Conservation of Water and Nutrients in Greenhouses Through Plant and Climate Based Irrigation Control

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Abstract

The vegetable greenhouse industry in British Columbia is rapidly expanding to meet the world's demands for high quality fresh produce. This expansion puts environmental pressure on the region in the demand for fresh water, and the spread of excess nutrient fertilizer into ground and surface water. To help alleviate the problem, efficient irrigation systems which accurately match crop requirements, need to be developed. To establish a more precise algorithm, new and conventional sensors were examined for their ability to predict and/or measure water use. The sensors that showed the most promise were further developed into two new control algorithms. The first control algorithm utilized light, vapor pressure deficit, leaf, and air temperature, in a statistically developed model to estimate water use. The second control algorithm utilized an off-the-shelf electronic balance to directly measure water use. Water use was measured by summing the change in weight over short time-periods, rather than by examining the absolute weight of the media. Experiments were then conducted to compare these two new algorithms to the current industry-standard light-based approach in terms of irrigation consistency and frequency. It was found that the scale-based approach produced the most consistent amount of leachate indicating that it was most able to supply water as the crop needed it. The equation-based approaches performance was similar to the traditional light-based approach. In terms of frequency the equation and scale-based approach did not always trigger an irrigation every hour indicating that setpoints would have to be adjusted. No algorithm allowed the plants to go for long periods without watering. The scale-based approach has the added benefit of an ability to trigger irrigations at night. All algorithms seemed to work effectively; the water usage of the plants on all three systems was statistically similar. Because the new algorithms are based on different principles, their associated advantages and disadvantages are quite different. To improve irrigation efficiency, a control strategy encompassing all of the techniques evaluated is recommended.

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1 Introduction

1.1 Background

Currently the farm gate receipts for the greenhouse vegetable industry in British Columbia are valued at approximately 172 million dollars a year; it spans 147 hectares, and is still expanding rapidly (Papadopoulos, 1999). The demand for high quality produce results in a great strain on the natural resources of the region. Most of the vegetable production in BC greenhouses is through the use of hydroponics where inorganic nutrient fertilizers are applied through the irrigation water. Of particular concern are the water issues of use and pollution. British Columbia is regarded as a province with vast water resources, but in the summer months there are shortages of high quality fresh water. Of equal or greater concern, is the spread of ground and surface water pollution from the escape of excess fertilizer and other agro-chemicals. Supplying water to a crop at the correct time, and in the correct amount, are important goals of water management.

There are many systems available to the grower to determine when to irrigate a crop. The systems help to predict the needs of the plant; they range from the very simple to the extremely complex. For a technique to be useful, it must be proven reliable, meaningful, and relatively easy to understand and use. If the needs of the plant can be accurately predicted, it is possible to supply precisely how much the plants require at the correct time.

The water needs of a plant are not entirely for transpiration and growth. Leachate, or excess irrigation water, is required for proper plant health. The leachate removes the excess salts that accumulate in the growing media, and prevents physiological problems that occur when the electrical-conductivity (EC) is too high. A high EC prevents the uptake of water and certain nutrients by the plant's roots. However, irrigation water is expensive, as it contains both water and nutrients, and an operation will have to optimize its use, by ensuring that only enough excess water is applied to leach the salts. In some cases there is great uncertainty in predicting the watering requirements of plants, and over 40% of the irrigation water is leached (Fricke, 1996).

The current practice in BC is drain-to-waste where the leached water is not collected for re-use; therefore, improving the efficiency of water use is an extremely important goal. Even in systems which recycle the water and nutrients, the water must be treated to prevent the spread of disease, and treatment methods are relatively expensive. By reducing the volume of water requiring treatment, costs can be reduced.

It has been demonstrated that plants benefit from the effects of leaching and that there is a positive correlation between increasing leachate amounts and increases in yield (Fricke, 1996). By giving a grower better control over the timing and volume of leachate, we can allow them to calculate and apply the most cost-effective amount of water.

With the increasing automation of greenhouse production, and hence, the proliferation of sensors and computers, there is an expanding opportunity for the use of more complex algorithms for determining plant water requirements. Already the judgement of the grower, and the simple timer, long the mainstay of the industry, have been replaced by sensors which trigger waterings based on light sum. However, the water needs of a plant are not a function of light alone, and new algorithms taking into account other important environmental parameters need to be synthesized.

1.2 Problem Statement

There are a number of variables to be considered when deciding on an irrigation regime for a crop. The goal is not simply to reduce the volume of water used, or to maximize the crop yield; it is to maximize profits. To achieve this goal, both the water use and crop yield have to be considered.

Current irrigation control algorithms have been designed to provide the plants with excess water and nutrients to ensure that this does not limit their growth. However, these techniques are wasteful and lead to increased costs for the grower through greater water and nutrient use and increased water treatment costs. Improved control of irrigation and a better knowledge of when to irrigate, will give growers a more powerful tool to optimize their crop production. Optimized production will translate into less wastage of energy, water, and nutrients, and will lead to increased sustainability of production.

1.3 Objectives

The overall goal of this thesis research project was to devise an irrigation control strategy for water and nutrient conservation, in order to improve the environmental and economic sustainability of the greenhouse industry.

Experiments were conducted over the course of two years.

The objectives were:

1. To study the feasibility of using new and conventional sensors in the continuous and automatic detection of plant water status
2. To evaluate the sensors tested in the first year for further development
3. To develop new irrigation control algorithms
4. To implement and examine the function of these newly developed algorithms over the course of a season
5. To compare the new algorithms with the current industry standard.

Objective one was carried out in the first year, and objectives two through five were the research activities in the second year.

2 Literature Review

2.1 Control Algorithms

At the heart of every control algorithm is the sensor upon which the decisions are based. Whether it is a highly sophisticated and expensive instrument, or simply a grower's senses, no algorithm will function properly without some form of sensor.

Numerous techniques have been developed to cope with the difficulties of supplying adequate water to a crop in a timely manner. They vary widely in terms of complexity, expense, and performance. The selection of a strategy will be decided by the application it will be used for. The size of the operation, the crop grown, and even the time of the year are important considerations when selecting an algorithm.

Irrigation control strategies can be classified in four categories; simple (basic control), soil/growing media-based control, environmental-based control, and plant-based control. Because of the difficulties in directly detecting water stress, indirect means based on the plants' surrounding environment are generally used. These indirect methods are valid because of the close interaction of the plant and its surroundings.

2.1.1 Basic Control Algorithms

Before the widespread application of computer-based climate and irrigation control and the use of automatic sensors, growers relied heavily on personal expertise to determine when to water.

2.1.1.1 Grower Inspection

The most basic irrigation control technique involves a grower manually examining plants. Previous experience helps to decide when and how much to water a crop. A grower may utilize visual inspection or simple instruments to take measurements. However, grower experience varies widely and to complicate matters different crops may show different signs of stress. Grower inspection might be adequate for a small-scale operation with few plants, but in a large greenhouse it becomes extremely difficult to adequately judge conditions. In addition the use of high-yield varieties and soil-less media can require irrigations to be very frequent (sometimes more than forty events per day). At this watering frequency the task of deciding when to water manually becomes prohibitively difficult.

2.1.1.2 Timers

Timers can directly control the irrigation valves for high frequency watering. An experienced grower can greatly improve the performance of an irrigation system by setting the system to water at specific intervals or times. By examining whether or not the water applied at each event is adequate, they can adjust their system accordingly. Though this method is an improvement over simple observation, it still requires considerable monitoring and effort by the grower.

2.1.2 Soil/Growing Media-Based Control Algorithms

Because of the uncertainty in deciding whether or not a plant needs water, instruments were developed to reduce the reliance on a grower's instincts. One of the easiest means of determining if a plant needs water is to check the water content of its growing media. Because a plant draws the bulk of its water from this source, it is safe to assume that if the media lacks sufficient water the plant is either suffering from water deprivation, or soon will be. By examining the water content of plant growing media it is possible to replenish this source when it becomes depleted.

2.1.2.1 Tensiometers

Tensiometers provide the water content of a soil by measuring how tightly the water in a media is held. There are many types of tensiometers but they all work on the same principle. Tensiometers have a permeable tip which allows water to pass in and out. As water is drawn out under dry conditions, the pressure within the tensiometer drops; a negative soil pressure (tension), or water potential is recorded. An increase in tension signifies a decrease in the water content of the media. Original tensiometers used pressure gauges or mercury manometer tubes to show the tension, but modern devices utilize electronic pressure transducers.

Tensiometers have been widely used in both the greenhouse and field crop industry for many years. They have been used to control irrigation in many applications such as greenhouse tomato (Xu et.al., 1995; Papadoupoulos et.al., 1992), field vegetable crops (Luthra et.al., 1997), and even field strawberries (Kruger et.al., 1999) and orchard trees. (Van Der Gulik, 1999) The individual units are relatively inexpensive and the measurements do not require considerable interpretation. A very important benefit of tensiometers is that they can function as a continually monitored online device, which can allow them to be integrated well into a grower's automatic computer control system. Tensiometers can also respond quickly to changes in soil moisture. It usually takes only a few minutes for a change to be detected (Prevost, 1990). Tensiometers measure the tension that the water is held at, rather than just the absolute water content. This capability is advantageous for varying soil conditions where water is held differently depending on the soil texture. It gives a reading which is an indication of how difficult it is for a plant to withdraw water from the soil.

Tensiometers also have some major drawbacks. Temperature changes, especially rapid ones, can induce up to eighty percent error in the pressure measurement (Butters and Cardon, 1998). Air pockets present in the tensiometer can change pressure quickly when heated or cooled, to give a false reading. In addition the absolute temperature itself can affect the pressure readings. The electronic transducers are sensitive to temperature and will fluctuate accordingly (Hubbell and Sisson, 1998). Some media are also unsuitable for use with tensiometers. If there is poor contact between the porous cup and the media, water may not easily flow in and out, or else air may be allowed to enter the tensiometer (Hubbell and Sisson, 1998). Tensiometers in highly porous media suffer this problem, and the artificial medias normally used, such as rockwool and sawdust, are highly porous. The characteristics of some media also change over time. Sawdust is a popular growing media in the greenhouse industry; over the course of a growing season it degrades, and its water retention characteristics change. Because of these changes tensiometer response to irrigation and drying will change requiring interpretation and calibration.

Another difficulty is the conductance of the cup or tip of the tensiometer. If this tip is not conductive enough, then artificially high or low pressures can build up (Butters and Cordon, 1998)). There is concern that the conductivity of the cup may change with time as well (Timlin and Pachepsky, 1998). In soils with a fine component the pores may become blocked, reducing the conductivity, and increasing error. The dependence on temperature, and the fact that each tensiometer and media have different (and changing) properties, requires the use of extensive calibration. The process of calibration is tedious, and may require extensive disturbance of the growing media. Tensiometers are relatively high maintenance instruments requiring considerable time and expertise to operate effectively.

In addition to these technical difficulties there is a systematic problem with using tensiometers to schedule irrigation; tensiometers only measure the water tension at a single point. To base irrigation control on the water content of a single point, or even several, is risky. There is the problem of where to locate the sensor as well. Water is not evenly distributed throughout the media and moisture tensions may change rapidly as water percolates through.

2.1.2.2 Time Domain Reflectometry

Another means for non-destructively measuring the water content of a soil is Time Domain Reflectometry (TDR). This technology is more recent than tensiometers, and can provide reliable measures of soil water, as well as soil ionic concentrations. The basis of TDR is the measurement of the dielectric constant of the soil. The dielectric constant for soil varies with its water content. A dry soil might have a dielectric constant of three, whereas a saturated soil might be twenty-five (Dalton and Van Genuchten, 1986). The dielectric constant is determined by measuring the transit time of an electromagnetic pulse travelling along two metallic rods embedded in the soil. The signal is received by an oscilloscope, and from the display the dielectric constant, and hence the water content of the soil can be estimated. TDR is widely used in the field, laboratory, and greenhouse as a reliable means of measuring the soil water content.

There are a number of advantages associated with TDR. Probably the greatest advantage of TDR is its ability to measure the water content in a wide variety of soil types and saturation levels. This flexibility enables TDR to be used in the artificial media used by commercial growers without difficulty or accuracy concerns. Successful studies in rockwool have been carried out (Hilhorst et.al., 1992; da Silva et.al. 1998). Another benefit is the sample volume of TDR. Because TDR measures the water content along the length of its probes, it samples the water content of a much larger area. The measurement is much more representative than that taken at a single point with a tensiometer. The minimum recommended length for a TDR probe is 15 cm (Hilhorst et.al., 1992); this might be a benefit or problem depending on the geometry of the media container. With good calibration TDR can also give a value of soil water content in percent, rather than just the tension it is held at as with tensiometers. The TDR measurements can also be taken very quickly, capturing rapid changes in the moisture content.

The main drawback of TDR is the cost. The probes are inexpensive but the signal generator and receiver are not. This cost hinders the use of multiple sensors which are required to adequately characterize the media water content of a large crop. Inaccurate measurements can occur if the wave guides (probes) are not parallel to each other. This problem usually occurs in the field when long probes are used or hard soil is encountered. Fortunately in the greenhouse setting hard soil is not a major concern. TDR is apparently unsuitable for automatic measurements because of its reliance on graphical interpretation (Hilhorst et.al., 1992). Basically an operator is required to examine the wave output on an oscilloscope to determine travel time, and hence, water content. Newer TDR devices are more suitable for automated measurement as they have the ability to automatically interpret the signal and provide a direct output of water content (Wraith and Baker, 1991). But with automatic interpretation there is the risk of error if the wave pattern is not ideal. If the greenhouse media is well characterized these problems can be reduced. For accuracy, extensive calibration is required over the range of soil moistures that are to be encountered (Dalton and Van Genuchten, 1986). In some greenhouse applications the characteristics of the media change over the course of the season due to degradation and/or extensive root penetration. This introduces additional error into the measurements.

TDR is also subject to the same problem as tensiometers; it is difficult to know how many sensors are required and where to locate them. Although the TDR samples a much larger volume than the single point of a tensiometer, there will always be uncertainty because of the wide variation of moisture content within the media. TDR has apparently not yet been used for automatic irrigation control in a vegetable greenhouse setting. There would most likely be difficulty in automating the measurements, and high cost involved with the multiple sensors that would be required to adequately characterize the water status of the crop.

2.1.2.3 Soil Moisture Blocks

Another means of measuring soil water content is through the use of electrical resistance blocks. There are many varieties of this type of sensor but they all work on the same principal. Essentially these sensors consist of a porous material that allows soil moisture to seep in. As the soil water seeps into the sensor it affects the electrical resistance of the material between two probes. As the soil dries out and water leaves the sensor the resistance of the block increases; by comparing this resistance to previous calibration results, a water content can be estimated. Some of the more common types of these sensors are gypsum and fiberglass blocks, as well as granular matrix sensors. Though based on the same principle, these three different types of sensors have significant performance differences. The selection of a sensor will depend on the expected conditions under which the measurements are to be made. Of primary consideration are the temperature, salinity, acidity, coarseness of media, and expected water concentration range. Resistance blocks are suitable for online automatic measurements which make them very simple to operate and maintain. In addition the sensors are relatively inexpensive and accurate when used correctly. They have been used successfully in irrigation control applications but mainly for field crops (Van Der Gulik, 1999; McCann and Kincaid, 1991). Resistance blocks can also work over a greater range of moisture content than tensiometers. Fiberglass blocks can generally work over all tensions from 0 to 10 bars, gypsum between 0.3 and 3 bars, (Prevost, 1990) and Granular matrix sensors from 0.1 to 1 bar (Eldredge et.al., 1993). However, the extremely low tensions in which the resistance blocks are capable of working, should never occur in the greenhouse environment. Though capable of working in high saturations, the best performance of gypsum and fiberglass is in lower ranges whereas the new granular matrix sensors are supposed to work quite well under saturated conditions (0 to –1 bar) (McCann and Kincaid, 1991).

The main reason that resistance blocks are not used in greenhouse applications is their sensitivity. It can take hours for changes in the soil water content to register on the blocks (Prevost, 1990). This kind of sensitivity is not nearly good enough for the high frequency irrigation used in most greenhouse production. It is also recommended that resistance blocks not be used in porous, coarse, sandy or gravelly soils, or in peat (Van Der Gulik, 1999). There has to be good contact between the block and the surrounding soil.

A drawback of gypsum blocks is the fact that they dissolve over time. This problem has been overcome through the use of fiberglass, as well as the granular matrix sensors. But the fiberglass resistance blocks are more susceptible to error due to soil salinity. They also require extensive calibration for the particular media they are to be used in. With their possible degradation over time, and the changing media, the possibility of error increases as the season progresses. The blocks also respond differently during wetting and drying due to hysteresis. This is a critical flaw in artificial media with high frequency irrigation because of the many wetting and drying periods during the day. This problem is not so pronounced in field cropping with its far fewer watering events.

Like the tensiometer and TDR, this technique for determining soil moisture content only measures the value at a single point. Fortunately soil moisture blocks are quite inexpensive and require low maintenance; using several is not as prohibitive as for other sensors.

2.1.2.4 Lysimeter/Scale

Though not a direct measure of the water content of the growing media, lysimeters can be used to monitor the flow of water in and out of the media. Traditional lysimeters work by placing the growing media in large impermeable containers which allow the leachate or excess irrigation water to be collected. If the volume of added irrigation water is known, then the water use of the crop can be determined through subtraction. Modern weighing lysimeters use load cells or scales to simply measure the entire weight of the growing media (and sometimes the plant as well) and then monitor changes in this weight over time. A decrease in weight can mean that the plant has removed water from the system, whereas an increase can be a watering event. By measuring the change in weight of the media and the amount of water in the soil, the water use of the plant can be determined.

Though rarely used for control purposes, lysimeters have been widely used in the scientific community in the testing and calibration of other sensors and models (Baille et.al., 1992). Lysimeters are considered the most accurate and/or simplest means of determining the water usage of a crop. Lysimeters can be constructed on both a large and small scale, ranging from one or two plants on a single scale (van Meurs and Stanghellini, 1992), up to entire trees (Grimmond et.al., 1992), or rows of crops supported by multiple load cells. In the few cases where lysimeters or scales have been used to control irrigation, the absolute weight of the media has been the parameter measured. One technique is to use scales to measure the weight of individual pots automatically (Boukchina et.al., 1993; Zoon et.al., 1990). The current weight of the plant and pot is subtracted from the previous wet weight; the difference is assumed to be the water used, with corrections for plant growth under certain circumstances. In these cases the frequency of measurements has been relatively low, usually a half-hour or up to an entire day. In the study of crop transpiration, lysimeters based on off-the-shelf commercial balances have been developed which measure the water use every minute and can give a very accurate picture of when and how much water a plant uses (van Meurs and Stanghellini, 1992).

Because load cells and scales are readily available commercially they are quite moderately priced, depending on the capacity and the accuracy required. No expensive instruments are required to interpret the signals from the scales; values are easily output to dataloggers for storage or control purposes. Because of the electronic nature of the scales they are ideally suited for automatic measurement. Measurements are instantaneous and very quickly show changes in the weight of the system. In addition weighing lysimeters can be relatively low maintenance. There is no calibration required for separate soils, and the accuracy can be easily verified with the simple addition of known weights. A maintenance task which has to be performed is to allow the drainage of the excess irrigation or leachate from the container. Even this task can be automated as in a system in use at the Pacific Agri-Food Research Centre, in Agassiz BC, where the leachate is pumped out by a wet/dry vacuum at set time intervals.

There are a few drawbacks associated with the use of lysimeters. Lysimeters do not necessarily give the absolute water content of the media. Though they can show the movement of water in and out of the system, they cannot indicate exactly how much water is present in the media, and/or where that water is located spatially. In addition the growth of the plant can affect the estimation of water content. Growth in the plant would incorrectly show up as an increase in weight that would be thought to be due to irrigation. The plant would then receive less water in subsequent irrigations than it needs.

Another problem with lysimeters, weighing or otherwise, is that they are awkward to work with because they are quite bulky. Since they are supporting the entire growing media of the plant and need to be free standing, they can interfere with the production of the crop. Because of their size in typical greenhouse conditions they may be susceptible to jarring, wind, traffic, and handling which may cause incorrect readings. Although several plants and their media can be monitored by a single balance, variation within a greenhouse can be very wide; several stations around the greenhouse would be required to accurately estimate the water use.

In non-weighing lysimeters, the techniques used to measure water flow in and out are more subject to breakdowns and other problems which might increase maintenance requirements (de Graaf, 1988). However the data that they provide can be useful for more than irrigation control. Crop transpiration is a very important variable in greenhouse production and generally growers seek to optimize it through climate control. With a direct measure of transpiration the process of selecting and then measuring the effects of an optimal temperature and humidity regime can be simplified.

2.1.2.5 Other Technology

There are many other types of sensors such as thermal conductivity probes, neutron probes, and frequency domain, used for the determination of soil moisture content which could possibly be used for irrigation control. Thermal conductivity probes are similar in theory to soil moisture blocks but instead of using electricity they use heat to determine the water content of the media. Frequency domain is similar to the TDR in that electromagnetic pulses are used to measure water content. Thermal conductivity has essentially the same advantages and disadvantages as soil moisture blocks, similarly for Frequency Domain and TDR.

Neutron probes are quite different in that they use a radioactive source and a Geiger counter-like instrument to measure water content. Water molecules block the radioactive particles emitted by the source; the more molecules present, the more blockage occurs. Because of the radioactivity associated with this system it is highly unlikely that this would be considered as a long-term irrigation control sensor.

2.1.3 Environment-Based Control Algorithms

Predictive based control algorithms seek to estimate the water use of the plant-based on measurements of its surrounding environment. This technique works because of the close relation between a plant and its environment, especially in greenhouses. Plants in a greenhouse are not just subject to their environment but can actually dramatically modify surrounding conditions, both on a small and large scale. By closely monitoring this ever-changing environment, it is possible to determine relationships between the plant and its surroundings. Once these relationships have been determined in the form of models, it is possible to predict the water status of a plant.

2.1.3.1 Predictive Models using PET Calculations

Rather than attempt to directly measure the water use of a crop, many models have been developed that predict it. The earliest models were developed for predicting the irrigation requirements of field crops, but their use quickly spread to greenhouse applications as well. Probably the most famous model is the Penman-Moneith equation which was developed in the 1940's, and whose basic form is still used today (Penman, 1948). The Penman-Monteith form calculates evapotranspiration based on physical principals. By dividing the driving force for transpiration (light) by the resistances to transpiration (humidity, temperature and other thermodynamic properties) evapotranspiration can be estimated (Norrie et.al., 1994). Most other models are also based on physical principals but some are just based on empirical observations. Either way, predictive models have been used successfully for many years to predict and control irrigation, both in the field and the greenhouse.

Because of the many varieties of crop produced, it is necessary to scale the estimated evapotranspiration determined by these models with a specific crop coefficient (Tan and Layne, 1981). A crop coefficient is simply a factor that is applied because various crops transpire at different rates. The Penman-Moneteith equation was originally developed to predict the transpiration of grassy crops. Because other crops such as fruit, vegetables, and trees obviously transpire at different rates, extensive work in determining crop coefficients has been done. For best results with the Penman-Monteith equation the crop coefficient should be derived from previous data.

There are many advantages associated with using predictive models to estimate evapotranspiration. They are usually very easy to implement in the greenhouse, since the variables used are normally part of standard environmental monitoring. In addition calibration of these models can normally be accomplished through the use of previously collected grower data. It is also easier to acquire climatic data than soil and plant-based measurements. The instruments are usually quite simple and inexpensive, requiring little maintenance and do not directly interfere with the crop.

There are some disadvantages in relying on models to control irrigation. Probably the biggest disadvantage is the fact that models may not be able to take into account such effects as disease, plant age, and seasonal effects. These problems can be dramatically reduced because of the uniformity and control of the environment within a greenhouse. If models do attempt to account for these variables, they may become extremely complex and/or require additional manual measurements or adjustments.

Another problem with predictive models is that they usually have difficulty predicting water use at night because the primary driving force of most models is light. Considerable water uptake occurs at night and may not be accounted for by the model. In an attempt to alleviate this problem some models replace their calculated transpiration with a simple constant when light levels drop below a set value (Norrie et.al., 1994). But this reduces the control algorithm to little more than an expensive timer system. Another potential drawback is the reliance on several sensors all working correctly.

Predictive models are also just that, predictive. They are a best guess as to the water status of a crop; no matter how good they are they are still just an estimate and not an actual measurement of what is going on with the plant. In addition they may not be able to respond quickly enough to rapidly changing conditions or situations that are outside the norm.

2.1.3.2 Neural Network Predictive Tools

Neural network predictive tools are similar to predictive models in that they utilize commonly and easily measured climatological data and estimate the resulting transpiration of the crop. But rather than use set equations and rules, neural networks 'learn' how to control. This learning process is conducted by exposing the algorithm to previously collected data, and known data of the variable that is to be controlled, similar to the development of statistical models. Neural networks work by being able to figure out patterns, generalize and use approximate values.

Neural networks have been used for control purposes within the agricultural industry but mostly in the sorting of produce, and optimization of profit (Davidson and Lee, 1991). They are well suited to use as an irrigation or climate control algorithm. They have the benefit of utilizing sensors which are already in place as well as the ability to handle unexpected events. Of course the better trained the network is, the more events and time it has been exposed to, the better it will be able to function.

There are drawbacks associated with Neural Networks. As with the other environmentally-based algorithms there is little or no direct feedback from the crop itself which means that the algorithm might not be operating correctly. Neural networks are just as dependant on their sensor input as the other systems, however they may have the ability to notice errors in the sensor data and act accordingly. There is also little experience with them compared to other techniques. Growers are not willing to hand over control to a system that has not been well proven, or that they do not understand. As neural networks gain acceptance it is likely that they will spread to nearly all aspects of the greenhouse.

As in the case of predictive models, neural networks are only as good as the data they were created from. If inadequate data is used, the network might not behave well with unknown conditions or act strangely or unpredictably. Neural networks require considerably more complex computer resources than traditional sensors. This is becoming less of a problem as cheaper and more powerful computers are being integrated into greenhouse operations.

2.1.3.3 Pan Evaporation

One of the oldest methods of estimating the transpiration of a crop is to measure the evaporation from a pan. The theory behind this technique is that the forces which cause and affect the evaporation from a pan also affect the evapotranspiration from a crop. By multiplying the pan evaporation by a crop coefficient an estimate of the crop's transpiration can be obtained. Pan evaporation has become very systematic with guidelines and standards for pan characteristics and location. The more modern equivalents of pan evaporation are atmometers and evaporimeters which basically act upon the same principles. They are slightly more complex systems that seek to more closely mimic evapotranspiration by utilizing a green surface to attempt to simulate leaves as well as automating measurement. Pan evaporation principles are easy to understand and the sensor itself is uncomplicated and inexpensive. Atmometers are a little more complex and are quite a bit more expensive but they require less maintenance and are more suitable for online datalogging.

By far the most common use of pan evaporation is in field crops where irrigation has successfully been controlled (Locascio and Smajstrala, 1996). Tomatoes have been grown in greenhouses using pan evaporation as an irrigation control algorithm (Chirandà and Zerbi, 1981). Simple evaporation-based irrigation control is currently rarely used in the greenhouse due to the uncertainties and weaknesses associated with the sensors, in comparison to newer ones. Modern atmometers work by measuring the evaporation from a small calibrated reservoir which is usually on the order of 0.1 ml. When the volume in this reservoir falls below a certain level a switch is activated which refills it from the main reservoir. The refilling of the reservoir sends out an electronic pulse which is measured by the datalogger. This process counts as a "tip" and by summing the number of tips it is possible to measure the transpiration.

Probably the biggest drawback to these sensors is the fact that they do not directly take into account the resistance to transpiration that the leaves present. The leaves themselves limit transpiration for a variety of reasons, the most important being to conserve water. If a plant is water stressed, its stomata will close preventing the loss of even more water. Resistances may also be affected by plant age, disease, and even the CO_2 levels in the greenhouse. These factors are all very important in modern greenhouse agriculture where fruit quality depends on inducing slight water stress, and CO_2 levels are enhanced.

There is also a relatively high maintenance requirement associated with refilling the pans with water of the correct salinity. Another major reason why evaporation is not used in intensive greenhouse agriculture is that there is not a fine enough timescale for high frequency irrigations. It is hard to measure the amounts of evaporation from a small surface necessary to trigger forty waterings per day. Usually pans are graded every millimeter, however, it is difficult to record when that millimeter of water has evaporated.

As with most of the other sensors there is the concern about where the sensors should be located. Because of the different light levels throughout the canopy it is difficult to determine at exactly what elevation to locate the pan.

2.1.3.4 Light Integral

A simple form of the predictive model is the light integral method for determining irrigation frequency. Instead of estimating the transpiration based on a complex formula involving many different variables, the light integral method merely sums up the incident radiation and triggers an irrigation when some pre-determined value is reached (Portree, 1996). It assumes that given a set amount of radiation the crop will use a set amount of water. This really is not too different from the more complex predictive models because even though it uses just light, light is by far the dominant factor in most models. Because light is so dominant in these models they have difficulties at night. In periods of low light where the plants might not receive enough water, a timer is usually used to ensure that at least minimal watering occurs. This approach is a different strategy from the predictive models in that it does not attempt to quantify transpiration as much as just recognize that given a certain interception of light energy, the crop will use a certain amount of water.

The light integral method is relatively new in terms of the other sensors such as tensiometers, moisture blocks and lysimeters. As recently as 1981, the method was dismissed because there was, "no constant relation between radiation and evapotranspiration" as well as the fact that it was "difficult then to obtain reliable radiation data" (Chirandà and Zerbi, 1981). Light sensors such as pyranometers are currently readily available and quite accurate, and the relation between light and evapotranspiration, though not constant, is apparently good enough for control purposes.

There are benefits to using such a simple system. There is only one sensor type to worry about and they generally require very little maintenance. In addition the sensors are electronic in nature and are normally already present in most greenhouses. The sensor sampling time can be as fast as required and the sensors are sensitive enough to cope with the demand for high frequency waterings.

There are drawbacks to using such a simple system, because many important factors are not taken into consideration. There is no accounting for other environmental parameters which have been shown to have an effect on transpiration such as humidity and temperature. The state of the crop in terms of its health and age are also important. The time of day is generally not taken into consideration; the time is important because there is a lag between when the plants receive sunlight and when they consume water. All of these problems can be managed through experience with the system and grower knowledge. By adjusting the setpoints throughout the day and using timers to ensure minimal watering, the light integral method can work. Though much simpler and perhaps not as accurate as more complex models, light integral irrigation has found extensive use in the greenhouse industry.

2.1.4 Plant-Based Control Algorithms

Plant-based control algorithms have the advantage of monitoring the plant itself which is the true focus of a grower's attentions. The environmental conditions might be perfect but the plant may still be stressed due to disease or other factors. Plant-based monitoring is more direct than the other techniques, but it is usually more difficult to implement.

2.1.4.1 Sap-Flow Meters

Sap-flow meters are a direct way of measuring the flow of water through a plant. There are several different techniques for doing this but the two most common use heat to track the flow of the sap. In the first technique the stem is subjected to a constant heat source and the temperature of the sap before and after the heater is measured. By examining the temperatures and performing a heat balance on the stem, the mass flow rate of sap can be deduced. The second technique uses a heat source that turns on and off, and a temperature sensor above the heater. The time it takes a heat pulse generated by the heater to reach the sensor is recorded, and based on the sap-conducting cross-sectional area of the stem, a mass flow rate can be determined. Of these two techniques only the first is applicable to greenhouse production as the heat pulse technique is restricted to plants with woody stems. (Smith and Allen, 1996)

Commercial sap-flow meters have been around since 1990, and have become commonplace in studies of vegetation water use. Though commonly used in scientific endeavors they have not seen widespread use in irrigation control. Through the use of sap-flow meters it is possible to actually see when and how much water flows through the plant instead of merely the secondary effects of water flow, that climate and soil-based approaches use. The heterogeneity of irrigation application and distribution is not a concern when using sap-flow. Sap-flow measurements can be easily automated as all of the sensors involved are electronic. It requires interpretation of the signals from several sensors to obtain a value, though this task can be easily carried out by a datalogger or microcomputer.

Of course there are shortcomings associated with sap-flow measurements. Probably the biggest concern that prevents sap-flow meters from widespread greenhouse use is the fact that they are very plant intrusive. The sensor itself is attached to the stem and may restrict growth and/or diurnal stem diameter changes. In addition it may cause wounds in the plant and create an entry point for infection. There is also the question of whether leaving the meter in place will affect the health of the plant and in turn affect the rate of sap-flow, or make the plant no longer representative of surrounding sensor-free plants. Another problem is the number of sensors involved because it requires several temperature sensors (usually thermocouples or thermistors) and the heater to all be working at the same time. If one element ceases to work it is impossible to extract values.

Several articles point out some of the complications with sap-flow sensors and some of the precautions that need to be taken to ensure valid readings. Most of the errors arise from the fact that many assumptions and simplifications are made to make the heat-balance equations workable. If any of these assumptions or simplifications are violated, then errors can occur. From the theory it has been demonstrated that when the sap-flow rate is large and when the temperature difference between the upstream and downstream temperature sensors is small (low flow-rates), the mass flow rate becomes more uncertain (Grime and Sinclair, 1999). It has been suggested that variable power heaters be used to increase the temperature difference at both high and low flows. Each aspect of the heat balance equation uses assumptions, and hence potentially has error associated with it. Successful use of sap-flow sensors requires a good understanding of the theory behind them so that potential sources of error can be spotted and appropriate filters applied or adjustments made. Fortunately there have been numerous publications that explain potential pitfalls (Grime and Sinclair, 1999; Cohen et.al., 1993; Smith and Allen, 1996; Clearwater et.al., 1999).

Once the sensors have been installed, the correct assumptions made and the limitations of the sensors accepted, sap-flow meters have been used to successfully control irrigation. Though they have apparently not been used in a greenhouse setting, they have been used to schedule vineyard irrigation using the heat pulse method (Eastham and Gray, 1998). Of course there is the problem of adequate representation of the crop. A sap-flow meter measures the flow within a single stem whereas a greenhouse crop might have many thousands of such stems.

2.1.4.2 Thermal Imaging

A newly emerging technique for the detection of water stress in plants is thermal imaging. Through the use of infrared thermometers (IRT's) or cameras, the plant canopy temperature is measured and examined. Based on the difference of temperature between the measured leaf and the air surrounding it, it is possible to determine if the plant is undergoing stress.

The theory behind this method is that when plants undergo water stress they close their stomata to reduce further water losses. The leaf temperature of a healthy transpiring plant is usually below that of the surrounding air because the leaf undergoes a cooling effect when its transpiration water evaporates from the surface of the leaf. If the stomata are shut and water is no longer being allowed to evaporate from the leaf surface, then the leaf will heat up and become warmer relative to the ambient air. By detecting the increase in leaf temperature relative to air temperature, the stress of a plant can be detected.

Infrared thermometers have also been used in the calculation of "Crop Water Stress Index" or CWSI, which requires a canopy temperature measurement (Baille, 1992). Infrared thermometers are ideally suited to this measurement because they can take an average value of leaf temperature rather than just the temperature at a single point as with contact sensors. Though the calculation of CWSI is more complex than simply examining the leaf-air temperature differential, it is based on the same theory that if the crop is stressed its leaf temperature will be affected.

Remote sensing of leaf temperature through the use of infrared technology can provide many benefits. First of all the sensor can measure the leaf surface without contact. This is important because there is the possibility that the sensor itself might be influencing the material of which it is measuring the temperature. The infrared thermometer also measures the average temperature of a surface (covering a number of leaves), rather than just a single point. This provides a much more representative value for consideration. Infrared thermometers are also easy to use and because of their electronic nature they are suitable for automatic measurement.

Of primary concern when using infrared thermometers is the field of view and the angle with which the IRT is aimed at the surface to be measured (Hatfield, 1990). If the field of view is too wide then irrelevant surfaces such as the floor or sky might be incorrectly included. The angle is important because it affects the ability of the IRT to correctly read the temperature. A preferable angle is ninety degrees where the IRT is positioned directly above or below the surface to be measured. Care must also be taken to ensure that the IRT does not shade the surface being measured.

Another complicating factor is the effect which some environmental parameters such as relative humidity have on leaf temperature. A high relative humidity will mimic the effects of water stress because it becomes more difficult for the plant to transpire. Even though the plants are not water stressed, they will appear so because of the reduced evaporative cooling. Hence leaf temperature is not always a good indicator of water stress.

It is unlikely that infrared thermometers by themselves will be used for irrigation control. In an experiment to test their ability to manage a high frequency drip irrigation system it was found that "the resolution of the IRT was insufficient to detect small differences between well irrigated treatments," and that, "it was unable to assess transpiration on a short time-scale," (Ben-Asher et.al, 1992). The inability of an IRT to detect stress on a small timescale was also confirmed in another experiment where water stress was detected after three days (Kacira et.al., 1999). Watering when stress is finally detected is probably too late for optimal growth. Although it might be important to induce water stress at certain times of the day or stage of crop, IRTs are incapable of detecting water stress at this fine a level. Errors may result because of stomatal closure during periods of peak solar radiation (De Rijck et.al., 1998), disease, or CO_2 concentration.

Even if infrared thermometry is not used to directly control irrigation it certainly provides a useful tool in an automated greenhouse. It might be useful to identify plants within a crop that are suffering water stress due to clogged emitters or other problems. It has been demonstrated that the stress of a plant can be identified by infrared thermometers before visual signs are present. By identifying a single plant whose foliage is warmer than the plants surrounding it, it is possible to diagnose a plant with faulty drippers or disease.

2.1.4.3 Linear Variable Displacement Transducers

A plant does not use water solely for the purpose of transporting nutrients or as a source of hydrogen for photosynthesis. Water also plays an essential role in providing support and structure to a plant's tissue. As the amount of water within a plant changes so does the shape of the plant. The water content of a plant is in a constant state of flux with water taken up by the roots, stored in fruit and tissue, and used for photosynthesis and transpiration. During peak transpiration in the mid-afternoon, the water content of the plant is known to drop as water is drawn from storage to keep up with demand. Significant water is taken up at night to replenish those losses. Linear Variable Displacement Transducers (LVDTS) are instruments which are capable of measuring minute changes in the thickness of a sample. They are capable of measuring the changes that take place when the plant loses and gains water. In this way they can be used to detect a plant's water status. Generally LVDTs are placed on the fruit of the crop to measure growth, but they can also be placed on the stem to measure its contraction and expansion to estimate water use.

LVDTs have apparently not been used for irrigation control purposes, and have mainly been used for scientific experiments only. This is most likely due to the many complications associated with them. As with the sap-flow meters, LVDTs may interfere with natural expansion and contraction processes, expose plants to disease through wounding, and generally reduce the representativeness of the plants in question. LVDTs are also quite sensitive to disturbances and cannot be moved around. This is a problem for regular maintenance and harvesting of the crop when it is likely that fruit would need to be picked or vines lowered. Representativeness is again a question here: A single LVDT measures only the change in shape of a single organ on a single plant within a large crop. Numerous LVDTs would have to be employed to get adequate representation. By themselves LVDTs would not be a reliable means of controlling irrigation due to the many changes that take place during the day. However it has been suggested that using LVDTs in conjunction with other sensors such as light and temperature may then provide a better estimate (Baille, 1992).

2.1.4.4 Machine Vision

Machine vision usually consists of a digital camera which is capable of automatically capturing images which are then sent to a computer for analysis. Complex software then analyzes the images for change, in terms of colour and/or shape (Kacira et.al., 1999). As the plants become stressed they start to wilt with their shape and colour change accordingly. Machine vision systems which are used to detect colour changes are usually applied to fruit ripeness determination and not irrigation control. It is conceivable that size changes in the fruit or stem could be detected by these systems and the water status determined in a way similar to that used for the LVDTs. Machine vision has the potential to provide benefits to growers. It is a non-contact sensor which can detect effects associated with water potential changes in entire leaves.

But there are many drawbacks associated with this technology. Machine vision is still in its relative infancy, so systems and software are expensive. A considerable amount of computer power is required to interpret the images that the system captures. The cameras themselves are usually very expensive and may not be robust enough for day to day use in a commercial environment. The camera image may also be affected by the light levels in the greenhouse. Such a system may not be able to work at night without supplemental lighting. Like the IRT, machine vision is incapable of detecting stress before it is too pronounced in the crop. Another major drawback is the extreme susceptibility of such systems to disturbance from such things as air movement and workers going about routine maintenance. For such a system to work it is critical that the target leaf or organ remain in exactly the same position. Another flaw is that these systems typically monitor very few leaves in the entire canopy of the crop. Many expensive cameras would have to be employed to adequately represent the canopy as it not possible to use one camera and move it around to several locations. In addition it is likely that such a system would have to be extensively calibrated for different crops and possibly even varieties. For these reasons it is unlikely that machine vision will be used to control irrigation scheduling in the near future.

2.1.4.5 Other Technology

There are many other techniques that are used to monitor the water status of plants directly such as: microphones to measure xylem cavitation, stomatal resistance probes, stem hygrometers, and even Nuclear Magnetic Resonance Imaging. These techniques are generally too complex for the greenhouse environment and are unlikely to be applied in a commercial greenhouse application in the near future.

2.2 Industry Status

With the plethora of sensors available to quantify the water requirements of a crop, it is interesting to note that nearly all of the local producers use similar light integral systems. This is most likely due to the fact that there are extensive guidelines in place for this technique which work quite well. However because of narrowing profit margins, producers are beginning to look at reducing their costs. One way to achieve this goal is to improve irrigation efficiency. To implement efficiency the local (and foreign) climate and irrigation control companies have begun to investigate and examine new techniques.

2.2.1 Current Common Practice

The current local industry practice is to utilize a combination of light sensors and simple timers to decide when to irrigate. The system is called light integration and triggers irrigation based on the amount of light energy that the crop has received. Light level is measured by a light sensor such as a pyranometer, usually in the units of [W/m^2]. This value is then converted into [J/cm^2] by multiplying the average level of light by the frequency of the measurement and is added to previous values to create a light sum. This light sum represents the amount of energy the crop has received from light. Once this light sum accumulates to a set value an irrigation is triggered. In this way based on the amount of light that the crop receives, it can receive a scaled amount of water. Growers usually vary the setpoint throughout the day to reflect changing conditions and when they want their crop to be watered. On extremely low light days where the accumulation is slow, the system reverts to a simple timer. This practice ensures the crop will not be damaged for lack of irrigation, by watering at least once every hour, or whatever the grower decides to be the longest lapse his crop should go without water.

This system works quite well. It is capable of adequately supplying the crop with water as long as care is taken in selecting and maintaining its setpoints. Even with constant adjustment leachate levels are set at a very high level to account for the uncertainty of this method and to ensure that the crop is never overstressed.

2.2.2 New Developments

Although the current industry practice of using the light integral is quite effective in supplying a crop's needs, there is considerable room for improvement. To meet the demand of improved irrigation scheduling several greenhouse climate and irrigation control companies have developed new techniques to improve matching irrigation demand with supply.

2.2.2.1 Argus Advanced Irrigation Table

To improve the industry standard light-based approach, Argus Control Systems (White Rock, BC) has devised a novel way of coping with the time delay effect of light on transpiration. Because transpiration does not occur immediately with light, there is a staggering effect that takes place. In the afternoon, light levels begin to drop but transpiration might not respond immediately. In the morning, light levels might be quite high but transpiration has not yet caught up. To adjust the irrigation timing to remediate this problem Argus uses an advanced irrigation table which essentially lets the grower enter scaling factors for the light throughout the day. The grower can decrease the value of the light that is integrated in the morning to reflect reduced transpiration and increase the value of the light in the afternoon. Another benefit is that the stage of the crop and the season can be taken into account in these factors. Each day of the entire growing season can have a unique table of factor values. By using this table the task of constantly adjusting the setpoints throughout the day can be simplified. These values must be entered manually and must be estimated from trial and error and previous experience.

2.2.2.2 Hoogendoorn Agronaut

Climate control companies have begun to appreciate the importance of including other sensor data in irrigation control. Hoogendoorn (a Dutch climate control company with local representation) has developed an advanced climate-based predictive system for control of both irrigation and climate. This system examines multiple sensors and long term trends to decide on control actions such as irrigation. The system also takes into account that the instantaneous status of the plant may not be as important as the integrated conditions of the past; for example, if the current temperature is too low the system will compensate by increasing the temperature beyond the setpoint to ensure that the average temperature meets the target.

2.2.2.3 Shanyray Technologies Phytomonitoring

Because almost all climate and irrigation control is based on sensors that measure the environment, there is inadequate measurement of the plant itself. To give a grower an actual measure of crop stress and performance, several companies have created systems which focus many sensors directly on the crop. One such company is ShanyRay Technologies, Ltd. of Israel, with their phytomonitoring equipment. Their system utilizes a large number of sensors which are placed on the plant itself. Through the use of many sensors they monitor such variables as: fruit growth, sap flow, fruit, flower, soil and leaf temperature, soil moisture (TDR), boundary resistance, and photosynthesis, in addition to the usually monitored variables. By measuring a large amount of variables on a single plant it is hoped that a good picture of the instantaneous status of the crop can be achieved. Another goal of this close scrutiny is to allow a grower to identify any problems with the crop and then determine if their remedial action is having the desired effect. This system relies on the focus of sensors on single plants within a very large canopy; it may not be a good representation of the crop. As discussed earlier there are considerable drawbacks and dangers associated with sensors in contact with the plant. In addition there is already a great expanse of sensor data which needs to be interpreted by the grower. This is a task that takes considerable time and it is unlikely that most growers would want to analyze even more sensor data. On the other hand, the Phytomonitoring technology does bring its considerable amount of data into a format that is simple to view and use. Sensor data can be plotted and compared easily with previously recorded values. Even though it does not analyze the crop's performance for the grower, it at least makes this task much easier.

2.2.2.4 Van Vliet Leachate Feedback to Light Integral Method

Part of the criteria that a grower uses to establish light-based irrigation setpoints is the volume of leachate that is produced after each watering. Growers seek to control this volume to ensure that the crop receives enough water (safety factor), and that enough water is applied to leach the excess salts from the media (leaching requirement). This volume is very important to a grower, therefore, it is a regularly monitored variable. In most greenhouses a grower will check leachate volume manually and periodically, adjusting their setpoints accordingly. A new system by Van Vliet, (another Dutch firm) does this automatically for the grower. The leachate volume that occurs after every irrigation is monitored by the system, then compared to a desired value. If there is too much leachate the light integral setpoint is increased to allow the plant more time to use its applied water. If the leachate volume is too low the lightsum setpoint is reduced so that less light is required to trigger an irrigation. By placing this feedback into the irrigation control it is possible to match the needs of the crop with supply much more closely. There is still the complication of rapidly changing conditions which might make this system perform less admirably; for example, if light levels in the morning are high, and the light-based setpoint was automatically adjusted to cope, then light levels dramatically decrease, the plant might undergo a long period without watering. This system can greatly ease the task of determining setpoints for the grower but it is still based on the light integral technique which does not work at night.

3 Materials and Methods

The experiment was conducted over two growing seasons starting in December, 1997 and ending in October, 1998; it then started again in December, 1998 and ended in December, 1999. The experiment was carried out in two separate locations: the Agriculture and Agri-Food Canada, Pacific Agri-Food Research Center (PARC) in Agassiz, BC, and at the University of British Columbia Plant Science Greenhouse on campus.

3.1 Year 1

In the first year of the study new and conventional sensors were examined for suitability at PARC. From the experience gained, the sensors which showed the most promise were further developed for application in the second year.

3.1.1 Agassiz

3.1.1.1 Greenhouse Set-up

The data collection and evaluation of sensors took place at the PARC greenhouse in Agassiz, BC, in two separate compartments (nine and ten) in the vegetable greenhouse. Each compartment was isolated from the other; its environmental parameters were monitored and controlled by an Argus Control System. Irrigation was controlled and administered by the Argus system using the light integral algorithm currently in use by most commercial growers. Each compartment had a crop of approximately 120 plants (Tomato, *c.v. Trust,*) which were maintained as recommended in the vegetable growers guide (Portree, 1996).

Two compartments were used to attempt to detect the effects that relative humidity might have on the various parameters under evaluation. The two compartments were kept at differing relative humidities by the Argus system, which was set to maintain one house at a higher humidity, and one lower. The difference in relative humidity was typically ten to fifteen percent.

Within each house two scales were used to monitor the water uptake of two separate media bags containing three plants each. The electronic balances used were off-the-shelf (Ohaus model "Champ") with a capacity of 25 kg each. Leachate was collected in a tray which had to be manually drained every day or two depending on the amount of water applied. The tray and media bag were enclosed in a styrofoam and plastic covering which greatly reduced temperature fluctuations as well as preventing evaporation from the trays. Because the plants were supported by crop wires, and the lower portion of the plant vines were angled to approximately parallel with the ground, it was assumed that any weight changes were due to variation in the water content of the growing media, and not weight changes in the plant itself. Even though the measured water uptake was in units of mass (kg), for simplification and comparison it was also expressed as a volume (L). Throughout this thesis these terms are used interchangeably.

The Argus control system monitored and recorded the separate air temperature, relative humidity, and vapor pressure deficit of each compartment, as well as the global light levels outside the greenhouse. The Argus system also recorded the time irrigation events occurred. Within each compartment additional parameters were recorded by the datalogger (Campbell Scientific models CR 10X and CR 21X and multiplexer model AM 416) (Figure 3-1).

Figure 3-1 Campbell Scientific Dataloggers

Inside light levels were recorded with the use of a pyranometer (Li-cor Model LI-200SB) located above the canopy. The leaf temperature was also monitored in each compartment using both standard copper-constantin type thermocouples, as well as infrared thermometers (Omega, model OS36-5) (Figure 3-2).

Figure 3-2 Infrared Thermometer

Two thermocouples and two infrared thermometers were used in each compartment. The thermocouples were physically attached to the leaves to determine temperature. The infrared thermometers were supported by a laboratory stand placed slightly away from the plant but aimed at the leaf area in question. Typically these temperature sensors were located at approximately the middle of the canopy. The leaf temperature was measured on the same plants which were monitored for water use with the electronic balances.

To monitor the moisture content of the media, tensiometers (Omega, model 236PC15GW - 9718) were used. In total six tensiometers were located in bags not on the scales. The tensiometers were located at approximately half the depth of the bag. Load cells (Revere, model 363-B10-50-20P1) were also used to monitor plant weight changes (Figure 3-3).

Figure 3-3 Sbeam load cell used to monitor plant weight

The S-beam load cells were suspended from the overhead crop wire which supported the spool of twine on which the individual plants were suspended. The load cells were located on plants whose water uptake was being monitored by the scales.

An atmometer (ETgage, model E) was used to measure potential evapotranspiration. This atmometer was located within the canopy in order to better represent a leaf surface. Because there was only one atmometer, it was moved back and forth between the two houses several times throughout the growing season.

3.1.1.2 Data Collection

Data was collected from the two compartments between Julian day 152 and day 243 (May-August). Complete records exist for this period with the exception of a few short periods when the Centre power went out or when there were difficulties with the datalogger, Argus System, and/or individual sensors.

The sampling and recording times of each sensor were different, based on the sensor itself as well as the system that recorded the data. Because the Argus system is set up to record data every fifteen minutes (although it measures the sensors much more frequently) the collected data is a fifteen-minute average value. This sampling frequency is adequate for analysis because the measured variables, light, air temperature, and humidity do not often change dramatically within this time frame. Other sensors required a much more frequent sampling to get a true picture of what happens. The electronic balance was the most frequently sampled sensor with values being measured and recorded every minute. This frequency was important because of the rapid weight changes that could take place with irrigation. Other sensors such as the tensiometer and load cell were initially sampled and recorded at five-minute intervals, but this was adjusted to fifteen minutes when it was found that a fifteen-minute period was adequate. In addition the thermocouples and IRTs were also sampled and recorded every fifteen minutes. Collected data was downloaded from the dataloggers every day and then loaded and converted into Microsoft Excel format. The data from the Argus system was downloaded approximately every week, as these files were much smaller due to the lower frequency of sampling and fewer sensors monitored. In addition to the parameters mentioned previously, fruit yield was also monitored and recorded manually.

3.1.1.3 Data Analysis

When the data for the growing season was collected the Microsoft Excel files were manipulated and combined so that all of the data for an individual day was located in the same file. Individual day files then contained both the Argus and datalogger data, from 12:00 am to 11:59 p.m. To simplify some analyses the sampling period of all measured variables was converted to fifteen minutes by taking averages. In the case of the electronic balance this was accomplished by averaging the fifteen values that occurred in the single sampling period of fifteen minutes.

Once the data was in daily fifteen-minute average format, the files were combined into weekly files, and then into a single file representing all collected data. In this format it was possible to attempt to develop relationships between the water use, as measured by the scales, and the various parameters we had monitored. In its raw form the electronic balance data was not a direct measure of water usage. It was only by calculating the weight change of the balance from minute to minute that a value for water usage could be determined. This was carried out in Excel on a minute to minute basis, and then run through a simple filter to ensure that the data was valid. The check was required because events such as waterings, draining of the leachate, and moving the scale would create impossible values of water usage. Invalid measurements were replaced with the last correct value. Initially individual variables were compared with water use as measured by the electronic balance. Light level, vapor pressure deficit, leaf temperature, air temperature, leaf-air temperature differential, tensiometer tensions, and plant weights were all plotted versus water use. Attempts were made using linear, logarithmic, square, cubic, power and exponential relations to obtain the best-fit lines. The r^2 (coefficient of determination) for each relation was computed using the least squares method, and the results tabulated. In addition the entire process was repeated using only the data from the daylight hours. Initially, the correlation between light and water use was found to be "artificially" high because of the large number of zero transpiration and zero light level data points. Data with light levels below 10 W/m^2 was then deleted and the analysis carried out again. Because previous work had pointed to the possibility of a time delay with transpiration and some variables (Cheng, 1995), some staggering of the data was also attempted by moving the values of these variables forward by the amount of desired stagger. In addition to these analyses carried out at UBC, a consultant was hired to analyze the collected data with the help of a neural network (Ashcan, 1999).

3.1.2 UBC

3.1.2.1 Greenhouse Setup

The greenhouse at UBC was used in the first year primarily to gain experience in the production of tomatoes, and the use of the datalogger and associated sensors. Thirty tomato plants (c.v. *Trust*) were raised on approximately fifteen square meters of floor space in compartment five of the new plant science horticulture greenhouse. The environment was monitored and regulated with an Argus control system which was responsible for maintaining temperature and relative humidity. Irrigation was controlled with a simple timer (Chrontrol model XT) which controlled the operation of a pump (Little Giant model PP-1). The plants were cultivated as per the guidelines in the BC Hothouse Vegetable Grower's guide. Parameters similar to those measured at Agassiz were monitored at the UBC greenhouse, using like sensors. Light levels were monitored with a pyranometer. Leaf temperature was measured with thermocouples and IRTs. Relative humidity was monitored with a relative humidity probe (Vaisala, model HMP 35A). In addition, two tensiometers, one electronic balance, and two load cells were used.

3.2 Year 2

In the second year of the experiment the experience and results gained in the first year were utilized to develop and implement new irrigation control strategies. Based on the relations that were developed, as well as the experience gained in working with specific sensors, two new algorithms were created and compared against the industry standard light integral technique. Two new algorithms were developed so that we could demonstrate approaches to irrigation control using both a predictive and direct measurement of water uptake.

3.2.1 Development of New Algorithms

3.2.1.1 Predictive Equation-Based Algorithm

The various individual measured parameters were compared to the measured transpiration from the scale and an attempt was made to correlate the parameters with water use. If a good relation was found then the sensor was considered to have potential for control. Simple multivariable linear relations were then attempted using the Microsoft Excel function LINEST, which creates a best fit line of the form:

$$Y = b_o + b_1 X_1 + b_2 X_2 + \ldots + b_n X_n$$

Where Y is the quantity that is predicted (water use), X_1 to X_n are the parameters such as light level and temperature, and b_0 to b_n are the constants generated by Excel to produce the best-fit line. Several combinations of the previously examined variables were attempted.

From this procedure it was found that four variables together provided a good estimate of the water use of the plants: light, vapor pressure deficit, air temperature, and air-leaf temperature differential. They were combined together in the form of a simple multiple variable linear relation:

$$E_t = b_o * I + b_1 * vpd + b_2 * \Delta T + b_3 * T_p + b_4$$

where E_t is the transpiration rate, I is light level, vpd is the vapour pressure deficit, ΔT is air-leaf temperature differential, T_p is leaf tissue temperature and b_0 to b_4 are the constants determined earlier which made the best fit line. More complex non-linear relations were not attempted although they might have given slightly better results. It was felt that a simple linear model would be easier to implement; the correlation provided by this simple linear model was adequate for control purposes. The predictive abilities of this approach were verified by leaving out various days of data from throughout the season, determining the best values of these constants from the remaining data, and then using this equation to predict the water use within the suspended weeks. In selecting days to exclude for comparison, two high light days, two medium light days, and two low light days were chosen. In this way we could see the true performance of the equation, not just how well it performed on the data from which it was developed.

3.2.1.2 Direct Measurement Scale-Based Algorithm

From the experience of using our multitude of sensors it was determined that the electronic balances were a simple and reliable means of directly measuring the water uptake of the plants, suitable for control. Rather than look at the absolute weight of the media and then trigger a watering when a certain decrease from this initial value had occurred, as has been done in potted media (Boukchina et.al., 1993; Zoon et.al., 1990) a different approach was chosen. Water use was measured by taking weight measurements on a small timescale (less than one minute) and then determining the difference between successive measurements. This difference was then compared to a check value to see if it was a valid transpiration. Previous experience allowed us to determine maximum transpiration rates and ensure values that are larger than this were not passed through. This error checking prevents impossibly huge or negative transpirations due to plant growth over time, decomposition of the media, disturbance of the scale, plant, or media during normal greenhouse operations, and the removal of leachate water. If the difference was invalid it is replaced with the most recent valid difference. Differences are also discarded and replaced during irrigation. These differences were then summed up to give the water use of the plant. Upon reaching a setpoint of water use an irrigation was triggered.

3.2.2 Implementation of Algorithms

Because the existing Argus control system at the UBC horticulture greenhouse was not flexible enough to implement these control algorithms, the control abilities of the Campbell Scientific Datalogger were utilized. Not only was the datalogger capable of measuring and recording the data from all the sensors, it also had the ability to act upon the collected results. The algorithms were run by the Campbell Scientific CR 10 X datalogger which allows control ports to be switched as a result of the program running on it. These control ports were hooked up to a solid state relay box which could turn the irrigation pumps on as required by the algorithms. The sensor reading and control program was programmed in the Campbell Scientific datalogger code with the assistance of the program EDLOG (Campbell Scientific). This program allowed the easy introduction and manipulation of the various individual instructions required of the program, in a user readable form on a standard personal computer. Once the program was entered, EDLOG automatically checked it for errors and compiled it into the form that the datalogger itself required. The program was then uploaded onto the datalogger using the Campbell scientific datalogger interface program PC200W, which also acted as a means of downloading collected data from the datalogger.

3.2.2.1 Light Integral-Based Algorithm

The measure against which the new algorithms were to be compared was the industry standard light integral approach. As described earlier this method works by accumulating the light energy intercepted by a light sensor; upon the fulfillment of a preset level the irrigation system is prompted to begin a watering.

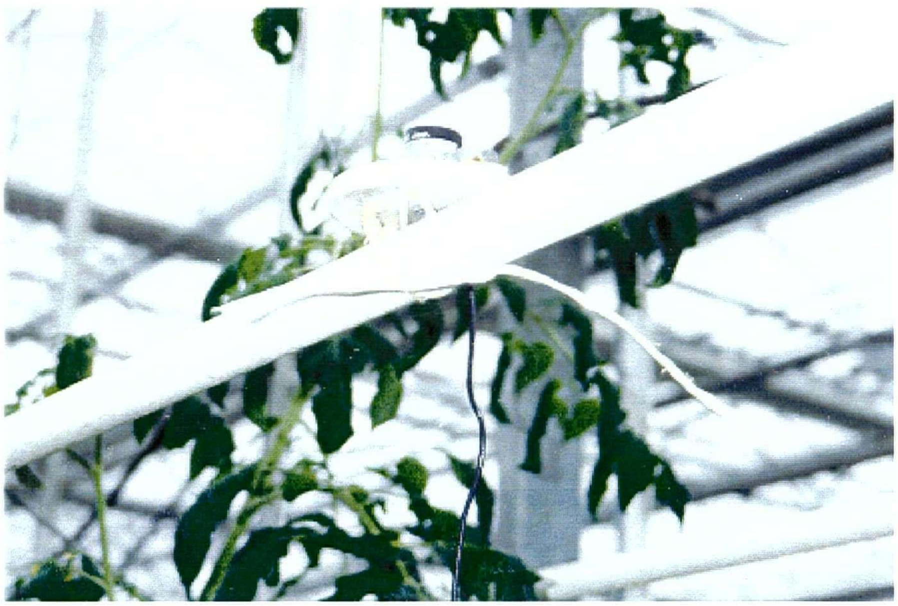

Figure 3-4 Li-cor Pyranometer for Light Measurements

In the UBC greenhouse two light sensors measured the light level every twenty seconds. (Figure 3-4). The maximum value of the two was taken, the values converted into Joules per centimeter squared, and then added to the integral. The reason for using two sensors and for taking the maximum value of the two was that the sensors were located inside and would occasionally be subjected to shading from overhead beams. When the target of 80 to 100 J/cm^2 had been accumulated a watering would be triggered. In addition the light-based approach had a few safety factors built in as per the recommendations in the BC Hothouse Growers Guide. To ensure adequate watering in low light conditions, a watering was triggered if one hadn't occurred in the past hour. Because it is not necessary to water every hour at night, this feature was disabled after dusk, and then started again at dawn. The datalogger would record a watering that occurred due to this constraint as a forced irrigation so that distinction could be made and examined later.

3.2.2.2 Equation-Based Algorithm

This method was applied in a similar way to the light-based approach. A sampling frequency of twenty seconds was chosen for the measurement of all sensors; the coefficients derived earlier based on fifteen minute data were scaled down accordingly. The value for light was the same as used for the light-based approach. Humidity was measured with the humidity probe and then converted into vapor pressure deficit based on the air temperature at the sensor (measured with an integral Pt 100 thermistor). Leaf temperature was measured with several different sensors. Two IRTs, two thermistors (Omega, model Pt 100 K2010 Ceramic RTD), and two thermocouples were all used to measure the leaf temperature. The air temperature used in the leaf-air temperature differential calculation was that measured in the relative humidity probe. Sensor readings were taken every twenty seconds; the values checked and then placed into the equation. The resulting value of water use was then integrated in a similar fashion to the light sum. Once the set sum had been reached, an irrigation event was triggered and the sum reset back to zero. There was no forced irrigation in use with this method. Because the equation was derived from data collected during the day, it tended to greatly overestimate transpiration at night. For this reason it was disabled after dusk and then reinitialized at dawn.

3.2.2.3 Scale-Based Algorithm

The scale-based algorithm performed in a similar manner to the equation-based approach except the water uptake was directly measured instead of predicted. The scale was arranged to measure the weight of the media and its collected leachate (Figure 3-5). Every twenty seconds the measured water uptake would be added onto a sum, and once this sum reached the desired level an irrigation event would occur. To ensure that no erroneous measurements created impossibly high or low transpirations, the measured water uptake was compared to a pre-determined maximum. If the absolute value of the measured transpiration exceeded this check then the previous valid transpiration was used in its place. A benefit of the scale-based approach was that irrigation amounts could be verified by recording the weight of the scale before and after watering. This algorithm had no irrigation forcing capabilities.

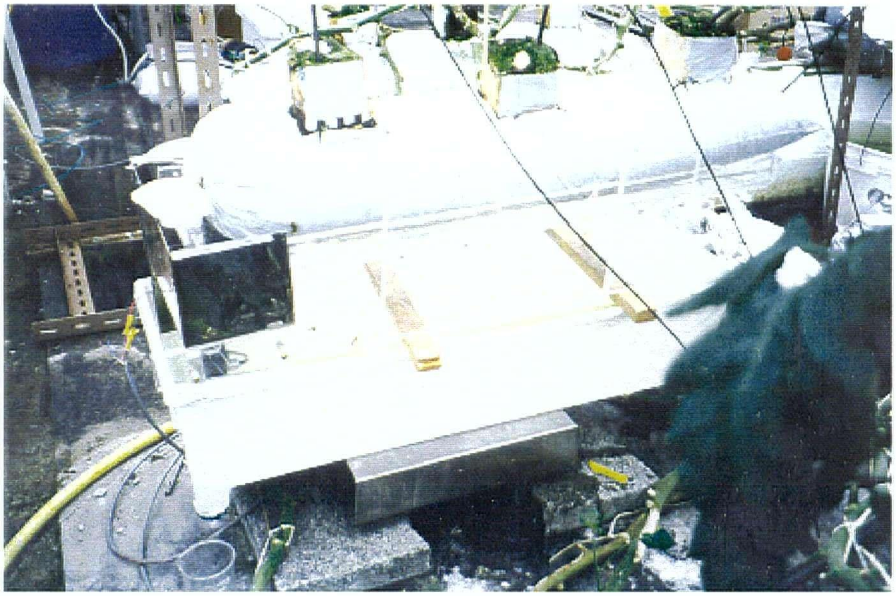

Figure 3-5 Scale setup at U.B.C. (with insulation removed)

3.2.2.4 Greenhouse Setup

The UBC greenhouse was arranged similarly to the previous year but in the second year there were three plants per bag. Thirty tomato plants (*c.v. Rhapsody*) were arranged in five rows of six plants, over an area of approximately fifteen square meters in compartment five of the UBC greenhouse. Because there were three treatments, each irrigation system was responsible for watering nine plants (three bags), with the exception of the scale-based approach which administered twelve plants. The rows were arranged to mix the three methods; the plants controlled by each system were switched halfway through the experiment. Irrigation was supplied by three separate independent systems drawing from the same irrigation tanks. Each irrigation system had its own pump that could operate whenever required by the controller, without any interference from the other systems. The pumps were controlled by a solid state relay box which was in turn switched by the control ports on the CR 10X datalogger. The leachate was measured from six bags with the use of elevated fiberglass trays which collected leachate and funneled it into buckets supported by loadcells (Figure 3-6).

Figure 3-6 Leachate monitoring station

Leachate from a single bag containing three plants was collected and accumulated in a bucket which was automatically weighed by the loadcell. The datalogger recorded the weight of the bucket every five minutes so that it was possible to track the weight change of the bucket over time, and hence, the amount of leachate received. In this way the leachate produced would show up as an increased weight on the loadcell. There were two leachate stations for each irrigation control system. In the case of the scale algorithm the plants used for the control (the plants on the scale), were different from the ones being monitored for leachate. Leachate was also measured from two additional bags with the assistance of spoon counters. Leachate water from a bag is collected and drips onto a small spoon which when full, tips, and automatically registers this tip by breaking a magnetic switch. By recording the number of tips and the time they occur, it is possible to determine the volume of leachate and when it occurred. Spoon counters are the traditional means of measuring leachate in commercial greenhouses but were felt to be unreliable; they do not provide a quick enough response to indicate when the leaching occurred. For this reason they were only used as a comparison with the uncomplicated load cell technique.

Another important measurement in the determination of the plant water use is the amount of irrigation water that is applied each watering event. Irrigation amount was verified every second day by manually triggering an irrigation event with the drippers out of the media and in a collection cup. The volume produced after the set irrigation time period of 80 seconds was then measured and recorded by hand.

Sensors for the equation-based algorithm were located near the plants that were controlled by this algorithm. The humidity sensor was located on a stand placed adjacent to the upper canopy. Also mounted on this stand were the two IRTs, the two thermistors, and the two thermocouples (Figure 3-7).

Figure 3-7 Sensors Utilized by the Equation-Based Algorithm

3.2.3 Evaluation of Algorithms

To evaluate the effectiveness of the control algorithms and to compare and weigh their relative abilities, we needed criteria with which to judge them. Since one of the goals of the project was to create a system that better matched the supply of irrigation water to the needs of the crop, the ability of a system to meet this goal would provide a good means of assessment. To adequately meet the demands of the crop there are two major factors: how much irrigation is applied, and when it occurs. If a plant does not receive enough water it will become stressed; it will close its stomata to reduce water use. Closed stomata mean that the flow of carbon dioxide for photosynthesis will be slowed down and growth will be negatively affected. In extreme cases the plant will become desiccated and die. Too much water can also be a problem. A plant's roots respire and use the assimilates produced through photosynthesis. To release the energy of these sugars, oxygen is required. If the root zone is saturated with stagnant water the oxygen transfer rate will be greatly reduced and the roots will suffer. A constantly saturated root zone also increases the susceptibility of the crop to fungal and bacterial infection. A healthy root zone will undergo periods of drying and wetting to ensure that both enough water and oxygen is available. Irrigation frequency is especially important in the porous artificial media used in modern greenhouses which are normally set up to facilitate good and quick draining.

To show that all algorithms performed adequately, we compared the water use values of the various methods. If an irrigation system was performing poorly and the plants suffered, it would show up in reduced water usage by the crop. If the volume of water used by the three methods is quite similar then we can assume that the methods were at least supplying adequate water amounts.

3.2.3.1 Irrigation Consistency

For comparing the effectiveness of each system in supplying water to the plant, the rate at which the plant uses water was required. Because of limited resources it was not practical to measure each bag with a scale to determine the water use. It was possible to monitor the leachate volume from each bag. With the leachate, the irrigation volume, and timing known, it was possible to create a water use curve from the difference between irrigation and leachate amounts. Since a primary goal of the project was the conservation of water, the algorithms had to be able to accurately supply the crop's needs. By monitoring the leachate it is possible to see when the plant is using water, and then compare that to when the irrigation system is supplying it. By reducing the uncertainty in predicting the water use of the crop, more precise amounts of leachate can be applied and the size of the safety factor used can be reduced, resulting in savings.

By comparing the standard deviations of the leachate produced we can see how the algorithms vary. For an algorithm to be successful this deviation needs to be minimized. Ideally if the leachate fraction is set at a certain percentage, the system will supply that percentage, hour after hour, and day after day, under all conditions. Since each bag of three plants uses water at a differing rate (due to differing plant size, health, and fruit load), it would not be valid to compare bags directly. In addition because there is variation in the volume of irrigation water received by each bag, leachate amount will vary and the leachate setpoint will be different. To compare the systems, the leachate fractions were calculated for each irrigation event by summing up the overdrain that occurred up until the next irrigation. Daily standard deviations were then determined; it was then possible to establish if there are periods in the day when leachate is either too much or inadequate. Analysis of the daily standard deviation of the leachate fractions allowed comparisons to be made between the systems, as well as demonstrated each system's performance under different levels of light.

3.2.3.2 Irrigation Frequency

Also important is the irrigation frequency and when irrigation occurs. Irrigation frequency is important because it affects the health of the roots and ensures that the plant does not undergo long periods of stress.

The frequency of irrigation was recorded by the datalogger which created an output every time each method triggered an irrigation. By plotting these outputs versus time, the irrigation frequency can be observed. To compare the frequencies of irrigation all of the irrigation events for the entire season were copied into a single Excel file. They were then sorted by type and the period between successive irrigations was determined. The minimum, maximum, standard deviations could then be calculated. In addition to looking at the period between irrigations we also examined when irrigation occurred throughout the day.

4 Results and Discussion

4.1 Year 1

4.1.1 Selection of Sensors for Initial Examination

There are many means of determining plant water status whether it be direct or indirect monitoring of the plant or its environment. Because it was impossible to examine all of the techniques described in the literature review, we had to decide what sensors to initially examine. In choosing these sensors there were a number of considerations. The requirements for a successful irrigation control algorithm provide a means of immediately discarding some technologies. Of primary importance is the ability of the system to be automated. From this requirement all of the technologies requiring manual measurements or frequent intervention could be dismissed. In addition some of the more complicated instruments that required extensive signal processing could also be abandoned. Reliability was also a consideration. There would be no point in evaluating a sensor for greenhouse operation if it only worked some of the time, required constant calibration and/or attention. Another consideration was the fact that some sensors are already pre-existing in many greenhouses. A system based on pre-existing sensors would be easier to implement than one demanding totally new sensors. Cost and availability were also concerns. Many sensors used in previous scientific endeavors have been collected by the Pacific Agri-Food Research Centre and were readily available for use. To try and provide as wide an investigation as possible, sensors were chosen which attempted to span the soil, plant, environment continuum. By selecting sensors that monitored all of these areas, it was hoped that the benefits and disadvantages of sensor location could become evident.

After consideration it was decided that initially we would examine: tensiometers, thermocouples, IRTs, load cells, atmometers, as well as the commonly measured light, humidity (vapor pressure deficit), and air temperature. Sap-flow meters were not chosen for evaluation at this time because they had been examined previously at Agassiz (Cheng,

1995) and adequate results and experience had been acquired to judge the usefulness of sap-flow sensors for irrigation control.

4.1.2 Evaluation of Sensors

To evaluate the merits of each sensor we compared its output with the water use of the crop, and attempted to formulate correlations between the two. It was felt that if a sensor could adequately predict or measure water usage, it would be a good candidate for further examination. Correlations of the sensor data with the water use as determined by the scale were carried out on both the data set spanning the entire season as well as individual days. The results were plotted and best fit lines were attempted.

4.1.2.1 Water Use By Scale

The water use of the crop is the variable that is of most interest in designing and implementing an irrigation control algorithm. It is an indication of how much water the crop uses as well as when it is used. These are essential factors in determining when and how much to water. For this reason the water use of the crop is the basis on which all of the sensors and algorithms are compared. Perhaps the most meaningful method of illustrating water use is to show how the water uptake rate varies with time.

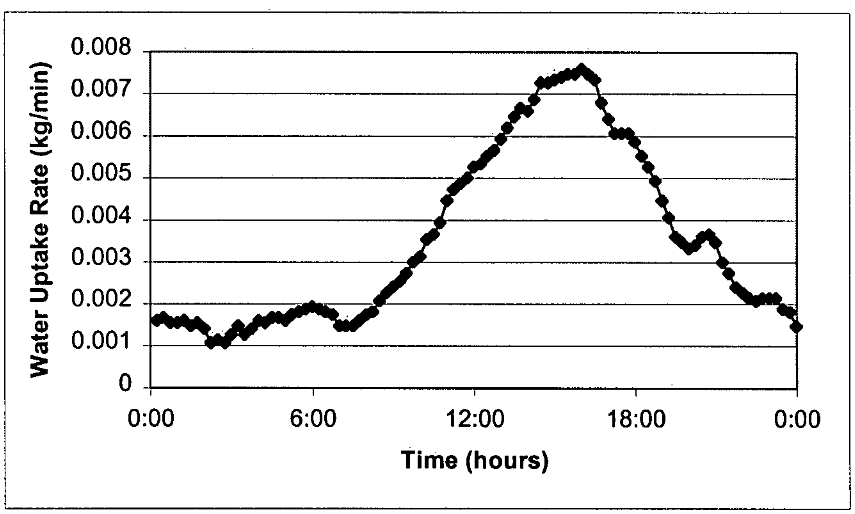

Figure 4-1 Water Uptake Measured by Scale on a Typical day

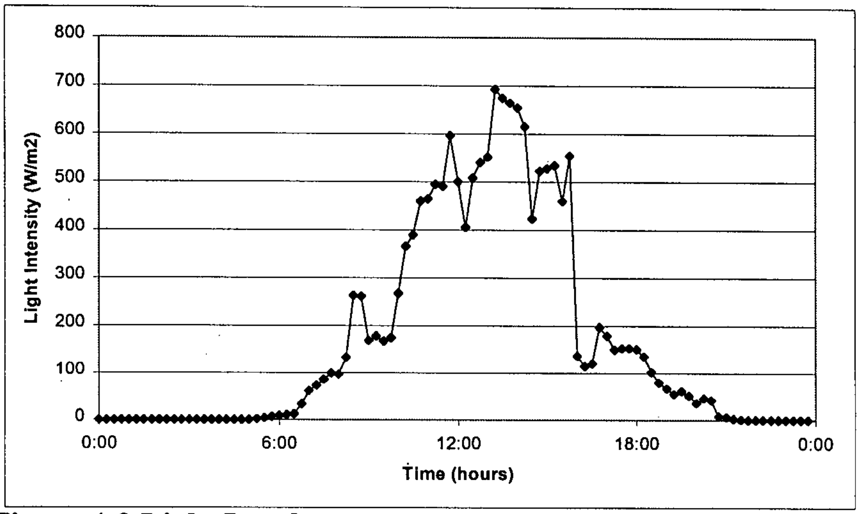

Figure 4-2 Light Level

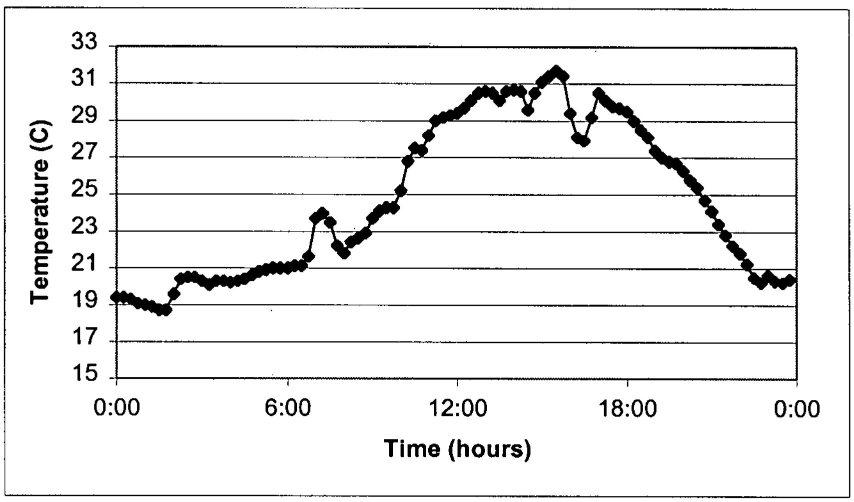

Figure 4-3 Air Temperature

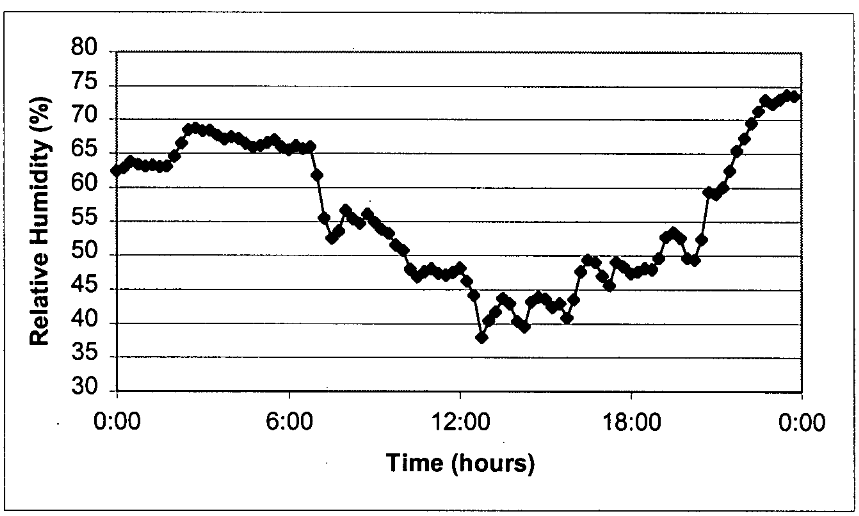

Figure 4-4 Relative Humidity

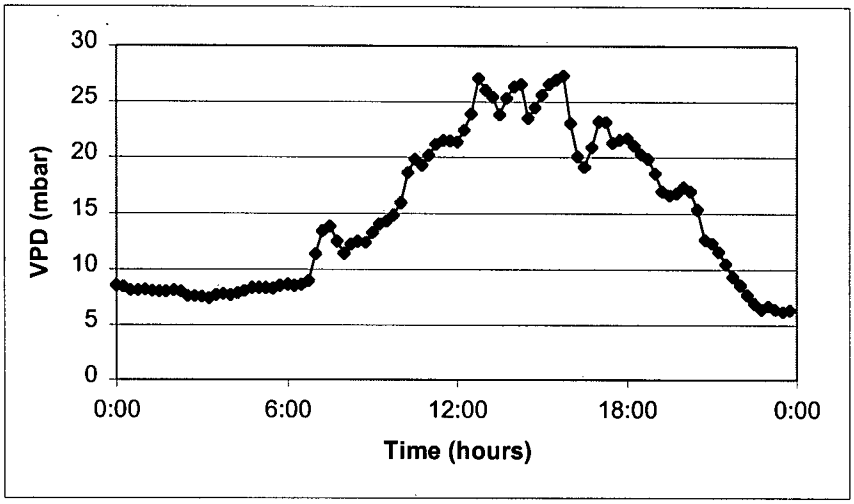

Figure 4-5 Vapor Pressure Deficit

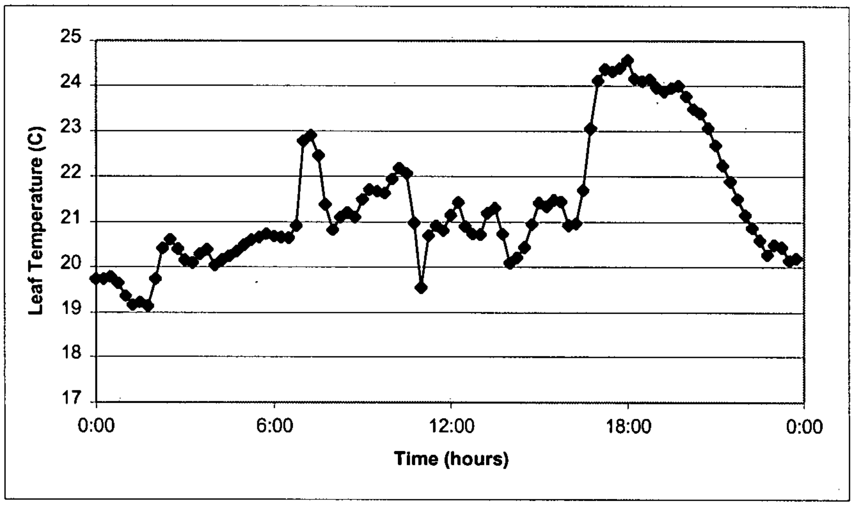

Figure 4-6 Leaf Temperature

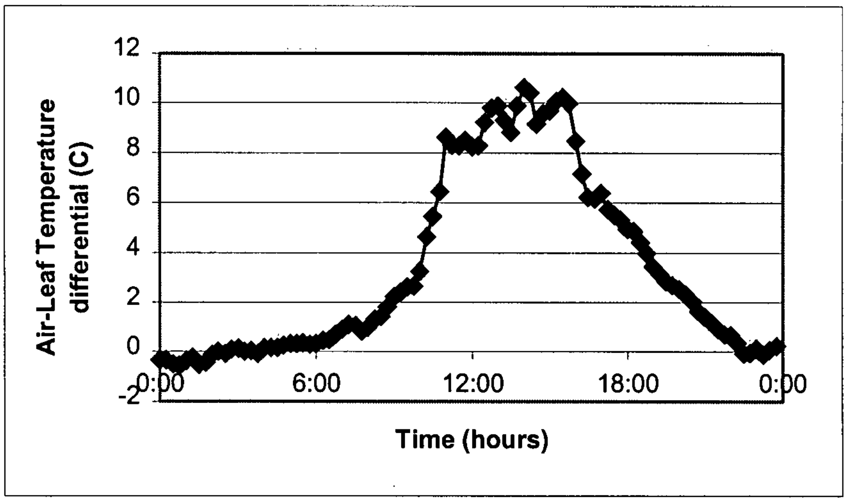

Figure 4-7 Air-Leaf Temperature Differential

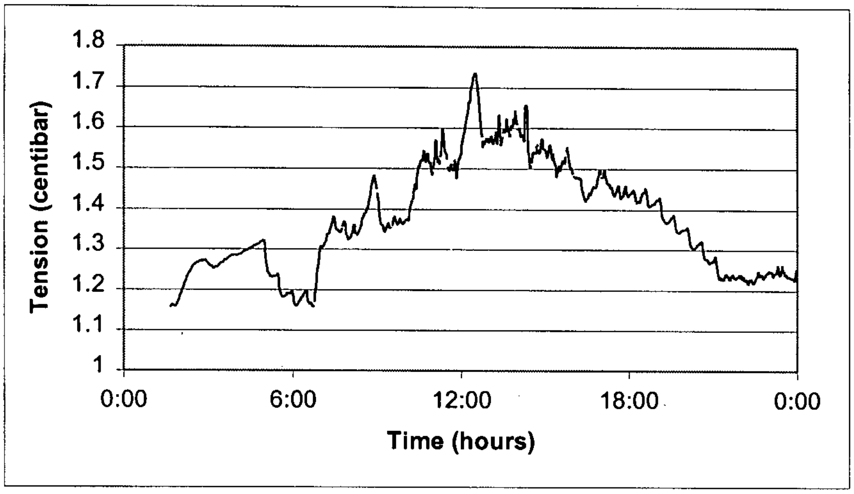

Figure 4-8 Moisture Tension

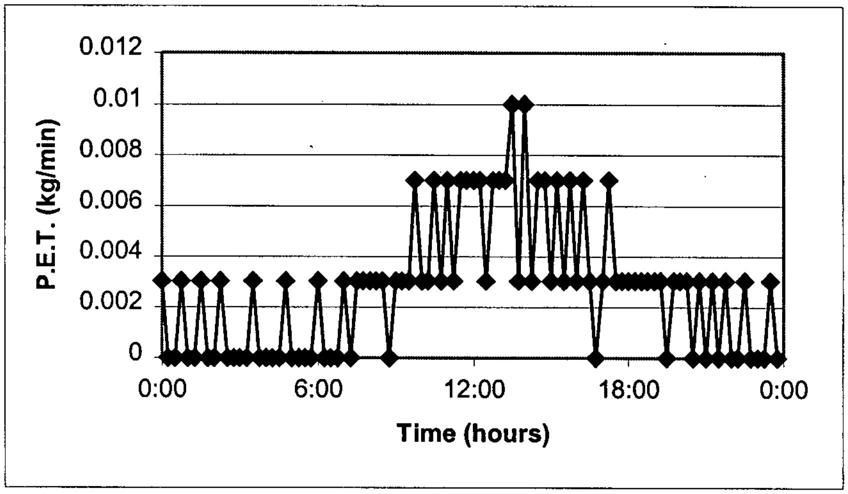

Figure 4-9 Atmometer P.E.T.

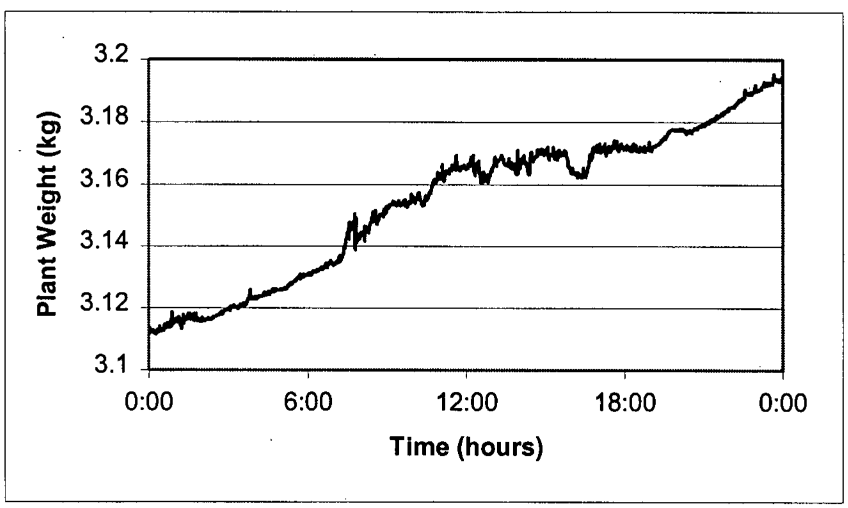

Figure 4-10 Plant Weight

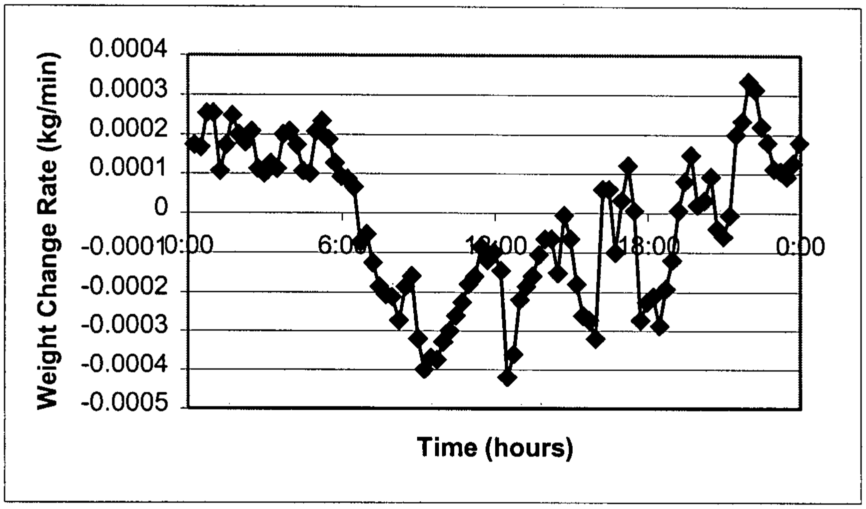

Figure 4-11 Plant Weight Change Rate

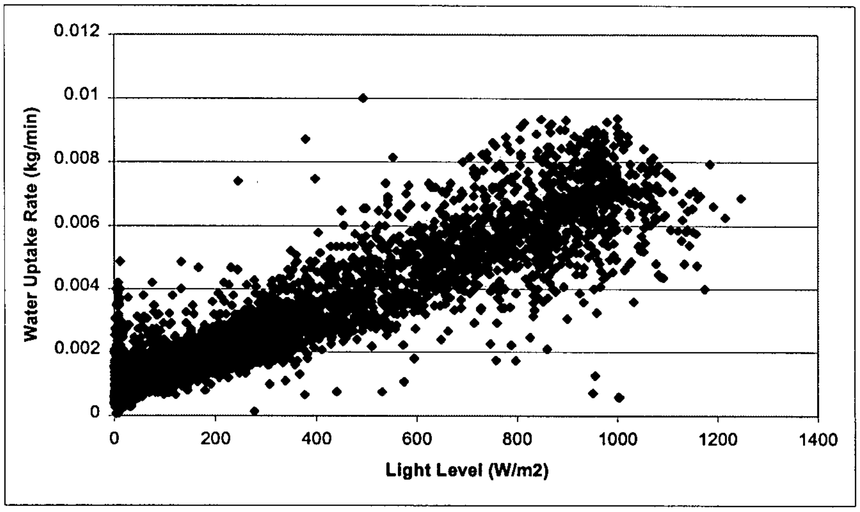

Figure 4-12 Variation of Water Uptake with Light (Entire Experimental Period)

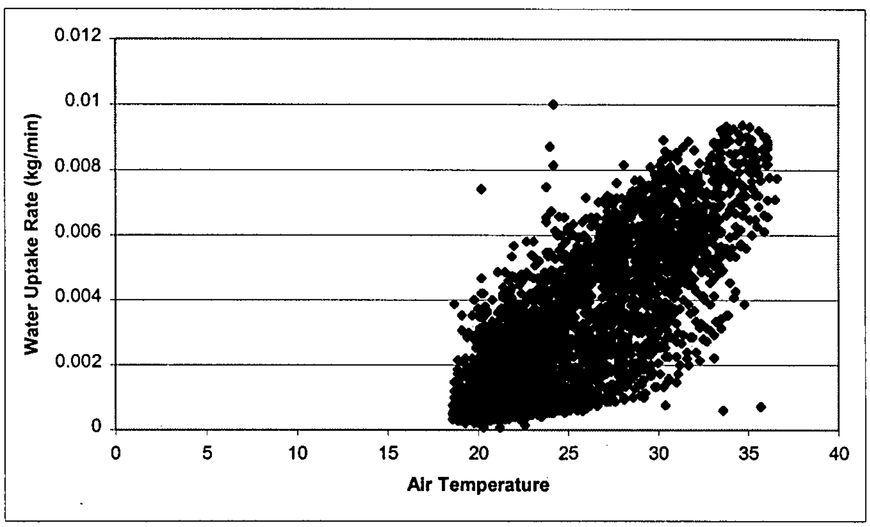

Figure 4-13 Air Temperature

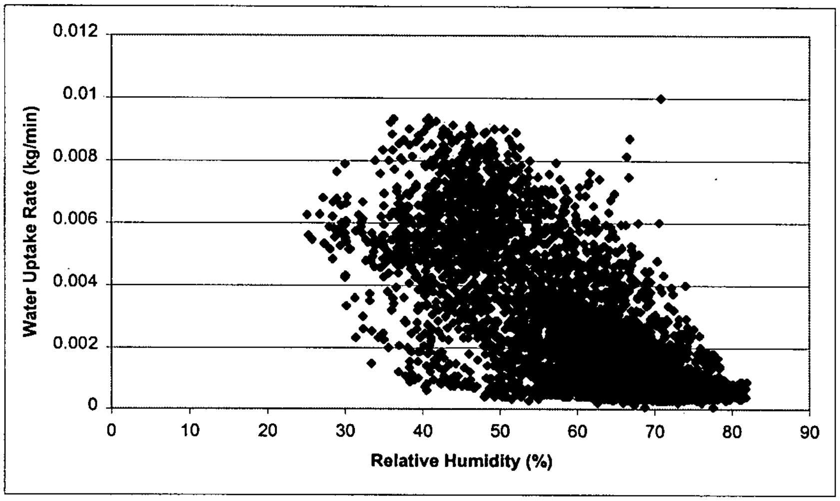

Figure 4-14 Relative Humidity

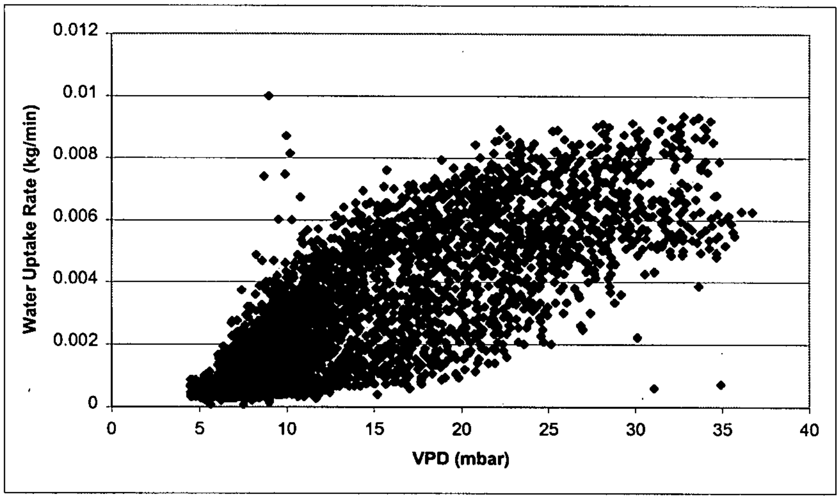

Figure 4-15 Vapor Pressure Deficit

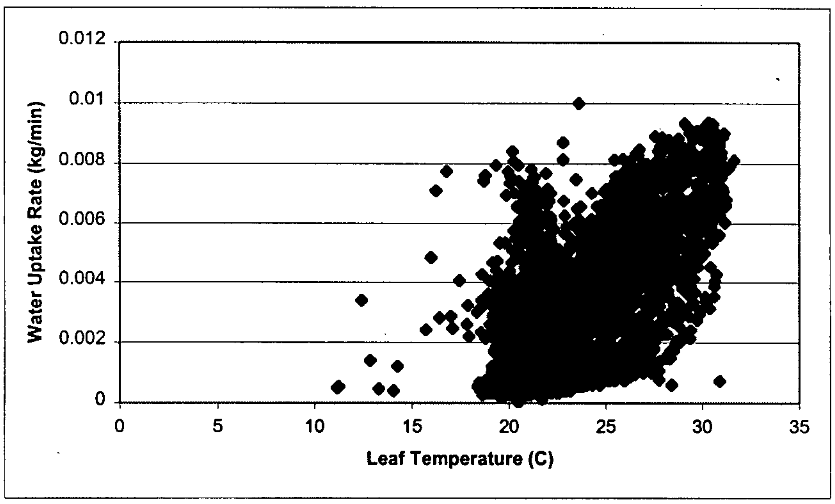

Figure 4-16 Leaf Temperature

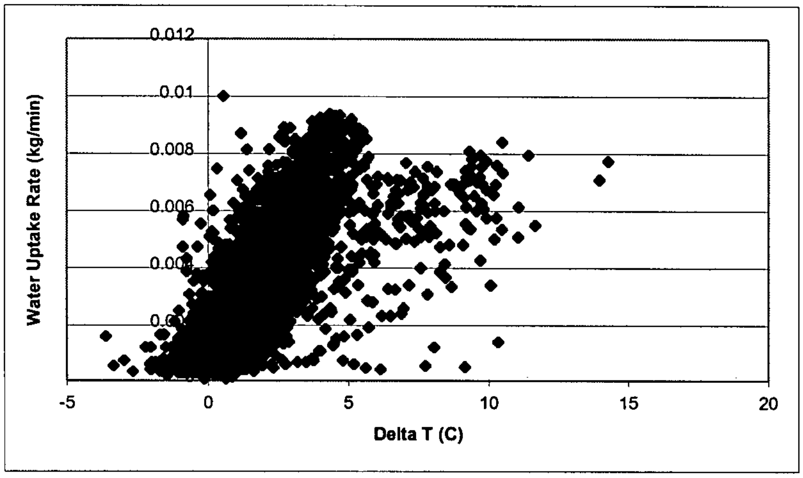

Figure 4-17 Air-Leaf Temperature Differential

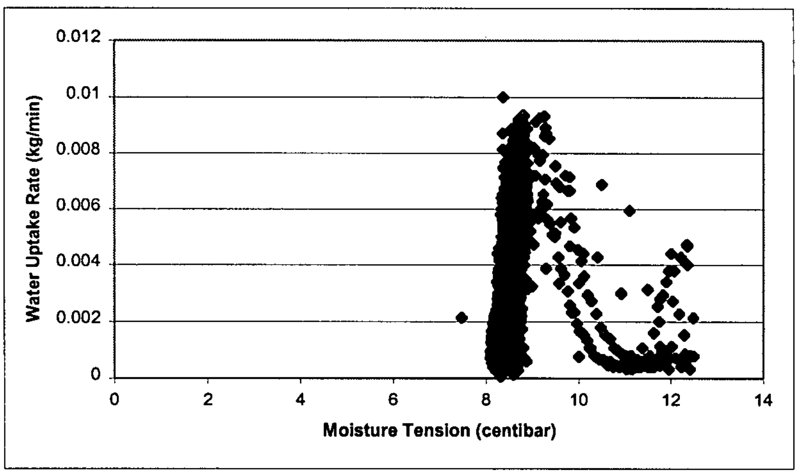

Figure 4-18 Moisture Tension

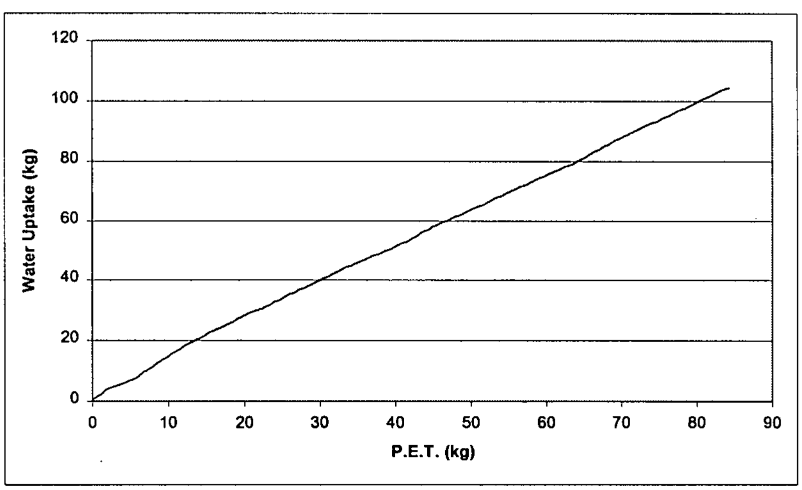

Figure 4-19 Atmometer P.E.T.

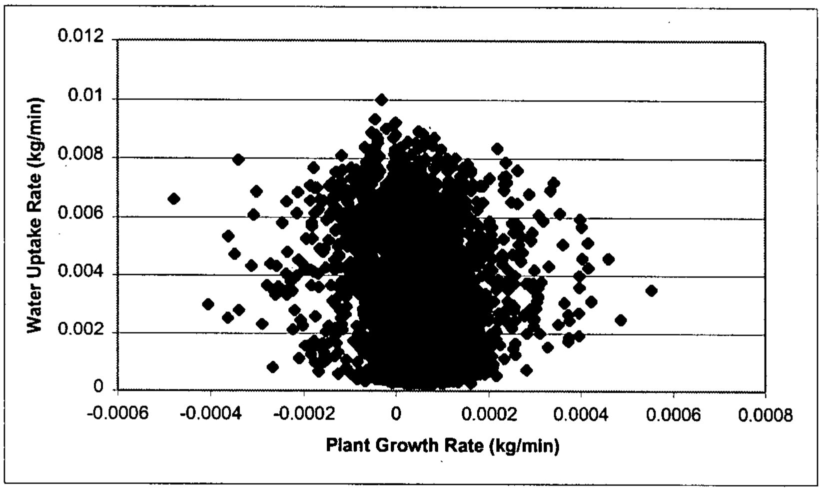

Figure 4-20 Plant Weight Change Rate

Figure 4-1 shows a typical day of water uptake rates. By examining this figure we can see when the plant is using water the fastest. This rate tends to jump around considerably during the course of the day, and may have many peaks and valleys. Water use can also be expressed as a cumulative value over the entire day as is shown in Figure 4-21.

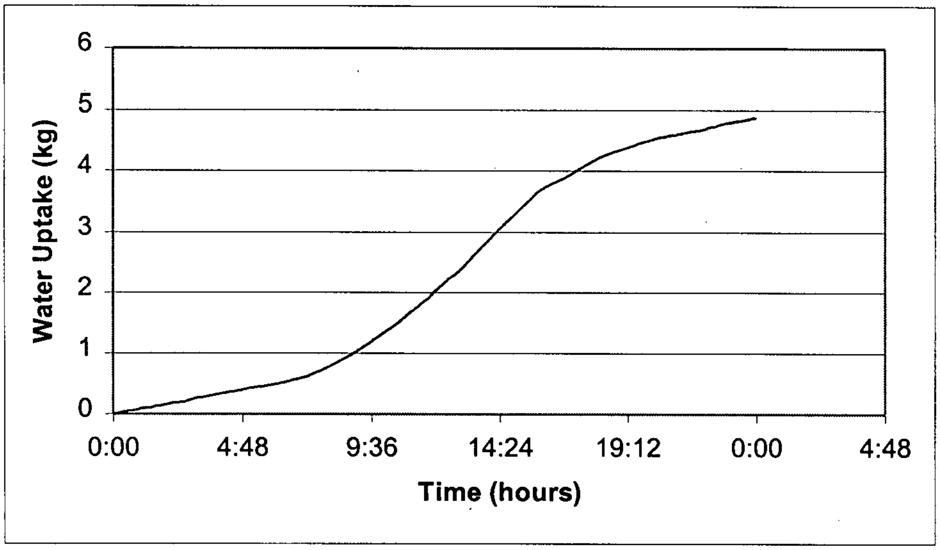

Figure 4-21 Cumulative Water Uptake

It might be more valuable to express water uptake this way, as small dips and peaks are removed from the graph. From this figure the mass of water used can be easily seen.

4.1.2.2 Light

Light is the driving force behind transpiration and correlates very well with the water usage of a plant. Light supplies the energy the plant requires for photosynthesis as well as evaporating water from the leaves to draw more water-borne nutrients from the roots. It is because of this good relationship between light and water use that irrigation systems based solely on light level are successful and widespread throughout the industry. However the relationship is not perfect and other factors affect transpiration as well. Light levels change dramatically over the course of a day (Figure 4-2). Not only is there the transition from day to night, but also there are seasonal and weather effects as well. As the season changes from summer to fall the days become shorter and less light is available. Overcast days can severely reduce the amount of light; even on relatively clear days the occasional cloud can pass by and interrupt the flow of light. Light is usually expressed in energy received per surface area exposed, the most common units being Watts per square meter. When we try and correlate light with water uptake rate, we can see that there is a strong relationship (Figure 4-12). This indicates that light is a good estimator of water use ($r^2 = 0.875$). At night when the light levels are extremely low and transpiration is also low these points introduce an invalid form of weighing into the relation. In addition we are primarily interested in the daylight hours, when light might be high or low. For this reason the correlations with light were done with the night data removed. When this is done the correlation is not as high ($r^2 = 0.797$), but it gives a much more realistic point of view.

4.1.2.3 Air Temperature

Air temperature is another important factor in crop production. If the temperature is too low then important metabolic processes will not occur as quickly as required, and the plants will suffer. If temperatures are too high then the plants may experience tissue damage and/or heat stress. Although temperature is not a driving factor of transpiration such as light, it does have an effect. The temperature can be likened to a resistance to transpiration, as is used in the Penman-Monteith equation. Greenhouse control systems seek to maintain a relatively constant temperature throughout the day, with lower temperatures at night. The control and selection of temperature is a skill that is very important in the production of good quality produce. As can be seen in Figure 4-3 the temperature did fluctuate throughout the day, as control is not perfect and the greenhouse is not a perfectly uniform environment. Uneven heating, lighting, and cooling all affect the temperature throughout the greenhouse.

Air temperature also correlates moderately well with water uptake (Figure 4-13) ($r^2 = 0.698$). This high correlation is most likely due to the fact that the high temperature days usually correspond with days where the light levels are high and considerable transpiration occurs. Increases in temperature also affect the relative humidity of the air and its ability to hold moisture as discussed below.

4.1.2.4 Humidity

Humidity is another important variable in the determination of transpiration. Humidity affects the rate at which the plants can convert liquid water in their leaves into water vapor which transpires from their leaves. If the humidity is high then the air is nearly saturated with water vapor and there is little room for more, making transpiration more difficult. Low humidity means that water will evaporate quickly making transpiration much easier. If the humidity is too low and the plant is transpiring quickly, then it runs the risk of losing too much water. To prevent this the stomata on the plant leaves shut, slowing down the rate of water flux. Humidity can also be likened to a resistance to transpiration.

The humidity is another greenhouse environmental variable which the climate computer seeks to control. This is usually done through the use of roof vents which allow moist air to escape and draw in drier air. The humidity may also be increased through the use of fogging systems which seek to cool the greenhouse through evaporative cooling. If the temperature is too high and the humidity is low then misting systems pump out small droplets of water which flash evaporate, cooling down the air, and increasing the humidity. Although this is a set parameter it, too, varies notably throughout the day depending on conditions (Figure 4-4). The relative humidity by itself is not a good estimator of water usage (r^2 =0.525), but as can be seen in Figure 4-14 it certainly has an effect upon transpiration.

4.1.2.5 Vapor Pressure Deficit

The vapor pressure deficit (VPD) is a combination of both the humidity and the air temperature of the greenhouse. Because it takes into account these two factors it gives a better result than either alone. The VPD is a measure of the vapor pressure of the leaf minus the vapor pressure of the air. The air within the leaf is assumed to be saturated with vapor, or have a relative humidity of 100%. The vapor pressure of the air is calculated from the humidity and the air temperature. To simplify calculation the leaf temperature is assumed to be at air temperature (although this is certainly not always the case).

The vapor pressure deficit varies throughout the day and night depending on outside climate conditions as well as inside control (Figure 4-5). If we compare the water use of the individual day as measured by the scale, with the VPD (Figures 4-5 and 4-1) we can see that they both follow the same trend and there is a clear relationship between the two. This suggests that the VPD plays an important role in determining the rate of transpiration of the crop. When correlated with water use over the whole season, the relationship is relatively good (Figure 4-15), ($r^2 = 0.697$), although not nearly as strong as that for light.

4.1.2.6 Leaf Temperature

Throughout the course of the day as the greenhouse receives light, heating systems turn on and water is transpired, the temperature of the plant tissue varies. The air temperature and humidity of greenhouses are monitored closely and maintained at a desirable level through controls such as venting, misting systems and/or heaters. The leaf temperature is not generally monitored and does not play a feedback role in the control of the greenhouse climate. Because it is a function of multiple factors, the leaf temperature varies erratically throughout the day (Figure 4-6). The leaf temperature changes with the ambient temperature as well as the light intercepted and transpiration occurring. It is probably because of these many interacting factors that the relationship between the leaf temperature and water uptake is so poor ($r^2 = 0.517$). As can be seen in Figure 4-16, there is a wide distribution, which means that as long as leaf temperature is within an acceptable range it is not a transpiration rate-limiting factor.

4.1.2.7 Air - Leaf Temperature Differential

The leaf temperature is perhaps more useful when expressed as the air-leaf temperature differential. As a plant transpires water is drawn up through the roots into the leaves where it is evaporated. Through the process of evaporation the leaf cools down (evaporative cooling). When a plant is transpiring the difference between the leaf and air temperature increases. By examining the difference between these two temperature measurements it is possible to see when the plant transpires. Figure 4-7 illustrates quite well that under certain conditions the leaf-air temperature differential can predict the transpiration rate quite efficiently. It is possible to see that the air-leaf temperature differential increases in the middle of the day when water use rates are highest. By comparing Figure 4-7 with Figure 4-1, we can see that they are very similar; this is only a single day and on a longer-term basis, the correlation coefficient is not as good as this individual day might suggest ($r^2 = 0.575$). Figure 4-17 shows that over the course of the season the correlation appears to be quite strong, but the presence of many outliers adversely affects the coefficient. The correlation is still quite good when compared to simply the leaf or air temperatures alone.

4.1.2.8 Tensiometer

Tensiometers seek to measure the water tension in the media of the plant. This is an indication of the water content of the media, and indirectly we can see that when this value is increased, the plant has depleted the water in its growing media. If we look at Figure 4-8 it is difficult to detect a pattern in the moisture tension. There are no sudden changes in tension as might be expected after a watering event. To better see the effects of irrigation Figure 4-22 contains the moisture tension over the day, as well as when irrigation events occurred. Over the course of the day we should see marked increases and decreases in the moisture tension that correspond closely with the watering regime. On this particular day it is possible to see that the tensiometer follows the general trend of water use, but it is not a strong relation.

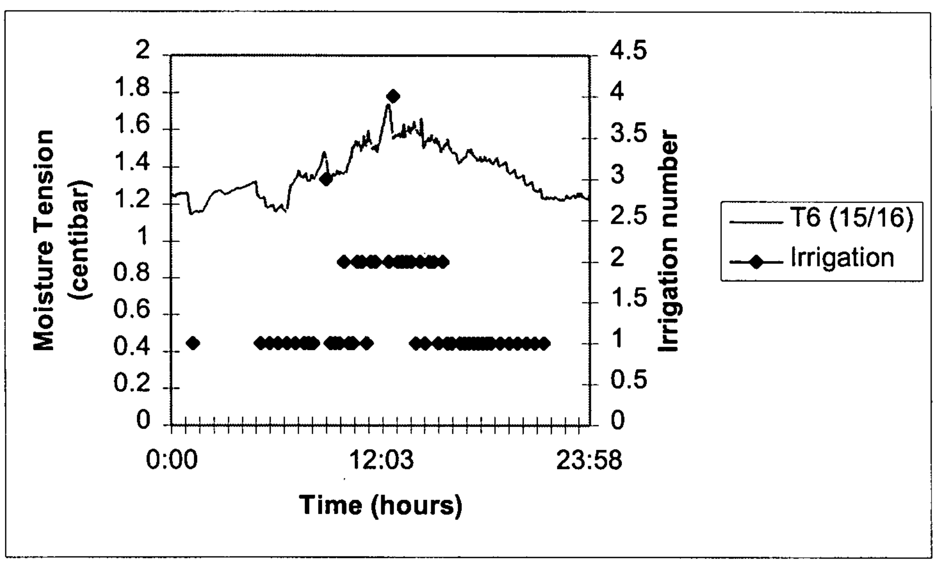

Figure 4-22 Moisture Tension vs. Time with Irrigation Events

In a longer term relation there was very little correlation between water use and moisture tension (Figure 4-18) ($r^2 = 0.032$). These poor results seem to indicate that there may have been problems with the tensiometers, and how they interact with the media. Of the tensiometers used, there seemed to be different or conflicting responses from them. Because the response is not large, it is difficult to pick up all of the variation due to changes in the water content of the media.

4.1.2.9 Atmometer

At first examination the raw atmometer data does not appear to be well related to water uptake (Figure 4-9). Because the evaporation is measured in tips, the data is quite choppy and does not appear as smooth as the data from the scale. The sensitivity of the atmometer is what controls this, and it is not as fine as would be desired. For this reason a simple graph of the atmometer events versus time only shows the major trends of the water uptake chart. When the cumulative evaporation from the atmometer (Figure 4-23) and the cumulative water uptake from the scale (Figure 4-21) are compared the relationship is nearly perfect (Figure 4-20)($r^2 = 0.999$). This good correlation is the case not just for single days but for longer periods of time as well. The correlation is good because evaporation from the atmometer is regulated by most of the same factors which influence the transpiration rate in crops. The correlation for cumulative water uptake is much better than for instantaneous water use (Table 4-1)($r^2 = 0.45$). This is most likely due to the discontinuity of the water use measurement.

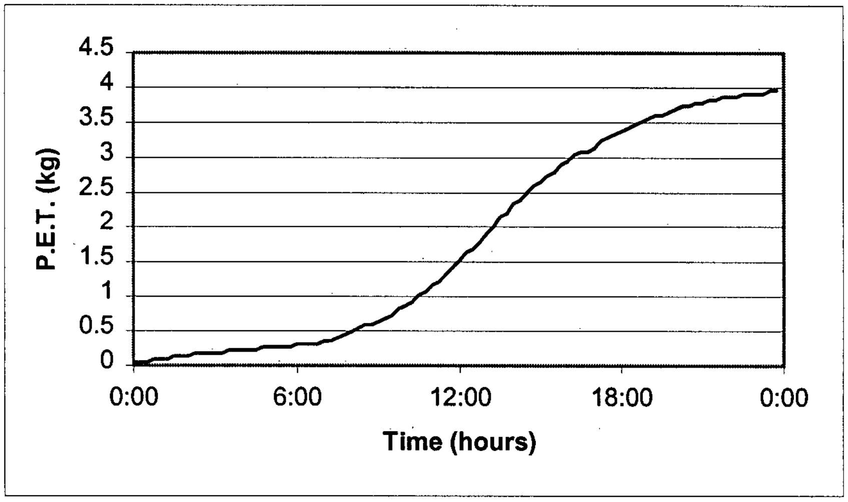

Figure 4-23 Cumulative Atmometer P.E.T. vs. Time

Because of its good predictive abilities pan evaporation has been used for many years in estimating the water use of crops. However, the slope of the line of the transpiration versus evaporation is not one, which means that a scaling factor would have to be used. Again this was to be expected and such values are actually published. The atmometer seems to have the best long-term correlation of all of the sensors tested.

4.1.2.10 Load Cell

The load cells were used to weigh the plant and detect the changes due to growth and water uptake. It is possible to see in Figure 4-10 the steady increase in weight over time as the plant grows and takes up water, as well as events that reduce the weight such as pruning and harvesting.

From the smaller changes in weight (not man made,) it was possible to determine the rate of weight change of the plant (Figure 4-11). It was hoped that a correlation with the water use and this weight change could be derived. The weight of a plant is greatly affected by its water content, as over 90 percent of the plant is water. But the weight changes of the plant do not seem to correlate well with the water uptake. (Figure 4-20) ($r^2 = 0.017$).

It is possible to observe that the greatest water use of the day occurs in the early afternoon (Figure 4-1) although the rate of weight gain becomes negative at this time. This negative rate is probably due to the fact that the plant becomes water stressed at this peak time and withdraws water from its tissue. At night when the demand is much lower the tissue regains this lost weight. This reasoning would also explain why the greatest weight gains appear to be during the night. The lack of correlation is most likely due to the fact that the load cells measure is affected by processes which depend on the previous conditions that the plant has experienced. For this reason it is impossible to state that given a specific weight change, the water uptake will be known.

Over a longer term it is possible to correlate the water use of the crop and the increase that the load cells measure. By summing the weight gain and water use of the entire day and correlating these results, we can get a reasonable relationship. This appears to be a long-term process. In fact the best correlations seem to occur when data from four days is summed up.

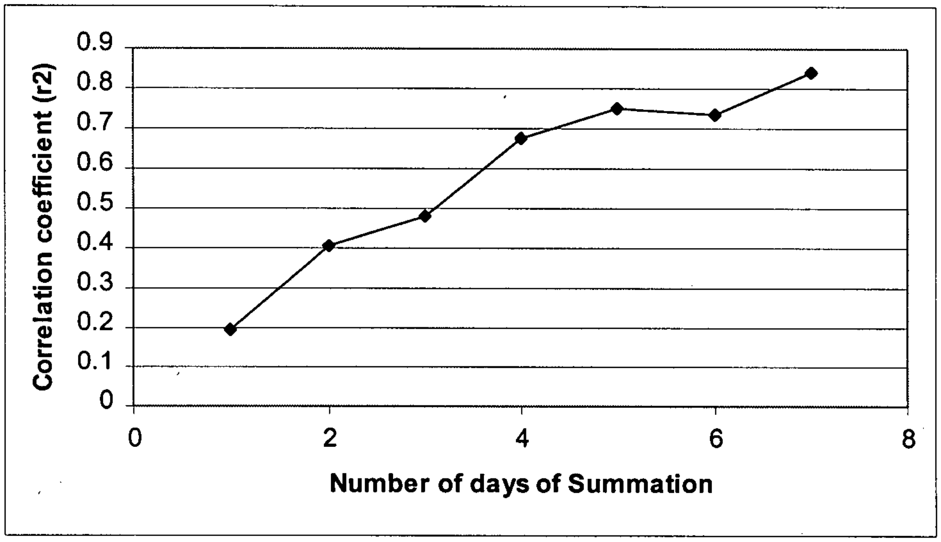

Figure 4-24 Correlation Coefficients vs. Sum Time

Summations longer than seven days do not result in improved correlations (Figure 4-24). This data might be useful to a grower for other purposes but it is much too long-term for an effective irrigation control algorithm.

4.1.2.11 Summary

Table 4-1 provides a summary of the correlations of the various sensors with water use.

line type	Method	Light	Air Temp	Humidity	VPD	Leaf Temp	Air - Leaf	Tensiometer	Atmometer	Load Cell
linear	all data	0.875	0.698	0.525	0.697	0.517	0.575	0.032	0.444	0.017
	day only	0.797	0.644	0.465	0.627	0.432	0.502	0.057	0.454	0.016
logarithmic	all data		0.692	0.516	0.700	0.502	0.630	0.045		0.008
	day only	0.668	0.643	0.444	0.641	0.418		0.043		0.008
Polynomial 2	all data	0.808	0.625	0.430	0.623	0.502	0.630	0.029	0.456	0.023
	day only	0.799	0.644	0.467	0.646	0.428	0.581	0.005	0.458	0.020
Polynomial 3	all data	0.809	0.642	0.525	0.639	0.512	0.643	0.086	0.462	0.024
	day only	0.799	0.644	0.493	0.646	0.434	0.585	0.005	0.463	0.022
Exponential	all data	0.755	0.615	0.519	0.599	0.453	0.510	0.028	0.345	
	day only	0.693	0.560	0.459	0.612	0.366	0.451	0.040	0.370	
Power	all data		0.632	0.493	0.673	0.450		0.039		
	day only	0.784	0.579	0.426	0.538	0.361		0.052		

Table 4-1 Correlation Coefficients of Sensors with Water Use

It is possible to see that the linear model performs nearly as well, and in many cases better than the other types of best fit lines. In general there was normally only a small decrease in correlation when data from the day only was used. The data used for the day only calculations was screened from the overall data set by removing data that occurred when light levels were below 10 W/m^2. In all cases there was at most a five percent improvement with the different types of correlations. However the correlation of the sensor reading with water use was not the sole means for deciding whether or not to continue developing the sensor. There were many other considerations of which the correlation was only a part.

4.1.3 Selection of Sensors for Model Development

In the previous section (Figures 4-2 to 4-23), it was shown that a number of parameters correlate well with plant water uptake. A good correlation does not automatically make a sensor an excellent candidate for irrigation control applications. As discussed previously there are other criteria that must be satisfied for an effective system. Of the sensors we evaluated some performed better that others in terms of predictive abilities but fell short when experience showed that they were either high maintenance, difficult to apply, or unreliable. In selecting the sensors to be used for the development of a control algorithm all of the pros and cons had to be weighed.

4.1.3.1 Sensors that were eliminated

Because of limited resources it was not practical to develop all of the evaluated sensors into irrigation control algorithms. Even though some sensors showed promising results, for one reason or another it was decided that other algorithms would be better, or even just easier to implement. This is not to say that the rejected sensors do not have a place in a modern and efficient greenhouse, just that they may not be suitable for control, or other systems might be easier to work with.

Sap-Flow meters:

Though sap-flow meters were not directly tested here they were previously examined on a tomato crop at Agassiz (Cheng, 1995). This experience showed that the sensors could be quite accurate and give good results in terms of measuring the water use of a plant. It would be relatively easy to set up an irrigation algorithm based on this sensor as discussed in the literature review. The volume of water moving up through the stem would be measured, and when this volume reached a setpoint, irrigation would be triggered. Such a system would be direct and easy to use.

Sap-flow meters were not chosen for further evaluation because of the potential drawbacks associated with them. The greatest drawback for this method is the fact that the sensor has to be in close contact with the plant for the duration of the season. There is a very real danger of the sensor affecting the plant being monitored, and thus, reducing that plant's ability to represent the crop. There is also the unknown effect of heating of the sap on the characteristics of the plant.

The reliability of the heat-pulse method is also a consideration. The sap flow system requires that several sensors all work properly together. Heaters and temperature sensors must behave well and not be affected over time. Another problem is the low sap flow encountered at night. From the literature the accuracy of these sensors can drop off when the flow is very low. Readings under low light conditions might be affected as well. But a main consideration is the problem of representation. How many sap-flow sensors would be required to adequately represent a crop? A sap-flow sensor only measures the rate of flow in a single stem among a crop of hundreds or thousands.

Atmometer:

As we could see earlier the atmometer provided a very good correlation with the water use of the crop. Correlating the cumulative water uses provided an extremely high r^2 value suggesting that the atmometer is a good tool for predicting water usage. The atmometer was not selected for further development because of its operational drawbacks. Though the atmometer is an automatically monitored sensor, it is relatively high maintenance when compared to other sensors. It consumes water (through evaporation) and its reservoir needs to be regularly checked. Because the atmometer measures the evapotranspiration through the use of a mini reservoir, the coarseness of its measurement is determined by the volume of this bulb. If the volume of the mini reservoir is too large then the measurement of transpiration will not be accurate enough on the short-term time-scale required for modern irrigation. If a tip is too small then the instrument is likely unreliable, and/or requiring considerable maintenance. The instrument may also be sensitive to the application of greenhouse pesticides by spraying. If the evaporating surface becomes clogged with spray residue then the P.E.T. estimated by it will be greatly affected. The atmometer also does not take into account the physiological conditions which affect the crop such as disease, plant age and stage of development. Scaling factors would have to be estimated and adjusted as the crop grew and matured. This task would require manual estimation through trial and error.

Tensiometer:

Although tensiometers have been applied elsewhere with apparent success, we found them difficult and unreliable to use, and they appeared to give a very poor correlation with the water use of the plant, and/or the irrigation of the media. The reason for our difficulties might lie with the fact that we used artificial media for our cultivation instead of soil. Tensiometers do not seem to be well suited to the highly porous environment of the greenhouse root zone, requiring much better contact with the media.

As mentioned in the literature review tensiometers can be strongly affected by temperature and may exhibit large error when exposed to relatively rapid temperature changes. Rapid large temperature changes are ordinarily not a problem in greenhouses, but can occur in the root zone, especially when it is heated by a pipe, following the growers guidelines. Tensiometers are also high maintenance. In a highly porous media there is the risk that the water within the tensiometer will be drawn out and an air bubble introduced. Not only will this affect pressure readings, it will also make the tensiometer more susceptible to temperature effects. To ensure that bubbles do not enter the tensiometer they have to be frequently checked. This may or may not entail removing the tensiometer from the media. When part of the problem is usually due to improper contact with the media, removing the tensiometer regularly to check it is a considerable undertaking. A more systemic problem is again that of representation. When working properly the tensiometer only gives the moisture tension at a single point. Porous media drain quickly, and there might be large differences between the moisture content in the top of the bag, or near the bottom. It is not only difficult to decide how many tensiometers need to be placed around the greenhouse to characterize the water use of different plants, it is a problem to decide where to locate the sensor within each individual bag itself. Due to the tensiometers' unreliability, and the problems inherent with using them, they were not selected for further development.

Load cells:

Load cells to measure crop weight do not appear to be useful for determining the short-term water status of a crop; they are unlikely to be useful for the purposes of direct irrigation control. The reason for this apparent lack of short-term correlation is probably due to the fact that weight changes are a result of two factors, water uptake and growth. As the plant takes up water, it increases in weight, but then this water is lost through evaporation. So even if a plant is taking up water at a high rate, it is likely that this water is being lost just as quickly through transpiration; a weight increase does not show up on the load cell.

On a longer term basis (four to six days), there was a reasonable correlation between the growth as measured by the load cell, and the water uptake as measured by the scale. Water use and growth are both related to light levels, so even though water use and growth are not directly related, they are certainly linked. The correlation improves with greater periods of time because plant growth is likely on a longer-term scale.

Even though load cell data could not be directly correlated to short-term water uptake data, the sensors themselves are still useful for monitoring the crop yield and growth. The weight changes that do show up on the load cell plots are due to events that are of great interest to growers. Not only can they see the growth rate of their plants, they can also determine fruit yield due to the instantaneous weight loss (harvesting).

Neural Network:

The neural network analysis that was carried out showed quite promising results. The analysis showed that the neural network could predict water usage quite well, and produce correlation coefficients that were in the high nineties. These were among the best correlation results achieved with all the sensors. In addition the neural network has the ability to learn, and adapt itself to changing conditions. This adaptability would mean that it would be much more flexible than a set irrigation algorithm based on an equation. If properly equipped with a system to measure water uptake in a feedback role, neural networks would have the capability to adjust for changing crop condition, and unexpected events. The neural network was not in a form that could be used for control yet, and in addition we did not have the resources to implement a neural network-based irrigation control algorithm.

4.1.3.2 Sensors that were retained

The sensors selected for further study were not necessarily the ones with the best correlations, but rather they seemed to be reliable, easy to administer, and many are already present in most greenhouses.

Light:

As was to be expected, light provided a good correlation with the water use of the crop. It is for this reason that commercial growers use light sensors to schedule their irrigation. But the correlation of light and water use is certainly not perfect, and there is room for improvement. By itself the light-based approach to irrigation works quite well, but on low light days it starts to fall apart. By using other sensors in addition to the light sensor it is hoped that the strengths of these sensors can be combined to give a more robust and accurate system.

Leaf temperature:

By itself the leaf temperature did not have a strong correlation with the water uptake of the plant, and would not be an adequate means of controlling the irrigation.

However, there was a relation present, and in concert with other variables such as the air temperature, to give the air-leaf temperature differential, it becomes much more practical.

The leaf temperature may also have additional applications within the greenhouse. Currently the VPD is a commonly monitored and used parameter. However the VPD used in the greenhouse industry is merely an approximation. The VPD is a measure of the amount of moisture held in the air within the leaf minus the amount of moisture held in the air. For a VPD measurement to be truly accurate it has to be based on the leaf temperature. Measuring leaf temperature and recording the true VPD would allow a more standardized measure, make it easier to compare between greenhouses, and hence, better recommend what a good VPD is.

The IRT is a much improved means of measuring leaf temperature than the traditional thermocouple or thermistor. By avoiding contact with the leaf there is less opportunity for sensor influence, wounding, or otherwise interfering with the normal operation of the leaf. In addition because of the nature of the IRT, the temperature measured is an average of the leaf area the IRT is pointed at, rather than a single point, as for other temperature sensing equipment. This average temperature further helps to make the IRT a more representative technique for monitoring leaf temperatures.

Air temperature:

By itself the air temperature is not a good sensor for determining when to irrigate. The correlation between the air temperature and the water use is actually quite poor. The air temperature is certainly a very commonly monitored parameter in most greenhouses. When used with other sensors, however, its usefulness for controlling irrigation can increase. The air temperature is also an important factor in the calculation of both the VPD as well as the air-leaf temperature differential.

Humidity:

As is the case with the air temperature, humidity by itself is not a good means of estimating the water use of crops. When used in conjunction with other sensors, the humidity can play a significant part in the prediction of transpiration. Humidity is another variable that is very commonly measured and recorded. A more popular use of the humidity reading is in the calculation of the VPD, which is normally used more that just humidity by itself (the growers are more interested in the moisture-holding capacity of the air which is also a function of the temperature). The VPD also shows quite good correlation with the water use of the crop.

4.1.3.3 Summary

A sensor's ability to predict the water use of a crop was not the sole criteria upon which the sensors to be developed into a control algorithm were chosen. The ease of use, implementation and availability were also considered.

By themselves variables such as the air and leaf temperature and the humidity cannot predict water use very well, but they are commonly measured greenhouse parameters. Even though individually these sensors do not perform remarkably well, when they are used together the results they give are a dramatic improvement, especially when used in conjunction with a light-based system. These additional sensors can also operate at night and under low light conditions; they can improve the light-based system more-so on these days than on high light days. This ability has important consequences for irrigation control systems that are to be used year round through the periods of relatively low light in the winter months.

4.2 *Year 2*

In the second year of the experiment new irrigation control algorithms were developed, implemented, and evaluated.

4.2.1 Development of Algorithms

Once the individual sensors that showed the most promise for developing an irrigation control algorithm were decided upon, more complex relationships involving combinations of these variables were attempted. By using the output from many different sensors it was hoped that the resulting estimation of the transpiration would incorporate the strengths of each sensor, and improve the estimate. It was also desired that sensors monitoring the span of the plant-environment continuum would be evaluated; the new control algorithms would not just be a variation on a single technique.

For this reason two new control algorithms were developed. The equation-based multi-sensor algorithm used sensors which monitored the plant's environment, as well as the plant itself with the leaf temperature sensors. Since no reliable soil moisture monitoring sensors were found, it was decided to use the scale itself to indirectly monitor the moisture content of the media and water uptake of the plants.

4.2.1.1 Development of Equation-Based Algorithm

Based on the previous evaluation of the individual sensors, it was decided that the remaining sensor results would be combined together into a multivariable equation of the form:

$$E_t = b_o * I + b_1 * vpd + b_2 * \Delta T + b_3 * T_p + b_4$$

To check the relative weight of each sensor in improving the estimate of transpiration, a number of models were developed using combinations of the sensors. Based on these tests it was found that light was by far the most important variable with a light alone estimate giving an r^2 of 0.765. If the VPD (simply calculated), was added to this relation then the r^2 would improve to 0.794. Further improvement was possible with the addition of the leaf-air temperature differential to r^2 =0.801, and with the addition of the air temperature, r^2 = 0.814.

When used on all the data, the leaf-air temperature differential, and the air temperature do little to improve the r^2 value. However, on days where the amount of light received is low (> 10 MJ/m^2), they do improve the correlation coefficient. For this reason they were retained in the final model.

A more complicated model might have given a slightly better correlation coefficient but it was felt that the correlation coefficient from this model was sufficiently high for a control algorithm. As was the case of the individual sensors being fitted to more complicated models such as logarithmic and polynomial relations, the improvement in the correlation coefficient was quite small. In addition it would have been considerably more effort to develop a non-linear relation. There was also the difficulty in implementing a complicated equation on the datalogger for control purposes. Overall the simple linear equation-based algorithm was felt to be adequate for control algorithm comparisons.

To verify the ability of the equation to predict the water usage of the crop, several days of data were left out of the development of the model. Days with high, low and medium light were excluded. The model was then applied to the collected data and the predicted water usage compared to the actual water usage.

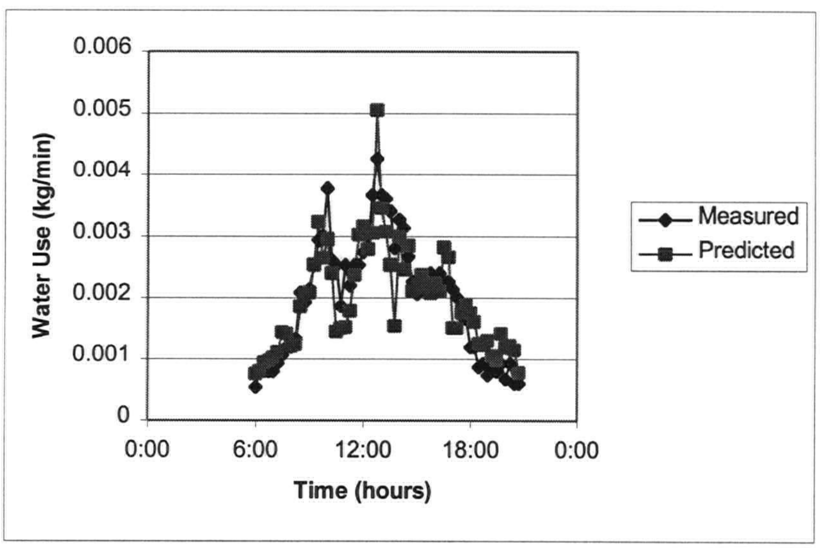

Figure 4-25 Predicted and Measured Water Uptake

Figure 4-25 shows the predicted and measured transpiration on a typical medium light level day. Based on the similarity between the two lines the model appears able to predict the transpiration quite well.

Julian day	Day light type	Correlation Coefficient
167	high	0.734
181		0.913
185	low	0.771
196		0.892
241	med	0.973
243		0.940
all 6		0.910

Table 4-2 Correlation Coefficients of Predicted and Measured Water Uptake on Days Used for Model Validation

For the six days that were excluded from the development, the correlation coefficients are shown in Table 4-2. It is possible to see that the model performed well on both the high and low light days with the best performance on typical medium light days.

4.2.1.2 Development of Scale-Based Algorithm

The development and implementation of the scale-based algorithm involved a number of considerations. Though no model development was required an algorithm for operating the scale and interpreting its raw output had to be created.

One consideration was the sensor scanning frequency, or how often the weight of the scale would be checked and then used for a transpiration estimation. If the measurements were too far apart then important data might be lost during an error event. In addition the frequency of the measurements had to allow for the high frequency waterings required by modern greenhouses. Based on the precision and accuracy of the scale, it was felt that a measurement every twenty seconds would be adequate. At this rate irrigation events that lasted one minute could easily be observed and filtered out.

Also of importance was the determination of a valid maximum transpiration. This number was important for filtering out error values. The maximum transpiration was determined by examining the previous year's data and finding the maximum transpiration rates on a single plant basis for many days. Once this value was found, a safety margin of 20 % was added to it. Most disturbances created much more variation in the weight than this number.

To ensure adequate watering of the plants, the setpoint for irrigation was set at least 30% lower than the irrigation volume supplied by a watering event. This surplus water was then used for leaching the media of excess salts. For the experiment here the leaching fraction was set quite high to ensure that there was always adequate leaching occurring.

4.2.2 Evaluation of Algorithms

To evaluate the control algorithms there were a number of comparisons that we developed. Comparing irrigation control systems that are based on differing concepts is not straightforward. The different systems have their own strengths and weaknesses, and the selection of comparisons has to be as impartial as possible, and try and take into account as many conditions as possible. It is, therefore, impossible to say that one system is better than another, rather, one system performs better under certain circumstances. For this reason we attempted to compare various aspects of the system's performance, under differing environmental conditions.

Measuring the water use of the plant is very important in judging whether or not it requires water, and hence in comparing these algorithms. To examine the validity of estimating water use as calculated from irrigation and leachate amount, correlations were done between the water use measured in this method and also by the electronic balance. The correlation was very high (>0.95), (Figure 4-26) so it was felt that this was a valid means of determining water use. Two bags from each algorithm were measured for leachate, for a total of six bags monitored. It was much easier to monitor the water use this way, and required considerably less datalogger resources to accomplish.

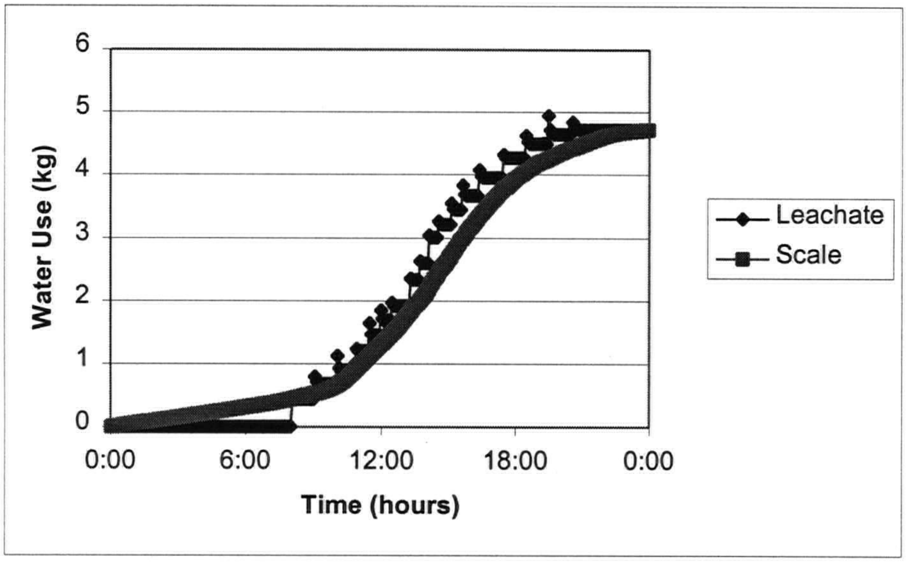

Figure 4-26 Cumulative Water Use as Measured by the Scale and Leachate Collection Techniques

4.2.2.1 Environmental Comparisons

To compare the effectiveness of the three algorithms under differing environmental conditions we selected light as a basis for comparison. We chose light as a parameter for comparison because it is the one over which the growers have the least direct control. The light levels are still heavily influenced by weather, and though the use of artificial lighting can increase the level of control a grower has, it is very expensive. Most other environmental parameters are much more readily adjustable.

Because light varies dramatically throughout the day, we used a light sum approach to compare the light levels from day to day. All of the light energy for a single day is summed up in a method similar to the technique used for controlling the light integral method. This is a relatively good means of comparison as we can see in Figure 4-27, where the water use of the entire day, calculated from irrigation-leachate, is correlated to the radiation received on that day.

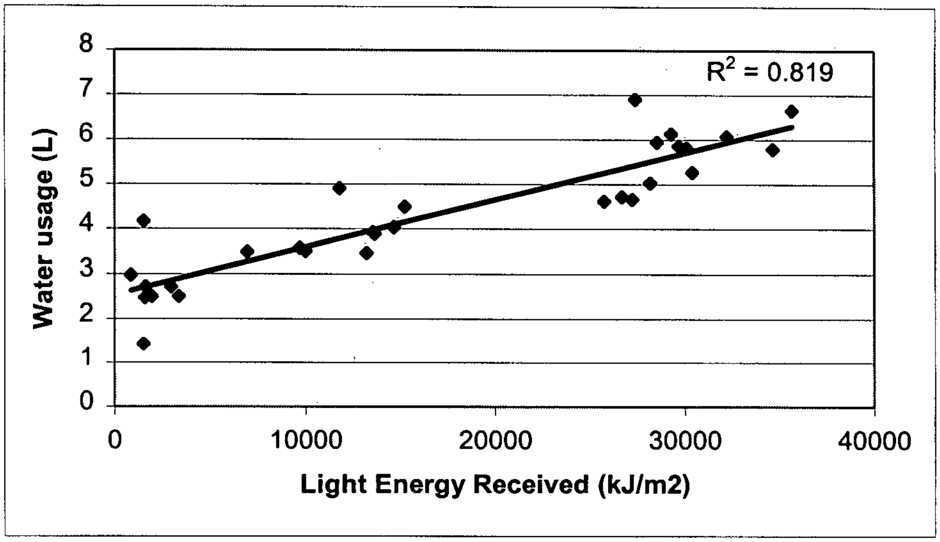

Figure 4-27 Water Use Versus Light Sum

Over the course of the experiment the light levels varied considerably as the season changed from summer to fall. Figure 4-28, illustrates how the light levels varied over the course of the experiment.

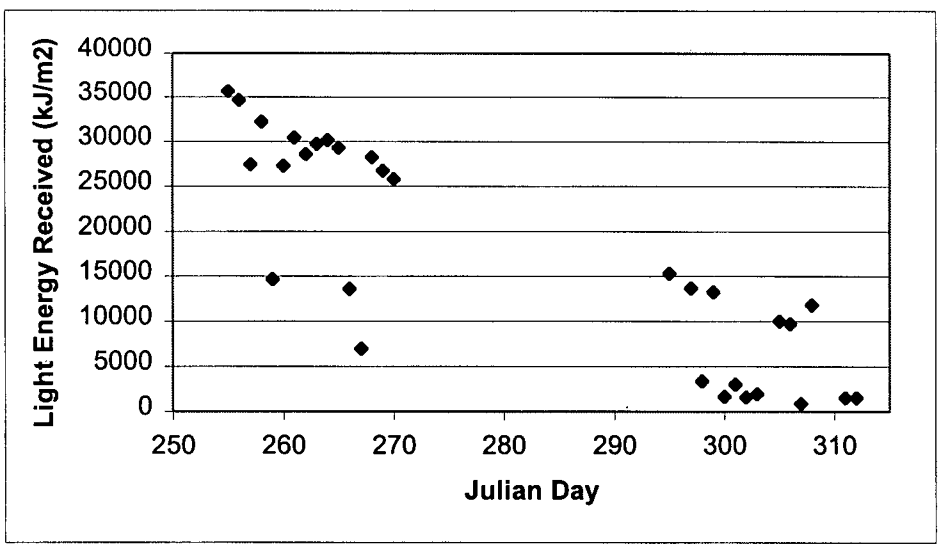

Figure 4-28 Daily Light Sums During the Experiment

4.2.2.2 Simple Performance Evaluation

Before comparing the individual aspects of the control systems, it was necessary to evaluate how the systems worked in general. To compare the overall ability of the system, we examined the water use of the individual bags. Because the crops were all grown under the same environmental conditions, were all of the same age and variety, the water use of all of the bags should be approximately the same.

As can be seen in Table A-1 (Appendix A), there was some variation among the algorithms, but on the whole the water consumption was approximately the same for the three systems at a 95% confidence level. We can show that not only was the crop relatively homogeneous, but that all the algorithms worked successfully. If we examine the systems in terms of light we can see that all systems used more water on high light days, and less on the low light days, as should be expected.

4.2.2.3 Irrigation Occurrence Comparison

To compare the irrigation frequencies of the various control algorithms, we looked at all of the irrigation events that took place during the course of the experiment. One requirement of the greenhouse growers guide is that the plants are watered at least once per hour during the daylight hours. Because the light-based approach had this safety mechanism built into its program, it obviously satisfied this requirement. The other two algorithms did not have this built in safety mechanism, so they had to be checked. To do this, the periods between the irrigation events during daylight hours were determined, and their minimum, maximum, and average values calculated (Table 4-3).

	Light	Equation	Scale	Scale *
average (min)	0:51	0:46	1:25	0:56
minimum (min)	0:21	0:20	0:13	0:13
maximum (min)	1:02	2:13	8:31	4:22
st. deviation (min)	0:14	0:19	1:21	0:39
# of events	479	510	377	325

* Day only

Table 4-3 Comparison of Irrigation Frequencies

From Table 4-3 and the maximum times between irrigation, we can see that the equation-based approach nearly satisfied this requirement, and the scale-based approach did not come close. However this is not to say that these methods are invalid; it only means that during certain hours of the day, the setpoints should have been adjusted. This also indicates that the crop may not require irrigation as frequently as the grower guide recommends. However irrigation water also supplies oxygen to the roots, and this may be where the one hour limit was developed from. As can be seen from Table 4-3, the average time satisfied the one hour limitation, and none of the control methods resulted in extremely large gaps of irrigation occurring (other than overnight), which means that all algorithms worked adequately.

We also compared when the irrigation events took place during the day. Again the light-based approach was different from the other two systems in that it had the ability to force an irrigation if one had not taken place in a specified time. The light and equation-based approach were also both disabled at night. The light-based was disabled because of the fact that there is too little light to trigger an irrigation. The equation based system was disabled because it was developed excluding night data. Initially it was run at night, however too many irrigations were triggered at this time, and because this posed a health risk to the plants it was discontinued.

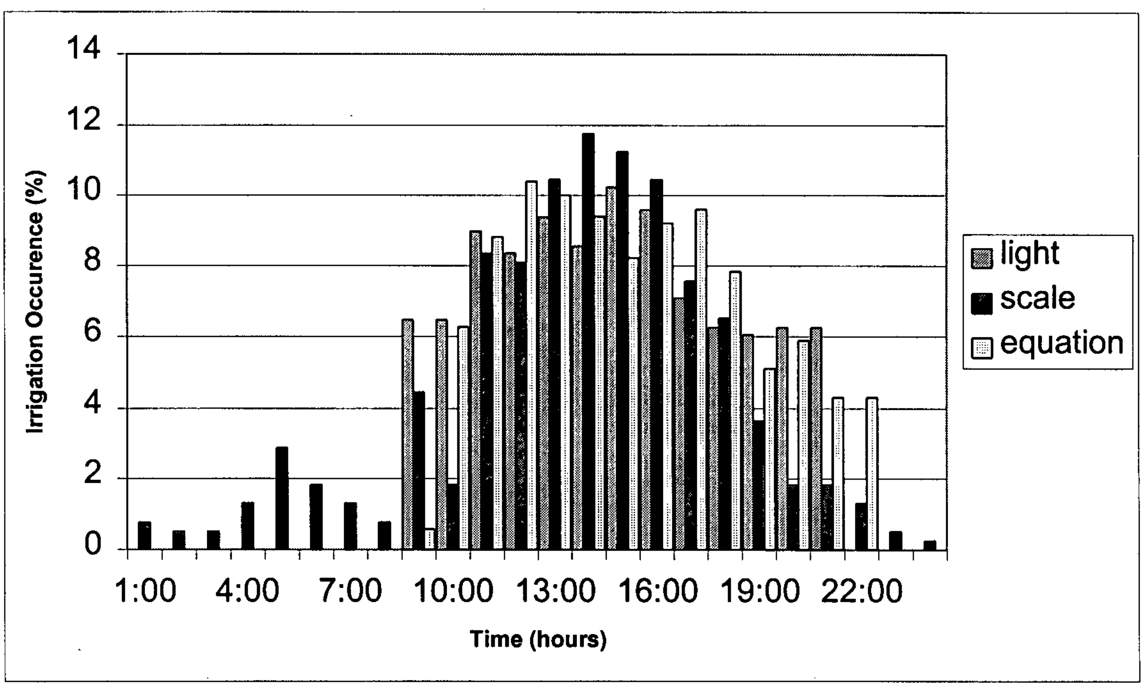

Figure 4-29 Histogram of Irrigation Events Over the Entire Experiment

To better illustrate when the irrigation events took place for each method over the entire experiment, a histogram was created from all of the irrigation events. (Figure 4-29) All of the irrigation events and their times for the entire experiment were used to create the histogram which represents the percentage occurrence. As can be seen from Table 4.3, the number of irrigation events, for the three algorithms were different. For this reason, the percentage of occurrence was used rather than the absolute number of events.

As was to be expected the light and equation-based approaches were limited to certain hours of the day, with the highest frequency of irrigation taking place in the early afternoon. The scale-based approach is quite different; it was not limited in its ability to operate at night, as can be seen from the chart. The bulk of its irrigation also took place in the early afternoon, like the other two systems. It is interesting to note that the scale-based approach quite frequently triggered a pre-dawn watering at approximately 6 a.m. and that this night watering was more likely to occur at this time than at any other time during the night. It is also interesting to note that the peak of the scale base approach seems much more defined around 3 p.m. and is much sharper that the other two methods whose peak seems spread over several hours.

Based on the histogram we can see that all methods demonstrated their ability to provide adequate water during the high demand middle of the day. We can also see that the scale-based approach has the unique ability to reliably supply water at night, and that according to the scale significant amount of transpiration occurs at this time, enough to trigger 7% of the scale's watering events.

4.2.2.4 Comparison of Consistency

For most greenhouse operations, the frequency of irrigation is the most important consideration. The frequency check does not take into account whether the crop actually requires water at that time, and whether or not enough or too much water is applied. To determine how well each algorithm can provide this information we have to look at the volume of leachate produced by the irrigation systems.

Compare within a day

Normally within commercial greenhouses the irrigation setpoints are adjusted to provide varying volumes of leachate throughout the day. Growers generally like to start with very little leachate in the morning and increase up to even 40% on bright days by the afternoon. On dark days they generally like to keep the leachate fractions quite low (Portree, 1996). Because it was not possible to constantly adjust the irrigation setpoints on our control systems, our setpoints remained constant, and were not adjusted to lower the leachate fraction in the morning or adjust for variable weather. Theoretically all of the control algorithms should have maintained a constant level of leachate fraction throughout the day.

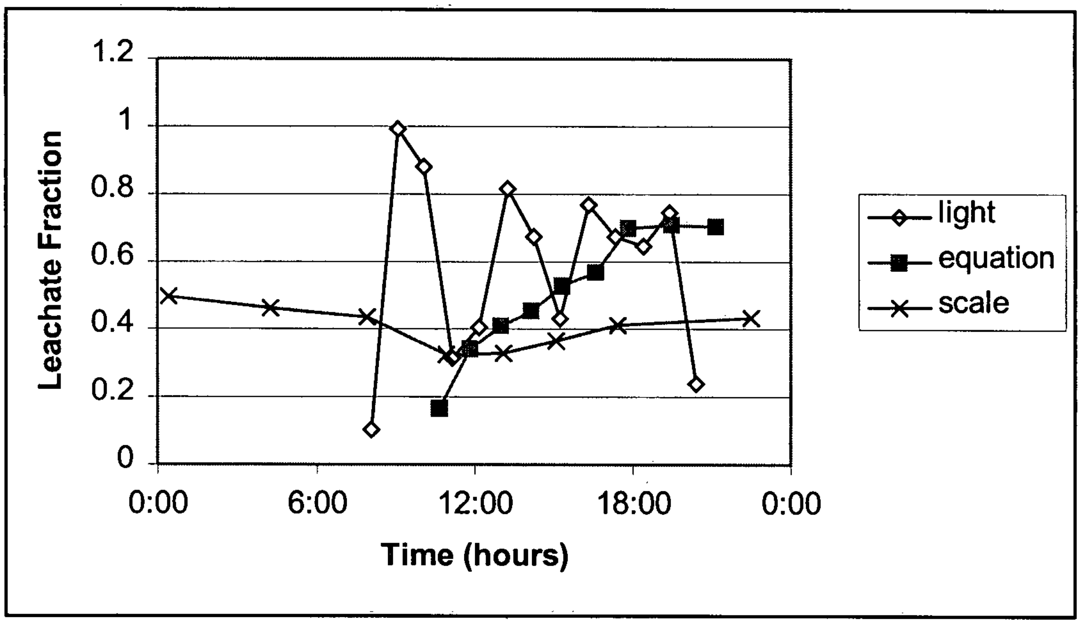

Figure 4-30 Leachate Fraction Throughout a Typical Day

Figure 4-30 is a chart of a typical days leachate fraction. The absolute values of these can not be compared because of the differing setpoints, however the variability within them can be seen. The light and equation-based algorithms appear to be quite similar in terms of starting out with a low value of leachate, which steadily increases throughout the day. This is due to the fact that no waterings occurred during the night for these algorithms, and the media has dried out considerably. It takes a few waterings before enough water has passed through to adequately saturate the media. The scale-based approach tends to maintain a more constant level because of the fact that the media is not allowed to dry out as completely as the other methods. From these charts we can see that the scale-based approach tends to have the least amount of variability of leachate fraction within a day.

Comparison over the entire experiment

Only by examining the three methods over the course of the entire experiment, can the true competency of each algorithm be seen. Because of the variability of the irrigation amount and the resulting change in the leachate fraction it was not possible to directly compare how the absolute value of the leachate fractions changed from day to day. Instead we have chosen to examine how the variability of the leachate fractions changed.

To do this calculation the leachate fractions within a day were calculated by dividing the amount of leachate produced until the next irrigation, by the amount of water applied after every irrigation. Once these were calculated throughout the day, the standard deviation of the leachate fractions was determined. This was carried out for all of the days. The results are presented in Table A-2 (Appendix A).

From this table we can see that overall the scale-based approach had the least variability followed by the light and equation-based approaches. There was little difference between the light-based approach and the equation-based approach whereas the scale-based approach apparently had half as much variability as the other two methods. A large source of the error for the light and equation-based approaches is the fact that in the morning their leachates were quite high because they could not be watered during the night. This was not an issue with the scale-based approach and so it was able to better maintain a steady leachate fraction. The lack of improvement of the equation-based approach might be due to the fact that it was developed with data from a different location than from where it was applied. The equation based approach also did not have an irrigation forcing constraint which might have assisted it in the morning and afternoons.

To see the effect that light has we can compare the light sums versus the standard deviations for each of the days. By attempting to correlate the light sum to the standard deviation we can see if there is a relationship between the leachate fraction variability, and the environmental conditions. A high correlation coefficient means that the variability of the algorithm is highly dependant on the light levels or that on low light days the system is unable to perform efficiently.

Algorithm	Light	Scale	Equation
Correlation Coefficient	-0.437	0.015	-0.333

Table 4-4 Correlation of Water Use Coefficient Standard Deviation with Daily Light Sum

The results of this correlation are presented in Table 4.4. The correlations are negative because as the light levels increase, the standard deviations decrease. It is immediately apparent that the relationship is much stronger with the light and equation-based approaches than with the scale method. This demonstrates that the light-based approach does not do as well in low light conditions, and that accordingly the predictability and consistency of the water use coefficient decreases. The equation-based approach is a small improvement on the light-based one. The scale-based approach is not affected as strongly, and indeed the relation is quite poor, suggesting that the scale-based approach is not nearly as affected by low light levels as the other two techniques.

4.2.3 Advantages and Disadvantages of Algorithms

When all three systems are considered as a whole, it is apparent that there are several advantages and disadvantages associated with each technique. The choice of a specific control system will depend on the priorities a grower has, as well as the application it will be used for. It requires judgement on the part of the grower if the advantages of one system outweigh its associated disadvantages.

4.2.3.1 Light-Based

Pros

- It is simple to administer and performs quite well.
- Only one sensor type is required to operate this algorithm, and a few located around the greenhouse can adequately estimate the light levels.
- There is considerable experience in using this algorithm; growers know what irrigation setpoints to use, and how to use them.

- The light sensors do not need frequent calibration; they are very reliable and do not have moving parts, or come into contact with substances such as sprays or water which might affect their readings.

Cons

Inefficient application of irrigation water can lead to unnecessary costs and complications for a grower. Such inefficiencies arise out of the following disadvantages of the light-based approach.

- Because of its simplicity, it does not take into account other important environmental factors which affect transpiration.
- It does not work as well during the night, and under low light conditions; as growers switch to year round production, these can be the conditions experienced for several months of the year.
- It requires specific setpoints for different kinds of crop, growth stage, season, etc. It is no longer as easy to predict setpoints, as growers switch to continuous cropping systems or staggered production.
- Considerable expertise is required to administer and adjust setpoints everyday based on the weather forecast, and the previous performance of the crop.
- Growers have discovered a need for occasional night watering, which the light integral method is incapable of delivering.

4.2.3.2 Equation-Based

The Equation-based approach is very similar to the light-based approach in terms of its relative strengths and weaknesses. Both of the systems are based on indirect measurements used to predict the water use of the crop.

Pros

- Its performance is less influenced by light level than the traditional light-based approach.

- It uses sensors (vapor pressure deficit, and air temperature) which are already in place in most commercial greenhouses, hence it does not require investment in new sensors or equipment.
- With further development it might be possible to develop a model which could administer irrigation at night.

Cons

- Because it takes into account more factors, this technique requires more sensors to be in place and working properly; operating and maintenance costs will increase.
- The infrared thermometers can pose a problem of representativeness, as they only cover a relatively small portion of the canopy surface area; if they are improperly aimed they might not pick up the correct temperature. They are also susceptible to disturbance from the workers.
- An equation-based algorithm is susceptible to error when conditions outside the norm (such as extremely hot days, or low light periods) are encountered.
- Like the light integral method, this technique suffers from the same problem in terms of different crops requiring different models and/or setpoints.

4.2.3.3 Scale-Based

Because the scale-based approach is based on different principles than the other two techniques, it has quite different advantages and disadvantages.

Pros

- It actually measures the water use of the plant, whereas the other two algorithms' performance suffers because they have to estimate the transpiration.
- Because transpiration is measured and not estimated, this algorithm is not affected by conditions that are outside the norm, it merely supplies water as the crop uses it.
- This algorithm has the ability to work at night, so it is no longer a guessing game as to when to apply night irrigations..

- The sensors are simple and reliable, and it is very easy to check their calibration, whereas light sensors need to be returned to the manufacturer on a regular basis for calibration.
- The information supplied by the sensor is valuable, not just for irrigation control, but for other greenhouse parameters as well. Through feedback of the water use, a climate control algorithm could adjust the environmental setpoints to produce an optimal transpiration (Stanghellini and Van Meurs, 1993).
- With the use of the scale, the irrigation amount may be verified every time there is a watering with no manual disturbance. This is especially useful for older irrigation systems where variations are much larger.
- The water use measured by the scale could be used to better calibrate other control algorithms such as the light-based approach, for instance, via adjusting the light-based setpoints automatically.
- The scale can be set up to examine multiple plants at once so that the measurements are more representative.
- This approach is also not crop specific and could easily be applied to other vined crops, as long as the crop weight is separated from the weight of the media.
- This algorithm can be readily applied, without being affected by the health of the crop, or the variety.

Cons

The scale-based system has problems that the other two algorithms did not have.

- Because the scale-based system measures the water use of some plants directly, if these plants cease to become representative of the crop then the system will not work as well. This means that the plants on the scale have to be closely monitored for signs of disease or insect infestations.
- If the system is not closely monitored and the irrigation amount supplied falls below the transpiration setpoint, then transpiration cannot occur as the soil becomes depleted of water. If transpiration does not occur then no further irrigations will be triggered.

- It involves maintenance tasks such as the draining of the collected leachate, which may have to be done daily, or at least every two days in bright weather.
- The scales might be difficult to locate in the greenhouse in that they can restrict the space available for workers to move and work within the aisles.
- This algorithm is very dependent on a single type of sensor, and will not function if this sensor is reading incorrectly. If part of the media is resting on the ground, or there is a slow leak allowing the leachate to leave the scale then the measured value will not be the transpiration.
- A more serious drawback occurs when the crop is just being started out and there is little canopy. A smaller canopy and very low transpiration rates will not register on the scales very well, and so this system could probably not be used for a starting crop. Some other system such as the light-based would have to be used for the beginning of the season.
- This system will only work on crops which are supported by a wire. The other algorithms do not have such a requirement, but for the scale-based method to give an accurate estimate of the water use, the weight of the plant has to be off the scale, whether that is resting on the ground, or supported by a wire.
- In terms of representation the scale-based approach requires considerable resources to look at several plants. Usually nine to fifteen plants can be supported by two scales and give good results. This means that to better quantify the crop transpiration many more scales would need to be employed.

5 Conclusions and Recommendations

5.1 Conclusions

The main objective of this thesis was to develop alternate irrigation control algorithms that could better match the supply of irrigation water with the needs of a crop. With such abilities the environmental and economic sustainability of the greenhouse industry could be improved.

To accomplish this goal new and conventional sensors spanning the entire soil, crop, and environment continuum were examined and evaluated. After consideration, it was decided that initially we would examine: tensiometers, thermocouples, IRTs, load cells, atmometers, as well as the commonly measured parameters of light, humidity (vapor pressure deficit), and air temperature. From this evaluation light, humidity, leaf, and air temperature sensors were selected for further development into functioning irrigation control algorithms. The reasons for sensor selection were based not only on their correlation with crop water use, but also with their availability, reliability, and ease of implementation.

Once identified as good candidates these sensors were used to create an equation-based irrigation control algorithm that sought to combine the strengths of these sensors into a more efficient control system. Through this composite, the predictive ability could be improved approximately ten percent more than simply by light alone.

An alternate control algorithm utilizing the water use as measured by an electronic balance was also developed. This algorithm functioned by summing the weight changes that occurred over a short duration, rather than by examining the absolute weight of the media. By functioning in this way erroneous data could be filtered out. In addition the complications of changes in weight of the media over time due to decomposition and root growth could be eliminated.

The two new irrigation control algorithms were evaluated and compared with the traditional light integral technique over the course of a growing season. All of the evaluated control algorithms functioned properly and did not result in any undue plant stress. The water usage of all of the plants used in the experiment was statistically consistent across methods suggesting that there were no ill effects due to a particular technique.

The two new irrigation control methods did not produce an irrigation event once per hour during the daylight hours as the growers guide suggests, although this did not appear to have a negative effect on the crop. To achieve hourly waterings the setpoints of the algorithms would have to be adjusted. The frequency of the scale-based algorithm seems to indicate that irrigating once an hour may be too frequent on low light days, and wasteful of water. All algorithms seemed able to supply water in the peak demand time of the early afternoon. The scale-based approach had the added benefit of being able to operate at night, whereas the other two could not.

The consistency of the irrigation was tested by examining the occurrence of leachate. If the leachate fraction remained relatively constant throughout the day then the control algorithm was judged successful. It was found that the scale/lysimeter-based approach to irrigation control had the least variation in the volume of leachate it produced suggesting that it could better match the needs of the plant to supply. The equation-based approach performed nearly as well as the light-based technique.

The results have demonstrated that the concept of using plant water uptake for irrigation control is feasible, and such control algorithms could be successfully implemented on a greenhouse climate and irrigation control computer.

This research found that it is feasible to use load cells to measure leachate amounts, and to use such measurements as means to determine plant water use. By monitoring the leachate, it is possible to see when the plant is using water, and then compare that to when the irrigation system is supplying it.

All of the algorithms have their associated advantages and disadvantages and the quality of their performance is a function of the conditions under which they run. None of these systems alone is superior to the others under all situations. A successful irrigation control algorithm will utilize the techniques and information that all of these systems can provide to better judge when to water.

The goal of conservation of water and nutrients will be achieved by giving the growers a more precise means of matching supply with their crops water needs.

5.2 Recommendations

Several aspects of the project could be investigated further. Better comparisons and refinements of the existing algorithms should be carried out, as well as the implementation of new developments.

To truly compare these algorithms fairly, they need to be tested in a full-scale commercial greenhouse, and be implemented on a system that would allow frequent adjustment of their setpoints. The traditional light-based approach requires constant adjustment, whereas we could not provide such attention throughout the experiment. Further tests might be able to compare the ease of use, reliability as well as the time required to maintain the systems. A full-scale setting would also provide a means of detecting and quantifying any effects on crop yield or quality that the algorithms would bring about. Before any of the new algorithms could be implemented on a full-scale basis, work would have to be done to determine how many sensors would be required to adequately represent the crop. In terms of the scale-based approach, how many scales with how many plants would be required? In addition the influence of location in the greenhouse would have to be examined.

The scale and equation-based algorithms should also be tested with leachate fractions that vary throughout the day. This is the usual commercial practice and would be a true test of their predictive abilities.

With more development it may be possible to modify the equation-based algorithm so that it will function at night. This could be achieved by developing different coefficients for night periods. Once light levels drop to a certain level, the coefficients would be replaced with the low light ones.

All of the irrigation control algorithms developed and discussed here could be improved with feedback from an automatic leachate sensor. It would be possible to adjust the setpoints of the various algorithms automatically based on the amount of leachate received from the previous watering. If not enough leachate was produced, then the setpoint could be automatically lowered so that irrigation would occur more frequently. If too much leachate is produced, then the setpoint would be increased to space out irrigation and allow the plant a chance to use more of the water. A further step would be to examine the EC of the leachate and to set the leachate amount based on this information. If the EC remains quite close to that of the feed then the amount of leachate required would be less. If, however, the difference between the leachate and feed EC becomes too great, then the volume of leachate applied would be increased. The setpoint would then become the desired EC difference between feed and drain.

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Appendix A Summary Tables

Julian day	Light 1 kg	Light 2 kg	Scale 1 kg	Scale 2 kg	Equation 1 kg	Equation 2 kg	lightsum kJ/m2
255	6.66	9.31	8.22	6.49	5.72	3.50	35668
256	5.79	8.76	4.77	5.33	13.00	4.79	34656
257	6.90	5.62	5.62	5.02	12.50	4.43	27433
258	6.07	4.99	4.95	4.92		4.38	32230
259	4.04	4.08	3.60	3.60	8.50	3.21	14657
260	4.66	4.60	4.52	4.24	9.00	4.12	27263
261	5.27	5.53	5.18	4.94		4.99	30409
262	5.94	5.58	4.55	4.84		5.55	28568
263	5.85	5.25	5.17	4.81	4.43	4.82	29709
264	5.81	8.82	5.53	5.43	10.50	4.92	30120
265	6.13	5.46	6.05	5.68	11.50	5.03	29308
266	3.92	3.77	4.17	3.91	3.38	3.52	13567
267	3.48	3.29	2.83	2.72	3.00	2.83	6932
268	5.03	5.37	5.28	5.44	8.50	4.90	28188
269	4.71	4.59	4.94	4.74	8.50	4.75	26721
270	4.62	4.68	4.89	4.42	3.96	4.56	25774
295	4.48	4.27	3.70	4.30	4.71	4.72	15251
297	3.88	5.81	3.50	3.20	6.40	3.95	13665
298	2.51	2.12	1.56	1.45	0.99	2.22	3363
299	3.46	3.20	3.32	2.98	2.23	3.84	13236
300	2.71	2.31	2.01	1.97	1.10	2.09	1611
301	2.71	2.39	1.60	1.52	0.89	1.80	2976
302	2.48	2.61	1.70	1.51	5.94	1.61	1595
303	2.50	5.40	1.62	1.46	5.94	1.78	1940
305	3.50	4.42	3.71	4.14	2.62	3.10	10013
306	3.57	3.82	3.07	3.30		2.82	9717
307	2.98	3.04	2.02	1.81	4.50	1.79	857
308	4.90	4.96	4.84	3.44	5.85	4.29	11810
311	4.16	2.58	1.55	1.55	2.59	2.11	1510
312	1.42	2.23	1.52	1.44	4.50	1.58	1507
average		4.48		3.78		4.70	
min		1.77		1.48		1.24	
max		8.10		7.35		9.28	
stdev		1.65		1.60		2.39	

SUMMARY: Anova: Single Factor

Groups	Count	Sum	Average	Variance
Light1	30	130.14	4.34	2.02
Light2	30	138.84	4.63	3.52
Scale1	30	115.95	3.86	2.80
Scale2	30	110.56	3.69	2.35
Equation2	30	107.99	3.60	1.58

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	23.507906	4.00	5.88	2.3968	0.0530	2.4341
Within Groups	355.54539	145.00	2.45			
Total	379.05329	149.00				

Table A-1 Water Use Throughout Experiment

Julian day	Light 1 kg	Light 2 kg	Scale 1 kg	Scale 2 kg	Equation 1 kg	Equation 2 kg	lightsum kJ/m2
255		0.132	0.164	0.234	0.256	0.104	35668
256	0.239	0.111	0.108	0.119		0.183	34656
257	0.188	0.153	0.185	0.159		0.193	27433
258	0.136	0.184	0.116	0.066		0.161	32230
259	0.184	0.145	0.128	0.176		0.169	14657
260	0.165	0.119	0.037	0.042		0.213	27263
261	0.158	0.090	0.098	0.121		0.214	30409
262	0.172	0.125	0.066	0.032		0.171	28568
263	0.163	0.129	0.041	0.073	0.212	0.246	29709
264		0.141	0.063	0.059		0.215	30120
265	0.176	0.128	0.057	0.045		0.230	29308
266	0.217	0.133	0.029	0.059	0.097	0.186	13567
267	0.161	0.099	0.035		0.104	0.204	6932
268	0.197	0.109	0.115			0.285	28188
269	0.205	0.132	0.070			0.227	26721
270	0.205	0.119	0.042		0.218	0.214	25774
295	0.200	0.151	0.117		0.126	0.179	15251
297		0.209	0.207	0.150		0.252	13665
298	0.186	0.150	0.036	0.033	0.183	0.232	3363
299	0.249	0.181	0.127	0.140	0.195	0.208	13236
300	0.123	0.176	0.205	0.327	0.291	0.266	1611
301	0.178	0.146	0.079	0.065	0.201	0.233	2976
302	0.156	0.135	0.089	0.102		0.241	1595
303		0.149	0.085	0.085		0.232	1940
305	0.165	0.397	0.100		0.225	0.247	10013
306	0.175	0.308	0.051	0.137		0.240	9717
307	0.130	0.299	0.062	0.089		0.185	857
308	0.157	0.435	0.082	0.092			11810
311	0.196				0.257		1510
312	0.159	0.311	0.112			0.202	1507
average		0.18		0.10		0.21	
min		0.09		0.03		0.10	
max		0.44		0.33		0.28	

Table A-2 Standard Deviations of Water Use Coefficient Throughout Experiment