DYNAMIC ANALYSIS
OF WATER AND NUTRIENT UPTAKE FOR
NEW GUINEA IMPATIENS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

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* * * * *

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To

my parents,

my wife and my son
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ASAE Paper No. 88-1561. ASAE. St. Joseph, MI

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FIELDS OF STUDY

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Digital Measurement and Simulation
Environmental Control in Agriculture
Expert Systems
Heat and Mass Transfer
Greenhouse Management
Microclimatology
Plant Nutrition Studies
Plant Physiology
Soil and Water
Tractor Traction
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CHAPTER I
INTRODUCTION

Water and nutrient use in greenhouse production were the most important topics in this study because both are critical factors for the agriculture industry now and in the future. Global environmental protection regulations demand that agricultural industries reduce or stop the introduction of nutrients and pesticides into the environment. Excessive water and fertilizer leachate from the bottom of greenhouse floral crop pots and/or beds have resulted in localized ground water contamination in many locations (Nelson, 1991).

One of the most effective ways of achieving pollution abatement and quality production of greenhouse crops is to control the water and nutrient supply to the roots. This requires a through understanding of plant transpiration, or water vapor loss from the plant leaves and nutritional needs of the plants.

Today, controlled environment agriculture not only relies on the plant sciences and that relate solar radiation, temperature, humidity and carbon dioxide to production, but also uses a number of new technologies such as environmental physics, computer control and expert systems to achieve more
precise control. To better understand the scope of this study, it is important to describe some general environmental factors such as greenhouse microclimate and production systems such as hydroponic systems before getting into detailed discussions. In this chapter, the basic roles of the major environmental factors in modern, hydroponic production systems will be explained.

MICROCLIMATE FACTORS

SOLAR RADIATION

Solar radiation is one of the essential inputs to plant growth. Solar radiation is the primary source of energy for the process of photosynthesis in which carbon is fixed into carbohydrates. Solar radiation received at the earth's surface varies significantly with seasons because of the geographic relationship between the sun and the earth. Therefore, it is very important to estimate how much solar radiation is received for a given group of plants on the earth at a certain time of the year.

Some crops are reported to become light-saturated because photosynthesis does not increase significantly above specific light intensities (Nelson, 1991). For these plants, shading to reduce solar radiation intensity is necessary to increase plant quality and to save ventilation energy in summer. The most significant part of solar radiation is in the energy spectrum of 0.4 to 0.7 μm because plants use this spectrum in
photosynthesis (Takakura, 1989). This spectrum is usually referred to as the Photosynthetically Active Radiation, or PAR.

**TEMPERATURE**

Temperature is one of the most frequently and accurately measured variables in the environment. Temperature is widely available from standard meteorological observations. While transpiration is a major focus of this study and radiation and vapor pressure deficit are the dominant variables driving transpiration, temperature is generally correlated with both solar radiation and vapor pressure deficit (Jarvis, 1981). Hence, reasonable correlations between transpiration and temperature can usually be found for particular localities and crops.

**CARBON DIOXIDE**

About $5 \times 10^{16}$ grams (5 billion tons) of carbon are fixed into organic compounds in photosynthetic organisms per year (Nobel, 1974). Air is the primary carbon source for photosynthesis and is normally at a concentration of 0.03%. While outside CO$_2$ levels are fairly constant at about 300 to 350 ppm day and night, in greenhouses the level in a greenhouse may decrease to 150 ppm (Bauerle and Short, 1984) during daylight hours due to the process of photosynthesis. This lower level of CO$_2$ (below 300 ppm) can result in limited
plant growth. The level in a closed greenhouse went to about 400 to 450 at night due to respiration of the plants (Nelson, 1991). In commercial greenhouses, the daytime concentration of CO₂ is often artificially increased three fold to increase the yield and quality of plants.

HUMIDITY

Air holds significantly different amounts of water vapor at different air temperatures for the same relative humidity. This is because the capacity of air to hold water vapor increases with increasing air temperature. This also means that relative humidity can be highly variable when air temperature fluctuates significantly. Relative humidity is a major influence on plant transpiration and is known to be very important for controlling plant growth and quality (Nelson, 1991). It also has an indirect, but significant effect on plant disease susceptibility (Takakura, 1989).

GREENHOUSE SYSTEMS

Greenhouses, used for controlled environment agriculture, range in scale from small research greenhouses to commercial sizes as large as 12 hectares. Nationally, production in commercial greenhouses was a $2.8 billion industry in 1990 (Knebusch, 1991). The Ohio greenhouse industry was one of the highest in the nation with $126 million in revenues in that same year.
Some advantages of the greenhouse for plant production are: 1) The inside environment can be controlled to avoid severe weather damage; 2) The controlled environment can reduce the threat of diseases and insects; and 3) The quality and quantity of crops can be significantly improved with temperature, humidity, and CO₂ control (Takakura, 1989).

The major disadvantage of a commercial greenhouse production is the high expense of producing crops compared to ordinary field conditions. Consequently, greenhouses are limited to very high-value crops, such as vegetables and specialized nursery plants.

**SHADING IN GREENHOUSES**

Many plants are light-saturated at certain light intensities. Plants that require lower light for effective growth are called low-light plants. Much of the absorbed solar energy is converted to latent energy by water vapor diffusing out through fully opened stomata of the plant leaves. If the water diffusion rate is larger than the water supply from the roots a low-water potential in plant leaves results. In general, stomata area is insensitive to reductions in water potential until a threshold is passed; then stomata close rapidly and more or less completely (Raschke, 1975).

The need for reducing light intensity based on the plant variety are well documented (Salisbury and Ross, 1985, Nelson,
Plant production under a shading system over the greenhouse roof has been tested by many researchers. This type of shading is usually accomplished by either spraying a shading compound on the roof or installing a screen fabric that can be opened and closed mechanically over the greenhouse.

A unique automatic shading system developed at the Ohio Agricultural Research and Development Center (OARDC)/The Ohio State University (OSU) injects polystyrene pellets between two layers of acrylic plastic on a greenhouse roof (Short and Pang, 1990). The system, called Select-A-Shade (SAS), was used for this study. During the day, pellets could filter out radiation to keep sunlight levels near a desired level. He and Short (1989) investigated the solar radiation transmission characteristics of the SAS acrylic panels for each of five levels of shading with polystyrene pellets. They concluded that the total radiation transmissivity of the panel was about 80 percent without pellets and about 10 percent with full pellet insulation. Jewett and Short (1992) developed a feed-forward, set-point, personal-computer control system to control solar irradiance inside the SAS greenhouse. They evaluated particularly the response of this multistage shading system to highly variable outside solar radiation conditions. Elwell and Short (1988) evaluated anti-static treatments for the polystyrene pellets in order to keep pellets from sticking to the inner surface of the greenhouse panels.
Another form of greenhouse shading is filtering the light coming into the greenhouse with water or a copper sulfate solution. In one case, Heinemann and Walker (1987) investigated the water flow over the sloped glass surface. A thin layer of water is nearly transparent to wavelengths between 0.40 and 0.85 μm, but absorbs over half of the energy between 1.0 and 1.4 μm, and virtually all of the energy greater than 1.4 μm. In other words, the thin water layer over the glass transmitted solar energy primarily in the PAR and the very near infrared range.

HYDROPONIC SYSTEMS

Hydroponics were introduced into controlled environment agriculture to obtain high quality plants and conserve water resources. Hydroponics is the cultivation of plants without soil by using a water based nutrient solution to supply the moisture and mineral elements essential to plant growth. This production system can use much less water than traditional cultures due to constant recycling of the nutrient solution. It has been demonstrated that much better control of nutrients is possible using a soilless root medium instead of a soil-based root medium (Fynn et al. 1989).

There are two basic systems used to grow plants in a nutrient solution — closed loop and open loop. In both systems, plants are started from seed and then transplanted into a container. The open loop system uses individual
containers for each plant; a solution of water and nutrients is pumped to each plant regularly. Excess water and nutrients become leachate and are not recycled in this method. In a closed loop system, several plants are grown in a single container and the solution of water and nutrients is pumped through the container. This nutrient solution is collected, analyzed, blended with a new-solution and recycled.

Many crop cultivars have been developed for hydroponic production on a commercial scale. So far, crops commonly grown hydroponically are tomatoes, cucumbers, lettuce, leeks, celery and some nursery plants (Resh, 1991).

PROBLEM STATEMENT

The current models for predicting water use of greenhouse crops have critical drawbacks for some plants, especially for low light plants such as the African Violet, Gloxinia, Cyclamen, and New Guinea Impatiens. Some models are designed to use mathematical relations to predict a hard-to-measure variable by using some easily observed variables. In the greenhouse studies, two hard-to-measure, but important variables are transpiration rate and individual nutrient uptake by plants. Conversely, the variables air temperatures, relative humidity, and global solar radiation are easy to measure.

The relationship between individual nutrient uptake and the surrounding environment has not been established. It is
clear that the nutrient uptake is an energy dependent process that proceeds more rapidly in strongly illuminated plants. Unfortunately, research is needed on the general effect by each factor, although knowledge of nutrient uptake has been revised considerably in the last several decades.

OBJECTIVES

This study focused on the greenhouse potted plant, New Guinea impatiens, with the following objectives:

1) To predict the dynamic evapotranspiration of a "low-light" crop in a greenhouse environment;

2) To measure the dynamic evapotranspiration of the crop in a greenhouse environment;

3) To measure and predict the dynamic uptake of individual nutrients under varying conditions of photosynthetically active radiation (PAR);

4) To determine the reliability of using on-line electrical conductivity to predict dynamic uptake of all nutrients by New Guinea impatiens.

SCOPE OF THIS STUDY

The domain of this study included the plant canopy, the microclimate surrounding the canopy, the root zone and potting mixture, and the nutrient solution. Total evapotranspiration (ET) for a tray of 30 plants was measured. Nutrient uptake by the same plants was evaluated for the complete tray. The
experiment commenced with a plant 26 days old and concluded with a fully developed plant at 72 days from transplanting (Leaf Area Index from 0.75 to 4.2).

Three energy and mass balances were used in this study: energy, water and nutrients. The energy balance of the plant canopy was evaluated. The "big leaf" combination model was used to evaluate water uptake, and a lysimeter was used to measure the evapotranspiration rate, or water use, during the experimental studies. A nutrient mass balance for the recirculating irrigation solution was used to analyze the uptake of individual nutrient elements by the plants.
CHAPTER II
LITERATURE REVIEW

Although transpiration and nutrient uptake have been studied for several decades, the information available on transpiration and nutrient uptake for full size plants is limited. Many methodologies developed for water and nutrient research for other plants were helpful for this study. There are three parts in this chapter: physiological ecology, evapotranspiration and nutrient uptake studies.

PHYSIOLOGICAL ECOLOGY

A better understanding of the relationships between environmental factors and the physiological ecology of plants is important to the environmental engineer, greenhouse control designer and the horticultural manager. Appropriate control of the environment in the greenhouses require a precise understanding of plant response to environmental changes.

The response of plant to leaf temperature, photosynthetic rate and evapotranspiration to environmental factors has been studied for several decades. Bauerle and Short (1984) discussed the relationship of plant transpiration to various light intensities and CO₂ levels for several kinds of plants.
in greenhouses. These studies were necessary because the improved control of isolation leads to a decrease in heat demand and, consequently, to a decreased energy supply (Schapendonk and Gaastra, 1984).

Leaf physiology and plant growth of Photinia Dress were evaluated when plants were grown under solar intensity levels of 29%, 47%, 69% and 100% of full sunlight (Norcini et al., 1991). Results indicated that plants at 69% and 47% light levels usually had the highest midday net CO₂ assimilation rates. Stomatal conductance was often inversely related to solar radiation level, and intercellular CO₂ concentration was often elevated under 29% light level. Midday relative leaf water content and leaf water potential were unaffected by light regime. Net CO₂ assimilation rate was about 1550 and 1150 μmol.s⁻¹.m⁻² for 100% and 29% light level, respectively.

**EVAPOTRANSPIRATION (ET)**

**WATER USE MEASUREMENT**

Evapotranspiration is defined as the combined effect of transpiration from a leaf canopy and evaporation from a soil surface. Techniques to measure evapotranspiration (Jensen et al., 1989) are as follow:

1) Soil water depletion: Evapotranspiration under field conditions can be determined by measuring the changes in soil water over a period of time with soil samples and analyses. The major potential error was that the zone sampled has a
different condition from that of the average zones.

2) Tanks and lysimeters: Lysimeters (evapotranspirometers) are tanks filled with soil in which crops are grown under natural conditions with the amount of water lost by evaporation and transpiration being measured by changes in weight of the tank system. This method utilizes small areas and is typically very expensive.

3) Energy balance: The vertical energy balance at the canopy surface is the sum of fluxes of sensible heat, latent heat, net radiation, and other miscellaneous fluxes to or from the air and soil. The instrumentation requirements and technical procedures involved have typically limited this method to research studies.

4) Mass transfer: The evapotranspiration rate can be directly determined by using an eddy diffusion equation and meteorological data measured on site for a specific field and crop.

5) Eddy correction: This method has been done with commercial instrumentation which is based on the relationship between the vertical flux of water vapor and the vertical wind speed and instantaneous deviation of the partial water vapor pressure.

**EMPIRICAL MODELING OF EVAPOTRANSPIRATION**

In general terms, a model is an analogue of the system being studied. That is, it is another system which is used to
represent some aspects of a more complex system of interest. The purpose of a transpiration model is to predict the actual rate of evaporation from a leaf, plant or crop for particular wind, radiation, temperature and humidity conditions. Two main kinds of evapotranspiration models have been studied for many years. First, the empirical model is based on statistical relationships between evapotranspiration rate and microclimate factors surrounding the plant. Second, the energy model is derived from the physics and physiology of radiation, heat and water exchange by the crop surface.

A number of widely used empirical equations have been used to predict transpiration rate by average temperature, day length, latitude and time of year (Jarvis et al, 1981). Reasonable correlations between transpiration and temperature can be found for particular localities and crops because temperature is generally closely correlated with solar radiation and the vapor pressure deficit.

Another empirical approach to evapotranspiration estimation that has been studied is where the ratio of the latent heat flux to the net radiation was correlated with the soil water potential (Jarvis et al. 1981).

Transpiration of tomato plants grown on a rockwool media was studied by using a lysimeter under a variety of climatic factors (Okuya and Okuya, 1988). A model, based on the saturation deficit and the radiation received on each plant
surface, was used to predict the transpiration of the plants. An assumption was made that each plant surface was a rectangular parallelepiped. It was concluded that this method of the computer modeling was a practical method to estimate transpiration on an hourly basis, based on the comparison of the measured and predicted transpiration.

Although these impractical approaches are useful in many situations, they are generally limited to the specific case studied and may be grossly in error when other factors not examined are different from the conditions of the experiment.

ENERGY MODELING OF THE EVAPOTRANSPIRATION

Penman (1948) derived the first physically based equations for evaporation from soil surfaces and transpiration from crop canopies by the application of conservation of energy to heat and water vapor transport equations. His treatment included explicit radiation and diffusion terms but contained some empirical crop constants related to wind speed and day length. The overall conclusion, however, was that transpiration was essentially a physical process, largely dependent upon environmental variables.

Monteith (1965) gave an explicit presentation of transpiration in terms of stomatal and boundary layer resistances. In his model the canopy was condensed into a single leaf layer and the expressions for energy flux density from a single leaf layer were used. Sensible heat flux
density was proportional to temperature differences divided by the aerodynamic resistance. Latent heat flux was similar to that for sensible heat transfer, except that latent heat was dependent on the saturated water vapor density at leaf temperature and an additional stomatal resistance.

The Monteith evapotranspiration model was used by Meyer et al. (1991) to predict plant water use for New Guinea impatiens grown in a computer controlled growth chamber with root zone heating. The plants' growth parameters were dry weight, fresh weight, leaf area index and water use. The results indicated that plant water use correlated highly with plant dry matter production for both heated and control plants. Measured plant water use compared favorably with predicted values when root zone temperatures were close to air temperatures. Total plant water use was increased by increased root zone temperatures through increased soil evaporation. Examples of the use of the Monteith model in evapotranspiration studies include Stanghellini (1987), Yang et al. (1989) and Landsberg et al. (1974).

Transpiration rates under low light conditions were evaluated for potted foliage and floricultural species (Rajapakse et al., 1988). The light intensity of photosynthetically active radiation during the experiment was 20 \( \mu \text{mol.s}^{-1}.\text{m}^2 \). Leaf cuticular and stomatal morphology were characterized with scanning electron micrographs. The paper reported that the cuticular transpiration rate varied
significantly under low light conditions. Different transpiration rates for different floricultural species were found.

Recent research on transpiration and leaf temperature prediction by Al-Shooshan et al. (1991) indicated that the combination model reasonably estimated the evapotranspiration of a greenhouse grown potted chrysanthemum crop. The most significant variables were solar radiation incident on the leaves and vapor pressure deficit between the leaves and air. Stomatal resistance was highly correlated with solar radiation and forced ventilation was a minor factor affecting transpiration.

**MULTIPLE-LAYER MODEL**

A multiple-layer diffusion model of transpiration applied to a thinned Douglas-Fir stand with a tree height of 7-10 meters was evaluated (Tan et al., 1978). They claimed that the multiple layers for vegetation were necessary because vegetation has a different transpiration rate at different layers from top to bottom due to the different environmental factors surrounding the vegetation at each layer. In this model, the canopy was divided into three layers and the leaf area index of each layer determined. The transpiration rate per unit ground surface from a particular layer with leaf area index (LAI) and average stomatal resistance was calculated based on a simple diffusion equation. The inputs of the model
were only the vapor pressure deficit of the canopy air, the measured stomatal resistance, and leaf area index of the canopy.

Another multiple-layer evapotranspiration model was the soil-plant-atmosphere model (SPAM) which had been developed to simulate the energy transport and carbon dioxide exchange of vegetation (Sinclair et al. 1976). In this model, the vegetation was divided into several horizontal layers of equal leaf area. For each layer, the interception of solar and thermal radiation was calculated and partitioned into sensible heat, latent heat, and photochemical energy. Iterative procedures were used until an energy balance was achieved for all foliage layers. Total canopy gas exchange was obtained by summing the photosynthesis and transpiration of each layer. To solve for the microclimate, top boundary conditions were defined in the canopy aerodynamic boundary layer; the bottom boundary was set at the soil surface and was defined by the reflectivity of visible and solar radiation by the soil, the flux density of heat into the soil, the flux density of CO₂ from soil, and the aerodynamic roughness length of the soil surface. Several characteristics of the vegetation were also required in SPAM simulations such as the vertical distribution of the leaf area and stomatal resistance.

A cucumber plant with a height of 2 meters was divided into six layers to study the evapotranspiration (Yang et al., 1989). His model described vertical distribution of air
temperature, solar irradiance, air movement and humidity. Point source sensors and plant growth variables were used to characterize the microclimate and validate the models. Yang studied the crop canopy as a series of parallel rows with rectangular cross sections and variable architectural parameters. Agreement was found between predictions and measurements of the transpiration rates for a greenhouse row cucumber crop. In addition, canopy leaf temperatures with high solar radiation were considerably lower than greenhouse air temperature. This may be due to high transpiration rate.

In all cases, solving a series of equations for multiple layers requires substantial detailed input information, such as profiles of wind speed and solar energy within the canopy, that is not usually easy to obtain and is not, therefore, very practical. A simplified SPAM was evaluated by with no vertical gradients in air temperature, water vapor concentration, and CO₂ concentration (Sinclair et al. 1976).

No serious error (less than 10%) resulted from applying the simplified layer energy model when compared with a more complex layered model.

STOMATAL RESISTANCE

Most of the basic mechanisms involved in stomatal action are not fully understood. However, stomatal responses to various environmental factors have been investigated extensively. Raschke (1975) indicated that CO₂ level, light
level, water in the leaf, and air and leaf surface temperatures were the main factors effecting the leaf stomatal action. Jarvis et al (1981) indicated that light and vapor pressure deficit were the most important environmental variables determining stomatal resistances.

Landsberg (1974) concluded that transpiration should increase in response to vapor pressure deficit, reaching a distinct maximum value at an optimum deficit, and then, falling off again at higher deficits. Stomatal resistance and vapor pressure deficit were well correlated in certain soil, water potential ranges for a thinned Douglas-fir stand (Tan et al, 1978).

The stomata of the plant leaves open for photosynthesis which requires light and CO₂. The light level and CO₂ concentration influence both the opening rate and final aperture size. Raschke (1975) demonstrated with leaves of Zea Mays that stomata began to respond to changes in CO₂ in a time as short as 3 seconds; and the half-time of closing on response to an increase in CO₂ was 1.8 min. in the dark and 1.5 min. in the light. He also concluded that the CO₂ concentration in the guard cells determined stomatal aperture; stomata responded to light indirectly by responding to the reductions in the CO₂ in the mesophyll as well as in the guard cells. In terms of the leaf-water potential, stomata were insensitive to reductions in water potential until a threshold was passed; then they closed rapidly, more or less completely.
Stanghellini (1987) studied leaf temperature and transpiration of a canopy for tomato plant with details of describing external and internal resistance. Some physical aspects of greenhouse climate were analyzed to show the direct relationship between microclimate and crop transpiration. An energy balance of a greenhouse crop was shown to effectively quantify the impact of microclimate on transpiration and to identify the constraints of climate management by the thermodynamic behavior of the canopy. The external resistance (the resistance of the boundary layer) was introduced into the model and shown to restrict the sensible heat transfer. In addition, internal resistance was discussed which described the effect of the latent heat transfer from vapor produced beneath the boundary layer. The temperature of the greenhouse was considered as an output. Both the leaf temperature and transpiration were estimated by a combination model. The results were shown to accurately reproduce the temperature and transpiration of a greenhouse tomato crop.

Stomatal resistance was estimated from the mean irradiance on the leaves (Sinclair et al, 1976). It also can be calculated from the mean of the resistances averaged from estimates of sun-exposed and shaded irradiance. Further, stomatal resistance was evaluated from the weighted mean irradiance of unshaded and shaded area for a single leaf.
NUTRITION UPTAKE STUDIES

A recirculating nutrient solution system was employed by Noguera et al. (1986) to evaluate the nutrient content of tomato plants. Solution pH levels and electrical conductivity were maintained at 6.5 and 3800 µs/cm/25°C, respectively, after evaporative losses had been automatically replenished with tap water. It was concluded that the average levels of nutrients maintained in leaf tissue were higher for all major elements except for calcium when compared to plants grown in soil.

Larouche et al. (1989) conducted an experiment on the effects of nitrogen concentration and photosynthetic photon flux (PPF) in greenhouse tomato production on the plant nutrient uptakes. The plants were grown in growth chambers under two photosynthetic photon flux conditions (125 and 250 µmol.s⁻¹.m⁻² PAR) and four N fertilization regimes. The pH of the solution was adjusted to 5.8. The electrical conductivity of the solution were related to the four nitrogen levels, 1650, 1850, 2150, 2450 µs.m⁻² respectively. The solution was renewed twice weekly. The results showed that vegetative growth was limited at lower PPF and did not respond to N increments in the nutrient solution. At higher PPF, however, maximum leaf dry weight and yields were obtained at the same N concentration.

Four light intensity levels (600, 1600, 2400, 3500 ft-c) were installed in growth chambers to find their effects on
nutrient uptake by spinach plants (Cantliffe, 1972). The results showed that the total Nitrogen (N) and NO₃ of the leaves were increased by the addition of N to the root media. Less phosphorous (P) was found in spinach leaves as N fertilizer was added to 100 mg/kg of soil. The P content varied with light intensity.

The pattern of nitrogen metabolism in different plant parts was strongly dependent upon translocatory processes that were influenced, in turn, by light, nitrate concentration, water, growth substance levels (Fowden, 1977). Moreover, that the nitrate uptake was an energy-dependent process that proceeded more rapidly in strongly illuminated plants. The integrated process of nitrogen conversion from nitrate to amino acid and protein was strongly linked to light energy. Proteins form the most important N fraction of plants. Leaves usually contain about four-fifths of their total N in protein.

The Michaelis-Menten formula was employed by Gardiner et al. (1990) to describe phosphorous (P) uptake by plants. Two methods for estimating the Michaelis-Menten kinetics of P uptake were compared. In one method, uptake was measured from two P concentrations in a nutrient solution, with maximum uptake and a Michaelis-Menten constant estimated using a direct linear plot. In an alternate, multiple concentration experiment, uptake was measured using five P concentrations and the parameters were estimated by nonlinear regression. Gardiner et al. concluded that the steady state approach to
nutrient uptake measurements provided an acceptable estimation of the P uptake kinetic parameters. A correlation coefficient of 0.89 was obtained by a fit of the Michaelis-Menten model.

The relationship between the rate of photosynthesis and photon flux density was found for apple trees, which was represented by the rectangular hyperbola — Michaelis-Menten model (Landsberg, 1974).
CHAPTER III
COMPARISON OF PLANT RESPONSE AND NUTRIENT UPTAKE TO TWO
ROCKWOOL POTTING MEDIA IN A HYDROPONIC SYSTEM

ABSTRACT

New Guinea impatiens 'Equinox' plants were grown in two root media in an environmentally controlled greenhouse. One root medium consisted of 50 percent peat moss and 50 percent rockwool (V/V). The other root medium was 100 percent rockwool. Both root media were irrigated with a recirculated nutrient solution. Electrical conductivity and pH values were continuously monitored. Plant height, dry weight and leaf tissue nutrient content were recorded. The data showed 100 percent rockwool culture resulted in equal or better plant quality compared to the peat and rockwool root medium.

INTRODUCTION

During 1990, the greenhouse industry in the United States produced a total wholesale product value of $2.8 billion (Knebusch, 1991). This business, like any business, to withstand competition and survive must implement practices that reduce cost of production. Automation and other computerized control technology have been widely applied to
the greenhouse industry. However, the recent global attention to environmental protection presents the greenhouse industry with a new challenge — zero ground water contamination. Environmental protection regulations demand that greenhouses reduce or stop the introduction of nutrients and pesticides into the environment. One solution that has been recently introduced is the closed-loop, hydroponic system, also referred to as nutrient solution culture. It has been demonstrated that much better control of nutrients is possible using a soilless root medium instead of a soil-based root medium (Fynn et al., 1989).

Hydroponic culture involves the culture of plants in an inert substrate, such as water, gravel, sand, rockwool and air (Nelson, 1991). One of the most recently introduced root media for fresh flowers and vegetables is rockwool. Rockwool is a rock-based fibrous material produced by burning a mixture of coke, basalt, and limestone. At the time of this study rockwool has been used primarily as one component of a soil mix for floriculture crops; commercial use of 100 percent rockwool as a root media was very limited due to the lack of sufficient knowledge of management and control.

Two requirements of root media for nutrient uptake are: 1) the nutrient solution in each container must be aerated to ensure adequate root oxygenation; and 2) root media must hold water in such a way that it is available to plants (Nelson, 1991).
Nutrient solution culture systems have been studied by many researchers (Epstein, 1972). The plant must be supported at the root-shoot transition zone. This is usually done by wrapping cotton or synthetic batting around the stem and then inserting the plant into a hole in the cover of the irrigation container. However, this is inconvenient and time consuming. Alternative methods have been introduced such as sand culture, gravel culture and rockwool culture. Washed sand or gravel is placed in containers and periodically irrigated with the nutrient solution, often by means of pumps that fill the containers with nutrient solution at predetermined intervals. Plants grown in these systems are mechanically supported by sand or gravel. There is a disadvantage, however, in that even well-washed sand or gravel is likely to contribute contaminating elements.

A recirculating nutrient solution system was employed by Noguera et al. (1986) to evaluate the nutrient content of tomato plants. Solution pH levels and electrical conductivity were maintained at 6.5 and 3800 μS/cm/25°C, respectively, after evaporative losses had been automatically replenished with tap water. It was concluded that the average levels of nutrients maintained in leaf tissue were higher for all major elements except for calcium when compared to plants grown in soil.

The pattern of nitrogen metabolism in different plant parts is strongly dependent upon translocatory processes that
are influenced in turn by growth substances (Fowden, 1977). Rockwool manufactured with a surfactant to increase wettability has been used successfully as root substrates for vegetable and cut flower production. Two experiments were conducted to test plant responses to rockwool-amended media (Fonteno and Nelson, 1990). Six root combinations of media with loose rockwool were tested with seven bedding plant species for plant growth responses and nutrient uptake. The experiments indicated that the loose rockwool had a total porosity of 92% by volume and adequate water retention capabilities. Results showed that plant growth in the rockwool medium was superior to growth obtained in plants grown in two high-performing commercial media.

The objectives of this study were to evaluate loose rockwool as a greenhouse potting medium and compare it to a potting medium mixture of peat moss and rockwool for growing New Guinea impatiens. Plant growth responses and nutrient uptake were also monitored.

MATERIALS AND METHODS

PLANT MATERIAL

New Guinea impatiens 'Equinox' rooted cuttings with two fully expanded leaves were transplanted into a loose 100 percent rockwool medium and a 50 percent rockwool and 50 percent peat moss mixture (V/V) in 12 cm pots on separate benches. The cuttings were potted on August 16, 1991, and the
data collection was terminated on October 28, 1991. New Guinea impatiens was chosen for its characteristic rapid growth rate under low light conditions and poor growth habits under high light conditions.

The pots were placed on 1.0 meter wide and 1.25 meter long portable benches. There were four experimental zones in each bench with five plants per zone (Fig. 1). One nutrient solution emitter was placed in each pot. Each root medium treatment was implemented on separate benches. Since the black tube of the emitters had an inner diameter of 0.4 cm, a significant pressure drop resulted in nutrient solution dripping rates among the emitters. It was assumed that identical dripping rates would occur in all zones. The average dripping rate for each emitter was 1.125 liters per hour. However, the emitters in zone 4 averaged 10 percent less than the average dripping rate, while emitters in zone 1 averaged 10 percent higher.

The half sphagnum peat moss and half rockwool mixture was selected as the commercially acceptable root medium. This was selected because of reported successes using the mixture by Ohio growers. Both peat moss and rockwool have a high water holding capacity; peat moss contains some nutrients and rockwool does not. In this study, loose rockwool from Partek North America, Inc. (Pargro, Media) was used in 12 cm pots.
Figure 3.1: Test zones and irrigation pathways for each treatment
EXPERIMENTAL PROCEDURES

The nutrient solution consisted of Calcium Nitrate, Ca(NO₃)₂ (15-0-0), Potassium Nitrate KNO₃ (13-0-44), and Mono Ammonium Phosphate, (NH₄)₂HPO₄ (21-53-0). The individual element concentrations of nitrogen, phosphorus and potassium were 100 PPM, 25 PPM and 75 PPM, respectively.

Deionized water was used for the nutrient solutions. The recycled nutrient solution was completely replaced every week to prevent soluble salts from accumulating and reaching toxic levels. A 15 day cycle for replacing nutrient solutions was suggested by Noguera et al. (1986), who tested tomato plants with a continuous recirculating nutrient solution. The solution was changed twice a week by Larouche et al. (1989) who grew the tomato plants in growth chambers.

The pH value of the nutrient solution was adjusted daily to the range of 5.6 to 6.0 by the addition of small amounts of 80% phosphoric acid. Many species grow well in the pH range from about 5 to 7, and most nutrient solutions have pH values in this range (Nelson, 1991).

The nutrient solution was applied to the pots and drained back to the storage tanks on a continuous basis (Figure 3.2). The pump was housed in a sealed housing. A device attached to the pump housing ensured that the volume of water in the irrigation system remained constant.
Figure 3.2. Experimental set up with a recirculating irrigation system
DATA COLLECTION

The experiments were carried out in a polystyrene pellet greenhouse which had a floor area of 7 square meters, located at Wooster, Ohio (41 degree N Latitude). The structure consisted of a sloped, glazed surface facing south. To shade the greenhouse, polystyrene pellets were blown into square tubular (32x32 mm) air spaces separating the outer and inner surfaces of an acrylic panel. For the five shading stages (0, 25, 50, 75 or 100 percent) of the panel, each stage of shading blocked light transmission through predetermined tubular channels in the glazing. This made it possible to maintain the desired radiation striking the plant canopy (Short and Pang, 1990). The roof shading system was controlled by a computer and the irradiance level above plant canopy was normally maintained between 200 and 250 W/m² during the day time.

This greenhouse also had a Q-Com computer control system to regulate air temperature, relative humidity, and air velocity surrounding the plant canopy.

Air temperature and leaf temperature were measured by using "T" type thermocouples. In order to obtain the average leaf temperature of the plant canopy thermocouples with diameters of 0.7 mm (1/32 inch) were inserted into plant leaves located at different positions based on the height of the plant. Temperature set points were 17 °C during the night and 22 °C during the day. Temperature control was achieved by heating when the temperature dropped lower than the set point.
and by ventilation when the temperature rose above the set point.

Relative humidity data were collected by comparing wet bulb and dry bulb temperatures at a height of 0.4 m above the canopy. The relative humidity profile was monitored by employing three digital humidity analyzers (Model: EG&G, 911 DEW ALL™) to measure the dew point temperatures. Relative humidity (RH) was maintained above 55 percent. A spray nozzle was used to introduce water vapor into the air when the relative humidity level fell below the set point.

The solar irradiation on the canopy was measured by averaging the radiation output from three pyranometers (LI-COR, LI-200SZ). The PAR level was determined from three pyranometers (LI-COR, LI-190). Also, an Eppley pyranometer was mounted outside the greenhouse to determine the global incident solar radiation.

A hot wire anemometer (Model: TSI-1210) was used to measure the air velocity profile within the plant canopy. Air exchange was based on the ventilation needs and the inside temperature.

The electrical conductivity (EC) and pH values for the nutrient solution were recorded by the on-line conductivity transmitter (Model: SIGNET, 3-8800) and pH transmitter (Model: SIGNET, 3-8700). Carbon dioxide concentration inside the greenhouse was recorded. Atmospheric pressure was obtained from the weather station located 500 meters east of the test
Nutrient solution samples were analyzed by the Research Extension Analytical Laboratory (REAL) at Wooster. The special pump housing was designed for both solution sampling and the maintenance of a constant volume of the circulating solution.

Tissue samples were taken periodically to obtain the nutrient content of the leaf tissue. The two top most, fully-expanded leaves (40 total leaves from 20 randomly selected plants per bench) were collected and sent to the REAL laboratory for results. Dates of the tissue sample collection were August 28, September 26, October 4, and October 16, 1991. The plant pictures on September 11, and October 15, 1991, are shown in Figure 3.3. The individual nutrient elements in the leaf tissue including N, P, K, Ca, Mg, Mn, Fe, B, Cu, and Zn were examined.

The dry weight data represented the whole plant except for the roots. The plants were dried in a 65 °C oven for 96 hours.

Plant height was measured from the root medium surface to the average top surface of the plant including flowers. Plant diameters were the average of two perpendicular diameter measurements. One measurement was made on the longest plant axis and the other was made on the shortest axis. The number of fully expanded flowers on each plant was also recorded.

A datalogger (Model: Kaye, DIGITRIP III) was used to
Figure 3.3 The New Guinea impatiens on September 11, and October 15, 1991.
record the various sensor outputs on a strip chart and cassette tapes. The cassette tapes were downloaded to a floppy diskette through an RS-232 interface. To compare sample means, a student T-test was used.

RESULTS AND DISCUSSION

The plants exhibited healthy, vigorous growth. No root or foliar diseases were observed. The first flower was fully expanded on September 19, 1991, (34 days after transplanting) on the rockwool medium bench. However, the first flower from plants grown in the peat and rockwool mixture was not observed until six days later. This may have been due to the higher phosphate content in the rockwool medium nutrient solution because of frequent additions of phosphoric acid to adjust the pH level.

The initial pH levels of both media were 6.0. The desirable pH range for New Guinea Impatiens is 5.5 to 6.0. The pH value decreased from the an initial level to 5.0 for the peat-rockwool medium with speed of about 0.3 per day. Adjustments were made to raise the pH to the range of 5.5 to 6.0. In contrast, the pH value for rockwool medium increased from initial value to 7.0. The daily change in pH levels averaged 0.2, depending on weather conditions. The 80 percent concentration of phosphoric acid was used to buffer the nutrient solution to desired levels. The low pH value for the peat-rockwool mixture may have been caused by the acidic
property of the peat moss; peat moss typically has a pH level of 3.0 to 4.0 (Nelson, 1991).

There were no significant differences at 5 percent level in plant dry weights between the two root media (Table 3.1). The average dry weight was 16.0 grams in the peat-rockwool medium and 15.6 grams for the rockwool medium. This suggested that the pure rockwool medium would be acceptable for commercial use.

There were no significant differences at a 5 percent level in the nutrient content of plants grown in the two root media (Table 3.2). The reason for the higher leaf nutrient content from the peat-rockwool mixture may have been the contribution of the peat moss because it contains nutrients (Nelson 1991). For example, peat moss has a nitrogen content of 0.6 to 1.4 percent. The high phosphate content with the rockwool medium resulted from frequent adjustments by 80 percent phosphoric acid. There was not a significant change in nutrient content by plant age.

Location on the trays (zones) affected plant growth, plants grown with the peat-rockwool mixture in zone 2 and 3 had bigger dry weights, height, and diameters than plants in zones 1 and 4. For plants grown in rockwool, plants grown in zone 1 had the lowest dry weight. However, there were significant bigger at a 5 percent level in height and diameters of the plants in rockwool than that in peat-wool mixture. Plants grown in rockwool in zone 2 and 4 had the
most flowers per plant, while plants grown in the peat-rockwool mixture had the highest flower number in zone 2 (Tables 3.3 and 3.4).

CONCLUSION

Using pure rockwool as a root medium in a hydroponic system produced equal or better quality New Guinea impatiens compared to a 50 percent peat moss and 50 percent rockwool mixture based on dry weight, height, diameter and flower number. The plants grown in rockwool bloomed earlier than those grown in the peat-rockwool mixture.

The pH level of the nutrient solution used in the pure rockwool medium was easier to control than in the peat-rockwool mixture. This is because the pH level of the nutrient solution for the pure rockwool medium tended to change toward pH 7.0. To adjust this, phosphoric acid was added, a simple procedure.

There were no significant differences in plant response to the rate of nutrient solution application. Finally, there was no effect of the two root media on nutrient uptake by the New Guinea impatiens as determined by foliar analysis.

It can be concluded from these data that New Guinea impatiens can be grown successfully in a 100 percent loose rockwool medium hydroponically. Furthermore, these plants were no difference in quality to plants grown in a commercial rooting medium.
Table 3.1. Average dry weight per plant for New Guinea Impatiens grown in 50/50 rockwool peat and 100% rockwool (95% confidence interval, sample size of 4) for zones 1-4

<table>
<thead>
<tr>
<th>zone</th>
<th>50% peat</th>
<th>100% rockwool</th>
</tr>
</thead>
<tbody>
<tr>
<td>zone 1</td>
<td>13.8 ± 5.7</td>
<td>13.2 ± 3.4</td>
</tr>
<tr>
<td>zone 2</td>
<td>17.6 ± 3.5</td>
<td>16.5 ± 3.2</td>
</tr>
<tr>
<td>zone 3</td>
<td>18.2 ± 5.3</td>
<td>15.7 ± 1.6</td>
</tr>
<tr>
<td>zone 4</td>
<td>13.9 ± 3.9</td>
<td>17.1 ± 0.7</td>
</tr>
<tr>
<td>All zones</td>
<td>15.9 ± 2.4</td>
<td>15.6 ± 1.3</td>
</tr>
</tbody>
</table>

Table 3.2. Average nutrient content of leaf tissue with a 95% confidence interval for New Guinea Impatiens for two root media.

<table>
<thead>
<tr>
<th>Nutrient element</th>
<th>unit</th>
<th>50% rockwool</th>
<th>100% rockwool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N)</td>
<td>% dry wt</td>
<td>4.15 ± 0.17</td>
<td>3.86 ± 0.36</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>% dry wt</td>
<td>0.50 ± 0.09</td>
<td>0.69 ± 0.20</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>% dry wt</td>
<td>2.43 ± 0.24</td>
<td>2.30 ± 0.21</td>
</tr>
<tr>
<td>Calcium (Ca)</td>
<td>% dry wt</td>
<td>1.97 ± 0.36</td>
<td>1.86 ± 0.23</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>% dry wt</td>
<td>0.70 ± 0.18</td>
<td>0.47 ± 0.08</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>μg/g dw</td>
<td>122.0 ± 75.0</td>
<td>69.3 ± 5.2</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>μg/g dw</td>
<td>89.7 ± 39.8</td>
<td>77.3 ± 10.5</td>
</tr>
<tr>
<td>Boron (B)</td>
<td>μg/g dw</td>
<td>41.7 ± 6.9</td>
<td>22.8 ± 16.4</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>μg/g dw</td>
<td>8.7 ± 2.4</td>
<td>11.5 ± 2.1</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>μg/g dw</td>
<td>91.3 ± 20.1</td>
<td>31.8 ± 8.1</td>
</tr>
</tbody>
</table>
Table 3.3  Comparison of the root media on average plant height and diameters for New Guinea impatiens grown in 50/50 rockwool peat and 100% rockwool (95% confidence interval) for zone 1-4.

<table>
<thead>
<tr>
<th></th>
<th>Height (cm)</th>
<th>Diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50% peat</td>
<td>100% rockwool</td>
</tr>
<tr>
<td>zone 1</td>
<td>20.8 ± 1.0</td>
<td>23.1 ± 2.5</td>
</tr>
<tr>
<td>zone 2</td>
<td>25.9 ± 1.1</td>
<td>27.4 ± 1.3</td>
</tr>
<tr>
<td>zone 3</td>
<td>25.4 ± 1.4</td>
<td>27.2 ± 1.0</td>
</tr>
<tr>
<td>zone 4</td>
<td>21.8 ± 1.2</td>
<td>25.9 ± 1.9</td>
</tr>
<tr>
<td>All zones</td>
<td>23.5 ± 1.5</td>
<td>25.9 ± 1.1</td>
</tr>
</tbody>
</table>

Table 3.4. Average number of the flower per plant for New Guinea impatiens grown in 50/50 rockwool peat and 100% rockwool (95% confidence interval) for zone 1-4.

<table>
<thead>
<tr>
<th></th>
<th>Flower number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50% peat</td>
</tr>
<tr>
<td>zone 1</td>
<td>18.2 ± 7.5</td>
</tr>
<tr>
<td>zone 2</td>
<td>22.4 ± 6.0</td>
</tr>
<tr>
<td>zone 3</td>
<td>18.8 ± 9.8</td>
</tr>
<tr>
<td>zone 4</td>
<td>14.8 ± 1.1</td>
</tr>
<tr>
<td>All zones</td>
<td>18.6 ± 3.4</td>
</tr>
</tbody>
</table>
CHAPTER IV
MODELING EVAPOTRANSPIRATION FOR A LOW LIGHT CROP

ABSTRACT

A big-leaf evapotranspiration (ET) model was modified to predict the transpiration rate of a low-light crop under a greenhouse environment with environmental inputs including solar radiation, air temperature, relative humidity, and air velocity. Canopy area index (CAI) was introduced to account for intercepted solar radiation by small, growing plants. Average stomatal resistance of the plant canopy was estimated using a multiple layer diffusion model. The results indicated that solar radiation and water vapor pressure deficit of the air were the dominant factors effecting the ET. The model can be used to predicted the ET rate for the weather conditions studied in greenhouse.

INTRODUCTION

Modern agriculture requires precise control of water to conserve water supplies and to reduce ground water pollution. A computer model is one effective way of establishing water use and requirements for evapotranspiration by predicting the actual rate of evaporation from leaves, plants or crops in a
variety of wind, radiation, temperature and humidity conditions.

Empirical and mechanistic models are most commonly used to understand water use. The empirical models are based on statistical relations between evapotranspiration rate and microclimate factors surrounding the plant. The mechanistic models are derived from the physics and physiology of radiation and heat and water exchange by the crop surface.

A number of the widely used empirical equations predict transpiration rate using average temperature, day length, latitude and time of year (Jarvis et al., 1981). In another empirical approach estimating evapotranspiration Ritchie et al. (1972) and Davies and Allen (1973) used the ratio of the latent heat flux to the net radiation related with the soil water potential. Although this approach is useful in many situations, it is mostly empirical. A good model of evapotranspiration from crop canopies is dependent upon both surrounding microclimatic factors and the properties of the plant leaf surfaces.

Penman (1948) derived a set of physically based equations for evaporation and transpiration from crop canopies by the application of conservation of energy to heat and water vapor transport equations. His treatment included explicit radiation and diffusion terms but contained some empirical crop constants related to wind speed and day length. Monteith (1965) gave a wholly explicit presentation in terms of
stomatal and boundary layer resistances. In his model, the canopy was condensed into a single leaf layer. Stomatal resistance and saturated water vapor density at leaf temperature was introduced to describe latent heat transfer.

New Guinea impatiens were evaluated by Meyer et al. (1991) to measure and predict plant water use by using the Monteith model in a computer controlled growth chamber with root zone heating. The results indicated that predicted plant water use values were within one standard error of actual water use when root zone temperatures was close to air temperature. Other examples of using the Monteith model in evapotranspiration studies include Landsberg et al (1974), Okuya and Okuya (1988), Jensen et al. (1989), Al-Shooshan et al. (1991), Rajapakse et al. (1988) and Stanghellini (1987).

A multiple-layer diffusion model of transpiration applied to a thinned Douglas-Fir stand was evaluated by Tan et al. (1978). They argued that the multiple layers for vegetation were necessary because vegetation has different transpiration rates at different layers from top to bottom due to the different environmental factors surrounding the vegetation at each layer. The inputs to the model were only the vapor pressure deficit of the canopy air, the measured stomatal resistance, and leaf area index of the canopy. Another multiple-layer evapotranspiration model is the soil-plant-atmosphere models (SPAM) which were developed to simulate the energy transport and carbon dioxide exchange of vegetation
(Sinclair et al. 1976). Total canopy gas exchange was obtained by summing the photosynthesis and transpiration of each layer. Yang et al. (1989) divided a 2 meter tall cucumber canopy into six layers to study evapotranspiration. A series of parallel plant rows with rectangular cross sections were assumed. The vertical distribution of air temperature, solar irradiance, air velocity and relative humidity were modelled. Application of the equations, however, required detailed input information such as profiles of wind speed and solar energy within the canopy. Such information is not easy to obtain, making the approach sometimes impractical. Nonetheless, no serious error (less than 10%) resulted from applying the single layer energy model with comparison with more complex layered models (Tan et al., 1978).

Although these models were very different in their approaches and all can provide reasonable estimate of evapotranspiration under the conditions of their development, none were evaluated with a "low light" crop such as New Guinea impatiens. Further, these models assumed a low stomatal resistance with transpiration increasing monotonic with increasing light. Such transpiration responses may not be appropriate for low light crops.

This study focused on the greenhouse potted plant, New Guinea impatiens, with the following objectives: to predict the dynamic evapotranspiration of a "low light" crop in a
greenhouse environment and to develop an approach to model canopy stomatal resistance, especially at higher light levels.

The space domain of this study included the plant canopy, the microclimate surrounding the plant canopy, the root zone and potting mixture, and the nutrient solution. Total evapotranspiration (ET) for a tray of plants was evaluated. The energy balance of the plant canopy was evaluated. Since New Guinea impatiens have an average height of 0.3 meter, a multiple layer model was assumed to be unnecessary for this plant. Therefore, the "big leaf" combination model was selected to evaluate energy balances and model water uptake.

**EVAPOTRANSPIRATION MODEL DEVELOPMENT**

The first law of thermodynamics states that energy cannot be created or destroyed, but only changed from one form to another. The energy balance for a leaf is no exception and can be expressed by the following equation (see Figure 4.1):

\[
E_{in} - E_{out} = E_{storage}
\]  

(4.1)

where

\(E_{in}\) = radiation from both short wave and long wave.

\(E_{out}\) = heat lost by long wave radiation, convection, conduction and by water evaporation (latent heat).

\(E_{storage}\) = stored energy resulting from photosynthesis and metabolism, and energy stored by leaf temperature changes.
Figure 4.1 The first law of thermodynamics applied to a plant.
The energy storage from photosynthesis and metabolic processes, however, is relatively small and has been neglected (Nobel, 1974). Under normal conditions, the energy resulting from leaf temperature changes is also very small for a 15 minutes to one hour period and can be assumed equal to zero. Storage energy was, therefore, assumed to be equal to zero and Equation 4.1 was written as follows:

$$Q_i - (Q_m + Q_{et}) = 0$$  \hspace{1cm} (4.2)

where

$$Q_i = \text{the solar irradiation absorbed by the canopy},$$

$$Q_{et} = \text{the latent energy for evapotranspiration},$$

$$Q_m = \text{the convective heat transferred from leaf}.$$  

The convective heat loss, \( Q_m \) was

$$Q_m = c_p \rho (T_{3r} - T_{air})/r_m ,$$  \hspace{1cm} (4.3)

and

$$T_{3r} = \text{the plant leaf temperature},$$

$$T_{air} = \text{the air temperature away from the leaf surface},$$

$$r_m = \text{the air resistance to heat loss at the leaf surface}$$  

(Refer to Appendix B for detail).

The latent heat of evapotranspiration was defined as:

$$Q_{et} = c_p \rho (e(
T_{3r}) - e(T_{air})) / \gamma (r_s + r_a) ,$$  \hspace{1cm} (4.4)

where \( e(T) \) = the vapor pressure at temperature \( T \),

\( e_s(T) \) = the saturated vapor pressure at temperature \( T \),

\( r_s \) = the resistance to water vapor movement by air,

\( r_a \) = the resistance of the leaf stomata,

\( \gamma \) = the thermodynamic psychometric constant.
Based on Penman's transformation, it was sufficiently accurate to estimate the stomatal cavity water vapor pressure by the following equation when \((T_{air}-T_{s})\) was small (less than 5 °C) (Oke, 1987):

\[
e_s(T_{s})-e(T_{air}) = S(T_{s}-T_{air}) + (e_s(T_{air}) - e(T_{air}))
\]  

(4.5)

where,

\(S\) = the slope of the curve of the saturation vapor pressure against temperature as shown in Figure 4.2.

Combining Equation 4.2, 4.3, 4.4 and 4.5 for predicting the
energy used in evapotranspiration,

\[ Q_{et} = \frac{1}{r_s r_c} \left( Sr_n Q_i + c_p \gamma (e_s(T_{air}) - e(T_{air})) \right), \quad (4.6) \]

where \[ r_c = \left(1 + \frac{r_o}{r_s} + Sr_n \frac{r_e}{r_s} \right)^\delta \quad (4.7) \]

Note that the evapotranspiration rate in Equation 4.6 is for plant leaf area. In previous studies, units of gram of evapotranspiration per unit ground area per hour are normally used and both sides of each plant leaf must be taken into account. If the sensible energy absorbed by the leaf \( Q_i \) were expressed as a function of the global solar energy \( Q_{sol} \) available above the canopy, then the canopy could be considered as a "Big Leaf". The energy \( Q_m \) for latent heat for the canopy per unit area of ground was thus defined as:

\[ Q_m = \frac{1}{r_s r_c} \left( \alpha CAI Sr_n Q_{sol} + 2LAI c_p \gamma (e_s(T_{air}) - e(T_{air})) \right), \quad (4.8) \]

where CAI = canopy area index, and LAI = leaf area index.

**CANOPY AREA INDEX (CAI)**

Equation 4.8 is called the Big Leaf Combination Model and the first term is called the "energy term". The energy term is dependent upon the solar energy available for water transport and the Canopy Area Index (CAI) was introduced as the relevant area for this term.
The canopy area index (CAI) was defined as the plan area of the canopy per unit area of ground which can range from 0.0 to 1.0. A CAI of 1.0 indicated that the plants completely covered the ground. This is an index that cannot exceed unity, because the plant cannot receive more energy than that incident upon it. Values from 0.33 to 1.0 were used for this study.

The canopy area index was an important term in Equation 4.8. Some previous researchers had not had to consider a term such as CAI due to their use of only fully developed plants. Omitting the CAI in this study, however, introduced large errors in the prediction of evapotranspiration during early plant development. The CAI effectively took into account the canopy that intercepted solar radiation instead of the total ground area.

The canopy area index was evaluated by photographic means. Photographs taken of the plan view of the bench were developed at high contrast. These photographs were then touched up to eliminate the extra points that were not leaf surfaces. The photographs were viewed under a digital image analyzer device where the ratio of the black area to the total area on the photograph was assumed to be the canopy area index of the plants at that growth stage.
A LOW-LIGHT CROP AND STOMATAL RESISTANCE

Low-light plant leaves have a light-saturation characteristic for evapotranspiration when solar irradiance is higher than a threshold light level (Levitt, 1980 and Nelson, 1991). According to Salisbury and Ross (1985), plants open their stomata when the light level is just sufficient to cause some photosynthesis. Since the photosynthetic rate saturates at a certain light level, the final stomatal aperture size will be relatively constant. The control mechanism appears to depend on an inhibitor of stomatal opening which accumulates in leaves after a period of water stress, or alternatively, a deficiency of a substance which promotes opening.

Within a canopy, the upper leaves can be more easily saturated than lower leaves. Upper leaves cast shadows on lower leaves, thus reducing the light intensity at the lower leaves. Figure 4.3 shows the predicted evapotranspiration rate per leaf area of sun exposed leaves, shaded leaves and whole plants against the solar irradiance above the canopy. Leaves exposed to the sun (or top leaves) of the plants can be light saturated at a relatively low solar irradiance. However, since the transmission by leaves is fairly high from 0.7-2.0 μm (Oke, 1987), much of the solar radiation reaching a shaded leaf would be in a region not useful for photosynthesis. The leaf absorptivity in the range 0.7-2.0 μm is lower than would be the case for the solar radiation incident on an exposed leaf. The low light intensity on
shaded leaves, plus low absorptivity of the leaves results in lower solar energy absorbed by shaded leaves. Moreover, the stomates generally are partially closed at the lower light level, which increases the stomatal resistance and further decreases transpiration (Nobel, 1974). In summary, two factors tend to reduce water vapor loss from a shaded leaf: the increased stomatal resistance and high concentrations of water vapor (or relative humidity) around the leaf (Yang et al. 1989).

The evapotranspiration rate for a whole plant is in the range between the sun exposed leaf rate and shaded leaf rate as shown in Figure 4.3. The curve position for the whole plant, however, varies up and down depending on the ratio of the exposed leaf area to the shaded leaf area. The larger the ratio of exposed leaves to shaded leaves, the closer the curve of the whole plant is to the curve of the top leaves.

Figure 4.4 illustrates the diurnal evapotranspiration of a low light crop for a typical sunny day. The evapotranspiration increases (or decreases) based on solar irradiance in both early morning and late afternoon. The plant evapotranspiration rate was limited to a constant level between 10:00 and 14:00 of the day. The solar energy absorbed by the plant during that time period is greater than the latent energy required for transpiration. Therefore, the solar energy which cannot be released by transpiration is converted to sensible heat resulting in a leaf temperature
increase.

Figure 4.5 and 4.6 show the plant shape and the predicted leaf temperature profile under high solar irradiance. When the top leaves are exposed to a high solar intensity, leaf temperature is predicted to be up to 2 degrees centigrade higher than air temperature. However, the shaded leaf temperature is influenced significantly by the shape of the plant. The large leaf area results in a lower air temperature due to high cooling by evapotranspiration. The lowest leaf temperature for New Guinea impatiens was predicted to be 4 cm from the top of the plant and 2 degrees centigrade lower than the average air temperature.

Stomatal resistance of the whole plant is defined as the resistance of water vapor transfer between the intercellular air spaces of the leaves and its external surface. Figure 4.7 shows a high magnitude stomatal resistance during or near zero solar radiation (night). It decreases sharply until it reaches the lowest constant value between 200 and 600 W/m², and it increases above 600 W/m².

Equation 4.4 was used to calculate the stomatal resistance for New Guinea impatiens from measurements of air temperature, leaf temperature, evapotranspiration, and air velocity. The impatiens had an average height of 0.30 meter. Under well ventilated conditions, the air temperature and air velocity varied very little from top to bottom. However, the plant leaf temperatures were observed in Figure 4.5 to
have up to a 4 °C difference from top to bottom because of the solar regime difference. This same temperature difference resulted in a difference in water vapor pressure deficit of about 10 percent for saturated water.

To improve the accuracy of the transpiration prediction, a multiple-layer diffusion was developed to calculate the stomatal resistance. Figure 4.8 shows the electrical circuit analogue used to describe the flow of water vapor from the leaf to the atmosphere. The plant canopy was divided into one layer of sun exposed leaves and several \((i)\) layers of shaded leaves. The sun exposed leaf area was assumed equal to the canopy area index (CAI). Each shaded layer area was set equal to:

\[
\text{Area}_i = \frac{(\text{LAI-CAI})}{i}
\]

and the diffusion equation 4.4 for transpiration was modified to be:

\[
Q_{ct} = \frac{\text{CAI}(e_s(T_{sr}) - e(T_{sr}))}{(r_s + r_e)} + \sum_{i} \frac{(\text{LAI-CAI})(e_s(T_{sr}) - e(T_{sr}))}{i (r_s + r_e)}
\]

It is important to understand that the resistances of the stomates \((r_s)\) and the water vapor \((r_e)\) in Equation 4.7 and 4.8 are mean values of the parameters when applied to a population of leaves or canopy. The inputs required in Equation 4.4 are solar energy above the canopy, water vapor pressure deficit, air temperature and air velocity. A minimum of 15 minute average values of the inputs was usually required, depending upon the time scale of associated models.
RESULTS AND DISCUSSION

The model was tested by running with several typical weather conditions: sunny day, cloudy day, and days with rapidly varying solar radiation. Figures 4.9 and 4.10 show the predicted and measured evapotranspiration and solar radiation above the plant canopy on October 1, 1991, with CAI of 0.78 and LAI of 2.04. The measured inside air temperature and relative humidity were shown in Figure 4.10. The relative humidity was low during the day time and high during the night. The values of the evapotranspiration predicted by the model were close to the measured values. The results indicate that, overall, the model predicted fairly well for a sunny day based on an $R^2$ of 0.96 and a 95 percent confidence interval of $\pm 44.3 \text{ g.Hr}^{-1}.\text{m}^2$; however, the model did not predict the small time varying fluctuations in ET.

Measurements of air temperature, relative humidity, solar radiation for a cloudy day and model predictions of evapotranspiration are shown in Figures 4.11 and 4.12. The predicted and measured ET values had an $R^2$ of 0.50 and a 95 percent confidence interval of $\pm 30.2 \text{ g.Hr}^{-1}.\text{m}^2$.

Figures 4.13 and 4.14 show predicted evapotranspiration with a sudden change in solar intensity above the canopy achieved by removing the shading roof at 8:30 to 9:15, 12:30 to 13:00, and after 14.15. The data were for October 2, 1991 with a CAI value of 0.80 and an LAI value of 2.12. The predicted and measured ET values had an $R^2$ of 0.84 and a 95
percent confidence interval of \( \pm 53.5 \text{ g.Hr}^{-1}.\text{m}^2 \). The model is shown to be within the 15% error for this condition of sudden change in solar intensity, indicating that solar energy was obviously a major factor effecting crop evapotranspiration during the day. The water vapor pressure deficit was the major factor influencing the plant water use during cloudy days.

The model was tested using a sensitivity analysis (see Appendix B for detail). Two major factors are required to determine the vapor pressure deficit. First, air relative humidity affects vapor pressure linearly. ET changes 25 percent during the night and 20 percent during the day when relative humidity changes 20 percent. Second, the vapor pressure deficit is dependent on air temperature. \( \gamma \) is 65.6 and 66.2 Pa K\(^{-1} \), respectively, for temperatures of 10 and 20 \(^\circ\text{C} \); this difference is only less than 1 percent. However, the slope, \( S \), of the curve of the saturation vapor pressure against temperature is strongly dependent on temperature. For instance, \( S \) values increase about 75 percent from 82.21 and 144.76 Pa K\(^{-1} \) at 10 and 20 \(^\circ\text{C} \), respectively. The results indicated that an ET change of one to three percent may be introduced by a 1 \(^\circ\text{C} \) change in air temperature change.

Vapor pressure deficit influences the ET rate through both sides of the leaf therefore errors in measuring leaf area index can result in a large ET errors.

For a sunny day, solar irradiance changes of 10 percent
between 10:00 to 14:00 can result in 7 percent ET change.

ET is comparatively insensitive to the exact value of aerodynamic resistance. In a greenhouse environment, for example, the air velocity is usually within the range of 0.5 to 2.0 ms\(^{-1}\). A 50% error of aerodynamic resistance introduced into the equation results in only a 3% error in the calculation of ET rate.

**CONCLUSIONS**

A single layer big leaf combination model was modified to predict ET for a low light plant, New Guinea impatiens. The energy balance of a canopy was established to describe the balance of sensible energy and latent energy during plant ET. Canopy area index (CAI) could be used to describe the intercepted solar radiation by the canopy of small plants and could be measured photographically. Average stomatal resistance of the plant canopy could be estimated using a multiple layer diffusion model which divided the plant canopy into several layers of sun-shaded leaves and one layer of sun-exposed leaves having a area of CAI.

The modified big leaf combination model can be used to predict water use at different weather conditions. A sensitivity analysis indicated that the solar radiation and water vapor pressure deficit of the air were dominant factors affecting the ET.
Figure 4.3 Predicted effect of light intensity on the evapotranspiration of a top leaf, bottom leaf and whole plant.
Figure 4.4 Diurnal modeled plant evapotranspiration on a sunny day
Figure 4.5 The predicted typical leaf temperature profile under high solar radiation conditions
Figure 4.6 A black and white photograph of one New Guinea impatiens plant on side view
Figure 4.7 Proposed plant stomatal resistance relative to solar intensity for a low light plant
Figure 4.8 Electrical circuit analogue used to describe the stomatal and water vapor resistance
Figure 4.9  Predicted and measured evapotranspiration on a sunny day (October 1, 1991, 46 days after transplant, CAI=0.78 and LAI=2.04)
Figure 4.10 Measured diurnal air temperature and relative humidity on October 1, 1991
Figure 4.11. Predicted and measured evapotranspiration on a cloudy day (October 5, 1991, 50 days after transplant, CAI=0.85 and LAI=2.40)
Figure 4.12. Measured diurnal air temperature and relative humidity on October 5, 1991
Figure 4.13  Predicted and measured evapotranspiration on October 2, 1991 with CAI=0.80 and LAI=2.12
Figure 4.14  Measured diurnal air temperature and relative humidity on October 2, 1991
CHAPTER V

AN EXPERIMENTAL STUDY OF EVAPOTRANSPIRATION

FOR NEW GUINEA IMPATIENS

ABSTRACT

Values of a low light crop transpiration rate, calculated from a modified big leaf combination model that uses inputs including solar irradiance, air temperature, air relative humidity and air velocity, agreed (within 15%) with those measured for New Guinea impatiens grown in an environmentally controlled greenhouse. The plants irrigated by a closed loop hydroponics system were located on an accurate lysimeter weighing scale to measure the evapotranspiration rate over a 15-minute interval. Stomatal resistance characteristics were calculated with a diffusion model that had one sun-exposed layer and three equally divided shaded layers. The results indicated that transpiration responses of the New Guinea impatiens were different from those of high light plants. High-radiation periods, in particular, resulted in very high leaf temperatures and maximum possible transpiration rates.
INTRODUCTION

Energy modeling techniques have become widely used in studies of water evapotranspiration by plants associated with the surrounding environmental factors. Multiple layer diffusion models have been successfully used to predict water use for tall, rough plants and crops (Tan et al., 1978, Yang et al. 1989). However, application of those models requires detailed input information which is not easy to obtain. Greenhouse grown potted plants such as New Guinea impatiens typically have a well ventilated environment and the surrounding environment factors vary slightly with height. Therefore, a single-layer combination model was used and modified to predict the evapotranspiration rate for these short, well-ventilated plants.

This study focused on the greenhouse potted plant, New Guinea impatiens, with the objective to measure and predict the dynamic evapotranspiration of a "low light" crop in a greenhouse environment.

A big-leaf model was developed in Chapter 4 as:

\[
Q_{bL} = \frac{1}{\gamma r_c r_s} \left( aCAI \delta r_s Q_{rad} + 2LAIC_{pp} (e_s(T_{air}) - e(T_{air})) \right); \quad (5.1)
\]

where \( r_c = 1 + r_s/r_w + \delta r_s/\gamma r_w \), \( (5.2) \)

and \( Q_{bL} = \) evapotranspiration rate \( (\text{g.Hr}^{-1}.\text{m}^2) \) for latent heat for the canopy per unit area of ground,

\( \alpha = \) the average absorptivity of the New Guinea impatiens,

CAI = the canopy area index which was defined as the plan
area of the canopy per unit area of ground (unitless),
S = the slope of the curve of the saturation vapor
pressure against temperature with units of Pa.K',
r_w = the air resistance for heat diffusion (s m') which
was determined by considering the air flow condition on
the leaf surface,
Q_{rd} = the global solar energy available above the canopy
(W.m^2),
LAI = leaf area index (unitless) which was defined as the
ratio of total leaf area to the ground area.
C_p = the leaf specific heat J.kg'.K',
\rho = the water density (g.m^3),
e(T) = the vapor pressure at temperature T, e_s(T) was the
saturated vapor pressure at temperature T with unit of
Pa,

r_w and r_s = the resistance to water vapor movement by air
and the leaf stomata, respectively, with units of s.m',
\gamma = the thermodynamic psychometric constant with units of
Pa.K'.

This equation was essentially a modification of the Big
Leaf Combination Model described by Oke (1987). The first
term of Equation 5.1 is called the "energy term" because it
describes the energy available for water evaporation. The
second term of Equation 5.1 is called the "vapor pressure
deficit" term. Both sides of all leaves were considered as
contributing to water loss driven by the vapor pressure
deficit. This was done by using the Leaf Area Index (LAI) for this part of the equation and a factor of 2 to account for both sides of the leaf.

EXPERIMENTAL ARRANGEMENT

Rooted cuttings with two fully expanded leaves of New Guinea impatiens 'Equinox' were transplanted into a loose 100 percent rockwool medium in 12 cm pots. The pots and the plants were placed on portable benches which were 1.0 meter wide and 1.25 meter long. A hydroponic continuously recirculating nutrient solution system was used to grow the plants on a 100 percent rockwool soilless medium. The average dripping rate for each emitter was 1.125 liters per hour.

The experiments were conducted in a Selected-A-Shade (SAS) greenhouse, which had a floor area of 7 square meters located at Wooster, Ohio (41 degree N latitude). The roof-shading system was controlled by a computer with control software developed by Jewett and Short (1992). The irradiance level above the plant canopy was normally maintained between 200 and 250 W/m² during the day. In addition, the SAS greenhouse had a Q-Com computer control system to regulate air temperature at set points of 17 °C during the night and 22 °C during the day; relative humidity (RH) was maintained above 55 percent; and air velocity around the plant canopy was approximately 1 m/s.

The solar irradiation on the canopy was measured by
averaging the radiation output from three pyranometers (LI-COR, LI-200SZ). A hot-wire anemometer (Model: TSI-1210) was used to measure the air velocity in the plant canopy. The electrical conductivity (EC) and pH values for the nutrient solution were recorded by an on-line conductivity transmitter (Model: SIGNET, 3-8800) and a pH transmitter (Model: SIGNET, 3-8700). Carbon dioxide concentration (CO₂) inside the greenhouse was recorded to monitor major respiration and/or photosynthesis rates during the experiment. A water mass balance for the plant canopy was established by measuring water input (tank water), water output (ET) and water storage. Because the water retained by the plants was less than 1 percent of total water use, the actual water consumption was approximately equal to the ET rate. A highly accurate scale (Model: SARTORIUS F330s) measuring from 0 to 3,000 kgs in increments of one gram was employed to weigh the entire system to calculate the ET rate as shown in Figure 5.1. This data was collected at 15 minute intervals. The weight change with time was assumed to represent the water use by the plants.

The plant Leaf Area Index (LAI) was determined by a regression relation between leaf area and its length and width. Up to one hundred and nine plant leaves were collected with the lengths range from 2.3 to 9.7 cm and widths range from of 1.0 to 5.7 cm. The leaf areas were measured with an image monitoring system (Model: Ikegami, ITC-48 for camera and PM-930 for monitor). Leaf lengths and number of leaves were
Figure 5.1 Experimental setup with a recirculating irrigation system on a lysimeter
periodically measured during the plant growth period and used to determine LAI.

The canopy area index (CAI) was derived photographically. Photographs taken of the plan view of the bench were developed at high contrast. These photographs were then touched up to eliminate extra points that were not leaf surfaces. The photographs were then reviewed under an image analysis device and the ratio of black to white area in the photograph was computed. The ratio of the black area to the total area on the photograph was the canopy area index of the plant at that growth stage.

The stomatal resistance was calculated by measuring evapotranspiration rate, leaf temperatures, and all environmental factors for a sunny day. Thermocouples with a diameter of 0.7 mm were inserted into the plant leaves located at four different height positions on three randomly chosen plants to achieve the desired leaf temperatures of the plant canopy. Stomatal resistance was calculated based on the multiple-layer diffusion equation described in Chapter IV. One layer of sun exposed leaf and three equally distributed layers of shaded leaves were used.

A datalogger (Model: Kaye, DIGITRIP III) was used to record the various sensor outputs on a strip chart and cassette tapes. The cassette tapes were downloaded to floppy diskettes through an RS-232 interface. The cuttings were potted on August 16, 1991, and the data collection was

RESULTS AND DISCUSSION

LEAF AREA INDEX (LAI)

The relations between leaf area and leaf dimensions are shown in Figure 5.2 and Figure 5.3. The leaf area (A) in cm² shows a high correlation to the leaf length (L) and width (W) with units of centimeter (cm) expressed in the following equations:

\[ A = 0.0567 + 0.3378L + 0.2800L^2 \] \hspace{1cm} (5.3)

\[ A = -7.6638 + 7.1770W - 0.0737W^2 \] \hspace{1cm} (5.4)

The correlation coefficients for Equations 5.3 and 5.4 are 0.97 and 0.95, respectively. In a previous study by Al-Shooshan with chrysanthemum, the areas of the plant leaves were only highly correlated to the multiple of length times width (Al-Shooshan et al., 1991). In this study, the measurement could be simplified and Equation 5.3 was used to calculate the leaf area.

Figure 5.4 shows the LAI for the 72 days after the plants were transplanted. The first leaf area data was collected 28 days after transplanting. The low leaf area development in the first four weeks may have been caused by an inadequate nutrient supply to regulate plant root development. The leaf area index increased uniformly after 28 days. The last measurement of LAI was 4.21 at the 72nd day after transplanting.
CANOPY AREA INDEX (CAI)

Figure 5.5 shows the canopy area index (CAI) that developed slowly during the first four weeks, then, linearly increased for 5 weeks until leveling off when reaching unity which indicated total ground coverage by the canopy. The interesting fact was that the LAI increased rapidly while the CAI leveled off after day 55. The leaf canopy grew in all directions until horizontal room was unavailable; then after the CAI reached unity, the plant height increased.

ET CHARACTERISTICS AT HIGH SOLAR IRRADIANCE

Nonuniform evapotranspiration characteristics were found for New Guinea impatiens, a low light plant, during high solar radiation periods. This is shown in Figures 5.6 and 5.7 for one selected day in September. First, the ET rate was found to remain relatively low although it was quite variable regardless of the solar irradiance level at irradiance values higher than approximately 200 W/m². Second, the temperature of the upper leaves was approximately 2 °C higher than the air temperature during this same high radiation period. This indicated that the plant was much less capable of moving water to the leaf for the cooling compared to that reported by Yang et al. (1989) and Al-Shooshan et al. (1991).

The results indicated that the New Guinea impatiens low light responses may be strongly related to its transpiration limits, rather than other physiological factors such as
photosynthesis. For this plant, known as a low light plant, the transpiration rate was assumed to be limited by the maximum stomatal opening and the ability of the system to move water through the plant.

Essentially, the solar energy received by the plant was greater than the latent energy released by transpiration. The resulting solar energy was converted to sensible heat that resulted in a leaf temperature rise.

**STOMATAL RESISTANCE**

Figure 5.8 shows calculated stomatal resistances during a sunny day in the New Guinea impatiens canopy plotted against solar irradiance. These data were found to be best described empirically by a fourth order polynomial equation in which stomatal resistance \( r_s \) and solar irradiance \( Q \) have units of seconds per meter and watts per square meter.

\[
r_s = 1123.1 - 6.486Q + 2.243E-2Q^2 - 3.40E-5Q^3 + 1.938E-8Q^4
\]

(5.5)

The correlation coefficient \( R^2 \) for this equation was 0.86. There was no significant improvement in the fit of the equation by using a higher order polynomial. This relation was different from other studies such as the exponential relation developed for potted chrysanthemum by Al-Shooshan et al. (1991) and cucumbers by Yang et al. (1989). The primary difference was assumed to be due to the light saturation characteristics during high solar irradiance of New Guinea
impatiens.

ET MODEL VALIDATION

Figure 5.9 compares the predicted evapotranspiration with the actual measured values. A linear regression on the points gave a relationship of:

$$Q_{pre} = 6.15 + 0.99xQ_{meas}$$  \hspace{1cm} (5.6)

with an $R^2 = 0.85$. This figure contained all 20 days (every other day for 40 days) of data with 1920 points covering the LAI range from 1.0 to 4.21. The 95 percent interval on the slope was $\pm 0.0185$. The 95 percent confidence interval from all range is about $\pm 73.4$ gram per hour per square meter. There were more points for the lower ranges because of the lower evapotranspiration on cloudy days and during the early growth of the plant.

The model predicted water uptake by the input of easily observed and measured variables such as solar irradiance, air temperature, relative humidity and air velocity.

NIGHT EVAPOTRANSPIRATION

Figure 5.10 shows the average night transpiration rate and leaf area index plotted as a function of the plant transplanted day. The corresponding water vapor pressure deficit calculated using average night data from 23:00 PM to 5:00 AM in the morning are plotted as a function of the transplanted days in Figure 5.11. The night time
transpiration rates were significantly higher than reported in other studies such as Al-Shooshan et al. (1991), Yang et al. (1989) and Stanghellini (1987).

CONCLUSION

A linear relation between leaf area and both the leaf length and width was determined and used to record the plant leaf areas of the total canopy. The leaf area index (LAI) increased uniformly after the fourth week of transplant. Black and white photography was successfully used to monitor the canopy area index which developed rapidly after the fourth week of transplant, and then leveled off as it approached unity.

Transpiration saturated at solar irradiance above 250 W/m² for New Guinea impatiens. At higher levels of irradiance, the exposed leaf temperature was up to two degrees centigrade higher than the surrounding air temperature. As a result of this phenomenon, the conventional exponential type stomatal resistance curve as a function of solar radiation levels did not work as well as a fourth order polynomial relationship. This relationship was calculated by using a group of diffusion models, including one for the sun-exposed leaf layer and three other equally divided sun-shaded layers.

Reasonable agreement was found between the experimentally measured and the model predicted evapotranspiration.
Figure 5.2 Relation between the leaf area and leaf length for New Guinea impatiens 'Equinox'

\[ Y = -0.0567 + 0.3378X + 0.2800X^2 \]

\[ R^2 = 0.968 \]
Figure 5.3 Relation between leaf area and leaf width for New Guinea impatiens 'Equinox'

\[ Y = -7.6638 + 7.177X - 0.0737X^2 \]

\[ R^2 = 0.954 \]
Figure 5.4. Measured leaf area index (LAI) plotted for days after transplant
Figure 5.5 Measured canopy area index (CAI) plotted for the days after transplant
Figure 5.6. Evapotranspiration rate with solar irradiance above canopy on September 22, 1991 with CAI=0.58, LAI=1.35
Figure 5.7. Air temperature and upper leaf temperature for New Guinea impatiens on a sunny day on September 22, 1991
Figure 5.8. Relationship between stomatal resistance and solar irradiance.
Figure 5.9. Scatter plot of predicted and Measured ET rate.
Figure 5.10 Average ET rate during night (above) and LAI (bottom) for the days after transplant
Figure 5.11. Average night vapor pressure deficit for the day after transplant
CHAPTER VI
DYNAMIC ANALYSIS OF NUTRIENT UPTAKE
FOR NEW GUINEA IMPATIENS

ABSTRACT

Nutrient uptake rates were closely related to the Photosynthetically Active Radiation (PAR) input to New Guinea impatiens grown with a recirculated irrigated solution in a greenhouse environment. The relationship was shown to conform to the form of the Michaelis-Menten equation. The equation was adapted to be used to estimate the uptake of individual nutrients, including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg), based on microclimate parameters and plant characteristics. The quantity of nutrient uptake for each major element was measured during a three hour period each day. The results showed that nutrient uptake increased as PAR increased for low PAR levels and that the uptake rates tended to be constant for high PAR levels. Electrical Conductivity (EC) of the nutrient solution was recorded every 15 minutes illustrating the dynamic nutrient uptake differences between the night and day times.
INTRODUCTION

A detailed understanding of the relationships between environmental changes and the physiological ecology of plants is necessary for the environmental engineer and horticultural manager designing greenhouse controls. Appropriate control of the environment in the greenhouse must consist of a precise evaluation of plant responses to environmental changes.

The responses of plant nutrient uptake to environmental factors have been studied for many years. The role of light in ion absorption was first studied in plants in which the same cells performed the functions of both photosynthesis and the primary acquisition of mineral nutrients (Epstein, 1972). The synthesis of carbohydrates and other respiratory substrates depends on the energy of light trapped in the process of photosynthesis. Epstein indicated that the accumulation of nitrate by cells of green algae depends upon light as a source of energy. There is a similar conclusion for the absorption of phosphate (Epstein, 1972). Furthermore, Epstein reported that the leaf tissue of corn accumulated potassium in the light at twice the rate it did in the dark. He summarized that the transport of inorganic ions by plant cells was affected through mechanisms whose functioning depended upon energy made available through cellular metabolism.

A recirculating nutrient solution culture was employed by Noguera et al. (1986) to evaluate the nutrient content of
tomato plants. A comparison of nutrient uptake of plants grown using the nutrient film culture and the conventional soil culture under greenhouse conditions was made. The pH level and solution electrical conductivity were maintained at a desirable level after evaporative losses had been automatically replenished with tap water. It was concluded that the average levels of nutrients maintained in leaf tissue for the nutrient solution culture were higher for all major elements except calcium than that for the soil culture.

Larouche et al. (1989) conducted an experiment on the effects of nitrogen concentration on nutrient uptake under different photosynthetic photon flux (PPF) levels in greenhouse tomato production. The plants were grown in growth chambers under two photosynthetic photon flux (125 and 250 \( \mu \text{mol.s}^{-1}.\text{m}^{-2} \) PAR) conditions and four N fertilization regimes. The results showed that vegetative growth was limited and did not respond to N increments in the nutrient solution at lower PPF.

Four light intensity levels were installed in growth chambers to research their effects on nutrient uptake by spinach plants (Cantliffe, 1972). The results showed that at 6.5 \( \text{W/m}^2 \), the plants accumulated \( \text{NO}_3-N \) and total N at all nitrogen levels; however, response to nitrogen increments was greater at high light intensities. Less phosphorous (P) was found in spinach leaves as N fertilizer was added up to 100 mg/kg of soil.
Fower (1977) reported that the pattern of nitrogen metabolism in different plant parts was strongly dependent upon translocatory processes that were influenced in turn by light, nitrate concentration, water, and growth substance levels. Moreover, he stated that the nitrate uptake was an energy-dependent process that proceeded more rapidly in strongly illuminated plants. He explained that the integrated process of nitrogen conversion from nitrate to amino acid and protein was strongly linked to light energy.

The Michaelis-Menten formula was employed by Gardiner et al. (1990) for describing phosphorous (P) uptake by plants. Two methods for estimating the Michaelis-Menten kinetics of P uptake were compared. In one method, uptake was measured from two P concentrations in a nutrient solution, with the maximum uptake and the Michaelis-Menten constant was estimated by a direct, linear plot. In an alternate, multiple concentration experiment, uptake was measured for five P concentrations and the parameters were estimated by nonlinear regression. Gardiner et al. concluded that the steady state approach to nutrient uptake measurement provided an acceptable estimation of the P uptake kinetic parameters. A correlation coefficient of 0.89 between P influx and P concentration was obtained by a fit of the Michaelis-Menten model.

The relations between individual nutrient uptake and the surrounding environment have not been established. It is clear that nutrient uptake is an energy dependent process that
proceeds more rapidly in plants that have been strongly illuminated. Unfortunately, the results of this research still remain inconclusive on the effect contributed by each factor, although the knowledge of nutrient uptake has been revised considerably since 1972. Future research may find an acceptable solution for environmental control and greenhouse management in engineering aspects.

The objectives of this study were to measure and predict the dynamic uptake of individual nutrients under varying environmental conditions for New Guinea impatiens grown in a greenhouse.

MODEL DEVELOPMENT

ION TRANSPORT MECHANISMS

Three mechanisms of solute uptake were considered: diffusion, active transport and passive transport.

Active transport was defined as the process in which mineral nutrient transport required energy to drive solutes across a membrane against a high chemical potential. The energy required for the active transport of ions must be derived from metabolism, more specifically, from the oxidation of substrate metabolites. In photosynthetic cells, ATP that is produced in the chloroplast helps drive solute absorption. The solute transport into cells is strongly dependent upon ATP and the ability of the cells to respire aerobically and produce ATP (Nobel, 1974).
Passive uptake was the movement of solutes across the membrane without energy input. When ions penetrate a membrane, they do not move through the lipid bilayer as water does. Instead, ions are absorbed largely through channels in the proteins. The process is called "facilitated diffusion", whereby ions, combined with membrane proteins which then facilitated their movement across the membrane (Salisbury and Ross, 1985).

Diffusion was defined as the movement of water across a cell membrane influencing the movement of solutes. In other words, diffusion was the spontaneous movement of ions in the "downhill" direction, from regions of high to low concentration. If the concentration, or chemical potential, of a solute is lower inside than outside a membrane, the solute will diffuse inward until an equal concentration is attained (Salisbury and Ross, 1985).

MICHAELIS-MENTEN MODEL

It was proposed to model individual nutrient uptake as a function of the photosynthetically active radiation (PAR) available to the plant. As the Michaelis-Menten form of the rectangular hyperbola had already been used to describe the uptake of carbon dioxide by the plant (Landsberg, 1974), it was proposed that a similar formulation be used to relate active nutrient uptake to photosynthetically active radiation.

A constant volume recirculation system was designed,
built and used to evaluate individual nutrient uptake by the plants. Solution samples were taken at the beginning and end of a three hour period each day. This enabled the computation of the gram quantity of each individual nutrient taken up during the time window. The Michaelis-Menten relationship between individual nutrient uptake and photosynthetically active radiation is shown in Equation 6.1.

\[ Y_i = \frac{Y_{\text{max}} \cdot \text{PAR}_i}{(K + \text{PAR}_i)} \]  

(6.1)

where:

- \( Y_i \) = the individual nutrient uptake at time \( i \) with units of mg/hr.m^2 of ground area,
- \( Y_{\text{max}} \) = the maximum individual nutrient uptake with the same units of \( Y_i \),
- \( \text{PAR}_i \) = the photosynthetically active radiation level (PAR) at time \( i \) with units of \( \mu\text{mol/s.m}^2 \), and
- \( K \) = the Michaelis-Menten constant specific to the individual nutrient with the same units as PAR.

This relation is shown graphically in Figure 6.1 (a). As the photosynthetically active radiation (PAR) level increases, the rate of nutrient uptake follows a rectangular hyperbola, or Michaelis-Menten type of relationship. The constant \( K \) in Equation 6.1 is a constant characteristic of each individual nutrient uptake rate. The constants \( K \) and \( Y_{\text{max}} \) were determined by a reciprocal plot as in Figure 6.1 (b).
Figure 6.1. Individual nutrient uptake models showing the relation of uptake and PAR for active uptake based on Michaelis-Menten type kinetics. (a) linear plot. (b) reciprocal plot.

**MATERIALS AND METHODS**

Figure 6.2 shows the principle design used to measure the individual nutrient content in the irrigation system. The quantity of each individual nutrient element in the solution
was calculated from the solution concentration and the total solution volume. The experimental design was required to provide the exact solution volume for the whole system including solution in potting media, supply and return pipes, and pump housing at any time.

In this experiment, a constant solution volume in the recirculated irrigation system was used. Mechanically, a special pump housing was designed with a sensitive water level control device to supply the nutrient solution. The water level control was attached to a supply of fresh water which could be introduced into the nutrient solution when the system lost water due to the canopy evapotranspiration. The volume of the solution in the whole system was measured and was found to be 20.390 liters with 12 cm pots (Figure 6.2).

A uniform solution concentration throughout the system at any time was assumed since the solution was recirculated at a rate of 33.75 kilograms per hour. A nutrient mass balance was computed by measuring the concentrations of each nutrient in the nutrient solution at the beginning and end of a three hour period. A longer period was assumed to cause a greater measurement error due to environmental variation; whereas, a shorter sample period would result in less sensitivity to the solution concentration. Thus, three hours was chosen as the period in which PAR levels would not fluctuate too much while nutrient concentration changes would be sufficiently large to be measurable. Solution samples were taken at 11:00 am and
Figure 6.2 Recirculation irrigation system designed to keep the nutrient solution at a constant volume (above) and sample taking from the system.
2:00 pm EST each day. Six samples were also collected during the night period to determine nutrient uptake under zero PAR conditions. The solution samples were analyzed by the Research-Extension Analytical Laboratory (REAL) at Wocster.

A highly accurate lysimeter scale measuring from 0 to 3,000 kgs, in increments of one gram, was used to weigh the whole system in order to monitor the canopy evapotranspiration rate as shown in Figure 6.3.

Rooted cuttings of New Guinea impatiens 'Equinox', with two fully expanded leaves, were transplanted into a loose 100 percent rockwool media in 12 cm pots. Rockwool was selected for its characteristics of containing no significant quantity of soluble materials (Nelson, 1991) even in a short period of three hours. Deionized water was used for the entire experiment. The nutrient solution was completely replaced every seven days to ensure an adequate supply of all nutrients. Leaf tissue samples were taken periodically to ensure healthy plant growth. The nutrient solution was mixed using Calcium Nitrate, Ca(NO₃)₂ (15-0-0), Potassium Nitrate, KNO₃, (13-0-44), and Mono Ammonium Phosphate, (NH₄)₂HPO₄ (21-53-0). Individual element concentrations were nitrogen at 100 mg/l, phosphorus 25 mg/l and potassium 75 mg/l.

The PAR levels were determined using three pyranometers (LI-COR, LI-190). It was assumed that the solar energy intercepted by the canopy could affect plant growth and be the energy resource for nutrient ion transport. A plant Canopy
Figure 6.3. The experimental setup with a recirculated irrigation system on a lysimeter
Area Index (CAI) was introduced which was defined as the ratio of the plan area of canopy cover from a top view to the area of total level surface. Solar energy intercepted by the plants was equal to PAR x CAI x Area of the canopy. A CAI of 0.3 meant that 30 percent of the ground area was covered with plant leaves. A CAI of 1 indicated that the plant leaves covered the entire horizontal surface. The CAI was obtained from black and white pictures taken weekly above the canopy and analyzed on a Dapple image analysis system.

Experiments were carried out in a computer controlled greenhouse located at Wooster, Ohio, USA. Temperature set points were 17 °C during the night and 22 °C during the day. Relative humidity (RH) was kept above 55 percent. Air velocity was also controlled by considering the ventilation needs. Other environmental factors including air temperature, solar radiation, dew point in the canopy and carbon dioxide concentration were monitored.

The pH value of the nutrient solution was recorded every 15 minutes by an on line pH transmitter (Model: SIGNET, 3-8700). The pH value of the nutrient solution was adjusted daily to 5.6 to 6.0 using an 80 percent concentrated phosphoric acid.

The electrical conductivity (EC) of the nutrient solution was recorded by an on-line conductivity transmitter (Model: SIGNET, 3-8800). There was a direct linear relationship between the EC and nutrient concentration in water solutions.
under greenhouse conditions (Takano, 1988). A high EC represented a high concentration in the solution volume. Decreasing EC readings over time indicated nutrient loss (or plant uptake) from the constant volume irrigation system. A fast EC change indicated a higher nutrient uptake rate for the related environmental conditions. A constant EC over a period indicated no nutrient uptake under those conditions. The EC data were used to determine the dynamic uptake rates.

RESULTS AND DISCUSSION

NITROGEN MODEL AND ITS PARAMETERS

Figure 6.4 shows the nutrient model for nitrogen uptake as nitrate. The solution's nitrogen concentration was standardized to 150 mg/l. The plant nutrient uptake was normalized to CAI = 1.0. At low PAR levels the nutrient uptake rate increased rapidly as the PAR increased and was proportional to the PAR level. The uptake tended to level off with PAR increases, eventually approaching a maximum rate of uptake. The reciprocal plot in Figure 6.5 gave the regression Equation 6.2 with $R^2 = 0.80$.

$$(1/N_i) = 0.002589 + 0.124785 \times (1/\text{PAR}_i), \quad (6.2)$$

which, in turn, gave the Michaelis-Menten equation for Nitrogen uptake as:

$$N_i = \frac{386.25 \times \text{PAR}_i}{48.2 + \text{PAR}_i}, \quad (6.3)$$

The Michaelis-Menten constant, $K = 48.2$, had a low value,
The Michaelis-Menten constant, $K = 48.2$, had a low value, which indicated that the nitrogen uptake for New Guinea impatiens did not require a high light environment.

OTHER ELEMENT UPTAKES

The Michaelis-Menten type uptake for potassium ($K$) is shown in Figure 6.6. The concentration of $K$ in the nutrient solution was 65 to 123 mg/l during the experiment. The equation is:

$$K_i = \frac{846.7 \times \text{PAR}_i}{1446.4 + \text{PAR}_i} \quad (6.3)$$

where the constant of the Michaelis-Menten equation was 1446.4 μmol m$^{-2}$ s$^{-1}$; this indicated that when the PAR was equal to the Michaelis-Menten constant, the uptake was only half of the maximum uptake. This suggested that the New Guinea impatiens potassium uptake will not saturate under normal conditions.

Figure 6.7 shows the phosphorus uptake, which had a relatively large error under some conditions. This was assumed to be due to the low concentration of this element. In addition, a somewhat uncontrolled amount of phosphorus was added into the system in the form of phosphoric acid to adjust the solution pH levels.

Calcium uptake was high compared to the other element uptake rates as shown in Figure 6.8. The parameters for the Michaelis-Menten equation were 786.782 mg m$^{-2}$ h$^{-1}$ for maximum
with $R^2 = 0.87$ for the reciprocal linear regression.

**ELECTRICAL CONDUCTIVITY**

Figure 6.9 shows the change in electrical conductivity for every hour for September 27, 1991. The system error for electrical conductivity was ± 6 μm/cm. The EC data was normalized to 25 °C. The EC reading changes during the night period were within the error range with an average center of zero. This was consistent with the use of the Michaelis-Menten equation in the model. The nitrogen uptake was effectively zero when the PAR level was zero. This was corroborated by the fact that the electrical conductivity of the recirculating nutrient solution did not change during the night time hours in spite of the fact that the plant was transpiring significantly during this time. If the plant was taking up the nutrients at this time, the replacement of nutrient water by fresh water in this system would reduce the electrical conductivity of the recirculating nutrient solution. It was concluded that the transpiration during the night time hours was comprised only of water uptake, not nutrient uptake.

**CONCLUSIONS**

A recirculated irrigation system and soilless media were used to determine the nutrient uptakes of New Guinea impatiens and how they related to microclimate. Photosynthetically
active radiation (PAR), canopy area index (CAI), transpiration rate, and individual nutrient uptake rates were measured.

The Michaelis-Menten type equation was used to describe the nutrient uptakes. The equation parameters suggested that the nitrogen uptake increased as the PAR increased at low PAR levels, then uptake tended to be constant for high PAR levels. However, the uptakes of other major elements were different. The uptakes for potassium, phosphorus and calcium were not easily saturated under normal environmental condition.

The on-line electrical conductivity measurements suggested that nutrient uptakes were zero during the night and depended on the solar irradiance level above the plant during the day.
Figure 6.4. The nitrogen uptake against PAR level for New Guinea impatiens

Figure 6.5. Reciprocal plot of Figure 6.4 for nutrient uptake of New Guinea impatiens
Figure 6.6. Potassium uptake against PAR Level for New Guinea impatiens
Figure 6.7. Phosphorus uptake against PAR level for New Guinea impatiens
Figure 6.8. Calcium uptake against PAR level for New Guinea impatiens
Figure 6.9. Electronic conductivity (μS/cm.Hr/25 °C) decrease per hour and solar intensity on September 27, 1991 for New Guinea impatiens.
CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based on the results of these experimental and theoretical modeling studies the following conclusions were formulated:

1. A single layer big leaf combination model was used to predict the evapotranspiration for a low light plant, New Guinea impatiens. The energy balance of a canopy was shown to describe the sensible energy and latent energy transform. The evapotranspiration rate of the crop was mainly dependent upon the solar energy available to the canopy and the water vapor pressure deficit between the plant leaf surfaces and the surrounding environment.

2. Canopy area index (CAI) was introduced into the combination type model. The CAI took into account the canopy of a small plant separated from another plant that intercepted less solar radiation than the total ground area because solar radiation is only absorbed by the leaves. A photographic method was successfully used to measure the canopy area index.

3. Average stomatal resistance of the plant canopy was estimated using a multiple layer diffusion model which
divided the plant canopy into several layers of sun-shaded leaves and one layer of sun-exposed leaves having an area of CAI x Area of ground.

4. The Michaelis-Menten equation showed that nutrient uptake rates were closely related to the Photosynthetically Active Radiation (PAR) input for the New Guinea impatiens grown with a recirculated irrigated solution in a greenhouse environment. The equation can be adapted to estimate the active uptake of individual nutrients, including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg), based on the microclimate parameters and plant characteristics.

5. Electrical conductivity (EC) of the solution was directly proportional to the quantity of total dissolved solutes by weight (mg/l). An electrical conductivity sensor was helpful in monitoring the dynamic nutrient uptake rates during the night and the day time.

6. A highly accurate lysimeter scale measuring from 0 to 3000 kgs in increments of one gram was effective in measuring the dynamic evapotranspiration of a plant canopy while the water tank, nutrient tank and canopy were located on the scale.

7. The quantity of plant uptake for each major nutrient could be measured over a three hour period from the constant volume solution system by analyzing for each element at the beginning and the end of each period.
8. Using pure rockwool as the root medium in a hydroponic system produced no difference in quality New Guinea impatiens compared to the commercial root medium, based on dry weight, height, diameter and flower numbers.

9. High radiation periods resulted in high leaf temperatures and constant transpiration. The leaf area index (LAI) increases uniformly after the fourth week of transplant. The canopy area index developed rapidly after the fourth week of transplant and then slowed down when reaching unity.

10. The results indicated that the solar radiation and water vapor deficit of the air were dominant factors for driving evapotranspiration. On the other hand, aerodynamic resistance had a very low effect on evapotranspiration in a greenhouse.

11. Values of transpiration rate from a low-light crop, calculated from a big leaf combination model that uses inputs including solar irradiance, air temperature, air relative humidity and air velocity, have an $R^2$ of 0.85 and 95% confidence interval of ± 75 grams per hour per square meter of ground area when compared with values measured from New Guinea impatiens grown in an environmentally controlled greenhouse.

12. The nutrient uptake increased as PAR increased at low PAR levels and the uptake rates tended to slow down for higher PAR levels. The model parameters suggested that
the nitrogen uptake increased as PAR increased at low PAR levels, and then the uptake tended to plateau for high PAR levels. However, the other major element uptakes were different. The uptake rates of potassium, phosphorus and calcium were not easily saturated under normal environmental conditions. Nutrient uptakes depended on the solar level above the plant during day time.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Evaporation from locations other than plant leaves should be minimized to reduce the evapotranspiration measurement errors. The evapotranspiration rate was sensed by a weight change. Any vibration could bring frequency noise to the system. Objects such as sensors should not be hung on the frame or bench above the scale.

2. Leaf temperature measurement techniques need to be evaluated. There were nine thermocouples located on different plants and at different heights. Sometimes, one or two would give wrong readings.

3. Canopy area index (CAI) of the plant was measured by fixing a camera above the canopy. This needs to be verified with more frequent data collection and more crop canopies.

4. Practical methods must be developed to ensure water quality
so that unknown chemical elements do not enter the recirculated solutions. Distilled and deionized water was used throughout this experiment.

5. The volume of the recirculated solution used in this experiment should be further studied. The large solution volume reduced the calculation error due to variation from one time to another. However, the large solution volume may have reduced the sensitivity of nutrient uptake.

6. A three hour sample period around solar noon was used in this project. Longer sample times may be possible if there are relatively stable weather conditions. Two samples were collected daily because of the cost of analysis; three or four samples daily is desirable for future research if costs are lower and accurate instrumentation is available to analysis the samples.

7. Methods need to be developed to avoid regular replacement of the entire nutrient solution to avoid an ion toxic situation. Replacement time was one week for this experiment. However, it depended on the tank size. No metal apparatus instrumentation was permitted to touch the nutrient solution.
REFERENCES


# APPENDIX A

## NOMENCLATURE

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>UNITS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAI</td>
<td></td>
<td>The canopy area index — the plan area of the canopy per unit area of the ground</td>
</tr>
<tr>
<td>$C_p$</td>
<td>J kg$^{-1}$ K$^{-1}$</td>
<td>The specific heat</td>
</tr>
<tr>
<td>$dT/dt$</td>
<td>K Hr$^{-1}$</td>
<td>The rate of temperature change</td>
</tr>
<tr>
<td>LAI</td>
<td></td>
<td>Leaf area index — the ratio of total leaf area to the ground area.</td>
</tr>
<tr>
<td>$E_{\text{absorbed}}$</td>
<td>W m$^{-2}$</td>
<td>Energy absorbed by a leaf (long wave)</td>
</tr>
<tr>
<td>$E_{\text{cond}}$</td>
<td>W m$^{-2}$</td>
<td>The heat transfer by conduction by leaf</td>
</tr>
<tr>
<td>$E_{\text{emitted}}$</td>
<td>W m$^{-2}$</td>
<td>Emitted energy (long wave radiation)</td>
</tr>
<tr>
<td>$E_{\text{in}}$</td>
<td>W m$^{-2}$</td>
<td>Total energy into the system</td>
</tr>
<tr>
<td>$E_{\text{out}}$</td>
<td>W m$^{-2}$</td>
<td>Total energy out the system</td>
</tr>
<tr>
<td>$E_{\text{radiation}}$</td>
<td>W m$^{-2}$</td>
<td>The net radiation energy</td>
</tr>
<tr>
<td>$E_{\text{storage}}$</td>
<td>W m$^{-2}$</td>
<td>Total energy stored in the system</td>
</tr>
<tr>
<td>$E_{\text{thermal}}$</td>
<td>W m$^{-2}$</td>
<td>The energy stored (or released) due to the leaf temperature changes</td>
</tr>
<tr>
<td>$e(T)$</td>
<td>Pa</td>
<td>The vapor pressure at temperature T</td>
</tr>
<tr>
<td>$e_s(T)$</td>
<td>Pa</td>
<td>The saturated vapor pressure at temperature T</td>
</tr>
<tr>
<td>$k_{\text{air}}$</td>
<td></td>
<td>Air thermal conductivity coefficient</td>
</tr>
</tbody>
</table>
\( k_h \)  Molecular diffusion coefficients in air of heat transfer \( \text{mm}^2 \text{ s}^{-1} \)

\( k_w \)  Molecular diffusion coefficients in air of water vapor \( \text{mm}^2 \text{ s}^{-1} \)

\( L \)  The distance from leading edge \( \text{m} \)

\( LD \)  Leaf average length \( \text{cm} \)

\( L_v \)  Latent heat of vaporization \( \text{MJ} \text{ kg}^{-1} \)

\( \text{NIR} \)  Near infra-red radiation \( \text{W} \text{ m}^{-2} \)

\( \text{Nu} \)  Average Nusselt number \( -- \)

\( \text{PAR} \)  Photosynthetically active radiation \( \mu \text{mol} \text{ s}^{-1} \text{ m}^{-2} \)

\( \text{Pr} \)  Prandtl number \( -- \)

\( Q_{bl} \)  Evapotranspiration rate for latent heat for the canopy per unit area of ground \( \text{g} \text{ Hr}^{-1} \text{ m}^{-2} \)

\( Q_{et} \)  Latent energy for evapotranspiration \( \text{W} \text{ m}^{-2} \)

\( Q_h \)  Heat energy transferred by convection from leaf air \( \text{W} \text{ m}^{-2} \)

\( Q_i \)  Solar irradiation absorbed by the canopy \( \text{W} \text{ m}^{-2} \)

\( Q_{rad} \)  The global solar energy available above the canopy \( \text{W} \text{ m}^{-2} \)

\( r_o \)  Total resistance coefficient \( -- \)

\( \text{Re} \)  Reynolds number \( -- \)

\( \text{Rex} \)  Critical Reynolds number \( -- \)

\( r_h \)  The aerodynamic resistance for heat diffusion \( \text{s} \text{ m}^{-1} \)

\( r_s \)  The resistance of the leaf stomata \( \text{s} \text{ m}^{-1} \)

\( r_w \)  The resistance to water vapor movement by air \( \text{s} \text{ m}^{-1} \)

\( \text{Sh} \)  Sherwood number which is the ratio of actual mass transfer to the rate of transfer \( -- \)

\( T \)  The surface temperature \( \text{K} \)

\( T_{air} \)  Air temperature \( \text{K} \)
\( T_{\text{leaf}} \) The leaf temperature K

\( T_{\text{sky}} \) The temperature of the sky K

\( T_{\text{sur}} \) The temperature of the surrounding K

\( V \) The volume to area ratio m

\( \alpha \) The average absorptivity --

\( \alpha_\lambda \) The spectral absorptivity --

\( \gamma \) The thermodynamic psychometric constant Pa.K'\(^{-1}\)

\( \gamma_\lambda \) The spectral reflectivity --

\( \delta \) The slope of the curve of the saturation vapor pressure against temperature Pa K'\(^{-1}\)

\( \epsilon \) The leaf surface emissivity --

\( \mu \) Air velocity m s'\(^{-1}\)

\( \rho \) The water density g m'\(^{-3}\)

\( \sigma \) Stefan-Boltzmann constant, \( 5.67 \times 10^{-8} \) W m'\(^{-2}\) K'\(^{4}\)

\( \tau_\lambda \) The spectral transmissivity --

\( \nu \) Kinematic viscosity m'\(^2\) s'\(^{-1}\)
APPENDIX B
SUPPLEMENTARY INFORMATION
FOR EVAPOTRANSPIRATION MODELING

1. ASSUMPTIONS FOR A BIG LEAF COMBINATION MODEL:


1) The irrigation water was always available in the plant root zone for transpiration.

2) The leaves of the plants had uniform characteristics such as transmissivity, absorptivity, and reflectivity located from upper to lower parts of the plant.

3) The leaf of the plants has a uniform temperature distribution.

2. LEAF STORAGE ENERGY CALCULATION


Energy storage by plant leaves includes

1) energy resulting from photosynthesis,

2) energy stored (or released) by leaf temperature changes

3) other energy used for metabolism.

First, energy storage resulting from photosynthesis can be calculated as a function of total energy absorbed by
leaves. The solar constant is $1.98 \pm 0.02 \text{ cal.cm}^2\text{.min}^{-1}$. The average magnitude of solar radiation incident on the earth's atmosphere is considered to be $2.0 \text{ cal.cm}^2\text{.min}^{-1}$. 50 percent of the solar radiation may be absorbed by an exposed leaf during the day. On the other hand, a typical net rate of CO$_2$ fixation by a photosynthetically active leaf is $6.6 \times 10^{-10} \textmole.cm}^2\text{.min}^{-1}$ (Nobel, 1974). About 114,000 cal of energy are stored per mole of CO$_2$ fixed in the photosynthetic process. So leaves store $0.0075 \text{ cal.cm}^2\text{.min}^{-1}$ $(6.6 \times 10^{-10} \times 114,000)$ during the process of the photosynthesis. Therefore 0.75 percent $(0.0075/(2\times0.5))$ of the rate of solar radiation absorption is stored during photosynthesis. It is concluded that the energy storage from photosynthesis was less than 0.75 percent and could be neglected.

The second part is energy resulting from leaf temperature changes. This energy can be calculated with the following equation:

$$E_{\text{thermal}} = c_p \rho V (dT/dt)$$  \hspace{1cm} (B.1)

Where $E_{\text{thermal}}$ — The energy stored (or released) due to the leaf temperature changes.

$c_p$ — The leaf specific heat.

$\rho$ — The leaf density.

$V$ — the volume to area ratio.

$dT/dt$ — The rate of temperature change.

Assume leaves are mostly water and have a specific heat equal to that of water (1.0 cal.g$^{-1}$K$^{-1}$ at 20 °C). The New
Guinea impatiens leaf had an average thickness of 0.1 cm. And, it was assumed that the leaf was 50 percent air by volume. Hence, the mass per unit leaf area was 0.05 g.cm\(^{-2}\). Under normal conditions, the fast temperature change was 0.5 °C per minute or 0.025 cal.cm\(^{-2}\).min\(^{-1}\). So the energy stored (or released) in the form of leaf temperature changes can be assumed to be very small. Hence, it was reasonable to ignore the term.

However, the assumption was only for a long time interval, such as 15 minutes. The energy for storage might be significant for a short time interval with a large step or pulse input condition.

The energy used for metabolic processes, such as respiration and photorespiration, was less than that used in photosynthesis. Therefore, the energy for metabolic processes can generally be ignored also.

3. RADIATION BUDGET OF LEAVES


The primary source of energy for leaves is solar radiation and long wave length radiation.

Fig B.1 and Table B.1 shows the green leaf radiative properties. The pigments in a leaf are very effective absorbers of the blue (0.40-0.51 μm) and red (0.61-0.70 μm) bands of the visible portion of the electromagnetic spectrum.
Figure B.1. Idealized relation between wavelength and the absorptivity, transmissivity and reflectivity of a green leaf (after Monteith and Unsworth, 1990).

Therefore, the waveband between 0.40 and 0.70 μm is called photosynthetically active radiation (PAR). There is a small peak of reflection and transmission between 0.5 and 0.55 μm.
At 0.70 μm, absorption decreases sharply and then gradually increases until about 2.5 μm. Leaves absorb 95% of the incident radiation in the long wave length band.

Table B.1 Mean reflectivity, transmissivity and absorptivity of green leaves for different radiation wavebands (after Monteith and Unsworth, 1990)

<table>
<thead>
<tr>
<th></th>
<th>PAR (0.38-0.71)</th>
<th>NIR (0.71-4.0)</th>
<th>Short-Wave (0.35-3.0)</th>
<th>Long-Wave (3.0-100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflectivity</td>
<td>0.09</td>
<td>0.51</td>
<td>0.30</td>
<td>0.05</td>
</tr>
<tr>
<td>Transmissivity</td>
<td>0.06</td>
<td>0.34</td>
<td>0.20</td>
<td>0.00</td>
</tr>
<tr>
<td>Absorptivity</td>
<td>0.85</td>
<td>0.15</td>
<td>0.50</td>
<td>0.95</td>
</tr>
</tbody>
</table>

PAR -- photosynthetically active radiation

NIR -- near infra-red radiation

It was observed from Figure B.1 and Table B.1 that the total of the spectral reflectivity γ₁, transmissivity τ₁ and absorptivity α₁ was unity. That is:

\[ γ₁ + τ₁ + α₁ = 1 \]  \hspace{1cm} (B.2)

The magnitude of thermal radiation absorbed by leaves was determined from the Stefan-Boltzmann Law:

\[ E_{\text{radiation}} = εσ(T)^4 \]  \hspace{1cm} (B.3)

Where ε --- the leaf surface emissivity

T --- the surface temperature

σ --- Stefan-Boltzmann constant, equal 5.67 x 10⁻⁸ W.m⁻².K⁴.

Equation B.3 indicates that the amount of radiation emitted by a body depends on its temperature.

Employing the Stefan-Boltzmann law, the long wave
radiation emitted by a leaf was expressed as Equation B.3. Since long wave radiation was emitted by both sides of a leaf, the factor 2 was introduced to describe its energy loss:

\[ E_{\text{emitted}} = 2\varepsilon \sigma (T_{\text{leaf}})^4 \quad \text{(B.4)} \]

The energy absorbed by a leaf was equal to the radiation emitted by the surrounding surfaces and the sky, which was expressed as:

\[ E_{\text{absorbed}} = \varepsilon \sigma [ (T_{\text{sur}})^4 + (T_{\text{sky}})^4 ] \quad \text{(B.5)} \]

The net radiation was calculated by combining the all the terms involved radiation. That was:

\[ E_{\text{radiation}} = \alpha (I) + \varepsilon \sigma [ (T_{\text{sur}})^4 + (T_{\text{sky}})^4 ] - 2\varepsilon \sigma (T_{\text{leaf}})^4 \quad \text{(B.6)} \]

4. HEAT CONDUCTION


For the one-dimension case, the heat transfer by conduction from the leaf can be listed as:

\[ E_{\text{cond}} = 2K_{\text{air}} (-\frac{\partial T}{\partial X}), \quad \text{(B.7)} \]

or

\[ E_{\text{cond}} = 2K_{\text{air}} \frac{(T_{\text{leaf}} - T_{\text{air}})}{\delta}, \quad \text{(B.8)} \]

where \( K_{\text{air}} \) --- air thermal conductivity coefficient

2 --- the factor was considered the two side of the leaf.

\( \delta \) --- the average thickness of the unstirred air layer adjacent to a leaf.

For a calculation example assume:

\( \delta = 1.3 \text{ mm}, T_{\text{leaf}} = 25 \text{ °C}, T_{\text{air}} = 23 \text{ °C}, K_{\text{air}} = 3400; \) then

\[ E_{\text{cond}} = 2*3400*(2)/0.13 = 0.21 \text{ cal/cm}^2 \text{.min} . \]
It is clear that heat transfer by conduction is very small compared to transfer by solar energy. Hence, the term was neglected.

5. AERODYNAMIC RESISTANCE CALCULATION

Major reference from Monteith and Unsworth (1990), Yang et al. (1989)

The aerodynamic resistance to heat transfer by convection was given by Monteith and Unsworth (1990) with the equation:

$$ r_n = \frac{L}{k_n \cdot \text{Nu}} $$

(B.9)

where $L$ is the leaf average length, $k_n$ is the molecular diffusion coefficients of heat transfer in air (Oke, 1987) and Nu is the average Nusselt number. A flat plate model of Nusselt number was adapted for convection from plant leaves (Monteith and Unsworth, 1990).

$$ \text{Nu} = 0.66\text{Re}^{0.5}\text{Pr}^{0.33} \quad (\text{Re}<500000) \quad \text{(B.10)} $$

where Pr is the Prandtl number and Re is Reynolds number.

In the greenhouses, forced convection is dominate. Reynolds number (Re) is used to determine the type of flow which is defined as the ratio of inertial forces to viscous forces. The critical Reynolds number (Rex) is the value of Re for which transition from laminar flow to turbulent flow begins.

$$ \text{Re} = \frac{\mu L}{\nu} \quad (\text{Rex} = 5 \times 10^5) \quad \text{(B.11)} $$

where $\mu$ is air velocity ($\text{ms}^{-1}$), $L$ is distance from the leading
edge (m) and \( v \) is the kinematic viscosity (\( m^2 s^{-1} \)).

The typical flow over a leaf in a greenhouse is likely to be laminar flow. For instance, for New Guinea impatiens, at \( L=0.1 \) and \( \mu=2 \) ms\(^{-1} \) at 300 K, \( \text{Re}_x \) is \( 1.25 \times 10^4 \) (much less than \( 5 \times 10^5 \)). This flow is laminar and the flat plate model is used. Normally, air velocity in a greenhouse is less than 2.0 ms\(^{-1} \).

6. WATER VAPOR RESISTANCE

Major references from Monteith and Unsworth (1990), Yang et al. (1989) and Al-Shooshan et al. (1991).

Water vapor resistance \( (r_w) \) can be defined as (Monteith and Unsworth, 1990):

\[
r_w = \frac{L}{k_w \text{Sh}} \quad \text{(B.12)}
\]

where \( k_w \) is the molecular diffusion coefficients of water vapor in air and \( \text{Sh} \) is the Sherwood number which is the ratio of actual mass transfer rate to the rate of transfer that would occur if the same concentration difference is established across a layer of still air of same thickness boundary layer. For systems in which heat transfer is dominated by forced convection, the relation between \( \text{Sh} \) and \( \text{Nu} \) is given (Monteith and Unsworth, 1990):

\[
\text{Sh} = \text{Nu}(k_w/k_w)^{0.33} \quad \text{(B.13)}
\]

Combining the equations B.9, B.12 and B.13, results in

\[
r_w = r_h(k_w/k_w)^{0.07} \quad \text{(B.14)}
\]
7. INPUT SENSITIVITY EVALUATIONS

Major references: Oke (1987), Monteith and Unsworth (1990),

AIR TEMPERATURE

Because both temperature and vapor pressure vary with height, vapor pressure deficit changes little from above the canopy to the height of maximum foliage development. Both $\gamma$ and $\rho$ are weakly dependent on temperature.

$$\gamma = 64.993 + 0.0585*T; \quad (B.15)$$

$R^2 = 0.99$ for equation B.15. and $\gamma$ is the psychrometric constant with units of Pa K'. $T$ is air temperature with units of °C. $\gamma$ is 65.6 and 66.2 Pa K', respectively, for temperatures of 10 and 20 °C; this difference is only less than 1 percent. Consequently, a single temperature measurement above the canopy seems to be adequate in many cases.

However, $\delta$, the slope of the curve of the saturation vapor pressure against temperature is more strongly dependent on temperature as shown in Figure B.2:

$$\delta = 51.345 + 0.474*T + 0.204*T^2. \quad (B.16)$$

$R^2 = 0.999$ for equation B.16 and $\delta$ has units of Pa K'. For instance, $\delta$ values are 82.21 and 144.76 Pa K' at 10 and 20 °C, respectively. It increased about 75 percent; hence, a measurement of air temperature in or close to the canopy is
required.

Figure B.3 shows the evapotranspiration simulation results under various air temperatures. The results indicated that an evapotranspiration change of one to three percent may be introduced by a 1 degree centigrade air temperature change.

Many temperature measuring devices and procedures do meet precision requirements. In addition, temperature sensors in shielded-aspirated units must be correctly located.

**SOLAR IRRADIANCE**

For a canopy forming a continuous cover, the available energy can be readily obtained as the difference between the net radiation above and below the canopy. The average absorptivity for the canopy can be measured. The average solar radiation can be obtained by accumulating the number of solar-minutes in a certain time interval and then by dividing total solar radiation by time. This is important because the instant solar intensity may change greatly in the early morning, late afternoon or due to cloud passage.

Figure B.4 shows the simulated evapotranspiration rates. In Figure B.4 the top line simulated ET with full solar irradiance; the bottom line simulated ET with zero percent solar irradiance above the canopy. Thus, the bottom line shows that the evapotranspiration rate is affected by the water vapor pressure deficit. It can be concluded that solar energy dominates evapotranspiration during the daytime.
VAPOR PRESSURE DEFICIT

Two major factors are required to determine the vapor pressure deficit. First, the vapor pressure deficit is dependent on air temperature (Figure B.5). Second, air relative humidity affects vapor pressure linearly as shown in Figure B.6. Figure B.7 shows the simulation results with 20 to 100 percent relative humidities. When the relative humidity is 100 percent, the vapor pressure deficit is zero. There was no evapotranspiration at night and the evapotranspiration rate during the day time is regulated by the solar energy.

Vapor pressure deficit influences the evapotranspiration rate through both sides of the leaf therefore errors in measuring leaf area index can result in large evapotranspiration errors (Figure B.8).

AIR VELOCITY

Evapotranspiration is comparatively insensitive to the exact value of aerodynamic resistance. In a greenhouse environment, for example, the air velocity is usually within the range of 0.5 to 2.0 ms⁻¹. The combination equation predicting ET is essentially not sensitive the aerodynamic resistance (Figures B.9 and B.10). A 50% error of aerodynamic resistance introduced into the equation results in a 3% error in the calculation of evapotranspiration as shown in Figure B.10.
Figure B.2 Relationship between the slope of saturate humidity vs temperature curve and air temperature

\[ S = 51.345 + 0.474 \times T + 0.204 \times T^2 \]

\[ R^2 = 0.99 \]
Figure B.3  Evapotranspiration under various air temperature.
Figure B.4  Evapotranspiration for various solar radiation levels
Figure B.5 Relation between vapor pressure deficit and air temperature. Condition: RH=55%
Figure B.6 Relation between vapor pressure deficit and air relative humidity at temperature = 22 °C.
Figure B.7 Evapotranspiration rate under various relative humidity levels.
Figure B.8  Evapotranspiration rate under various LAI values.
Figure B.9 Relationship between air aerodynamic resistance and air velocity.
Figure B.10 Evapotranspiration simulation under various air velocities.
APPENDIX C

Pictures from the experiment.
Figure B.11 A Select-A-Shade greenhouse and instrumentations
Figure B.12  Side view and top view of New Guinea impatiens
Figure B.13  Experimental set up and air velocity profile measurement
Figure B.14  Plant leaf temperature profile measurement and plant under hot stress
Figure B.15  Top views on September 13 (top left), September 25 (top right), October 2 (bottom left) and October 25 (bottom right), 1991.