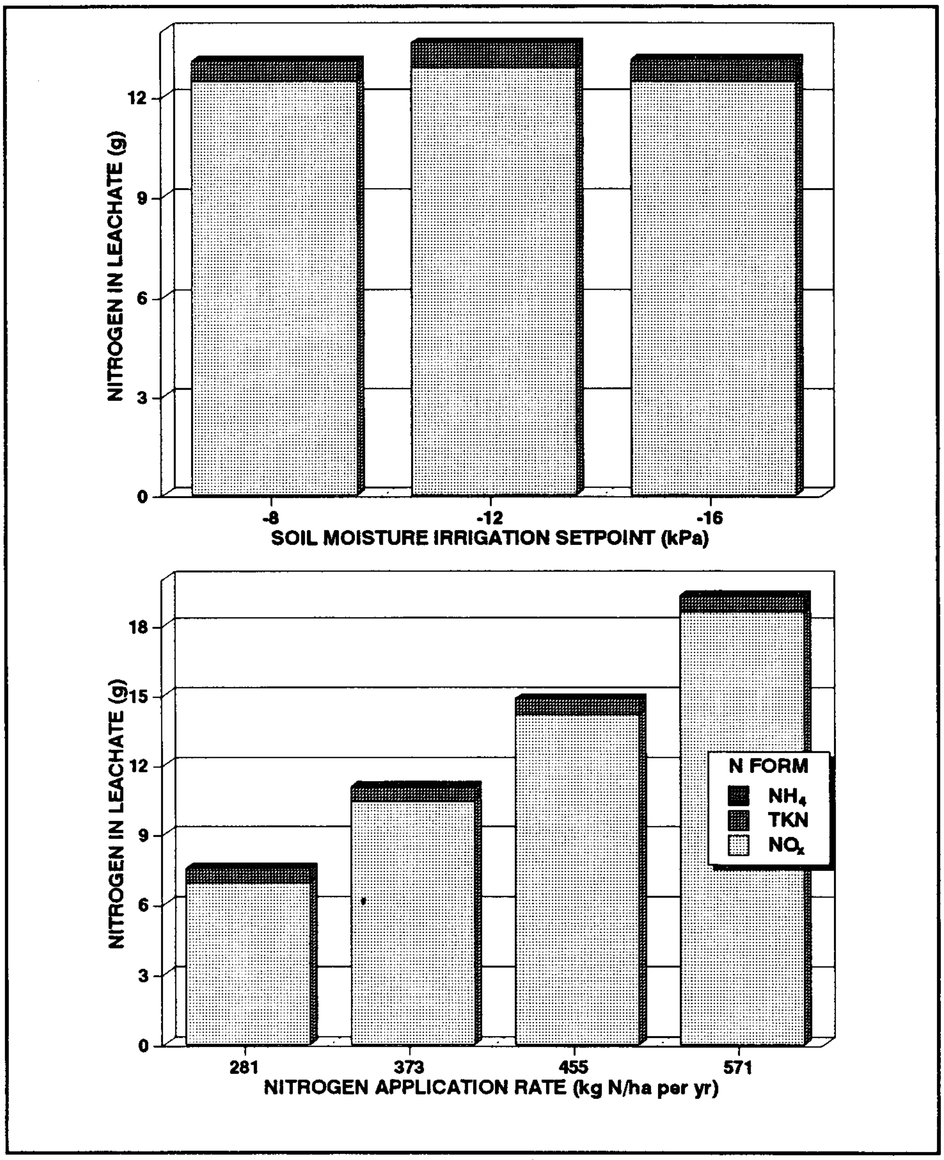

Figure 25. Nitrate nitrogen in leachate increased with increasing nitrogen application rate, but irrigation setpoint had no effect on nitrogen leaching.

application rate. The amount of nitrogen in leachate was not influenced by irrigation setpoint, $P<0.987$ (Figure 25).

Study 3 — Although the fertilizer application rates were lower in study 3 than in study 2, nitrogen leaching patterns from study 3 were also linear for NO_3–N ($y = -2.94 + 0.02\,x$, $P<0.0001$, $r^2 = 0.63$). Irrigation setpoint treatments had no effect nitrogen leaching (NO_3–N, NH_4–N or TKN) and NH_4-N and TKN leaching were not affected by fertilizer application rate (data not shown).

Percentage of applied N

The percentage of applied nitrogen that was found in the leachate collected from the lysimeters increased linearly with increasing fertilizer application rates and was not affected by soil moisture irrigation setpoint. The results from study 2 are representative of this ($y=0.32 + 0.0004\,x$, $P=0.02$, $r^2 = 0.17$) (Figure 26). Forty-two percent of the applied nitrogen was collected in leachate at the low (281 kg N/ha per yr) application rate while over half (53%) of the applied nitrogen was found in leachate from lysimeters fertilized at the high (571 kg N/ha per yr) rate. Similar results have been reported for turfgrass (Cisar et al., 1991). These percentages are higher than those suggested as a rule of thumb by Bouwer (1989), that about one-fourth of the fertilizer applied to a crop moves as nitrate to the groundwater (another one-fourth is lost due to denitrification, and the remaining one-half of the nitrogen is used by the crop). Greater leaching in this study may have been due to the low water-holding capacity of the soil, shallow root system of the crop, and low denitrification potential due to the well-drained characteristics of the soil.

Concentrations in leachate

Lysimeter studies. Study 1 — Overall average NO_3–N concentrations were above the 10 $mg\cdot liter^{-1}$ [10 ppm] Maximum Contaminant Level for drinking water for all treatments (Figure 27) and ranged from 12.8 $mg\cdot liter^{-1}$ for the low nitrogen application rate to 23.1 $mg\cdot liter^{-1}$ high N application rate. These results are not unusual. For example, simulations of the effects of various BMPs on NO_3–N leaching below the root zone in Maryland using the CREAMS model (Knisel, 1980) indicated that the 12-year average NO_3–N concentrations leaching under all of the considered BMPs were above EPA drinking water standards (Shirmohammadi et al., 1991). The average NO_3–N concentration for the highest N application level was about ½ that found in on-site monitoring wells at a commercial fernery in Volusia county (Hicks, 1985). NH_4–N concentrations were much lower than for NO_3–N, and the highest overall average NH_4–N concentration was 0.43 $mg\cdot liter^{-1}$ for the high nitrogen application treatment.

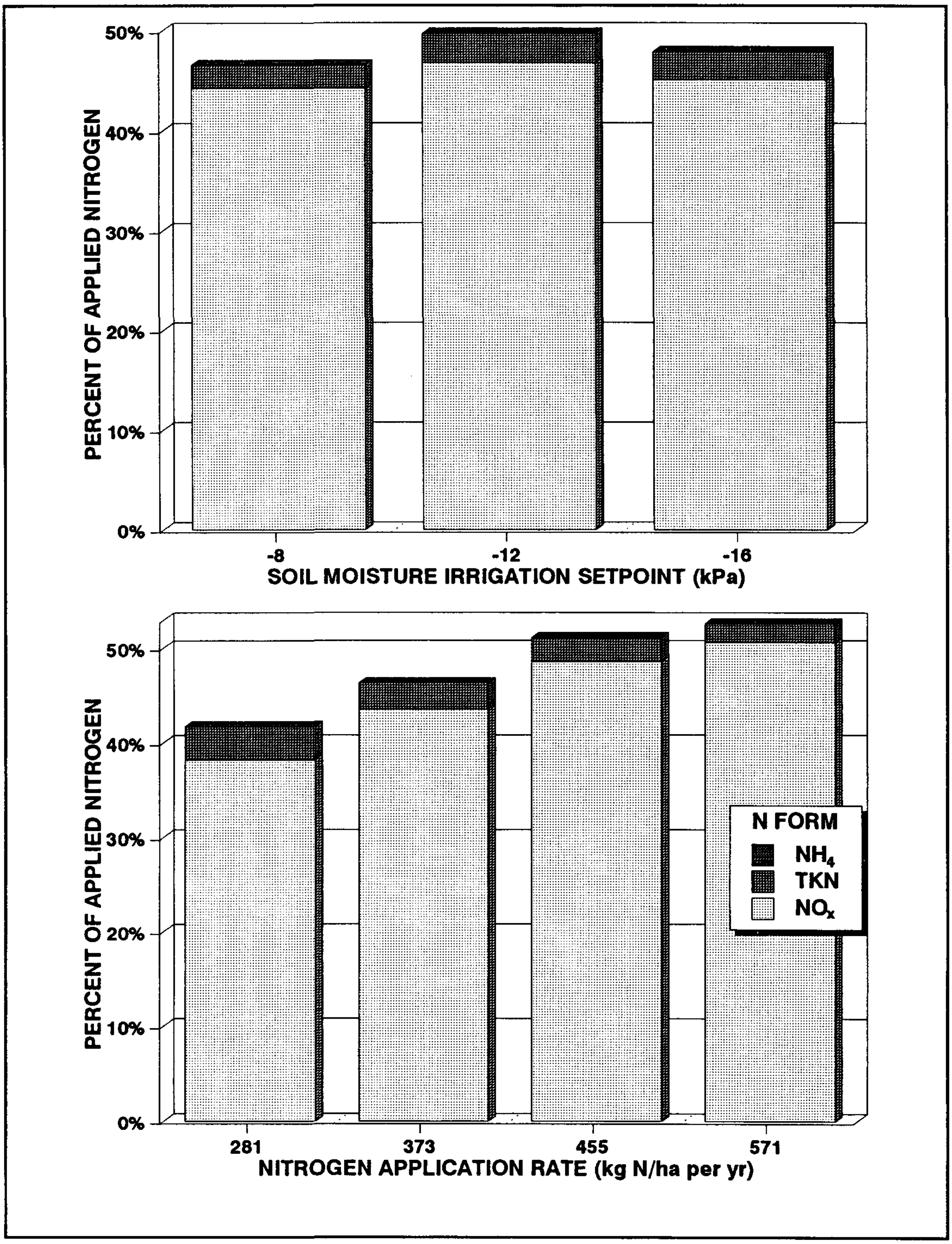

Figure 26. Percentages of nitrogen applied to the crop that were detected in leachate collected below the root zone.

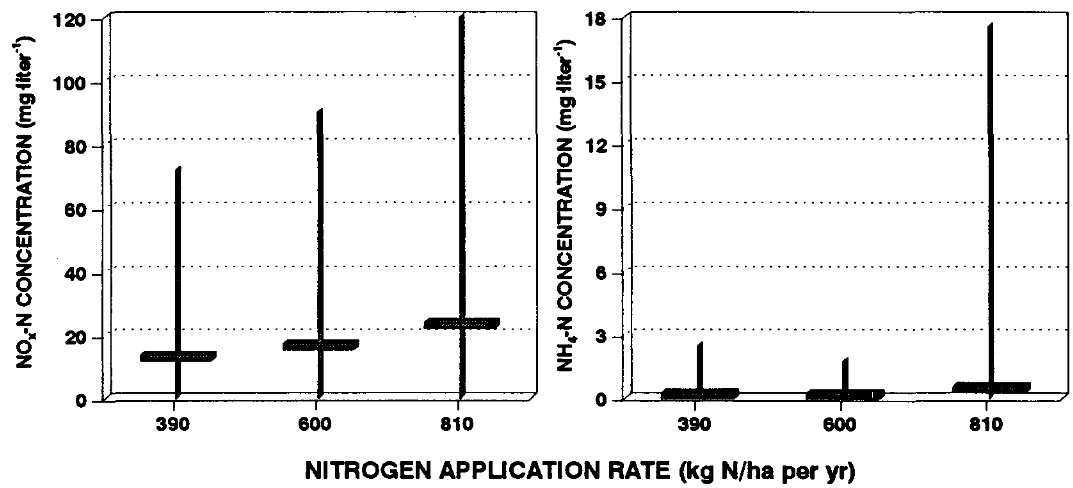

Figure 27. Minimum, average (horizontal bar) and maximum nitrate (NO_3-N) and ammoniacal (NH_4-N) nitrogen concentrations in leachate from lysimeter tanks receiving three nitrogen application rates (Study 1).

The wide range of NO_3–N and NH_4–N concentrations can be attributed to many factors including the range of application rates, rainfall and irrigation for cold protection. In addition, the high concentrations were due mainly to multiple weeks worth of fertilizer occassionally being applied at one time to achieve target annual N application rates.

Study 2 — There was no interaction between soil moisture irrigation setpoint and fertilization rate. Irrigation based on soil moisture setpoint had no effect on NO_3–N or NH_4–N concentrations in the leachate (Figure 28). NH_4–N and TKN concentrations were not affected by fertilization rates, but leachate NO_3–N concentrations increased with increasing fertilization rate ($y = -4.60 + 0.04\,x$, $P<0.0001$, $r^2 = 0.79$). NO_3–N concentration averaged below the 10 mg·liter^{-1} MCL for the lysimeters fertilized at the 281kg N/ha per yr [251 lb N/acre per yr]. The range of NO_3–N and NH_4–N were reduced in Study 2 compared to Study 1, mainly due to the lower range of N application rates.

Study 3 — NO_3–N and NH_4–N concentrations were not affected by soil moisture tension irrigation setpoint (Figure 29). Overall average nitrate concentrations in leachate increased linearly with increasing N application rate ($y=-2.94 + 0.024\,x$, $P<0.0001$, $r^2 = 0.63$), but NH_4–N concentrations did not increase (Figure 29). Leachate NO_3–N concentrations averaged below the 10 mg·liter^{-1} MCL at the 265 and 334 kg N/ha per yr [237 and 298 lb N/acre per yr]. The range of NO_3–N and NH_4–N were further reduced in Study 3 compared to the previous studies, again mainly due to the lower range of N application rates.

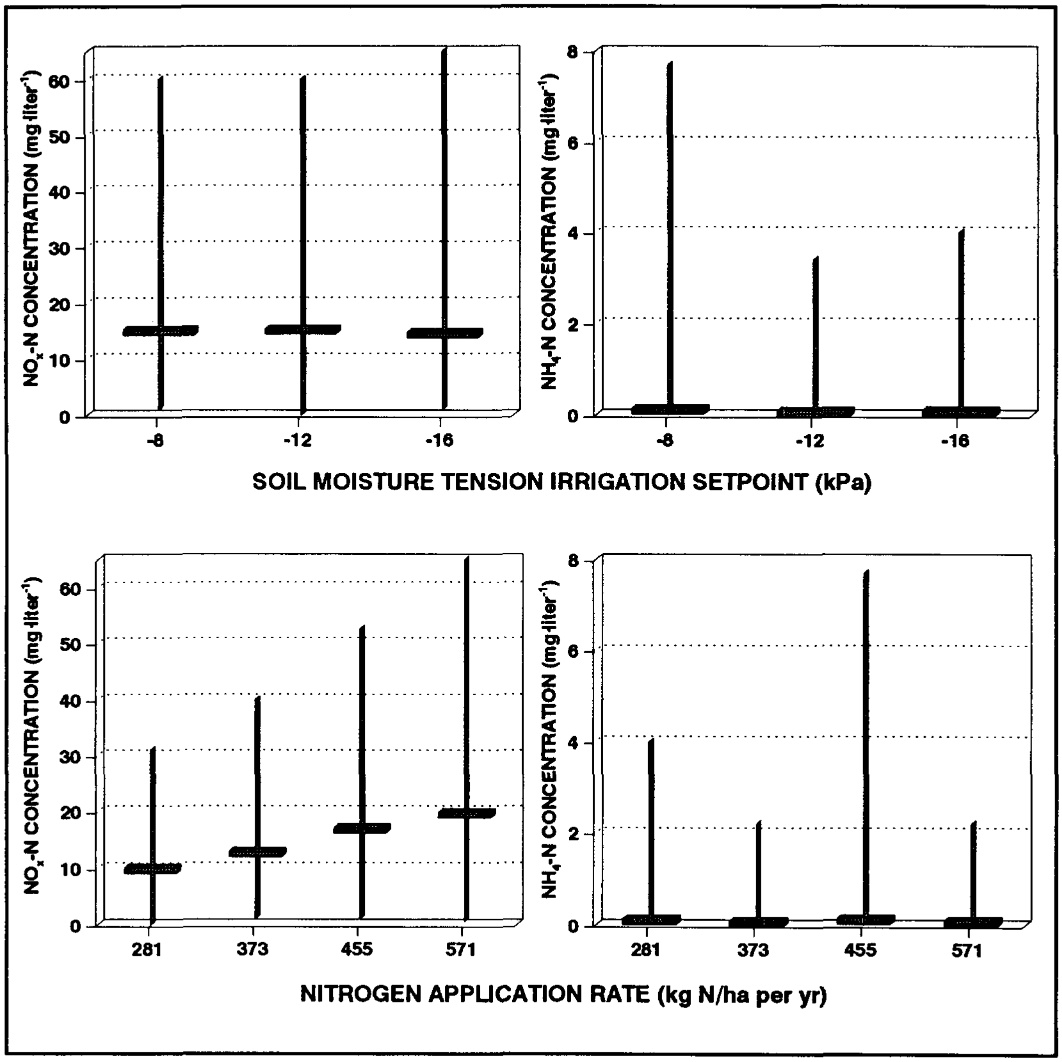

Figure 28. Minimum, average (horizontal bars) and maximum nitrate (NO_3-N) and ammoniacal (NH_4-N) nitrogen concentrations in leachate from lysimeter tanks receiving four nitrogen application rates and irrigated at three different soil moisture irrigation setpoints (Study 2).

Field Studies. Taylor Middle-Senior High School — Average NO_3–N concentrations at the top of the surficial aquifer under the shadehouses being fertilized with liquid fertilizer (applied at 114 kg N/ha per yr [102 lb N/acre per yr] never exceeded the EPA MCL (Figure 30). In fact, maximum values only exceeded the MCL for 3 out of 51 samples. The use of injectors to meter out the liquid fertilizer throughout each irrigation event (constant feed) did not appear to have any beneficial effect on NO_3-N concentrations (Figure 30).

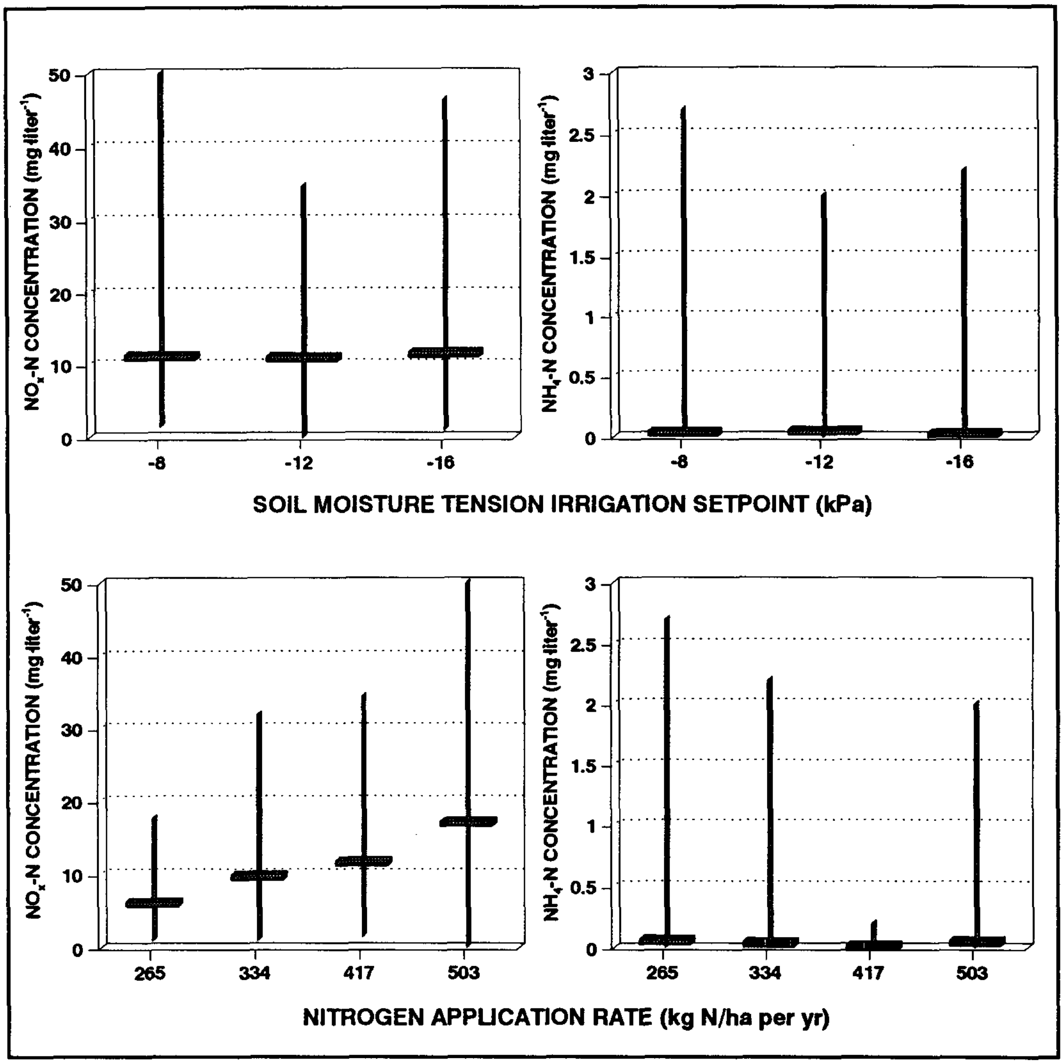

Figure 29. Minimum, average (horizontal bar) and maximum nitrate (NO_3-N) and ammoniacal (NH_4-N) nitrogen concentrations in leachate from lysimeter tanks receiving four nitrogen application rates and irrigated at three different soil moisture irrigation setpoints (Study 3).

Average surficial aquifer NO_3–N concentrations below the shadehouses fertilized with controlled-release fertilizer (CRF) applied at 396 kg N/ha per yr [354 lb N/acre per yr] exceeded the MCL mainly during the summer (Figure 31). Release of nutrients from resin-coated CRFs have been

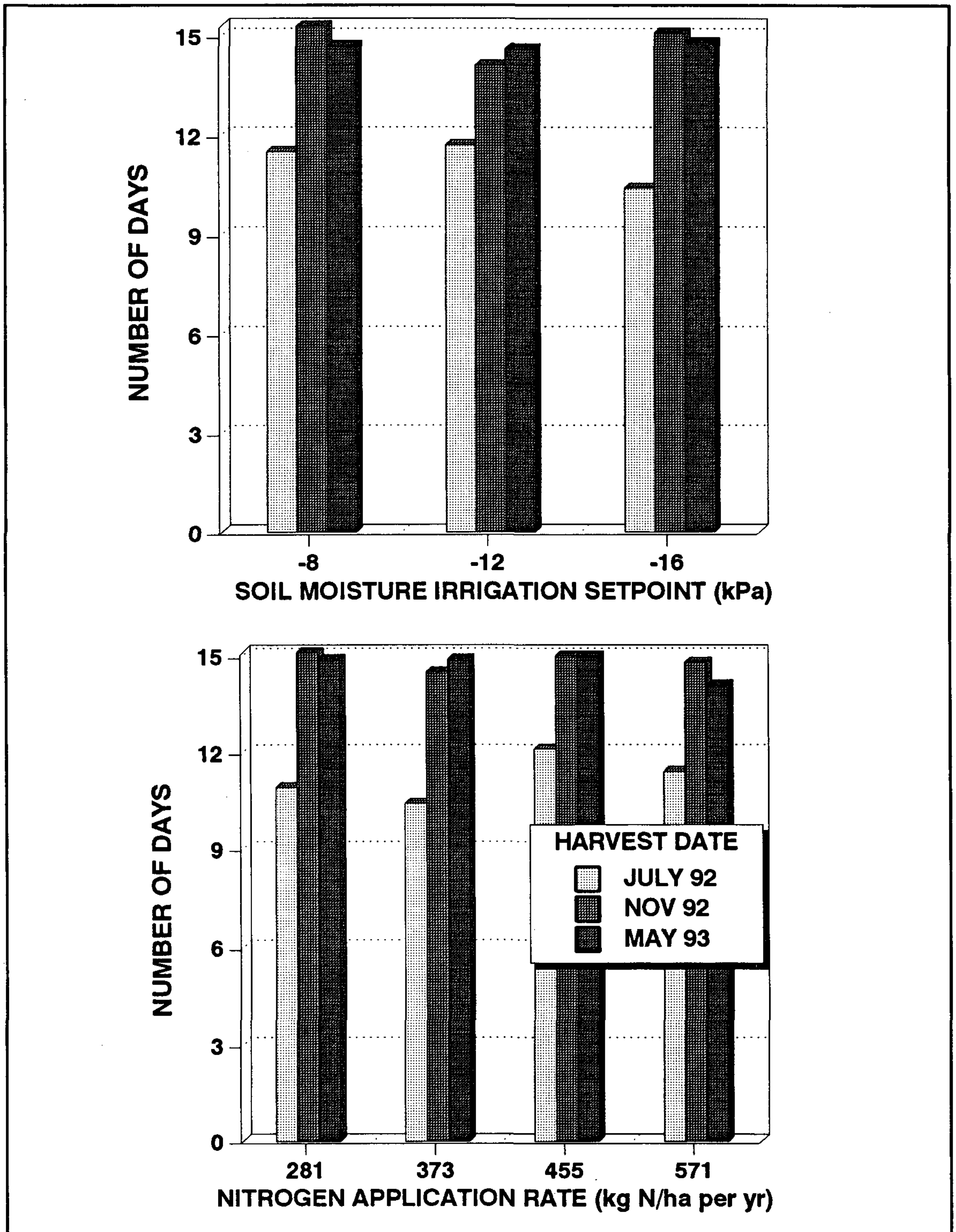

Figure 39. Fertilizer application rates did not affect leatherleaf fern frond vase life (Study 2).

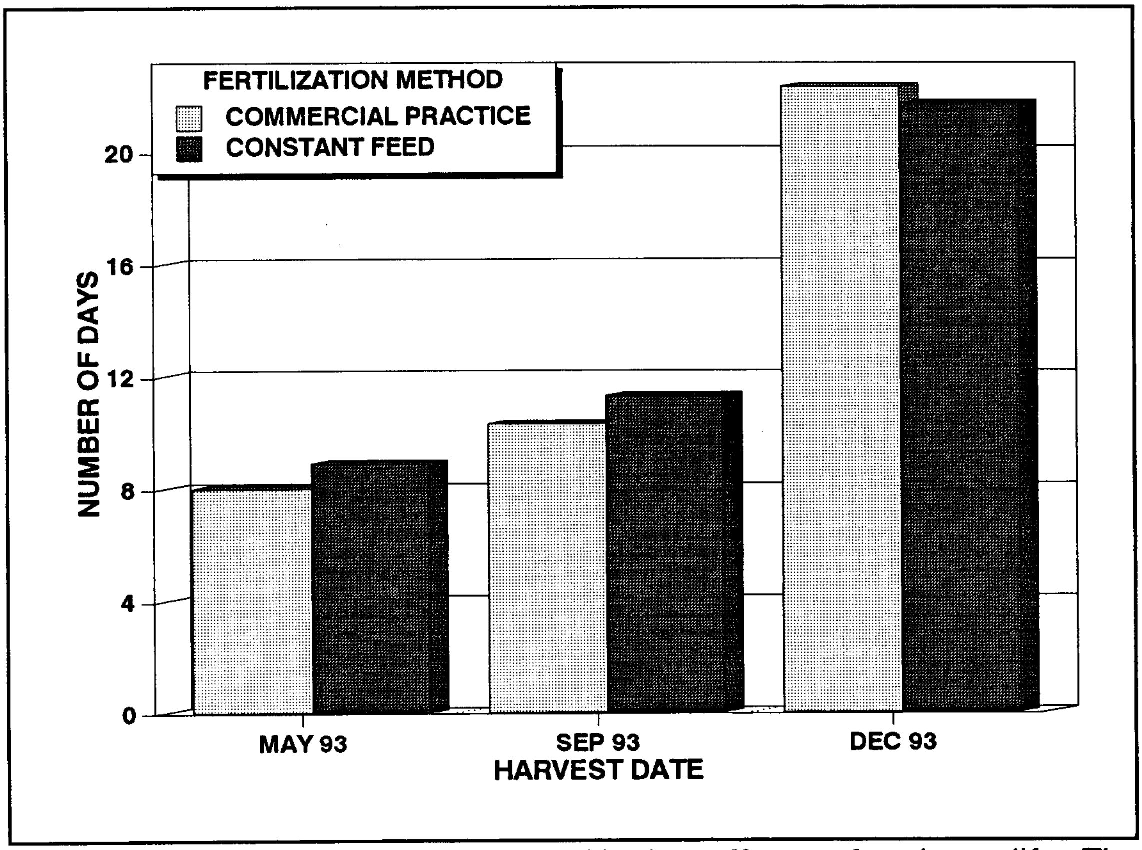

Figure 40. Fertilizer application method had no effect on frond vase life. The nitrogen application rates was 114 kg N/ha per yr [102 lb N/acre per yr].

GLOSSARY

Abaxial. Directed away from the axis, as in the lower surface of a leaf.

Anaerobic. Active in the absence of free oxygen.

Bar. Non-SI unit of pressure equal to 0.1 pascal (Pa), 0.987 atmospheres, or 750.076 millimeters (mm) [29.53 in] of mecury (Hg).

Blackbody. An ideal body or surface which completely absorbs all radiant energy of any wave length falling upon it, no energy being reflected.

Blue baby. Infant with methemoglobinemia.

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

Crop coefficient (K_c). The ratio of ET_{actual} to E_{pan}. Also the ratio of ET_{actual} to ET_p.

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

Denitrification. Reduction of nitrates to atmospheric nitrogen and oxides of nitrogen.

Emissivity ($\in$). Ratio of the emittance of a given surface at a specified wavelength and temperature to the emittance of an ideal blackbody at the same wavelength and temperature.

Evaporation (E). The physical process by which a liquid or solid is transferred to the gaseous state. The direct vaporization of water from a free water surface.

Evapotranspiration (ET). Rate of water loss through transpiration from vegetation plus evaporation from the soil ($ET = T_{plant} + E_{soil}$).

Evapotranspiration, reference or potential (ET_0, PET). The maximal evaporation rate that the atmosphere is capable of extracting from a well-watered field under given conditions.

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

Frond. Leaf of a fern.

Gram. Unit of weight equal to 0.0353 ounce (avoirdupois).

Hydraulic conductivity. The ability of soil to transmit water.

J (joule). SI unit of energy that is equal to 0.239 calorie and is the amount of energy necessary to raise the temperature of 1 gram of water 1 °C.

kPa (kilopascal). The SI unit of pressure equal to 1,000 pascals or 0.295 inch of mercury (Hg).

Leachate. Liquid (water) and included disolved/transported compounds that percolate through the soil past the crop root zone.

Leaching fraction (LF). LF = volume leached (V_l) ÷ volume applied (V_a).

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

Lysimeter. A device for measuring the movement of water through soils and determining plant water use and the soluble constituents in the leached water.

Methemoglobinemia. Condition that occurs when the iron in hemoglobin is oxidized, thereby reducing the oxygen-carrying capacity of the blood.

Megapascal. The SI unit of pressure equal to 1,000,000 pascals or 10 bars.

Net radiation (R_n). Incoming radiation minus outgoing radiation.

Nitrification. Biological oxidation of ammonia to nitrite then to nitrate.

Pan evaporation (E_{pan}). Evaporation from a National Weather Service standard Class A pan.

Percolation. Downward movement of water through soil, especially in saturated or nearly saturated soil.

Perennial. Continuing to live from year to year.

Permeability. Soil qualities that enable water to move through the soil. Permeability is measured as the flow of water ($cm \cdot hr^{-1}$ [inches/hr]) through saturated soil. Permeability terminology:

Description	$cm \cdot hr^{-1}$ [inch(es)/hr]
Very slow	< 0.15 [0.06]
Slow	0.15 to 0.51 [0.06 to 0.2]
Moderately slow	0.51–1.52 [0.2 to 0.6]
Moderate	1.52 to 5.1 [0.6 to 2.0]
Moderately rapid	5.1 to 15.2 [2.0 to 6.0]
Rapid	15.2 to 50.8 [6.0 to 20]
Very rapid	> 50.8 [> 20]

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

Photosynthetic photon flux density (PPFD). See photosynthetically active radiation, units are $\mu mol \cdot m^{-2} \cdot s^{-1}$.

Radiant flux density. Amount of energy received on a unit surface in unit time ($kJ \cdot m^{-2}$, $W \cdot m^{-2}$).

Radiation. Energy transferred through space as electromagnetic waves.

Relative humidity. The ratio of actual to saturation vapor pressure at a given temperature.

Root zone. Volume of soil from which the roots of a plant extract water and nutrients.

Saturation vapor pressure (e_s). The maximum pressure possible when equilibrium is reached between water and 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.

Transpiration (T). Water loss through plants. Movement of water vapor from the interior of the plant to the surrounding air.

Vadose zone. The portion of the soil that is above the level of permanent ground water and, therefore, unsaturated part of the time.

Vapor pressure deficit ($e_s - e_a$). Difference between the saturation vapor pressure (e_s) and the actual vapor pressure (e_a).

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 thermocouple in contact with moistened cotton material past which ambient air is drawn using a fan.

ABBREVIATIONS and SYMBOLS

BMP . . . . best management practice
cm . . . . centimeter
cbar . . . . centibar
e_a . . . . vapor pressure
e_s . . . . saturation vapor pressure
E . . . . evaporation
ET_o . . . . potential evapotranspiration
E_{pan} . . . . pan evaporation
ET . . . . evapotranspiration
ft^2 . . . . square foot
ha . . . . hectare
Hg . . . . mecury
IMP . . . . . improved management practice
in . . . . inch
J . . . . joule
K . . . . potassium
K_c . . . . crop coefficient
kg . . . . kilogram
kPa . . . . kilopascal
lb . . . . pound
LF . . . . leaching fraction
MCL . . . . maximum contaminant level
mm . . . . millimeter
m^2 . . . . square meter
MPa . . . . megapascal
mv . . . . millivolt
N . . . . nitrogen
NH_4-N . . . . ammoniacal nitrogen
nm . . . . nanometer
NO_3-N . . . . nitrate nitrogen
O . . . . oxygen
OM . . . . organic matter
P . . . . phosphorus
P . . . . atmospheric pressure
Pa . . . . pascal
PAR . . . photosynthetically active radiation
PPFD . photosynthetic photon flux density
R . . . . radiation
R_n . . . . net radiation
RH . . . . relative humidity
r^2 . . . . coefficient of determination

SE . . . . standard error
T . . . . transpiration
T . . . . temperature
TKN . . . . total Kjeldahl nitrogen
W . . . . watt
Ψ_{leaf} . . . . leaf water potential
Ψ_{soil} . . . . soil water potential

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shown to be affected by temperatures, with faster release of nutrients occurring at higher temperatures (Harbaugh and Wilfret, 1982). This release of nutrients, combined with summer rainfall, may explain these results and suggests that nutrient release characteristics of CRFs be taken into consideration before application. Use of less temperature sensitive CRFs and fall or early spring applications might reduce the N release during the summer. Besides reducing NO_3-N concentrations, this reduced N release may also be beneficial from a crop quality standpoint since It has been suggested that reducing fertilization during the summer might lessen rapid leatherleaf fern growth that may contribute to shortened vase life (Poole et al., 1984).

In this study, CRF was applied broadcast so that some of the material ended up in areas where there were no plant roots in the soil to utilize the nutrients as they were released. However, CRFs can be applied to specific areas (e.g., fern beds only); thereby, reducing the application rate per unit area of shadehouse and the potential for nitrogen to move through the soil profile without being taken up by the plants.

New commercial fernery — Initial nitrogen applications elevated root zone and vadose zone NO_3–N levels quickly (Figure 32). Increases in NO_3–N concentrations took several months longer to occur in the surficial aquifer which was about 1–1.2 m [3–4 ft] below the soil surface. Concentrations remained high at all levels until February, 1994. These reductions could be due to reduced N applications, to increases in the amount of plant material available to extract N from the soil and to dilution due to irrigation water being applied during cold protection. Further research is needed to determine how to prevent these elevated NO_3–N concentrations from occurring during the establishment phase of leatherleaf fern production, and if elevated concentrations do occur, if and how long it takes to have NO_3–N concentrations return to normal background levels.

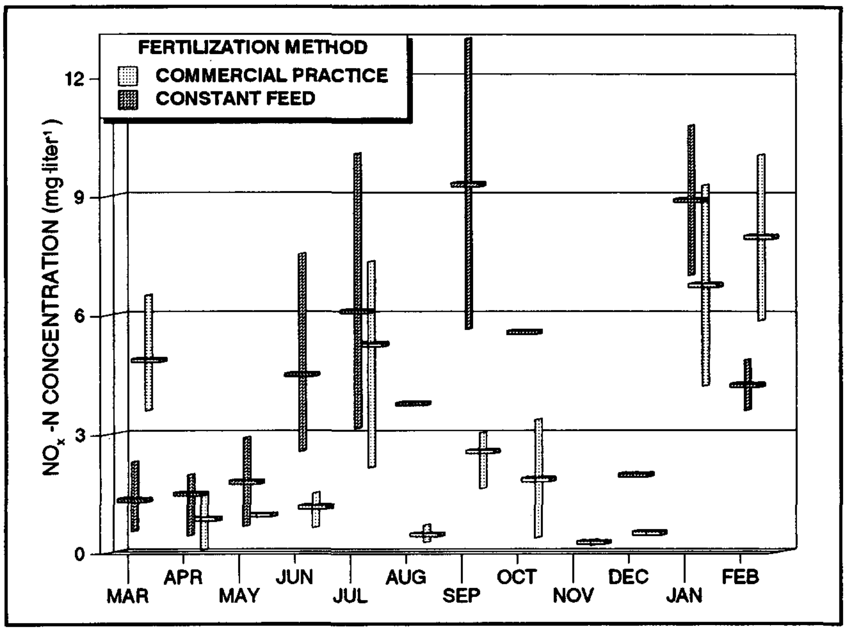

Figure 30. Minimum, average (horizontal bar) and maximum NO_x-N concentrations in the surficial aquifer under shadehouses fertilized with liquid fertilizer at Taylor Middle-Senior High School.

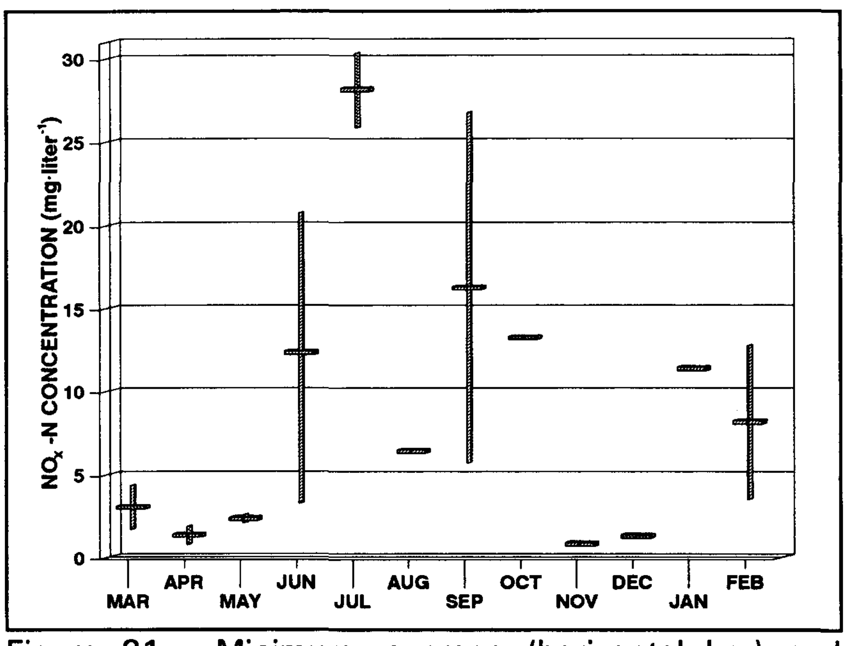

Figure 31. Minimum, average (horizontal bar) and maximum NO_x-N concentrations in the surficial aquifer under shadehouses fertilized with controlled-release fertilizer at Taylor Middle-Senior High School.

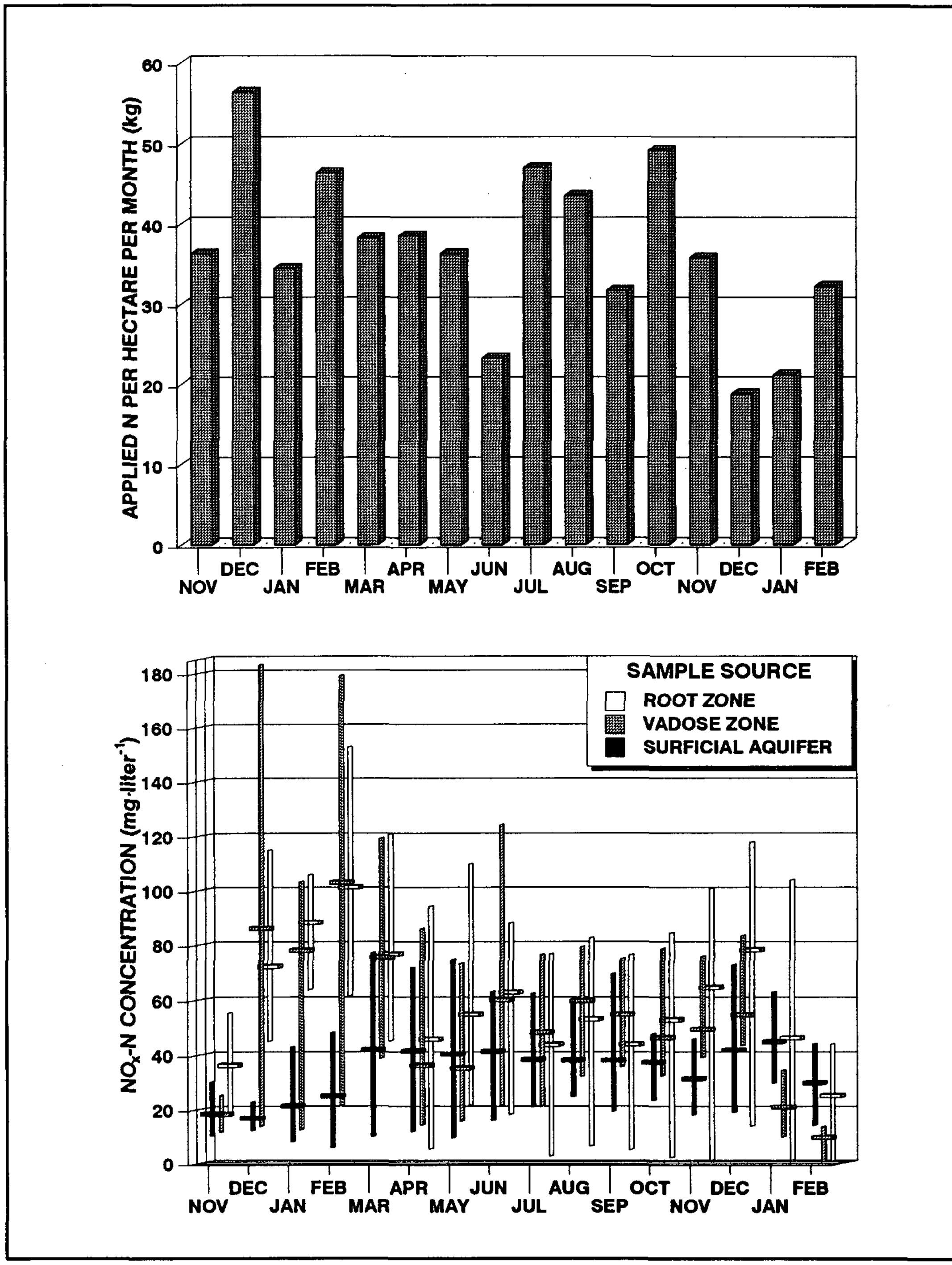

Figure 32. Effects of nitrogen applications on NO_3-N concentrations during the establishment of leatherleaf fern beds.

Physiology

Frond water potential (Ψ_{leaf}). Neither fertilizater application rate nor irrigation treatment affected Ψ_{leaf} in any of the studies (data not shown). Morning Ψ_{leaf} (Figure 33) were similar to those reported by Nell et al. (1983).

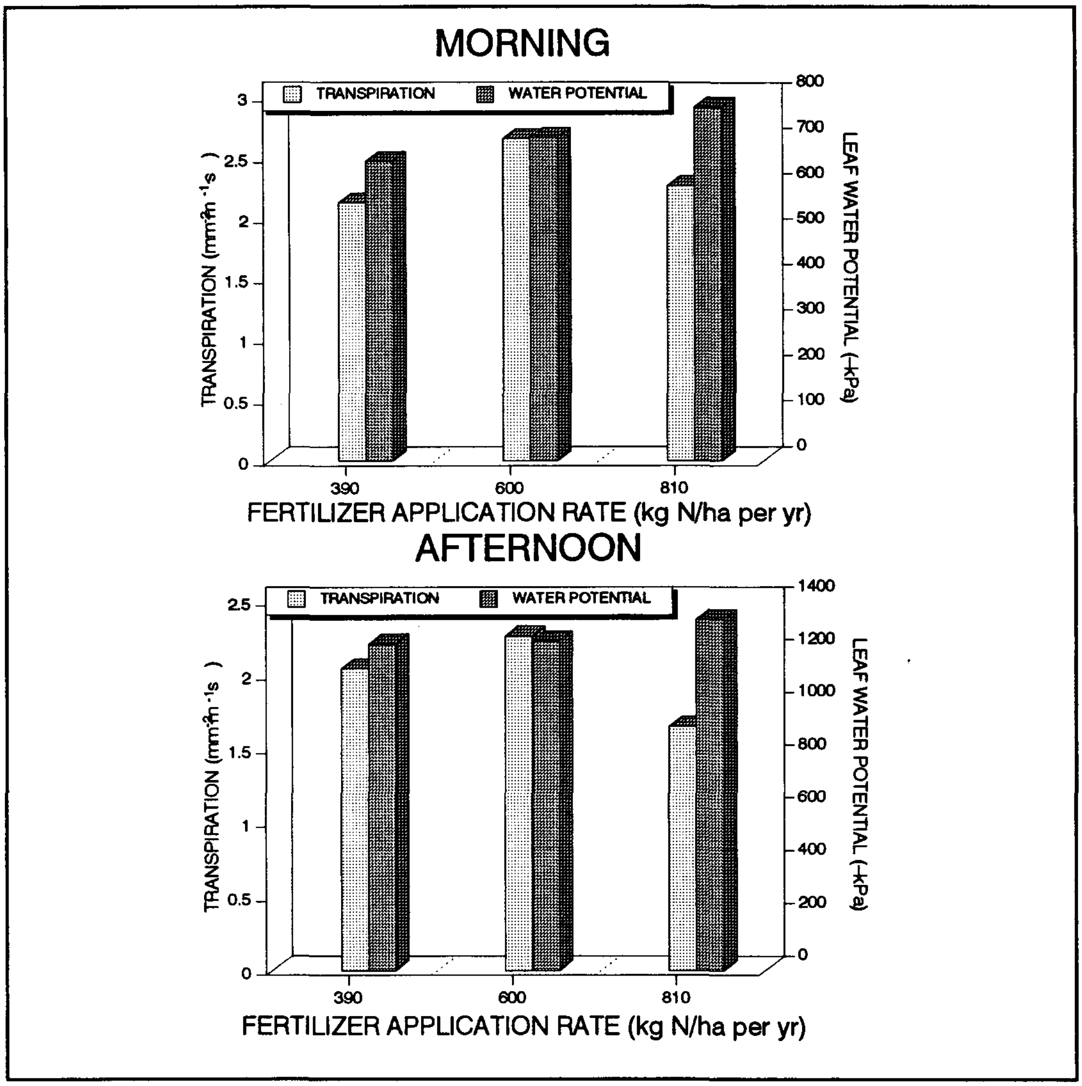

Figure 33. Fertilizer treatments had no effect on frond (leaf) water potentials or transpiration rates measured in the morning or the afternoon on 15 April 1992.

Transpiration (T). As with Ψ_{leaf}, neither fertilization application rate nor irrigation treatment affected T in the lysimeter studies (Figure 33). Measured transpiration rates were twice those of fronds grown in growth chambers (Stamps et al., 1994). In the field study at TMSHS, fertilizer sources (CRF, liquid) and application methods (commercial practice, constant feed) had no effect of transpiration by leatherleaf fern fronds.

Yield

Lysimeter studies. Study 1 — Fertilizer application rate had no effect on frond yield (Figure 34). The single harvest at the end of this 6-month study yielded about 111 marketable fronds per m^2 [10.3 fronds per ft^2]. Assuming that production beds account for about 70% of the area in a fernery (Stamps and Poole, 1986), the yield from this study is equivalent to about 777,000 fronds/ha per ½ yr [twelve 1,000 frond cases/acre per week].

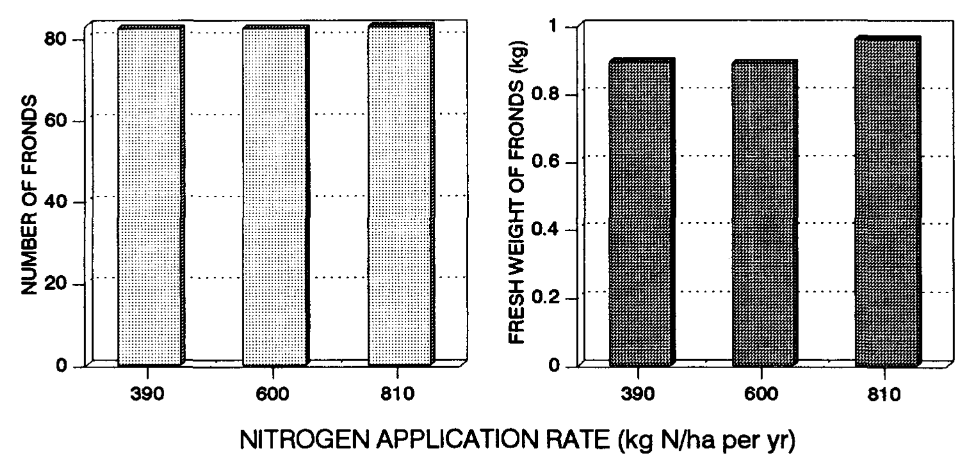

Figure 34. Fertilizer application rate had no effect on yield of leatherleaf fern fronds (Study 1).

Study 2 — Three harvests were made and no differences in yield due to treatments were detected (Figure 35). About 343 fronds per m^2 [32 fronds per ft^2] were produced during this year-long study. Assuming that 70% of the area of a fernery is actual production area, yield was equivalent to about 2.4 million fronds/ha per yr [eighteen and three-quarter 1,000 frond cases/acre per week]. Excluding the July harvest under the supposition that the previous fertilization regime might have influenced it, yield was still over 1.8 million fronds/ha per yr [fourteen and one-quarter 1,000 frond cases/acre per week].

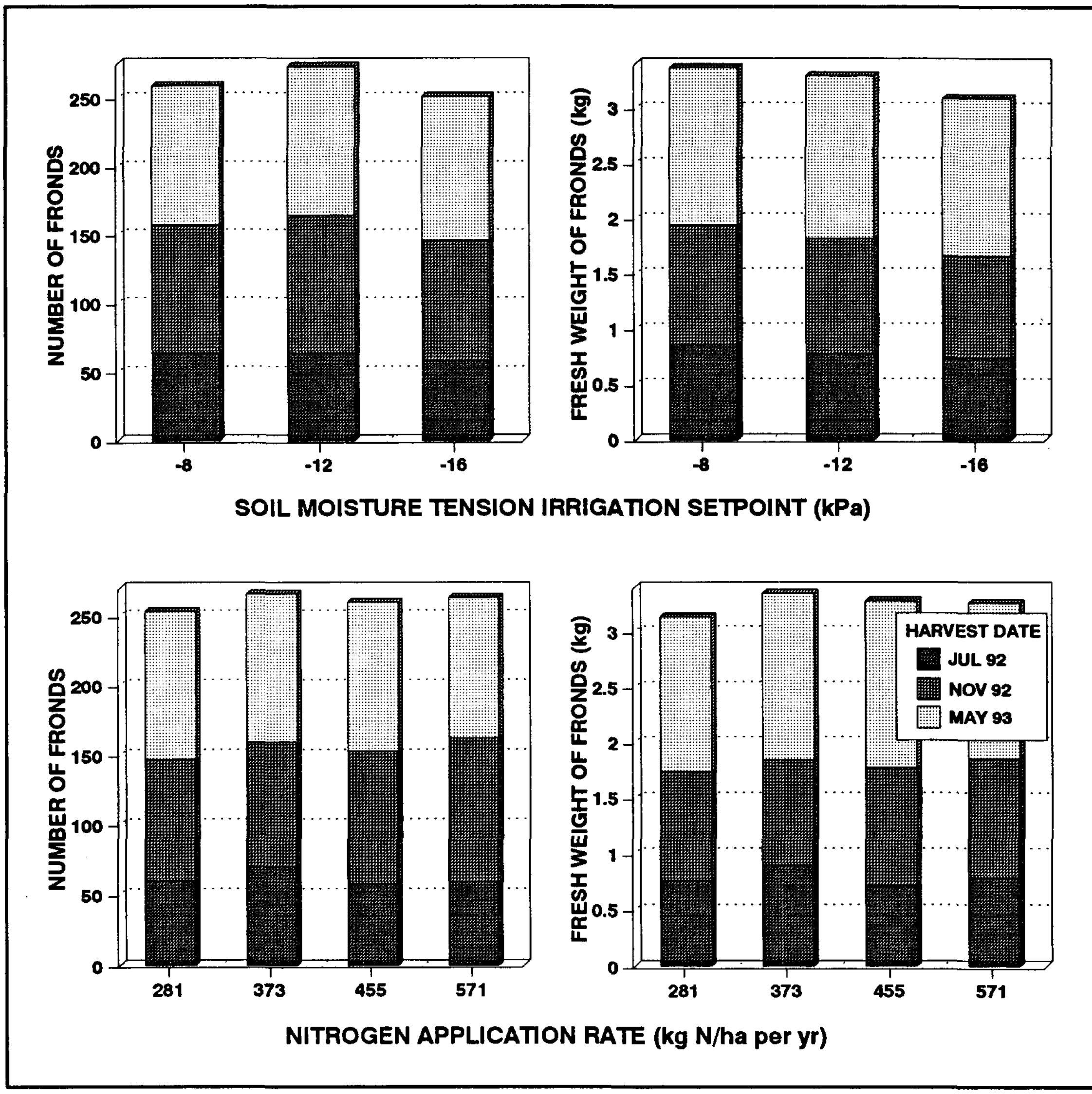

Figure 35. Nitrogen application rates and soil moisture tension irrigation setpoints had no effect on leatherleaf fern frond yields (Study 2).

Study 3 — As in the previous studies, N application rate had no effect on yield. Adjusting for duration of treatment and actual production area in a commercial fernery (as were done above), annual yield of about 400 fronds per m^2 [37 fronds per ft^2] were produced during this study. Yield was equivalent to about 2.5 million fronds/ha per yr [nineteen and one-half 1,000 frond cases/acre per week]. Equally important from a commercial standpoint, average frond weights were as high or higher than those produced at higher N application rates in studies 1 and 2 (Figure 36).

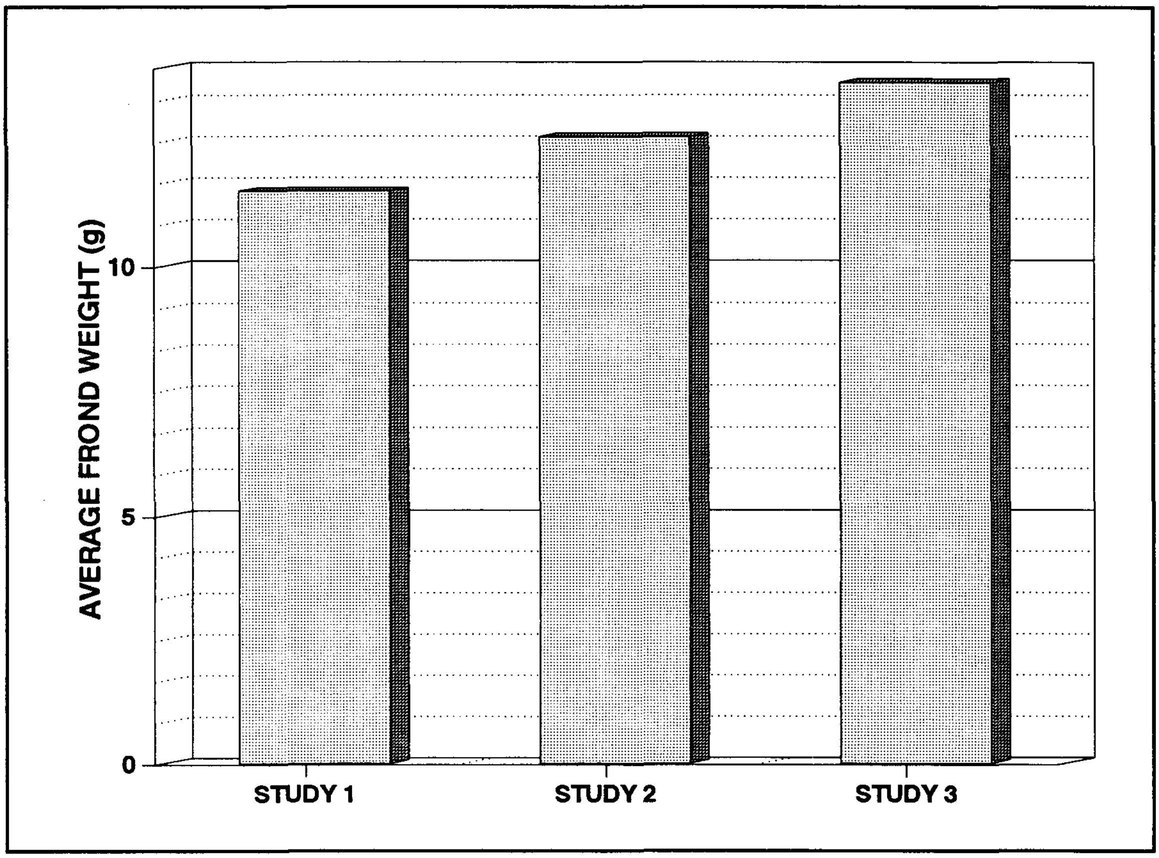

Figure 36. Although nitrogen and potassium application rates were reduced for each subsequent study, average frond weight increased with time.

Field Studies. Liquid fertilizer application method had no effect on yield of leatherleaf fern (Figure 37). After 4 harvests ($12^1/_2$ months of production since fertilization began in late March of 1993), production in the shadehouses averaged 4,442 bunches per house. This is the equivalent of about 20,995 bunches per acre or 9.7 forty-bunch cases per acre per week.

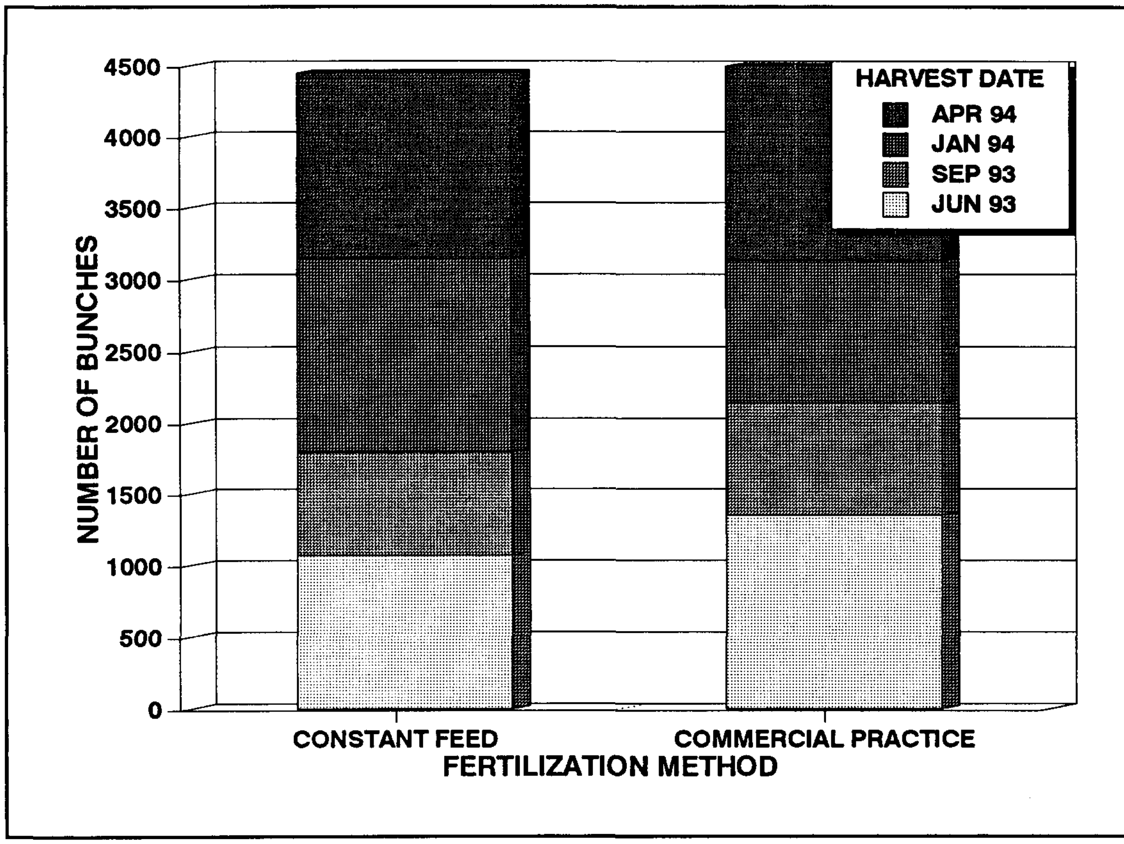

Figure 37. Liquid fertilizer application method had no effect on yield of leatherleaf fern fronds harvested from plots at Taylor Midddle-Senior High School.

Quality

Frond color. Lysimeter studies — Frond color was measured four times and neither soil moisture tension irrigation set point nor fertilization level affected leatherleaf fern frond color. Mean values for study 1 are listed in Table 6. Results were similar for the other color measurement events (data not shown).

Field studies — There were no differences between the color of fronds produced using commercial fertigation practice (injecting the fertilizer at the beginning of the irrigation cycle) and constant feed (injecting the fertilizer throughout the irrigation cycle) (data not shown).

Frond vase life. Lysimeter studies — Treatments had no effect on frond vase life. Fronds lasted an average of about two weeks (Figure 38).

Table 6. Soil moisture tension irrigation set point and nitrogen fertilization rate had no effect on leatherleaf fern frond color.

Irrigation set point (kPa)	$L^{\star}$	$a^{\star}$	$b^{\star}$	$c^{\star z}$
- 6	40.40	-15.87	18.88	24.66
-12	40.19	-15.73	18.84	24.54
-18	40.55	-15.96	19.35	25.08
Significance[y]	ns	ns	ns	ns
Nitrogen rate ($kg \cdot ha^{-1} \cdot yr^{-1}$)				
390	40.08	-15.88	19.14	24.87
600	40.66	-15.95	19.11	24.89
810	40.13	-15.63	18.73	24.40
Significance	ns	ns	ns	ns

[z] $c^{\star} = \sqrt{a^{\star 2} + b^{\star 2}}$

[y] ns = not significant

Study 2 — Treatments had no effect on frond vase life (Figure 39). Vase life of fronds harvested in July had reduced vase life compared to fronds harvested during cooler months. These seasonal differences in vase life are typical and have been reported previously (Mathur et al., 1982; Poole et al., 1976; Poole et al., 1984).

Field studies — Vase life of fronds harvested from the Taylor Middle-Senior High School plots also had seasonal variations, but none due to fertilizer application methods (Figure 40).

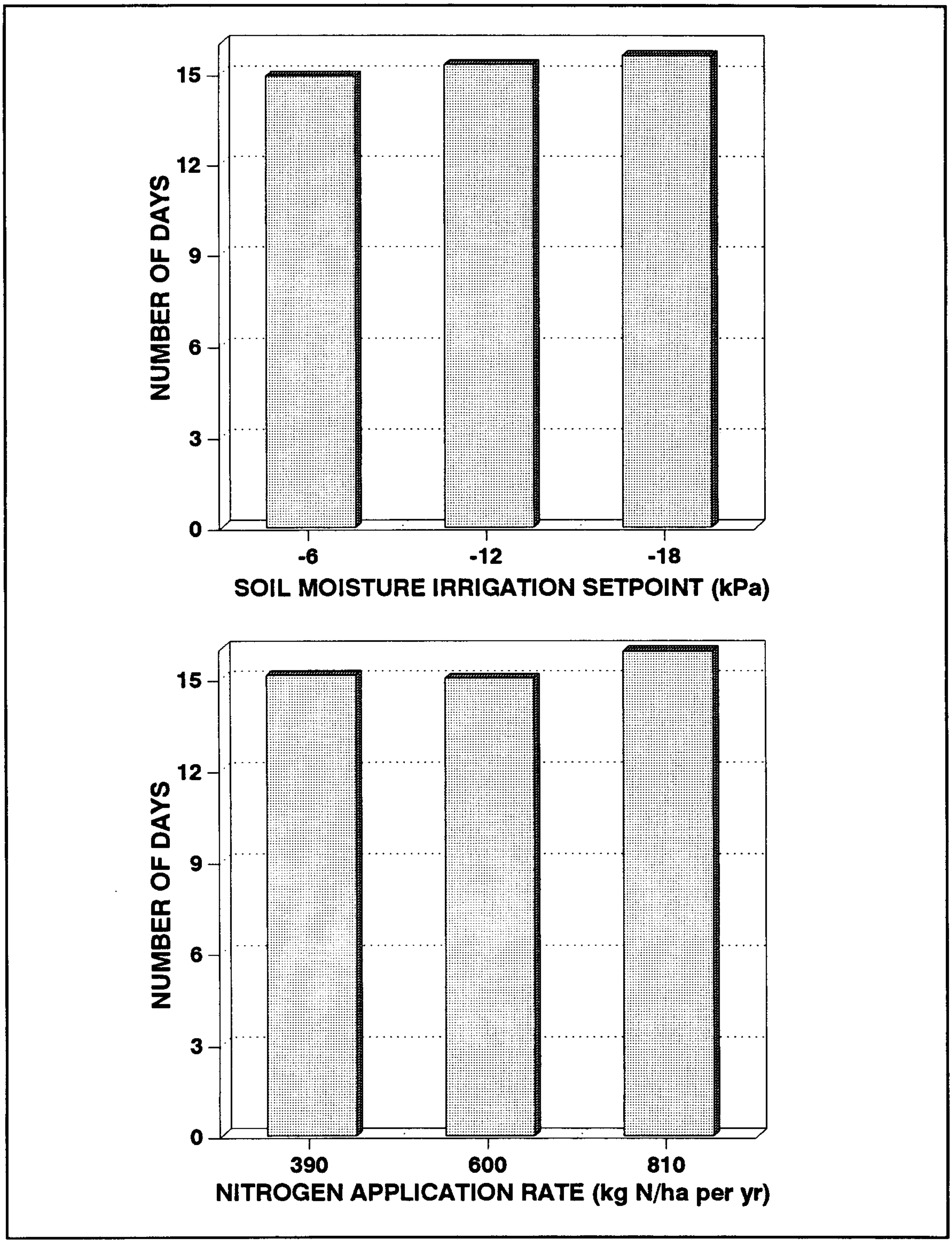

Figure 38. Soil moisture irrigation setpoint and fertilizer application rate had no effect on leatherleaf fern vase life (Study 1).

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APPENDICES

APPENDIX A: Characteristics of soils used for production of leatherleaf fern* in Lake, Putnam and Volusia counties.

Leatherleaf fern production soil type and acreage information is taken from the St. Johns River Water Management District's Geographic Information System (GIS) database. The GIS database is based on aerial photographs (shadehouses) and ground truthing (hammocks and shadehouses) of cut foliage operations with consumptive use permits and on United States Department of Agriculture Soil Conservation Service (USDA/SCS) soil surveys. The information in the list below was generated by combining soil type location information with leatherleaf fernery location information. Soil permeability ratings are those provided by USDA/SCS (Furman et al., 1975; Baldwin et al., 1980; Readle et al., 1990). Additional soil characteristics information was provided by Dr. Art Hornsby, Soil and Water Science Department, University of Florida.

*Only database entries strictly for leatherleaf fern are included in this list, entries for leatherleaf & others or mixed fern are not included in this compilation.

SOIL TYPE	HYDRO-LOGIC GROUP	1/10th BAR WATER CONTENT (% by wt)	MINIMUM K_{sat} ($cm \cdot hr^{-1}$)	MINIMUM K_{sat} (in/hr)	AWHC ($cm \cdot cm^{-1}$)	AWHC (in/ft)	PERME ABILITY[Z] (in/hr)	ACRES
Adamsville sand-P[Y]	A	6.23	14.70	5.79	0.05	0.6	6-20	60.4
Apopka sand-P	A	16.11	03.84	1.51	0.07	0.84	6-20	0.9
Apopka sand-L	A	16.11	03.84	1.51	0.07	0.84	6.3-20	31.4
Apopka fine sand-	D	15.8	0.01	0.00	0.09	1.08	6-20	213.8
Astatula sand-P	A	4.94	55.20	21.73	0.04	0.48	20 +	36.1
Astatula fine sand-	A	5.15	23.65	9.31	0.05	0.6	20 +	1220.4
Basinger fine sand-	D	11.39	0.06	0.02	0.09	1.08	20 +	5.2
Candler sand-P	A	4.88	04.28	1.69	0.04	0.48	6-20	18.7
Candler sand-L	A	4.88	04.28	1.69	0.04	0.48	20 +	98.3
Candler fine sand-	A	6.46	14.05	5.53	0.06	0.72	6-20	70.4
Cassia fine sand-P	A	14.77	0.96	0.38	0.12	1.44	6-20	11.7
Cassia fine sand-V	A	14.77	0.96	0.38	0.12	1.44	6-20	48.2
Centenary fine	A	7.25	07.12	2.80	0.07	0.84	6-20	123.1
Daytona sand-V	A	7.33	25.00	9.84	0.06	0.72	20 +	180.6
Deland fine sand-V	A	11.65	3.42	1.35	0.1	1.2	20 +	617.8

SOIL TYPE	HYDRO-LOGIC GROUP	1/10th BAR WATER CONTENT (% by wt)	MINIMUM K_{sat} ($cm \cdot hr^{-1}$)	MINIMUM K_{sat} (in/hr)	AWHC ($cm \cdot cm^{-1}$)	AWHC (in/ft)	PERME ABILITY[z] (in/hr)	ACRES
Deland fine sand-P	A	11.65	03.42	1.35	0.1	1.2	6 +	31.6
Electra fine sand-V	D	16.68	0.01	0.00	0.12	1.44	6-20	8.4
Electra fine sand-P	D	16.68	0.01	0.00	0.12	1.44	6-20	18
Farmton fine sand-	D	20.14	0.01	0.00	0.15	1.8	6-20	0.3
Hobe fine sand-P	D	10.07	0.09	0.04	0.06	0.72	20 +	25.8
Hontoon muck-V	A	72.46	18.33	7.22	0.64	7.68	6-20	23.7
Hontoon muck-P	A	67.38	02.85	1.12	0.58	6.96	6-20	5.1
Immokalee sand-L	D	14.5	0.09	0.04	0.12	1.44	6.3-20	8.8
Immokalee fine	C	12.86	0.17	0.07	0.1	1.2	6-20	33.9
Immokalee sand-V	D	14.5	0.09	0.04	0.12	1.44	6-20	25.2
Kendrick sand-L	D	30.46	0.01	0.00	0.17	2.04	6.3-20	12
Lake sand-L	A	7.23	75.95	29.90	0.05	0.6	20 +	17
Lochloosa sand-P	A	24.67	0.92	0.36	0.18	2.16	2-20	1.3
Lochloosa sand-L	A	24.67	0.92	0.36	0.18	2.16	6.3-20	14
Millhopper sand-P	D	14.8	0.05	0.02	0.1	1.2	6-20	106.2
Myakka fine sand-	C	17.21	0.22	0.09	0.14	1.68	6-20	14.9
Myakka fine sand-	C	17.21	0.22	0.09	0.14	1.68	6-20	61.2
Myakka sand-L	A	12.66	05.75	2.26	0.1	1.2	6.3-20	5.2
Narcoossee fine	A	12	04.14	1.63	0.1	1.2	6-20	4.8
Ona fine sand-P	B	17.84	0.41	0.16	0.16	1.92	6-20	0.2
Ona fine sand-L	B	17.84	0.41	0.16	0.16	1.92	6.3-20	1.6
Orlando fine sand-	A	13.3	17.35	6.83	0.08	0.96	6.3-20	32.2
Orsino fine sand-V	A	6.63	12.95	5.10	0.06	0.72	20 +	139.8
Orsino sand-P	A	4.73	68.40	26.93	0.04	0.48	20 +	24.9
Orsino sand-L	A	4.73	68.40	26.93	0.04	0.48	20 +	1.1
Paola fine sand-V	A	6.4	22.35	8.80	0.05	0.6	20 +	183
Paola fine sand-P	A	6.4	22.35	8.80	0.05	0.6	20 +	6.2
Paola sand-L	A	4.31	58.85	23.17	0.04	0.48	20 +	70.2
Placid fine sand-P	A	13.48	03.70	1.46	0.11	1.32	6-20	2
Placid sand-L	A	12.4	17.75	6.99	0.09	1.08	6.3-20	0.7
Placid fine sand-V	A	13.48	03.70	1.46	0.11	1.32	6-20	13.2

SOIL TYPE	HYDRO-LOGIC GROUP	1/10th BAR WATER CONTENT (% by wt)	MINIMUM K_{sat} ($cm \cdot hr^{-1}$)	MINIMUM K_{sat} (in/hr)	AWHC ($cm \cdot cm^{-1}$)	AWHC (in/ft)	PERME ABILITY[Z] (in/hr)	ACRES
Pomello sand-L	A	6.13	10.85	4.27	0.05	0.6	20 +	11.2
Pomona fine sand-	D	23.63	0.02	0.01	0.17	2.04	6–20	11.7
Pomona fine sand-	D	23.63	0.02	0.01	0.17	2.04	6–20 +	5.4
Pompano fine	A	4.84	12.50	4.92	0.05	0.6	6–20	3.4
Riviera fine sand-V	D	22.33	0.02	0.01	0.16	1.92	6–20	0.4
Samsula muck-P	B	37.46	0.47	0.19	0.33	3.96	6–20	0.9
Samsula muck-V	B	37.46	0.47	0.19	0.33	3.96	6–20	7.2
Satellite sand-V	A	5.37	35.20	13.86	0.04	0.48	20 +	13.7
Smyrna fine sand-	B	15.11	0.44	0.17	0.12	1.44	6–20	3.3
Sparr sand-P	C	13.25	0.35	0.14	0.09	1.08	6–20	14.3
Sparr sand-L	C	13.25	0.35	0.14	0.09	1.08	6.0–20	5.1
St. Johns fine	B	26.29	0.39	0.15	0.22	2.64	6–20	0.6
St. Johns fine	B	26.29	0.39	0.15	0.22	2.64	6–20	9.7
St. Lucie sand-L	A	4.1	69.00	27.17	0.03	0.36	20 +	22.3
St. Lucie fine	A	nd	nd	0.00	nd	nd	20 +	11.7
Tavares sand-L	A	6.85	20.70	8.15	0.06	0.72	20 +	28.7
Tavares sand-P	A	6.85	20.70	8.15	0.06	0.72	6 +	113.6
Tavares fine sand-	A	7.28	13.40	5.28	0.06	0.72	20 +	1287.2
Tequesta muck-V	A	39.53	8.6	3.39	0.27	3.24	6–20	0.4
Tomoka muck-V	A	nd	24.51	9.65	0.28	3.36	6–20	1.2
Wauchula sand-L	D	24.1	0.09	0.04	0.14	1.68	6.3–20	18.7
Wauchula fine	D	25.65	0.08	0.03	0.16	1.92	6–20	0.6
Winder fine sand-P	D	26.59	0.01	0.00	0.17	2.04	6–20	0.5
Zolfo fine sand-P	A	5.89	05.68	2.24	0.05	0.6	6–20	34.8

[Z]Permeablility ratings for root zone are from county soil surveys.
[Y]L = Lake county, P = Putnam county, V = Volusia county.

APPENDIX B: Summary of previous leatherleaf fern research dealing with irrigation.

A three-year study to determine the effects of reduced water application levels on yield and vase life of leatherleaf fern was initiated in 1979 (Mathur et al., 1983). One of the findings of this study were that irrigating with 150 cm [59 inches] of water per year produced the same size and number of fronds as an irrigation level of 310 cm [122 inches] of water per year. In addition, vase life of fronds produced using the lower irrigation level was increased 8–16% for 3 of 7 harvests, compared to fronds receiving the high irrigation level (Figure 41).

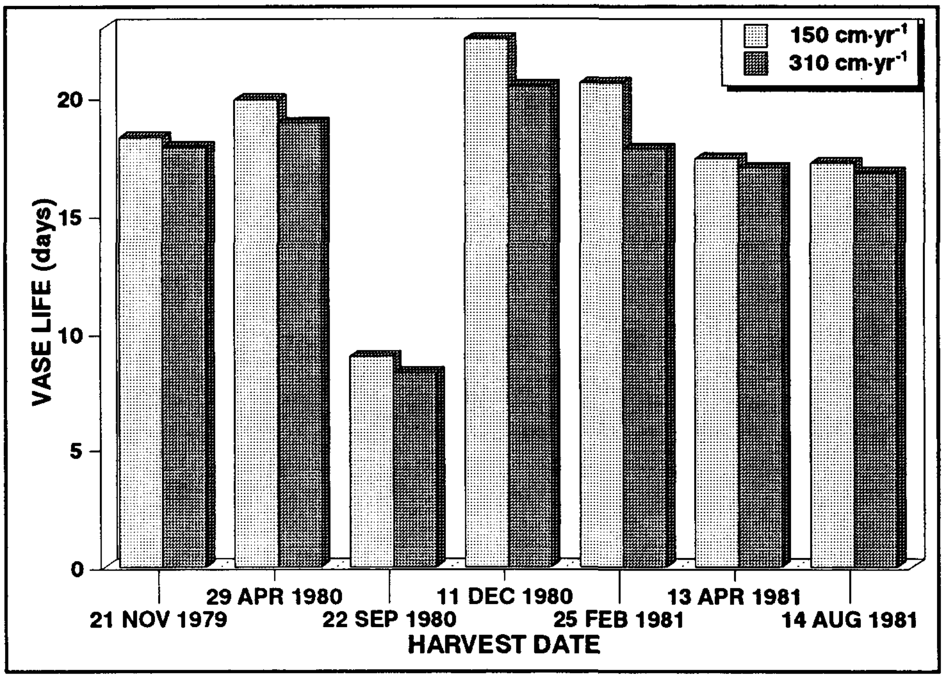

Figure 41. Effects of two irrigation regimes on subsequent vase life of leatherleaf fern fronds (Mathur et al., 1983).

Research regarding the use of tensiometers for scheduling irrigation of leatherleaf fern growing in Tavares-Millhopper fine sand was initiated in 1985 (Stamps, 1989b). Irrigation setpoints of −5, −10, −15, −20 and −25 kPa [−4.9, −9.9, -14.8, -19.7 and -24.7 atmospheres] were used. Although frond sizes were similar for all irrigation treatments, yields of fronds from the −5 and −10 kPa treatments were greater than from the plots irrigated at more negative setpoints (Figure 42). There has been no research conducted on the interaction of irrigation scheduling using tensiometers and nitrogen application rates on leatherleaf fern production and nitrogen leaching.

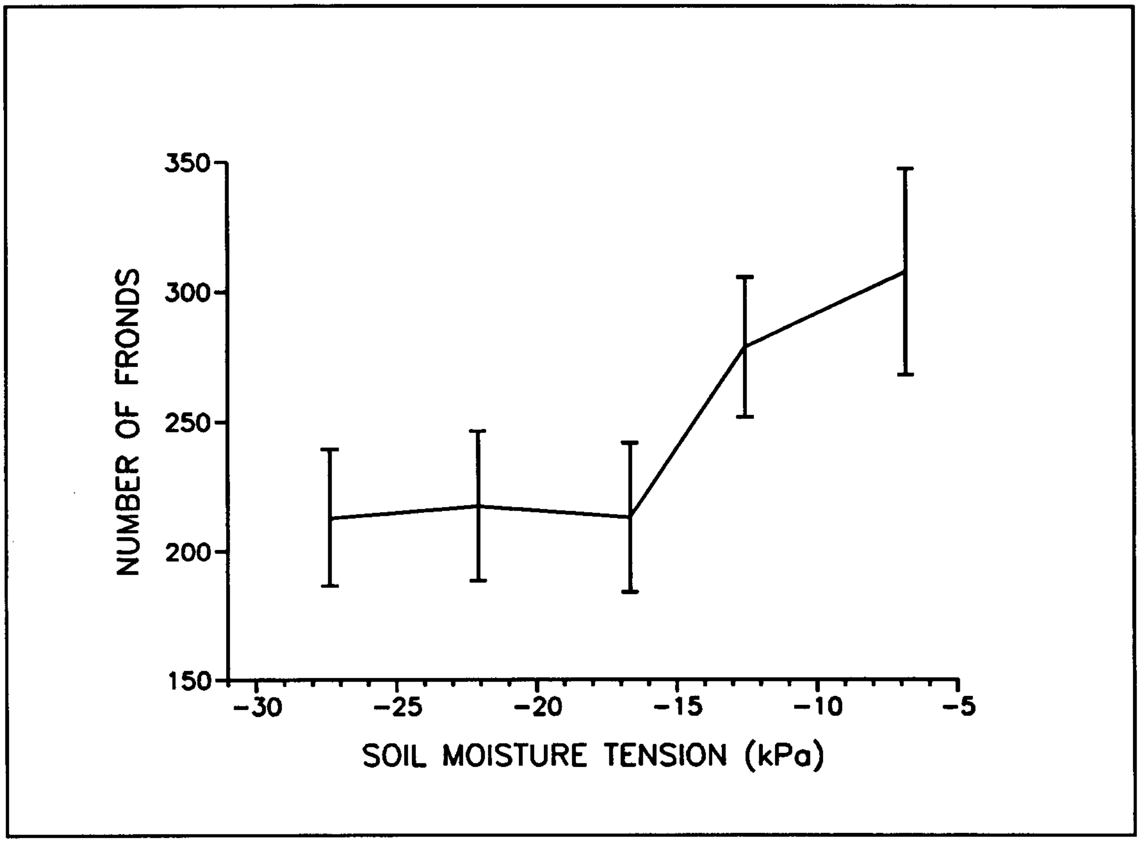

Figure 42. Effect of soil moisture tension irrigation setpoints on yield of leatherleaf fern (Stamps, 1989b). Vertical bars represent SE of the mean.

APPENDIX C: Summary of previous leatherleaf fern research dealing with fertilization.

A one-year study (Poole et al., 1971) compared liquid and dry 6N–41.8P–6.6K [6N–4P_2O_5–8K_2O] fertilizers applied at rates of 4032, 8064, 12096 and 16128 kg·ha^{-1}·yr^{-1} [3600, 7200, 10800 and 14400 lbs/acre/yr]. Those application rates are equivalent to 242, 484, 726 and 968 kg N·ha^{-1}·yr^{-1} [216, 432, 648 and 864 lbs N/acre/yr] and 268, 536, 803 and 1,071 kg K·ha^{-1}·yr^{-1} [239, 478, 717 and 956 lbs K/acre/yr]. Plants were grown in non-amended and peat-amended sandy soils (Millhopper-Tavares fine sand, formerly called Lakeland fine sand). Crop yield (frond number and fresh weight) was determined during the last six months of the study. Fertilizer source had no effect on yield, and yield was the same for all application rates except for the lowest level, where frond number and weight were reduced 17% and 27%, respectively, compared to the overall means for the other treatments (Figure 43). Unfortunately, no information was reported regarding the irrigation practices used or precipitation patterns occurring during this relatively short study.

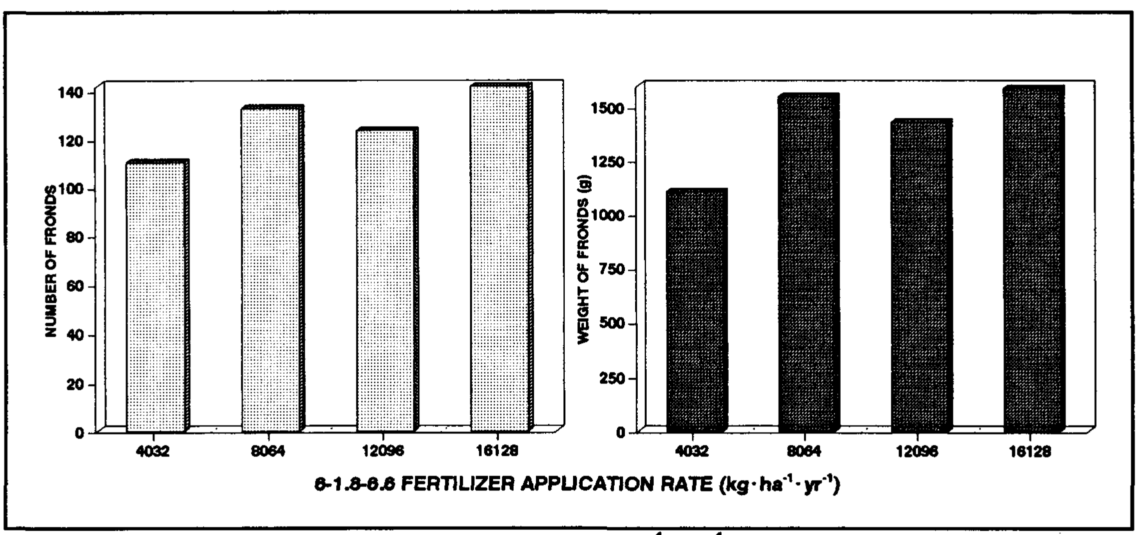

Figure 43. Fern treated at the 4,032 kg·ha^{-1}·yr^{-1} rate with a 6N–1.8P–6.6K fertilizer produced 17% fewer fronds that weighed 27% less than fern fertilized at the higher rates (Poole et al., 1971).

A follow-up study lasting one and a half year long was conducted on the then one-year-old ground beds that had been amended with 5.1 cm [2 inches] of peat (Poole and Conover, 1973). Fertilizer treatments consisted of factorial combinations of four N rates, 270, 540, 810 and 1080 kg·ha^{-1}·yr^{-1}

[241, 482, 723 and 964 lbs/acre/yr], and two K rates, 540 and 810 kg·ha^{-1}·yr^{-1}. N and K application rates had no effect on the number or weight of fronds produced (Figure 44). The lack of treatment effects may have been partially due to the incorporation of organic matter into the beds and the relatively young age of the fern beds. Amending of the soil contributed some nutrients and increased both cation exchange and water-holding capacities of the soil. Had the fern beds been older and filled with plants, interplant competition for nutrients would have been greater. As in the previous experiment, no irrigation or precipitation data were reported.

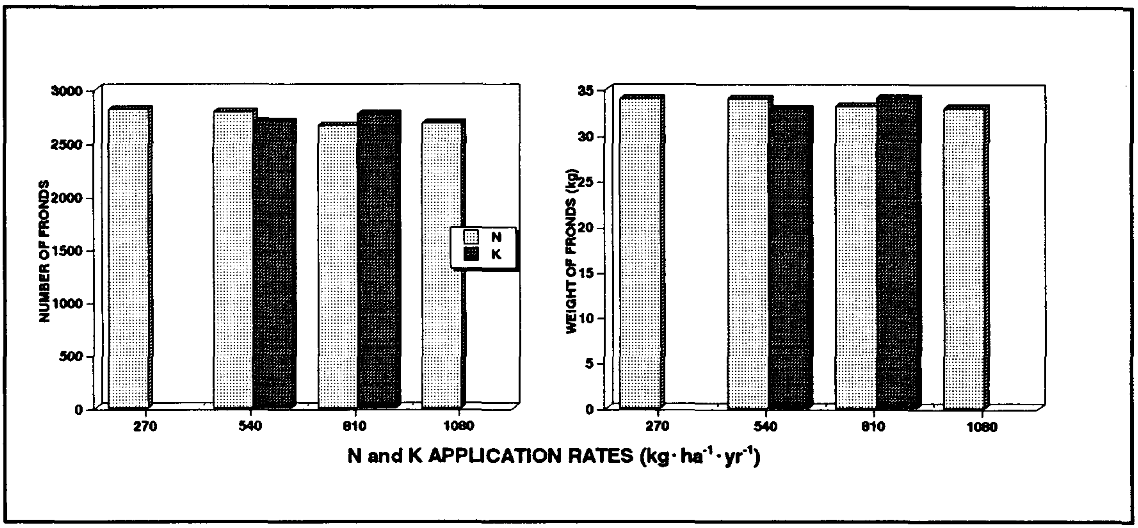

Figure 44. Nitrogen and potassium application rates had no effect on leatherleaf fern frond yield (Poole and Conover, 1973).

Research was started in 1983 that studied the interaction of three fertilizer rates and inoculation of container-grown leatherleaf fern with the vesicular-arbuscular mycorrhizal (VAM) fungus *Glomus intraradices* (Stamps and Johnson, 1984). VAM fungi-free tissue culture produced leatherleaf fern was used in this study. Half of the plants were inoculated with *G. intraradices* and half were not. The fertilizer levels were 0, 280 and 560 kg N·ha^{-1}·yr^{-1} [0, 250 and 500 lbs N/acre/yr]. Although *G. intraradices* colonized the roots of inoculated plants, they had no beneficial effect on frond yield, grade, chlorophyll content or vase life. All of these parameters, except vase life, increased with increasing fertilizer rate. Plants were graded on a scale from 1 to 4 (1 = yellow, not acceptable; 2 = light green, not acceptable; 3 = medium green, commercially acceptable; 4 = dark green, acceptable). Plants fertilized at the highest rate were closest in color to what the industry strives to produce, while those at the middle rate were over half a grade lower (Figure 45). The pattern for number of fronds produced was essentially identical to that of frond grade (Figure 45).

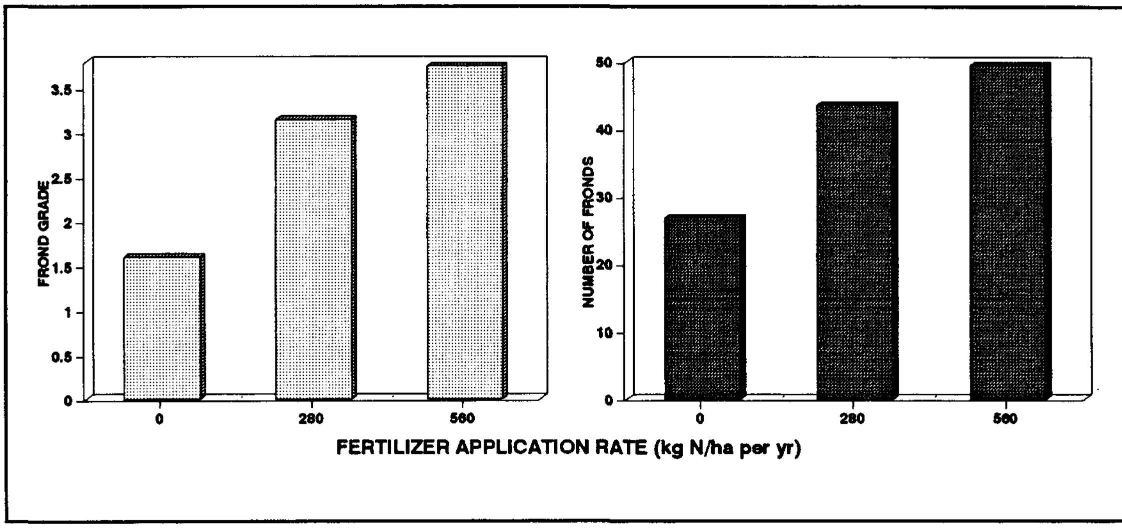

Figure 45. Frond color grade and yield (number of fronds) increased with increasing nitrogen fertilization rate (Stamps and Johnson, 1984).

Later research (Stamps, 1989a) using a biostimulant and relatively high controlled-release fertilizer application rates (so that nutrients would not be a limiting factor if the biostimulant worked) showed that the biostimulant had no effect on frond development, yield or vase life. In addition, there were no differences in frond growth, size, weight, numbers, morphology or vase life due to the two fertilization treatments of 840 and 1680 kg $N \cdot ha^{-1} \cdot yr^{-1}$ [750 and 1500 lbs N/acre/yr].

APPENDIX D: Summary of previous research dealing with nitrate leaching in sandy soils.

LIQUID VERSUS GRANULAR (non-CRF) FERTILIZER

N leaching was reduced by 82% when turfgrass was fertigated rather than fertilized with granular N (Snyder et al., 1989).

CONTROLLED- AND SLOW-RELEASE NITROGEN SOURCES

Controlled- and slow-release nitrogen sources can be used to reduce N leaching under certain circumstances. Rathier and Frink (1989) found considerably less nitrate in runoff water from container grown plants fertilized with slow-release N sources than in runoff water from containers fertilized with soluble-N sources. When container-grown chrysanthemums were fertilized with liquid fertilizer (LF) and controlled-release fertilzer (CRF), nitrogen-leaching losses from CRF were about half that from LF (Hershey and Paul, 1982). Snyder et al. (1984) showed that by using slow-release N sources in conjunction with irrigation based on evapotranspiration, NO_3–N leaching could be minimized during dry weather.

PLANT UPTAKE OF NITROGEN CAN REDUCE LEACHING

Bizzell and Lyon (1928) reported that leaching losses were more than 10 times greater from lysimeters when no vegetation was present compared to when it was present. NO_3–N concentrations below the root zone of fertilized birdsfoot trefoil plots were less that one-fifth that of fertilized bare-soil plots (McLaughlin et al., 1985).

APPENDIX E: Linear regression of precipitation and rain water collected at each lysimeter location (y = a + b x).

TANK	r^2	a	b	TANK	r^2	a	b
1	0.984	1.210	1.033	19	0.996	-0.463	1.298
2	0.999	-0.440	1.173	20	0.969	0.716	1.198
3	0.972	-1.617	1.338	21	0.996	-0.649	1.234
4	0.988	0.210	1.150	22	0.997	-0.865	1.193
5	0.996	0.030	1.062	23	0.993	-0.217	1.130
6	0.999	-0.526	1.182	24	0.972	-0.347	1.482
7	0.993	-0.207	1.266	25	0.923	2.313	1.212
8	0.999	-0.651	1.236	26	0.998	-1.185	1.409
9	0.995	-1.578	1.547	27	0.959	-0.919	1.602
10	0.993	-0.773	1.378	28	0.875	3.216	1.296
11	0.999	-0.323	1.262	29	0.999	-1.162	1.328
12	0.994	-0.207	1.282	30	0.943	-3.002	1.634
13	0.999	-0.631	1.199	31	0.994	0.661	1.152
14	0.999	-0.236	1.051	32	0.998	-0.434	1.244
15	0.995	0.272	1.088	33	0.975	-1.452	1.221
16	0.992	-0.260	1.224	34	0.952	1.267	1.126
17	0.976	-1.138	1.138	35	0.998	-0.775	1.302
18	0.962	-0.416	1.226	36	0.977	-1.675	1.411

APPENDIX F: Evaluations using LEACHN computer model of the effects of nitrogen source on NO_3–N leaching.

The LEACHN subroutine of the Leaching Estimation And Chemistry Model (Hutson and Wagenet, 1992) was used to evaluate alternative management practices for fertilizing leatherleaf fern. The input data used — soil properties and initial conditions, environmental conditions (rainfall, temperatures, etc.), crop details, coefficients, etc. — were those collected during the shakedown phase of the lysimeter project or taken from the literature. The effects on nitrogen (N) leaching of using N sources that contain less nitrate N (NO_3–N) than was used in the lysimeter experiments were determined using the above computer model. The composition of the standard fertilizer in the lysimeter experiments was essentially 50% NO_3–N and 50% ammoniacal N (NH_4–N). Using a 25% NO_3–N:75% NH_4–N fertilizer resulted in a 21% reduction in NO_3–N leaching and a 6% reduction in NH_4–N leaching compared to using the 50% NO_3–N:50% NH_4–N fertilizer. Using 100% urea as the N source NO_3–N and NH_4–N leaching were reduced by 15% and 5%, respectively, compared to leaching when using the standard fertilizer.

APPENDIX G: Simulation model for leatherleaf fern water use.

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Simulating Irrigation Requirements of an Ornamental Fern

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Additional Index Words: evapotranspiration, crop water use, sprinkler irrigation, numerical modeling, Rumohra adiantiformis

Abstract: A numerical simulation model was developed to estimate irrigation requirements (IRREQ) of an ornamental fern [Rumohra adiantiformis (Forst.) Ching] for soil and climate conditions of central Florida. The model was based on a daily water budget of the crop root zone for 22 to 25 years of climate record. Inputs required by the model include crop, soil, and irrigation management factors which affect crop water use. The model outputs statistical characteristics of IRREQ simulated. A sensitivity analysis was conducted to determine the relative effects of changes or errors in model inputs. IRREQ was demonstrated to be very sensitive to crop water use coefficients, time of year, and irrigation efficiency. IRREQ was less sensitive to irrigated root depth, soil water-holding capacity, and changes in allowable soil water depletion.

Introduction

Leatherleaf fern is a shallow-rooted perennial crop that is grown under shade on well-drained sandy soils in central Florida (Stamps and Conover, 1986). Shade is provided by oak tree canopies or by shadehouses constructed of polypropylene fabric. Of the approximately 5,000 acres of commercial production, 64% use shadehouses and 36% are grown under oak hammocks (Stamps et al., 1991).

Recommended fern production practices were published by Henley et al. (1980). They recommended irrigating to apply 1 inch of water every 3 days during the summer and 0.5 inches every 4 to 7 days during the winter, with adjustments for rainfall. Stamps et al. (1991) surveyed the Florida ornamental fern industry and reported that average intervals between irrigations in shadehouses was 3.9 days and 6.8 days during the dry and wet seasons, respectively. They reported average water application depths of 0.60 inches and 0.46 inches, respectively.

An irrigation requirement numerical simulation model (FERN-H2O) was developed in this research. The irrigation requirement (IRREQ) is the amount of water which must be applied by irrigation, in addition to rainfall, to meet a crop's water use requirements for growth and production without reduction in yield due to water stress. In this work, the definition of irrigation requirement is limited to irrigation applied to meet the evapotranspiration (ET) needs of a crop. Water applications for freeze protection, fertigation, leaching of salts or other beneficial uses are dependent on factors other than those which determine crop ET, thus they were not considered in this research.

The FERN-H2O model was based on a water budget of the crop root zone and on the estimation of fern ET from climate factors and crop water use coefficients. The water budget method used in this work is well-documented (Fickel, 1983; Hanks and Hill, 1980; Pair, 1983) and has been demonstrated to be applicable to irrigation scheduling in Florida (Allen et al., 1978; Jones et al., 1984; Koo, 1969; SCS, 1982; Shih et al., 1983). The estimation of ET from climate factors and crop water use coefficients is likewise well-documented (Allen et al., 1978; Doorenbos and Pruitt, 1977; Fickel, 1983; Pair, 1983; SCS, 1970). This approach has been widely used for Florida crop and climate conditions. The Florida Soil Conservation Service (SCS, 1982) used it to estimate IRREQ of major agricultural crops throughout the state. Jones et al. (1984) demonstrated that ET was accurately estimated for several crops using this approach, and that the Penman (1948) equation accurately estimated ET for Florida climate conditions. Smajstrla and Zazueta (1987a,b) used the water budget approach to simulate IRREQ for Florida container nurseries and agronomic crops.

Because irrigation requirements vary as a function of climatic conditions and management practices such as use of shadehouses, and because both long-term average and extreme values are required for irrigation system design, management, and water use permitting, the objective of this research was to develop a numerical model to simulate fern ET based on these factors. This approach also permitted the relative effect of each of the factors affecting fern IRREQ to be evaluated using a sensitivity analysis. Thus, the relative effectiveness of various management practices was evaluated, and data limitations and needs for future research efforts were identified.

Materials and Methods

The water budget method of analysis requires that all water inflows to and outflows from the fern root zone be known. Equation 1 lists the components of the water budget used in this work.

$$\Delta S = R + I - D - R - ET \tag{1}$$

where ΔS = change in soil water storage (inches),
R = rainfall (inches),
I = irrigation (inches),
D = drainage (inches),
R = runoff (inches), and
ET = evapotranspiration (inches).

The FERN-H2O model was developed as a daily water budget model. The soil water storage on any day was calculated from the previous day's water storage, plus the rain and irrigation, and minus the drainage, runoff, and ET that occurred since the previous day.

ET was calculated as the multiple of Penman reference ET (ETo) and a daily crop water use coefficient for fern. Crop water use coefficients were estimated from ongoing research studies of leatherleaf fern ET in shadehouses in central Florida. ETo was calculated from daily solar radiation, temperatures, and wind speeds using the form of the Penman equation reported by Jones et al. (1984). Climate data were obtained from the National Weather Service (NWS) SOLMET data base for 22 to 25 years of record at Orlando, Daytona Beach, Jacksonville, and Tampa. Rainfall data were obtained from the NWS HISARS data base for the same locations and periods of record.

Water storage in the fern root zone was calculated as the multiple of the available water-holding capacity of the soil times the depth of the fern effective root zone. Soils data were obtained from the Soil Conservation Service (SCS) mapped soil series of Florida. Under typical Florida conditions root depths range up to 12 inches (Harrison and Conover, 1970) for leatherleaf and plumosus fern in Florida.

The combination of runoff and drainage was calculated as the depth of rain in excess of that which could be stored in the fern root zone following each rain. This assumed that runoff did not occur until after the soil water content was restored to field capacity in the root zone. This assumption was valid for the high infiltration rate sandy soils and shallow root zones typical of these fern production systems.

Irrigations were scheduled on those days when the soil water depletions in the fern root zone exceeded the allowable water depletion. To avoid water stress, Harrison and Conover (1970) and the SCS (1982) recommended that water depletions not exceed 50 to 60 percent of the available soil water in the root zone.

Inputs required by the FERN-H2O model include monthly crop water use coefficients and allowable soil water depletions, from which daily values are interpolated for each day of the year. Soil type and effective root depths must also be input. The model contains default values for each of these factors, however, these can readily be changed by the model user based on site-specific conditions.

The FERN-H2O model computes seasonal, monthly, bi-weekly, and weekly statistical characteristics of IRREQ. The mean, median, standard deviation, maximum and minimum values for the period of analysis, and fraction of years with no irrigation are computed. These outputs permit the variability and the long-term average IRREQ to be used for irrigation system design, water use permitting, or other purposes.

The accuracy of the water budget in the FERN-H2O model was verified by maintaining a mass balance throughout each simulation. This procedure verified that all water additions to and extractions from the crop root zone were accounted for at the limits of computer accuracy.

The sensitivity of simulated IRREQ to various model inputs was studied to determine the effects of changes in each input and to determine the accuracy with which each input must be known to accurately simulate fern IRREQ. The sensitivity analysis was conducted by varying each input parameter over its expected range, while other parameters were maintained constant at standard values. This analysis permitted the effects of changes or errors in measuring factors which affect IRREQ to be determined on a relative basis. The standard values used in these sensitivity analyses were: climate data base location = Orlando, crop water use coefficient = 0.4, irrigated root zone = 8 inches, soil water-holding capacity (volumetric) = 0.07, allowable soil water depletion = 0.50, and irrigation application efficiency = 0.75.

Results and Discussion

The effect of geographical location on annual fern IRREQ is shown in Fig. 1. Four locations where sufficient long-term climate data were available were studied: Jacksonville, Daytona Beach, Orlando, and Tampa. These locations were selected to bracket the fern-growing region of Florida. From Fig. 1, IRREQ increased from northern to southern locations. However, there was little difference in the Daytona Beach and Orlando values which are nearest the principle fern-growing region.

The effect of time of year is shown in Fig.2 by graphing simulated monthly IRREQ for the Daytona Beach and Orlando locations. This figure demonstrates that fern IRREQ is very sensitive to time of year. Peak values occurred in Apr. and May when climate demand is high and rainfall is low. Lowest values occurred during the winter months. Monthly distributions were in close agreement at both locations from Dec. through June. Orlando values were lower in summer and higher in fall because of differences in long-term rainfall patterns between Orlando and Daytona Beach.

Fern IRREQ were found to be very sensitive to crop water use coefficients as shown in Fig. 3. This figure demonstrates that crop coefficients must be precisely known to accurately estimate IRREQ. Crop coefficients used in this work were determined from lysimeter studies of fern ET currently being conducted at the Central Florida Research and Education Center - Apopka. Monthly values of 0.4 were used in this project. Those values reflect the reduced climate demand that results from growing fern in shadehouses.

The effects of increasing root depth (Fig. 4) and increasing soil water-holding capacity (Fig.5) are similar. Increases in either of these will increase the soil water available to the plants. In a humid area like Florida, increasing the available soil water increases the effectiveness of rain, thus reducing IRREQ. Ornamental fern is shallow-rooted, with root zone depths typically in the range of 4 to 12 inches.

Figure 4 demonstrates that IRREQ was relatively insensitive to irrigated root depths in the range of 4 to 12 inches. IRREQ decreased from about 17 inches for a 4-inch root depth to 14 inches for a 12-inch root depth. This low sensitivity demonstrates that it is not necessary to precisely determine fern root depth to accurately estimate IRREQ unless the root depth is greatly different from the 8-inch standard value used in this analysis.

Figure 5 demonstrates that IRREQ was also relatively insensitive to soil water-holding capacities over the range typical of Florida sandy soils. IRREQ decreased from about 19 inches to 13 inches as the volumetric soil water-holding capacity increased five-fold from 0.02 to 0.10. This suggests that soil water-holding capacities obtained from soil survey data would be sufficient to accurately estimate fern IRREQ.

The effect of soil water depletion allowed between irrigations is shown in Fig. 6. Allowable soil water depletions typically range from 0.3 to 0.7, with 0.5 most commonly used. Over this range, IRREQ was shown to be relatively insensitive to changes in allowable soil water depletion for all three soil water-holding capacities studied. These results demonstrate that IRREQ is relatively insensitive to irrigation scheduling practices commonly used.

Figure 7 shows the effects of irrigation system water application efficiency on IRREQ. IRREQ was less sensitive to application efficiencies when efficiency was above the standard value of 75%, but sensitivity increased with lower efficiencies. These results demonstrate the need for proper irrigation system design, installation, and maintenance to minimize irrigation requirements.

From the sensitivity analyses conducted, IRREQ was demonstrated to be very sensitive to crop water use coefficients, time of year, and irrigation system efficiency for low-efficiency systems. IRREQ was demonstrated to be less sensitive to location within the primary fern-producing region of the state. However, because rainfall is much more variable than ETo, site-specific rainfall records are required. IRREQ was also demonstrated to be less sensitive to depth of root zone, soil water-holding capacity, and allowable soil water depletion for typical ranges of values.

These results suggest that research directed toward decreasing fern irrigation requirements should first consider the highest-sensitivity factors. The lower sensitivity to other factors demonstrates that those factors do not need to be precisely known in order to accurately simulate irrigation requirements.

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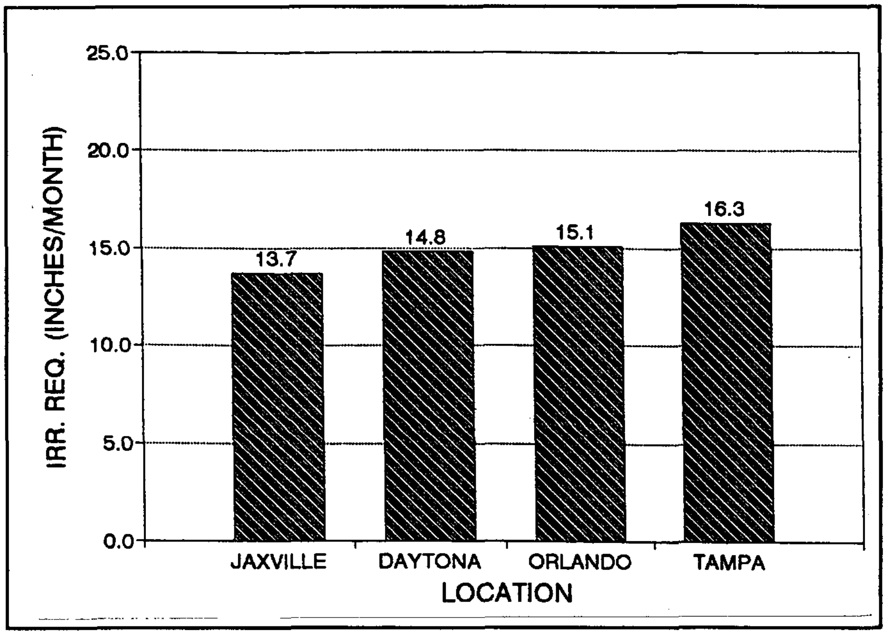

Figure 1. Long-term average annual irrigation requirements for locations from north to central Florida.

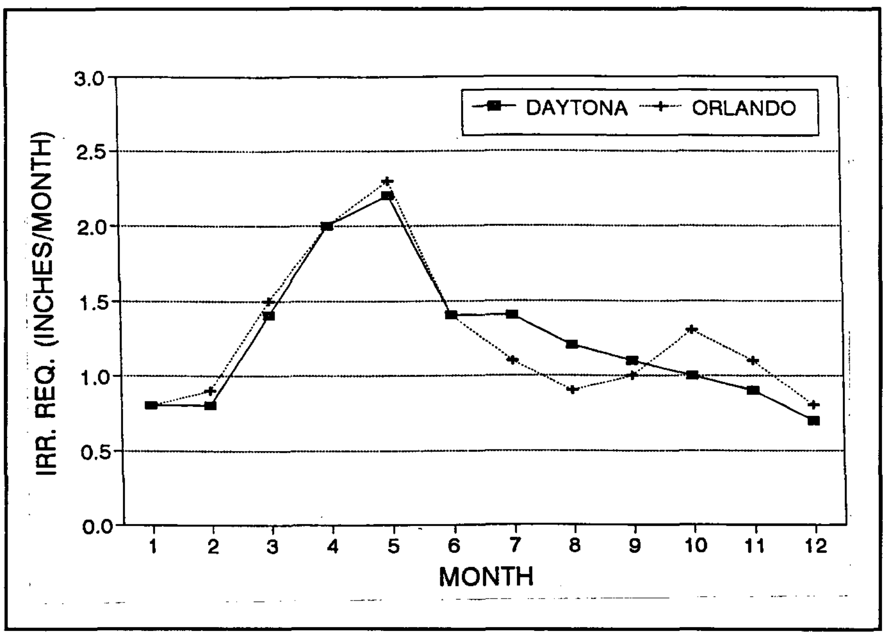

Figure 2. Effect of time of year on irrigation requirements using Daytona Beach and Orlando climate data.

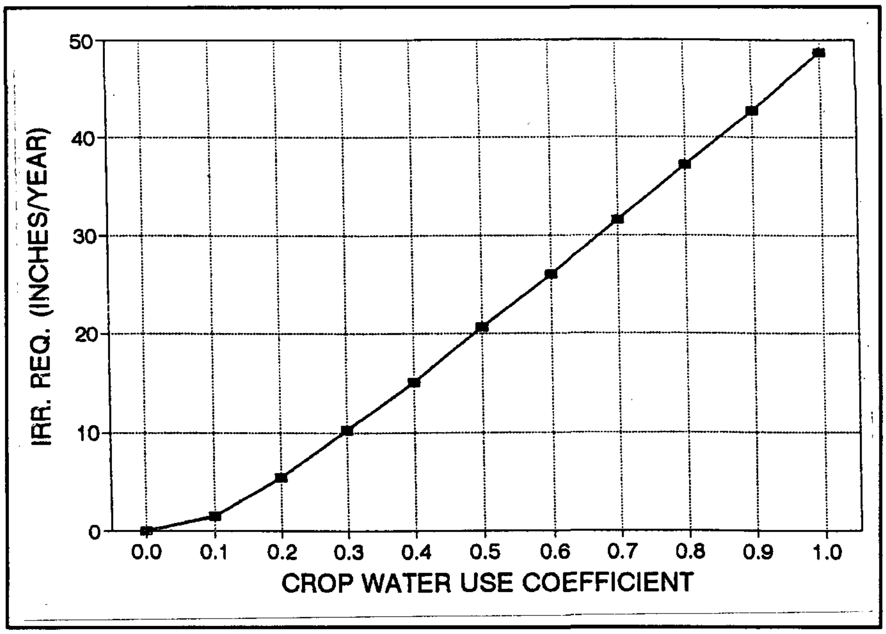

Figure 3. Sensitivity of irrigation requirements to changes in the crop water use coefficient.

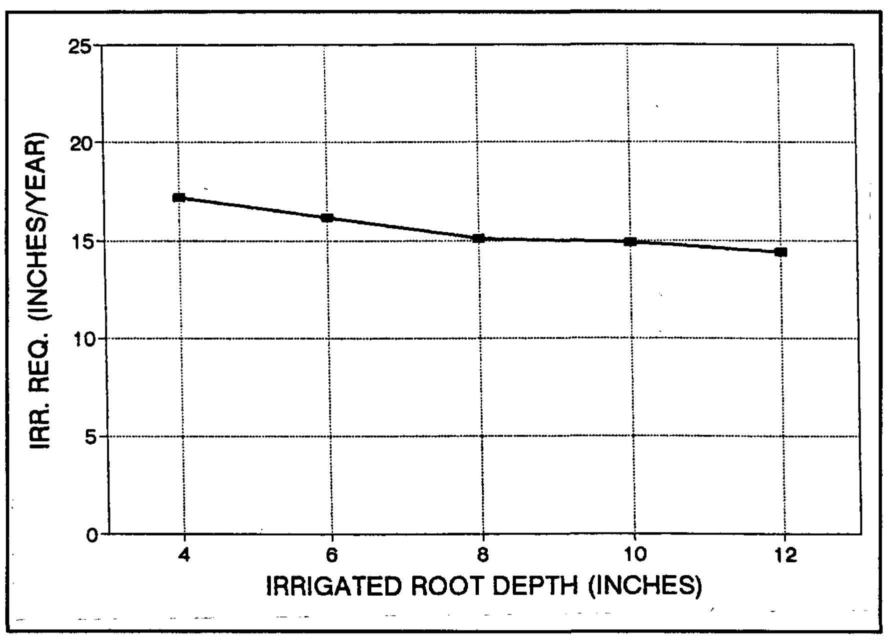

Figure 4. Effect of irrigation root depth on simulated irrigation requirements.

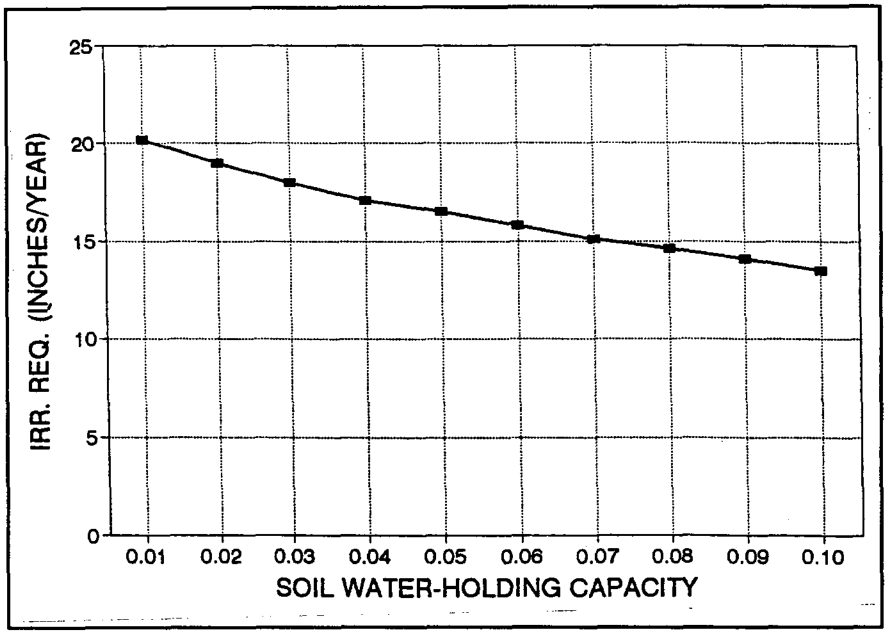

Figure 5. Effect of volumetric soil water-holding capacity on simulated irrigation requirements.

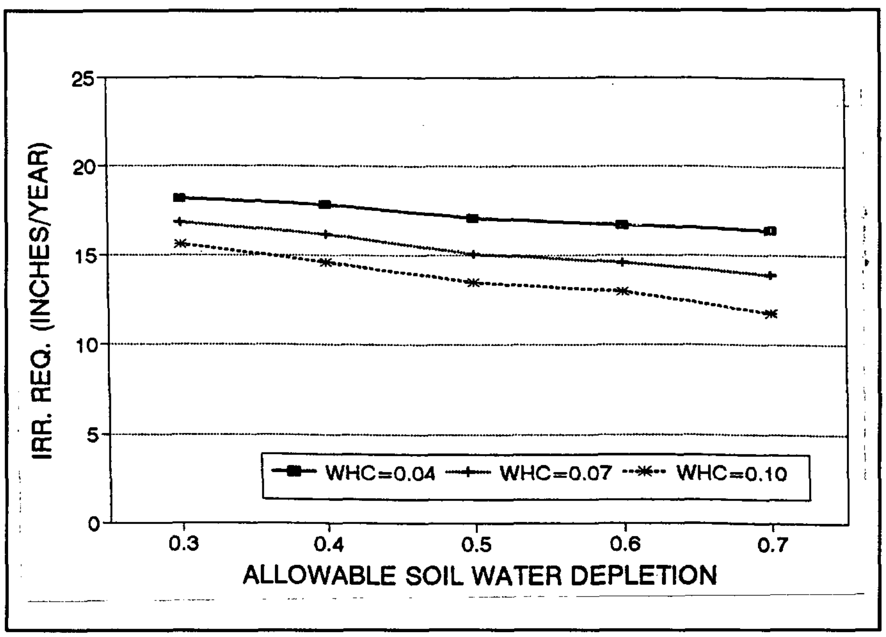

Figure 6. Effect of allowable soil water depletion on simulated irrigation requirements for three soil water-holding capacities.

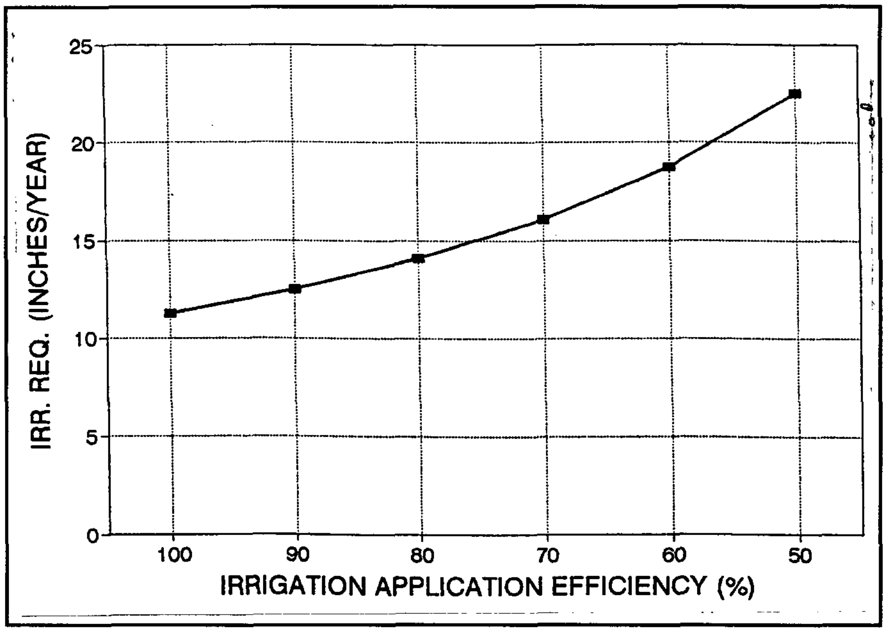

Figure 7. Effect of irrigation application efficiency on simulated irrigation requirements.

APPENDIX H: Maps of relative nitrate leaching potentials of soils in leatherleaf fern production areas of Florida.

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