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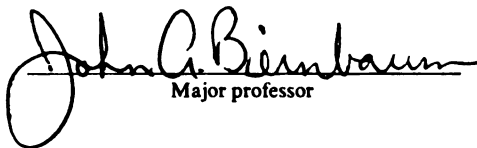


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**Modeling the Concentration of Nitrogen in the Root Zone
of Container-grown Chrysanthemum**

By

Mark V. Yelanich

A DISSERTATION

**Submitted to
Michigan State University
in partial fulfillment of the requirements
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ABSTRACT

Modeling the Concentration of Nitrogen in the Root Zone of Container-grown Chrysanthemum

By

Mark V. Yelanich

The production of greenhouse container-grown crops requires the frequent application of N applied to the medium in a water-soluble form in the irrigation water. The management of these crops requires that growers periodically monitor the medium to determine if the correct concentrations of nutrients are being applied. The goal of this project was to develop a better understanding of the mechanisms influencing the root zone medium N concentration. A model was developed to predict the root zone N content by integrating the rates of N application, movement into the top layer and plant uptake. The rate of N application was modeled as function a of the rate of water loss and the water holding capacity of the medium. The water volume of the medium was modeled as a function of the rates of evaporation and transpiration and were predicted using an empirical Penman equation. The rate of N movement to the top layer was modeled as a function of the rate of water evaporation and of irrigation rate and volume. Plant N uptake was based on the dry mass accumulation rate of the plant. The plant response to low concentrations of N in the medium is modeled through a decrease in shoot N concentration, followed by a decrease in the rate of leaf area expansion. The individual models were validated in

separate greenhouse and growth chamber experiments. The full model was validated by producing chrysanthemum 'Bright Golden Anne' at two times of the year (winter and spring), three fluence levels (70% shade, ambient and HPS) and with three N fertilizer concentrations (3.5, 7, 10.5 mol•m⁻³ N). Plants were evaluated biweekly for leaf area, total plant dry mass, plant Kjeldahl N, root zone NO₃-N and NH₄-N content. Water loss was evaluated daily gravimetrically. The model predicted the general trends of leaf area, dry mass and plant N as well as NO₃-N and NH₄-N contents. The model was used to develop fertilization strategies to apply N more efficiently to the medium.

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Guidance Committee:

The paper format was adopted for this dissertation in accordance with departmental and university regulations. The papers are to be submitted to the Journal of the American Society for Horticulture Science.

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INTRODUCTION

Introduction

The production of floriculture crops is an intensive process, requiring frequent applications of nitrate and phosphate fertilizer, micronutrient heavy metals, pesticides, and fungicides. The public's negative perception of fertilizer and chemical usage has resulted in legislation to limit the amount of chemical residue on the surface of fruits and vegetable. Laws have also been passed restricting and regulating the application of pesticides to plants in many states.

The increased regulation of chemical use and the poor public perception of these chemicals will force changes in the production of ornamental crops. One change is a reduction in the availability of chemicals used in crop production. For example, after the elimination of food crops from the label of Aldicarb (Temik) the manufacturer stopped Aldicarb production, preventing its use in ornamental production, even though it was still legal. This has resulted in dramatic changes in the way ornamental producers control pests in their crops and a long period of learning new methods of pest control. Another example was the use of Alar (B-Nine) on apples resulting in a negative perception of the whole apple industry. The "Alar-scare" briefly affected the ornamental industry for a period of time because of the uncertainty about B-Nine availability for non-food crops. The negative public perception of the apple industry did not pass on to the production of ornamental crops but the potential was there.

The other aspect of possible environmental contamination from ornamental crop production is through the use of fertilizers. Greenhouses are a point source of water and fertilizer runoff since the source of pollution is confined. Fertilizers are applied by a pre-

plant incorporation into the medium and in the irrigation water in the form of water-soluble nutrients. The most common way of applying the fertilizer in the irrigation water is by top watering with drainage of excess fertilizer out the bottom of the growing container.

In the 1960's, three major developments occurred changing the way growers produced flowering pot grown crops. One was the widespread availability of peat-based media, another was the use of drip irrigation, and the third was the increased use of water soluble fertilizers and proportioners. Peat-based media were designed to be very porous and very hard to over water. Water soluble fertilizers and drip irrigation allowed growers to easily apply fertilizer with every irrigation. These three developments, while revolutionizing the way a plant could be grown in a pot, triggered a trend for increasing water soluble fertilizer application.

One draw back with the use of drip irrigation is that high volumes of water are applied to provide uniform irrigation of a crop. With high volumes of water was applied in excess of the water holding capacity of the medium and fertilizer or excess salts are removed from the pot, so higher fertilizer concentrations are required. Growers not using drip irrigation or high volume applications, but trying the higher concentrations of fertilizer that were being recommended, found that higher volumes of solution were required to keep salts from building up in the media. Over the years a wide variety of irrigation methods and a range of fertilizer concentration have evolved and has led to confusion among growers.

To better understand how the fertilizer concentration applied and the leaching

volume influence medium nutrient concentration, experiments were carried out at Michigan State University from 1988 to 1991 (Yelanich, 1991; Yelanich and Biernbaum, 1993; Yelanich and Biernbaum, 1994). Poinsettias were grown using 3 fertilizer concentrations (100, 200, and 400 ppm N and K), and 4 leaching fractions (0.00, 0.10, 0.20 and 0.40). Plants were also grown using subirrigation at the 3 fertilizer concentrations. Leaching fraction is the volume solution leached divided by the volume of solution applied. Multiplying the leaching fraction by 100 equals the leaching percentage, therefore a 0.10 leaching fraction equals a 10% leaching percentage. Poinsettia was used in these experiments since it has a reported to have a “high” requirement for fertilizer and is produced by many growers.

There were several conclusions drawn from this work. The first conclusion was that leaching fraction and the fertilizer concentration applied interact in determining the concentration of nutrients in the medium. Historically fertilizer recommendations were made based on a fertilizer concentration to apply without regards to the leaching volume used. One finding from this work was that a range of leaching fractions and fertilizer concentrations could be used to achieve the same concentration of nutrients in the medium. However, combinations of “high” fertilizer concentrations and “high” leaching fraction resulted in higher quantities of fertilizer leaving the pot and potentially entering into the environment. It is therefore possible to reduce fertilizer concentration and leaching fraction to achieve a desired medium nutrient concentration while reducing nutrients being leached from the pot. The most interesting finding was that it was possible to eliminate leaching by reducing the fertilizer concentration and maintain the nutrients at

acceptable ranges in the medium. From this work a series of best management practices for fertilizing container-grown crops were developed:

1. Reduce the volume of leachate that occurs with every irrigation or use zero leaching systems when possible. Irrigation water quality will ultimately determine the amount of leaching required.
2. Reduce the concentration of fertilizer applied when using lower leaching volumes. The correct concentration of fertilizer applied will ultimately be determined by the weekly media tests.
3. Monitor the nutrient levels in the medium by media testing. Using more efficient methods of fertilizing crops requires closer monitoring of the medium to prevent troubles from occurring.

A greater reliance on medium testing requires a better understanding of the processes that influence nutrient intensity, balance and availability in the root zone of a pot grown plant. Since medium nutrient testing occurs at discrete intervals during the crop, how rapidly the medium nutrient concentration changes will influence what types of decisions can be made based on these tests. One way of understanding the way a system works is through construction of a model. Simulation models allow researchers to evaluate, in real time, how different strategies influence the outcome of some process (Ritchie, 1986). By constructing a model we hope to better understand what happens to the nutrients that are applied and through this understanding develop better fertilization recommendations for container-grown plants. These recommendations would be unlike fertilization recommendations made in the past in that they would:

1. Be based on the current medium nutrient concentrations instead of a concentration of fertilizer to apply,
2. Limit the use of fertilizer or at least apply the fertilizer in a way for the most efficient use by the plant,
3. Be based on best management practices and use a zero leaching system.

The use of a model will also allow researchers and growers to see in real time how the N concentration in the medium changes in response to some strategy and test various strategies quickly.

Plants provide color and beauty to the world. The very existence of public and private gardens, gardening clubs, books and magazines provide tangible proof of the value people attribute to plants. People have strong associations between plants and different events and holidays, such as roses at Valentines day, poinsettias at Christmas and lilies at Easter. People use plants to comfort people at a funeral or to cheer up some one who is sick. The main theme of all of these examples is there is generally a good perception of plants and the floriculture industry. A better understanding of fertilization of container-grown plants and a reduction of fertilizer runoff will promote this perception.

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SECTION I

A MODEL TO PREDICT ROOT MEDIUM EVAPORATION AND TRANSPIRATION FROM CONTAINER-GROWN CHRYSANTHEMUM

**A Model To Predict Root Medium Evaporation And Transpiration From
Container-grown Chrysanthemum**

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Soils, Nutrition and Fertilizers

A model to predict root medium evaporation and transpiration for container-grown chrysanthemum

Additional index words: Dendranthemum morifolium, peat-based medium, Penman equation, mathematical model.

Abstract

The empirical form of the Penman equation was validated for use in predicting water loss from container-grown chrysanthemum. Thirty pots of chrysanthemum were planted at one week intervals for 7 weeks. On the eighth week, all of the plants and medium were subirrigated, and then weighed 0.5 and 24 hours later to determine the amount of transpiration and evaporation occurring during that time period. This was repeated for 3 sequential days. To separate plant transpiration from medium evaporation, fifteen pots per planting week had an evaporative barrier placed on the surface of the root medium. Total leaf area, wet and dry bulb temperature and photosynthetic radiation were also measured. An empirical equation was used to estimate the net radiation. There were significant decreases in water loss by covering the medium surface only for fallow pots and for plants 1 and 3 weeks from planting. Regression equation slopes for covered and uncovered pots comparing the model predictions with the actual water loss were 0.99 and 1.03 indicating a near 1:1 relationship. The model predicts that as leaf area increases the water loss due to evaporation from the medium surface decreases and the water loss due to transpiration by the plant increases.

Many processes occurring in the production of container-grown crops are influenced by water loss from the medium surface and by the plant. Evaporation and transpiration, while obviously influencing the water balance of a container-grown plant, also influence the volume of water soluble fertilizer applied and the movement of fertilizer salts to the top layer of root-medium in a pot. When an evaporative barrier was placed on the surface of the medium of an Easter lily the average water applied was reduced by 37% and the average N fertilizer applied was reduced by 35% (Argo and Biernbaum, 1994). Bunt (1988) reported the electrical conductivity top-watered chrysanthemum built up more rapidly in the summer than in winter when the irrigation frequency was reduced.

Chen and Lieth (1992) constructed a model accurately predicting water loss from container-grown chrysanthemum using the Penman-Monteith combination equation. While this was a successful approach, often a more simplified form of this equation can be used where an empirical wind function replaces the more complicated resistance terms (Allen et al. 1989). The goal of this research was to test a simplified version of the combination equation to predict evaporation and transpiration of water from container-grown chrysanthemum.

The Penman equation provides the basis for the loss of water from the plant and medium surface. Potential transpiration from the plant is described by

$$\lambda \cdot ET_{\text{plant}} = \frac{\Delta \cdot R_{\text{plant}} + \gamma \cdot 6.43 \cdot f(u) \cdot (e_a - e_d)}{\Delta + \gamma} \quad [1]$$

where $\lambda ET_{\text{plant}}$ is the vapor flux density from the plant ($\text{MJ} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$), Δ is the slope of the saturation vapor pressure function, γ is the psychometric constant, R_{plant} is the net

radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), e_a is the saturated vapor pressure (KPa), e_d is the saturation vapor pressure at the dew point temperature (KPa), and $f(u)$ is the empirical wind function (Allen et al. 1989). The evaporation of water from the surface of the medium can be described by a similar equation,

$$\lambda \cdot ET_{\text{medium}} = \frac{\Delta \cdot (Rn_{\text{medium}} - G) + \gamma \cdot 6.43 \cdot f(u) \cdot (e_a - e_d)}{\Delta + \gamma} \quad [2]$$

in where Rn_{medium} is the medium net radiation, G is the medium storage of heat. The net radiation budget of the plant (Rn_{plant}) and medium (Rn_{medium}) are described by,

$$Rn_{\text{plant}} = \alpha \cdot (1 + r) \cdot S + a_{ir} \cdot \sigma \cdot [(T_{\text{sur}})^4 + (T_{\text{sky}})^4] - 2 \cdot e_{ir} \cdot \sigma \cdot (T_{\text{leaf}})^4 \quad [3]$$

$$Rn_{\text{medium}} = (1 - \alpha) \cdot S + a_{ir} \cdot \sigma \cdot [(T_{\text{sur}})^4 + (T_{\text{sky}})^4] - e_{ir} \cdot \sigma \cdot (T_{\text{medium}})^4 \quad [4]$$

in where S is solar radiation, α is the absorbance coefficient, a_{ir} is the infrared radiation (IR) absorbance coefficient, r is the reflectance coefficient, e_{ir} is emmissivity of IR, σ is the Stephan-Boltzman constant ($4.903 \times 10^{-9} \text{ MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1} \cdot \text{K}^{-4}$) and T_{sur} , T_{sky} , T_{leaf} , and T_{medium} are the surrounding, sky (glass), leaf and medium temperatures. One limitation to using equations [3] or [4] is that only air temperature is commonly available in commercial greenhouses. An alternative to using equations [3] and [4] is to estimate net radiation based upon the solar radiation, average daily air temperature (ADT) and saturated vapor pressure (e_d) using the form described by

$$Rn_{\text{plant}} = (1 - \alpha) \cdot RS_{\text{plant}} - \sigma \cdot (\text{ADT} + 273)^4 \cdot (0.39 - 0.158\sqrt{e_d}) \cdot \left(\frac{R_s}{R_{s0}}\right) \quad [5]$$

$$Rn_{\text{medium}} = (1 - \alpha) \cdot RS_{\text{medium}} - \sigma \cdot (\text{ADT} + 273)^4 \cdot (0.39 - 0.158\sqrt{e_d}) \cdot \left(\frac{R_s}{R_{s0}}\right) \quad [6]$$

were α is the crop or medium albedo, and R_{so} is the clear sky solar radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), R_s is the actual solar radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), $R_{s_{\text{plant}}}$ is the short wave radiation reaching the plant canopy ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), and $R_{s_{\text{medium}}}$ is the short wave radiation reaching the medium surface ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) (Jensen et al. 1989). $R_{s_{\text{medium}}}$ can be modeled as a function of the incoming R_s , the plant leaf area index (LAI) and the albedo of the medium (α_{medium}) (Chen and Leith, 1992) and is described by,

$$R_{s_{\text{medium}}} = \alpha_{\text{medium}} * R_s * e^{(-.22 * \text{LAI})}. \quad [7]$$

Chen and Leith found values of 0.25 for chrysanthemum α_{plant} and 0.2 for peat medium α_{medium} . R_s can be estimated from PAR measurement based on values found in Thimijan and Heins (1983).

The empirical wind function $f(u)$ generally has the form of

$$f(u) = a_w + b_w * u \quad [8]$$

in where u is the wind speed at 2 m above the ground. Air velocity has been treated as a constant value of $1.2 \text{ m} \cdot \text{sec}^{-1}$ by Chen and Lieth (1992) simplifying $f(u)$ to 1.4. Using a typical air exchange values of 1 to 2 exchanges per minute, greenhouse air velocities could range from 0.5 to $1 \text{ m} \cdot \text{sec}^{-1}$ and from 0.2 to $1 \text{ m} \cdot \text{sec}^{-1}$ due to horizontal air flow fans (Nelson, 1994). Values for a_w and b_w of 1 and 0.53 respectively were used by Penman (1948).

Materials and Methods

Ten pots of chrysanthemum "Kory" were planted each week for 7 consecutive weeks. Three unrooted cuttings were planted in a 100% sphagnum peat media in 110 mm tall by 130-

mm wide plastic-pots (690 cm^3) and placed under intermittent mist. After 1 week the plants were removed from the mist bench and placed in a 20°C greenhouse and then pinched to 6 nodes 1 week later. Plants were subirrigated every 3–4 days using a nutrient solution consisting of $5.7 \text{ mol} \cdot \text{m}^{-3}$ ($80 \text{ mg} \cdot \text{liter}^{-1}$) $\text{NO}_3\text{-N}$, $1.4 \text{ mol} \cdot \text{m}^{-3}$ ($20 \text{ mg} \cdot \text{liter}^{-1}$) $\text{NH}_4\text{-N}$, $0.7 \text{ mol} \cdot \text{m}^{-3}$ ($21.7 \text{ mg} \cdot \text{liter}^{-1}$) P, $2.1 \text{ mol} \cdot \text{m}^{-3}$ ($82 \text{ mg} \cdot \text{liter}^{-1}$) K (Peters 20-10-20, Scotts, Marysville, Ohio), plus a micronutrient mix at a rate $2.5 \text{ mg} \cdot \text{liter}^{-1}$ (STEM, Scotts, Marysville, Ohio).

Eight weeks after the start of the experiment a polyethylene film evaporative barrier was placed on the surface of the medium on 5 pots from each planting date plus the surface of 5 fallow pots. The plants were then subirrigated with water at 23:00 hr, allowed to drain, weighed, and weighed again 24 hours later. For plants without the evaporative barrier the difference between these two measurements was the amount of water lost by evaporation and transpiration for that time period. For plants with an evaporative barrier, the difference between these two measurements was the water lost only by transpiration. Irrigation and water loss measurements were repeated on three consecutive days. After the final water measurement on the third day, plant fresh mass, leaf area, shoot and root dry mass were measured. Wet and dry bulb air temperature and PAR radiation were measured throughout the experiment. Relative humidity and vapor pressure were determined from the wet and dry bulb measurements.

The model was run using the leaf area for each planting date and the average daily dry bulb temperature, average daily wet bulb temperatures and solar radiation for each house. Total water loss ($d\text{WL}/dt$) ($\text{liters} \cdot \text{day}^{-1}$) was calculated from,

$$d\text{WL}/dt = d\text{WL}_{\text{plant}}/dt + d\text{WL}_{\text{media}}/dt, \quad [9]$$

in where WL_{medium} is the medium water loss and WL_{plant} is the plant water loss. WL_{plant} was determined from,

$$dWL_{\text{plant}}/dt = \lambda ET_{\text{plant}} * f_{\text{plant}} * LA / (2.45 \text{ liters} \cdot \text{MJ}^{-1}), \quad [10]$$

in where LA is the leaf area (m^2) and f_{plant} is the correction factor for chrysanthemum.

WL_{medium} was determined from

$$dWL_{\text{media}}/dt = \lambda ET_{\text{medium}} * f_{\text{media}} * MA / (2.45 \text{ liters} \cdot \text{MJ}^{-1}) \quad [11]$$

in where MA is the exposed medium area (m^2) and f_{media} is the correction factor for chrysanthemum. To simulate pot covering, WL_{media} was multiplied by the effectiveness of the pot cover, a constant based on the covered and uncovered fallow pots.

The least squares estimates of f_{plant} and f_{media} were determined by using the NLIN procedure (SAS institute, 1990).

Results and Discussion

The three days water loss was measured provided a range of solar environments however the vapor pressure deficit (VPD) was fairly low for all three days due to humid conditions and rain on day 2 (Julian day 191) of the experiment (Table 1). Other studies (Stanghellini, 1987) had VPD range from 0 to 1.2 kPa, where our values range 0 to 0.3 kPa. The variability in leaf area from week to week was probably due to variation in temperature during the period from propagation to the start of the experiment and does not represent a typical growth curve for chrysanthemum (Figure 1).

The reduction in evaporation due to covering the medium was greatest for the younger plants and was nonsignificant when leaf area was greatest (Table 2). This appears

to contradict results for Easter Lily and poinsettia (Argo and Biernbaum, 1994, 1995) where covering the surface of the medium with an evaporative barrier reduced the quantity of water applied to the pot by up to 37%. In both studies with Easter Lily and poinsettia the cover was on for the entire duration of the crop and had an influence on the plant architecture and medium nutrient concentration and may have affected the results. In the current study, the cover was only placed on the medium surface for three days and had no impact on plant morphology. Also, since the pots were irrigated at the start of each day the medium nutrient concentration did not vary greatly between covered and uncovered treatments. Another possible explanation for these differences are the differences in architecture between chrysanthemum, poinsettia and Easter lily. It is possible that more solar radiation reaches the medium surface per unit LAI of poinsettia or Easter lily than in chrysanthemum, resulting in more evaporation.

The least squares estimates of f_{plant} and f_{media} were 0.46 and 1.43 and resulting in an R^2 of 0.97 ($n=240$). The cover was 74% effective in reducing the evaporation of fallow pots. Regression equations comparing the predicted evapotranspiration and the measured water loss (Figure 2) were determined for covered and uncovered pots. Regression equation slopes for uncovered and covered media were 1.14 and 1.07 indicating a near 1:1 correspondence between the predicted water loss and measured water loss. One consideration when covering the surface of the medium is the reduction of the vapor pressure of the air around the plant influencing the water loss due to transpiration (Ritchie, 1983). The assumption for this experiment was that covering only influenced medium evaporation of water and had no influence on plant transpiration. No measurements of

canopy humidity levels were made to determine if there was an influence of covering on humidity inside the canopy. If there was an influence of covering on transpiration the regression equation slopes for the plants with an evaporative barrier plants would have been less than the plants without an evaporative barrier since the VPD would have been greater resulting in more water loss via transpiration. A t-test comparing the two slopes (Steel and Torrie, 1980) was found non-significant ($t = 0.24118$, $n = 236$).

The evaporation of water from the surface of the medium is one driving force for the movement of salts to the surface of the medium (Guttormsen, 1969; Yelanich, 1994). To demonstrate the influence of leaf area on WL a simulation was run using the weather data from Julian day 190 and leaf area indexes from 0 to 12 (Figure 4). Increases in LAI resulted in decreased WL_{medium} and increased WL_{plant} . The potential for salt movement toward the medium surface is therefore greatest earlier in the crop and decreases as the leaf area increases. The magnitude of this salt movement with subirrigation was demonstrated by Argo and Biernbaum (1994) who found that a majority of the nutrients initially incorporated into the medium moved toward the surface within days of planting the crop.

Currently the model does not respond to the moisture status of the medium. The plants in this experiment were subirrigated at the start of each day so the medium moisture tensions were low throughout the day. Chen and Leith (1992) incorporated hydraulic conductivity terms into their model, and accurately simulated medium water loss as a function of the moisture content of the medium. A more simplified relationship is described by Priestley and Taylor (1972) where the drying cycle is broken down into a

maximum rate phase and a falling rate phase. After an irrigation the water loss from the medium is at the maximum rate and is only limited by environmental conditions. At some media specific water content the rate begins to fall as a function of the medium water content until the rate becomes zero.

The current model also does not take into account the possibility for high concentrations of fertilizer salt decreasing the osmotic potential of the water, thereby decreasing transpiration. Increases in medium EC would not be expected with subirrigation unless the concentration applied was dramatically increased. A simple empirical model could be constructed to reduce the potential transpiration rate as a function of the medium nutrient concentration.

This feasibility of using a simplified version of the Penman combination equation to predict evaporation and transpiration of water from container-grown chrysanthemum was demonstrated. The main benefit of using the simplified form of the Penman equation is that fewer environmental measurements are needed.

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Table 1. The 24 hour average of environmental parameters for the three days of the experiment. Averages are calculated from 15 minute readings. Numbers in parenthesis are the minimum and maximum values for the 24 hour period.

Julian Date	PAR mol · day ⁻¹	Solar MJ · m ⁻² · d ⁻¹	Dry Bulb C	Wet Bulb C	Average VPD KPa
	Mean				
190	18.3	9.4	21.4 (17.6-27.9)	19.8 (15.9-26.2)	0.35 (0.22-0.49)
191	5.4	2.8	22.1 (18.9-26.8)	21.0 (16.8-25.4)	0.25 (0.07-0.54)
192	12.4	6.3	22.7 (20.0-26.4)	21.4 (19.4-23.5)	0.31 (0.07-0.80)

Table 2. Mean (n=5) water loss per day (ml · day⁻¹) for the 3 days of the experiment for 7 consecutive planting weeks of chrysanthemum.

	Weeks Since Planting							
	fallow	1	2	3	4	5	6	7
Water Loss (ml/day) for Julian Day 190								
-Cover	41	66	87	77	102	84	86	84
+Cover	10	48	76	64	92	90	80	74
t-test	*	*	ns	*	ns	ns	ns	ns
Water Loss (ml/day) for Julian Day 191								
-Cover	12	24	28	25	27	26	26	28
+Cover	7	16	24	11	28	29	25	28
t-test	*	*	ns	*	ns	ns	ns	ns
Water Loss (ml/day) for Julian Day 193								
-Cover	25	48	61	52	63	54	51	49
+Cover	5	39	55	34	58	58	49	47
t-test	*	*	ns	*	ns	ns	ns	ns

ns and * refer to significance at 0.05 or nonsignificant, respectively

Figure 1. Total leaf area (cross hatched) and flower area (shaded) of chrysanthemum from 7 consecutive planting weeks on Julian day 190. The lines at the top of each bar are standard deviations of the mean (n=10). Leaf area did not decrease, plants were smaller due to environmental conditions during rooting and growth.

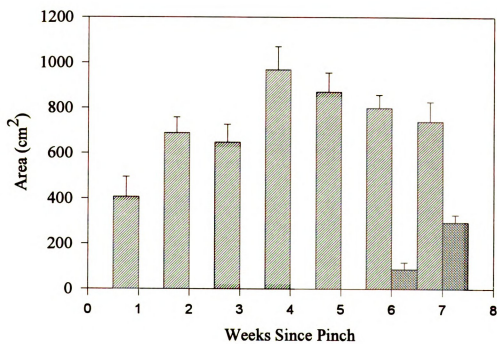


Figure 2. Actual water loss compared with the model predictions for pots with (upper graph) or without (lower) an evaporative barrier. The line in the upper graph corresponds to the regression equation *Actual Water loss = 1.14 * Predicted Water Loss - 9.05* ($R^2 = 0.87$ n=120). The line in the lower graph corresponds to the regression equation *Actual Water loss = 1.07 * Predicted Water Loss - 3.87* ($R^2 = 0.90$ n=120).

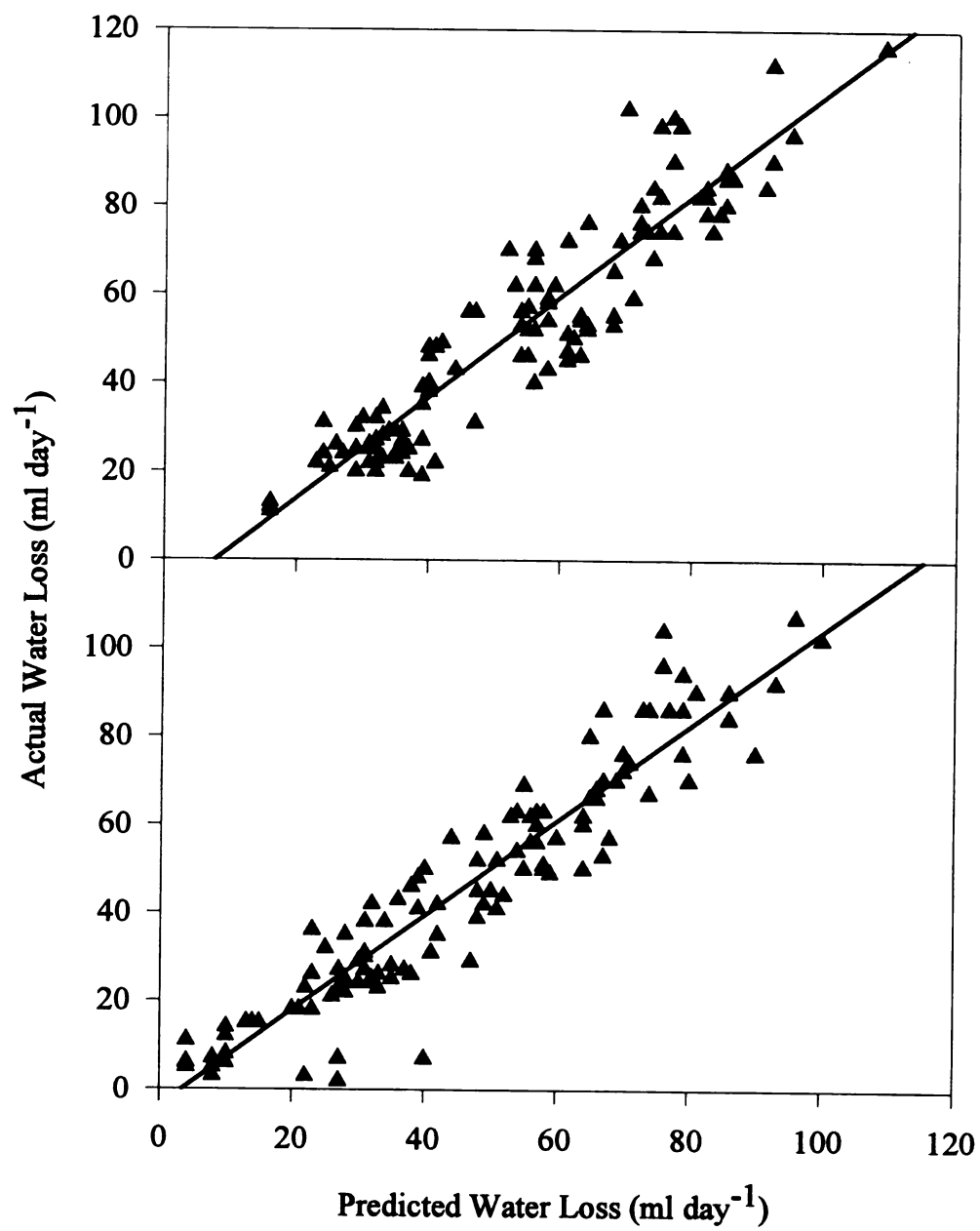
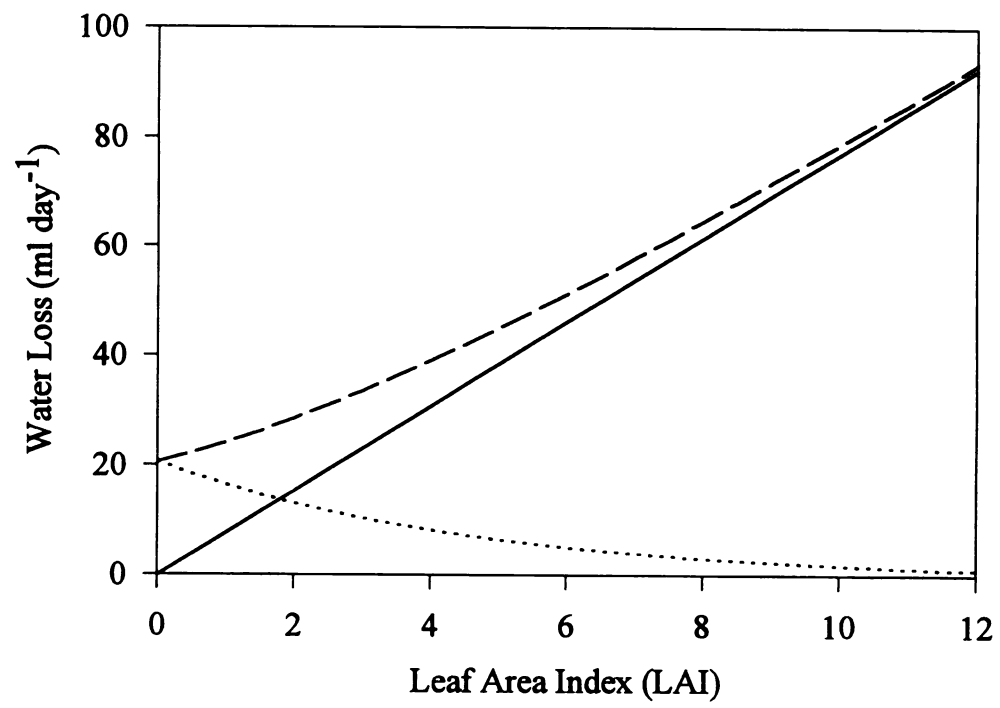


Figure 3. Simulated total (dashed line), transpirational (solid line) and evaporative (dotted line) water loss for leaf area indexes from 0 to 12. Weather data from Julian day 190 was used as model inputs. The leaf area was set to be 1000 cm² at a leaf area index of 12.



SECTION II

**A MODEL TO PREDICT CHANGES IN THE RATE OF LEAF
AREA EXPANSION OF CHRYSANTHEMUM 'BRIGHT
GOLDEN ANNE' IN RESPONSE TO SHOOT NITROGEN**

**A Model To Predict Changes In The Rate Of Leaf Area Expansion Of
Chrysanthemum 'Bright Golden Anne' In Response To Shoot Nitrogen**

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Soils, Nutrition and Fertilizers

A model to predict changes in the rate of leaf area expansion of chrysanthemum

‘Bright Golden Anne’ in response to shoot nitrogen

Additional index words: Dendranthemum morifolium, peat-based medium, mathematical model, subirrigation.

Abstract

A model was constructed to predict how changes in shoot N concentration influence the rate of leaf expansion of chrysanthemum. The model is based on a linear relationship between a minimum shoot N ($N_{\min}$) where no leaf expansion occurs and a maximum shoot N ($N_{\max}$) where there is no improvement in leaf expansion. To calibrate the model, the N in the root zone of chrysanthemum ‘Bright Golden Anne’ was removed at 5-day increments from 10 days after planting until 30 days after planting and also was added back at 5 day intervals, producing plants experiencing N deprivation from 0 to 20 days.. From this experiment, values of $N_{\min}$ and $N_{\max}$ were determined to be 2.7 and 6.8 % (dry weight basis), respectively. The model successfully simulated the changes in the rate of leaf area expansion occurring due to changes in shoot N.

One response of plants to N deficiency is a limitation of expansive leaf growth (Charles-Edwards, 1979) thus limiting ultimate biomass production and potentially reducing yield (Greenwood, 1976). In container-grown chrysanthemum (*Dendranthemum morifolium*), leaf area is also a plant parameter determining plant quality. Leaf area also influences processes such as transpiration and evaporation from the root medium surface (Cheng and Lieth, 1991). The chrysanthemum has been selected for dark green foliage with high N concentrations in the leaves, and is sensitive to low N availability (Elliot and Nelson, 1983). While models exist to predict various aspects of chrysanthemum growth and development, there are none available to dynamically predict the changes in the rate of chrysanthemum leaf area expansion in response to differences in N availability.

In crops such as corn and wheat, the equation

$$f_{LA} = \begin{cases} 0 & \dots \text{for } N_{shoot} < N_{min} \\ (N_{shoot} - N_{min}) / (N_{max} - N_{min}) & \dots \text{for } N_{min} < N_{shoot} < N_{max} \\ 1 & \dots \text{for } N_{shoot} > N_{max} \end{cases} \quad [1]$$

has been used to simulate the relationship between the rate of expansive leaf growth and the N concentration in plant tissue (Goodwin and Jones, 1991). In equation [1], N_{shoot} is the N as a percentage of dry mass in the shoot tissue, N_{min} is the percent N in the shoot tissue where no expansion occurs and N_{max} is the percent N in the shoot tissue where there is no improvement in leaf expansion. When N_{shoot} is greater than or equal to N_{max} the rate of leaf expansion is at the maximum potential rate, and when N_{shoot} is less than N_{max} the rate of leaf expansion is reduced as a function of N_{shoot} . When N_{shoot} is less than or

equal $N_{\min}$, the rate of leaf expansion is zero. The rate of leaf area expansion as a function of the shoot N concentration can be described by,

$$\frac{dLA}{dt} = \frac{dLA_{\max}}{dt} * f_{LA} \quad [2]$$

where $dLA_{\max}/dt$ is the maximum potential rate of leaf area expansion. When f_{LA} is equal to 1, dLA/dt is equal to $dLA_{\max}/dt$. The objective of this research was to determine $N_{\min}$ and $N_{\max}$ and to test the hypothesis that f_{LA} describes the response of chrysanthemum leaf area expansion to shoot N concentration. If successful, f_{LA} will be incorporated into a larger model of the N flow in container-grown chrysanthemum

Materials and Methods

One rooted cutting of chrysanthemum 'Bright Golden Anne' was placed in a 9-cm tall by 12.5-cm wide pot (754 cm³ volume) filled with a 100% sphagnum peat medium. Prior to planting, KNO₃ (0.06 kg•m⁻³), Ca(NO₃)₂ (0.06 kg•m⁻³), MgSO₄ (0.03 kg•m⁻³), CaSO₄ (0.06 kg•m⁻³), CaHPO₄ (0.06 kg•m⁻³), hydrated lime (0.21 kg•m⁻³) and a micronutrient mix (FTE 555, 0.01 kg•m⁻³ Scotts, Marysville, Ohio) were incorporated into the medium.

Plants were placed in a 1.3 by 2.5 m growth chamber with day and night temperatures of 20 C and exposed to 16-HR photoperiods for the first 7 days, after when the shoots were pinched to 6 nodes and placed under 10-HR per day photoperiods. Plants were pruned to 3 shoots per plant when the shoots were 1 cm in length. Irradiance in the chambers was supplied by cool-white fluorescent tubes (Philips VHO F96712/CW/VHO)

and incandescent bulbs (Sylvania 60-W) with an input wattage of 77% and 22%, respectively. The light source supplied an average fluence rate of $317 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{sec}^{-1}$ ($11.4 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$).

Plants receiving N were fertilized at every irrigation with $9.5 \text{ mol} \cdot \text{m}^{-3}$ ($133 \text{ mg} \cdot \text{liter}^{-1}$) $\text{NO}_3\text{-N}$, $4.5 \text{ mol} \cdot \text{m}^{-3}$ ($63 \text{ mg} \cdot \text{liter}^{-1}$) $\text{NH}_4\text{-N}$ and $5 \text{ mol} \cdot \text{m}^{-3}$ ($195 \text{ mg} \cdot \text{liter}^{-1}$) K made from KNO_3 and NH_4NO_3 . Plants not receiving N were fertilized $5 \text{ mol} \cdot \text{m}^{-3}$ ($195 \text{ mg} \cdot \text{liter}^{-1}$) K made from KSO_4 . Both solutions contained $0.48 \text{ mol} \cdot \text{m}^{-3}$ ($15 \text{ mg} \cdot \text{liter}^{-1}$) P from 85% phosphoric acid and micronutrients supplied from $50 \text{ mg} \cdot \text{liter}^{-1}$ of Compound 111 (Scotts, Marysville, Ohio). Water used to make the nutrient solution had an initial alkalinity of $1.7 \text{ mol} \cdot \text{m}^{-3}$ ($170 \text{ mg} \cdot \text{liter}^{-1}$) CaCO_3 , pH of 6.4 and an EC of $0.3 \text{ dS} \cdot \text{m}^{-1}$. Plants were weighed daily and irrigated when the mass of the plant, pot and medium was less than 350 grams. This weight corresponded to approximately 55% of the total water lost and resulted in no visible wilting. Plants were kept in individual water tight trays and were subirrigated by pouring 0.2 liters of solution into the tray, a volume of solution that could be absorbed by the medium within 0.5 hr of the application.

Groups of 25 plants were fertilized with the N solution until either day 10, 15, 20, 25 or 30 after planting when the N supply to the plant was withheld exposing plants to 20, 10, 15, 5 or 0 days, respectively, without N being applied. On the first day when the N supply was withheld individual plants were irrigated from the top one time with 3 liters of the minus N solution. All subsequent irrigations to these plants were made with the minus N solution and applied by subirrigation. An initial experiment determined that 3 liters of

the minus N solution removed more than 90% of the SME N. In addition to the above treatments, on day 10, 25 plants were leached with 3 liter of minus N solution and had the N supply withheld until either day 10, 15, 20, 25 or 30 respectively. This resulted in plants not being supplied with N for 0, 5, 10, 15 or 20 days. Five plants per treatment were collected at 5 day increments from day 10 to 30 for a total of 5 sampling dates. Total leaf area (Delta-T Devices, Cambridge, England), shoot Kjeldahl N concentration (Diamond, 1992), root medium $\text{NO}_3\text{-N}$, and $\text{NH}_4\text{-N}$ concentration (Warncke, 1986) were determined at each sampling date.

A model was constructed to predict N_{shoot} the shoot percent N as a function of the days since planting, days since termination of N supply and days of re-application of N after its removal, and is described by,

$$N_{\text{shoot}} = b_0 + b_1 * t + f_{\text{starv}} + f_{\text{rec}}, \quad [3]$$

where b_0 and b_1 are parameters to be estimated, t is the days since planting, f_{starv} is a function of days since the N supply was terminated, f_{rec} is function of the number of days since N supply was resumed after a period of no N application. The function f_{starv} reduces N_{shoot} as a function of the days of no N application and is described by,

$$f_{\text{starv}} = b_2 * t_{\text{starv}}, \quad [4]$$

where b_2 the parameter to be estimated and t_{starv} is the number of days since the N was leached from the medium and no other N being applied. The function f_{rec} increases N_{shoot} as a function of the days since the resumption of N application and is described by,

$$f_{\text{rec}} = b_3 * t_{\text{rec}}, \quad [5]$$

where b_3 is the parameter to be estimated and t_{rec} is the number of days of N re-application. The maximum value of N_{shoot} is described by,

$$N_{shootmax} = b_0 + b_1 * t. \quad [6]$$

The least squares estimates of b_0 , b_1 , b_2 and b_3 were determined by using the NLIN procedure (SAS institute, 1990). The values of b_0 , b_1 , b_2 and b_3 were used to predict N_{shoot} and allowed for the least squares estimates of LA_{max} , N_{max} and N_{min} to be determined using the NLIN procedure. The first derivative of a quadratic equation describing LA was used to estimate LA_{max} and was described by,

$$\frac{dLA_{max}}{dt} = L_0 + 2 * L_1 * t, \quad [7]$$

where L_0 and L_1 are the parameters to be estimated. LA was calculated by numerically integrating dLA/dt using the equation,

$$LA(t + \Delta) = LA(t) + \Delta * \left(\frac{dLA(t)}{dt} f_{LA} \right), \quad [8]$$

where the time step of integration (Δ) was 1 day and the period of integration was from day 10 to the time of the harvests (i.e. day 10, 15, 20, 25 or 30). The initial values of LA were based on the average leaf area for plants harvested on day 10.

Results and Discussion

Total leaf expansion was reduced by 58% and shoot N was reduced by 60% for plants with N application withheld the full 20 days. During the time period between days 25 and 30, dLA/dt for these plants was reduced by 87% when compared with plants

where the N supply was never removed. The average shoot N for plants with no N removal was 5.66% of dry mass.

Parameter estimates of 2.7% and 6.8% were found for $N_{\min}$ and $N_{\max}$, respectively (Table 1). The biological significance of $N_{\min}$ and $N_{\max}$ relates in many ways to critical concentration values reported in the literature. Lunt and Kofranek (1957) established leaf N values of 2.25 to 2.74% to be slightly deficient, and plants with values less than 2% to be seriously deficient, based on fresh and dry mass accumulation of the plant. Lunt and Kofranek found plants with leaf N concentration greater than 4 to 4.5% had the greatest fresh and dry mass. A higher desirable range of 4.5 to 5% was established by Woltz (1956). Willits et al. (1992) reported values of N for leaves near 6% from chrysanthemum produced in solution culture. While our values appear to be higher than those reported, most other reports have dealt with whole plant responses, such as fresh mass or dry mass, that may be less sensitive to shoot N than leaf area expansion.

None of the plants in this experiment displayed “classical” N deficiency symptoms, such as chlorosis of the lower leaf blades or the necrosis and abscission of lower leaves (Nelson, 1994). There is a possibility that in this experiment the decrease in leaf expansion may be due to some osmotic effects occurring in the leaf cells and not due to some physiological disruption in cell wall expansion caused by a deficiency of N. Since NO_3^- is the major anion accumulated by the plant and would balance cation uptake, a reduction in nitrate uptake would possibly influence anion uptake (Kirkby, 1968; Mengel and Kirby, 1979). Reducing the concentration of N applied has been shown to reduce the leaf K concentration in chrysanthemum variety ‘Bluechip’ as well as reducing stem length

(Joiner, and Smith 1961). This reduction in cation uptake, especially of osmotically important cations such as K, could have an impact on the osmotic potential of the cell and the rate of cell expansion. It should also be noted that in this study K supply was maintained while in production conditions N and K supply are usually related. Under commercial production conditions water may also be limiting.

The relationship used in equations [3] and [4] of a linear decrease in shoot N in response to N removal and a linear increase in recovery from N removal worked very well (Figure 1). The equation relating predicted shoot N to actual shoot N was $N_{\text{shoot actual}} = N_{\text{shoot}} * 1.00 + 0.00$, with an $R^2 = 0.89$ ($n = 250$). The linear functions used in this experiment worked well since the plants were kept under uniform environmental conditions in growth chambers. Under the variable environments found in greenhouses more elaborate functions may be needed.

The N_{shoot} parameters b_2 and b_3 give some indication of how quickly the plants respond to a N removal episodes. With a b_2 value of -0.132 %/day after N removal, a plant initially starting at the N_{max} of 6.8% would take 31 days to reach the N_{min} value of 2.7%. Once N was re-supplied, a plant starting at 2.7% would take 44 days to reach a shoot N of 6.8%, based on a b_3 value of 0.093%/day of recovery. Therefore a plant under going a N removal would take a slightly longer period of time to recover from the starvation episode once the N supply was replenished. The values of 31 and 44 days are specific to the growth conditions in this experiment, but the general relationship between starvation and recovery should be similar for other environmental conditions.

The function f_{LA} accurately simulated the reduction in leaf area occurring during N starvation and recovery from starvation (Figures 2). The equation relating predicted leaf expansion to actual total leaf expansion was $LA_{actual} = LA * 1.00 + 0.09$, with an $R^2 = 0.95$ ($n = 250$). Under the conditions of this experiment it would take 16 days for a 50% reduction in dLA/dt to occur after the start of a N starvation episode. The relatively long time frames for the influence of a starvation episode to be markedly seen in plant development (i.e. >50% reduction in dLA/dt) would indicate that weekly medium testing would be adequate to determine if N starvation conditions existed and allow for corrections to be made in the fertilization program. Chrysanthemums reportedly require high concentrations of N after pinch (Crater, 1980). In this study there was not a difference in the effect of N removal between day 10 and day 30.

One improvement to the model would be to include nitrate-N storage pools in the leaves since this storage supply would influence how quickly the plant would respond to a N deficiency in the medium (Elliot and Nelson, 1983). Previous studies using chrysanthemum have found nitrate-N to account for 13% of the total N in the leaves indicating that it could be a potential source of N for growth under deficiency conditions (Woodson and Boodley, 1983). Shoot tissue with nitrate reserves could take a longer period of time before a reduction in growth would occur. The actual dynamics of nitrate-N in chrysanthemums would be an interesting area for further research.

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Table 1. Least squares estimates of the nonlinear regression parameters used to determine shoot N concentration (N_{shoot}), rate of leaf expansion (LA_{max}), and the response of leaf area expansion to shoot N concentration (f_{LA}). Equation (eq.) numbers refer to equations found in text.

	N_{shoot} eq. 6		f_{starv} eq. 7	f_{rec} eq. 8	LA_{max} eq. 10		f_{LA} eq. 2	
	b_0	b_1	b_2	b_3	l_0	l_1	N_{max}	N_{min}
Parameter Estimate	5.10	0.027	-0.132	0.093	-6.8	1.13	6.8	2.7

Figure 1. Predicted (lines) and actual (triangles) shoot N concentration at different times since planting. The actual shoot N is the mean of 5 replicates with the bars above and below the points indicating the standard deviation of the mean. The arrows pointing upwards indicate when the N was removed and withheld. The downward pointing arrows indicate the time when the N supply was replenished.

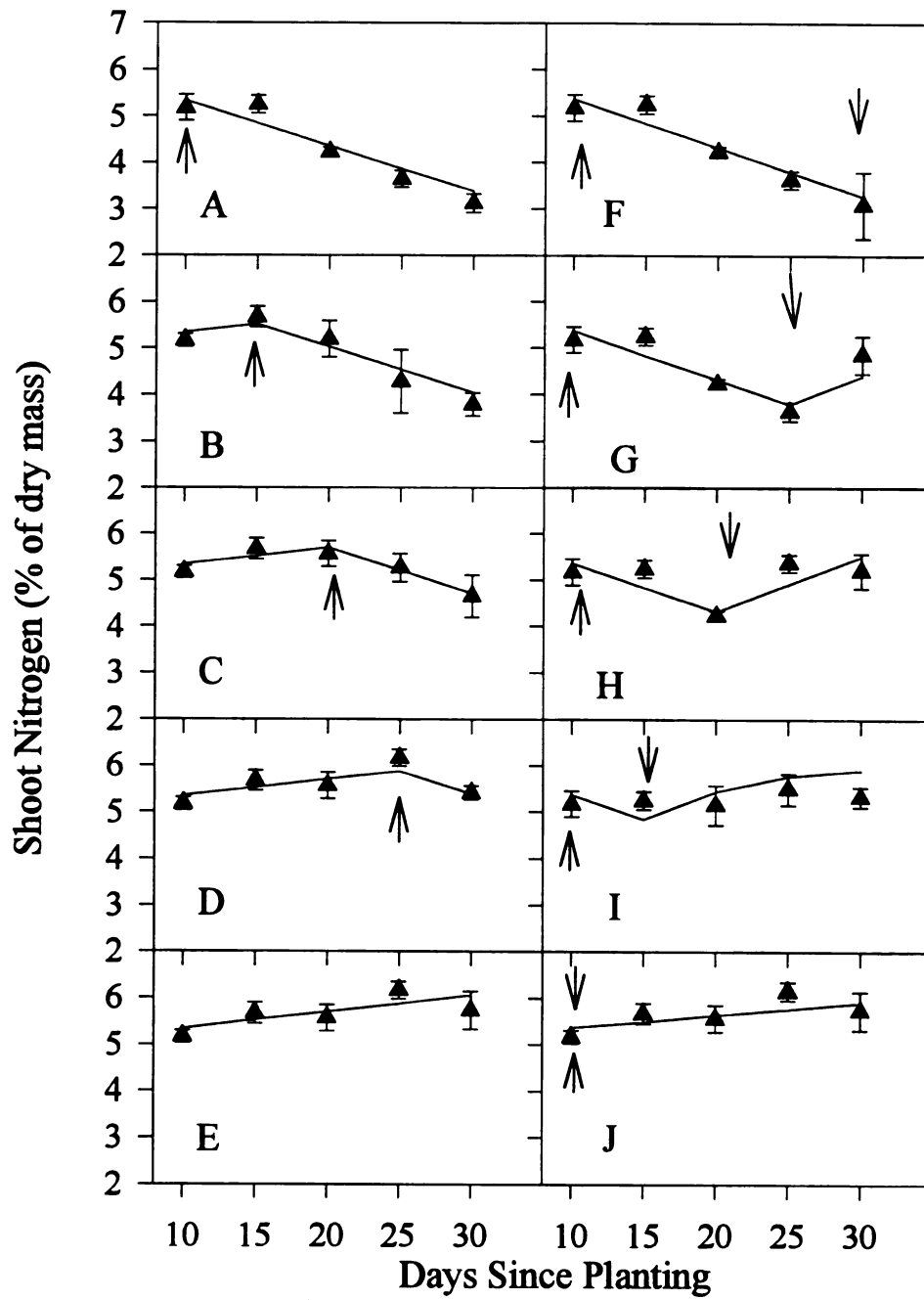
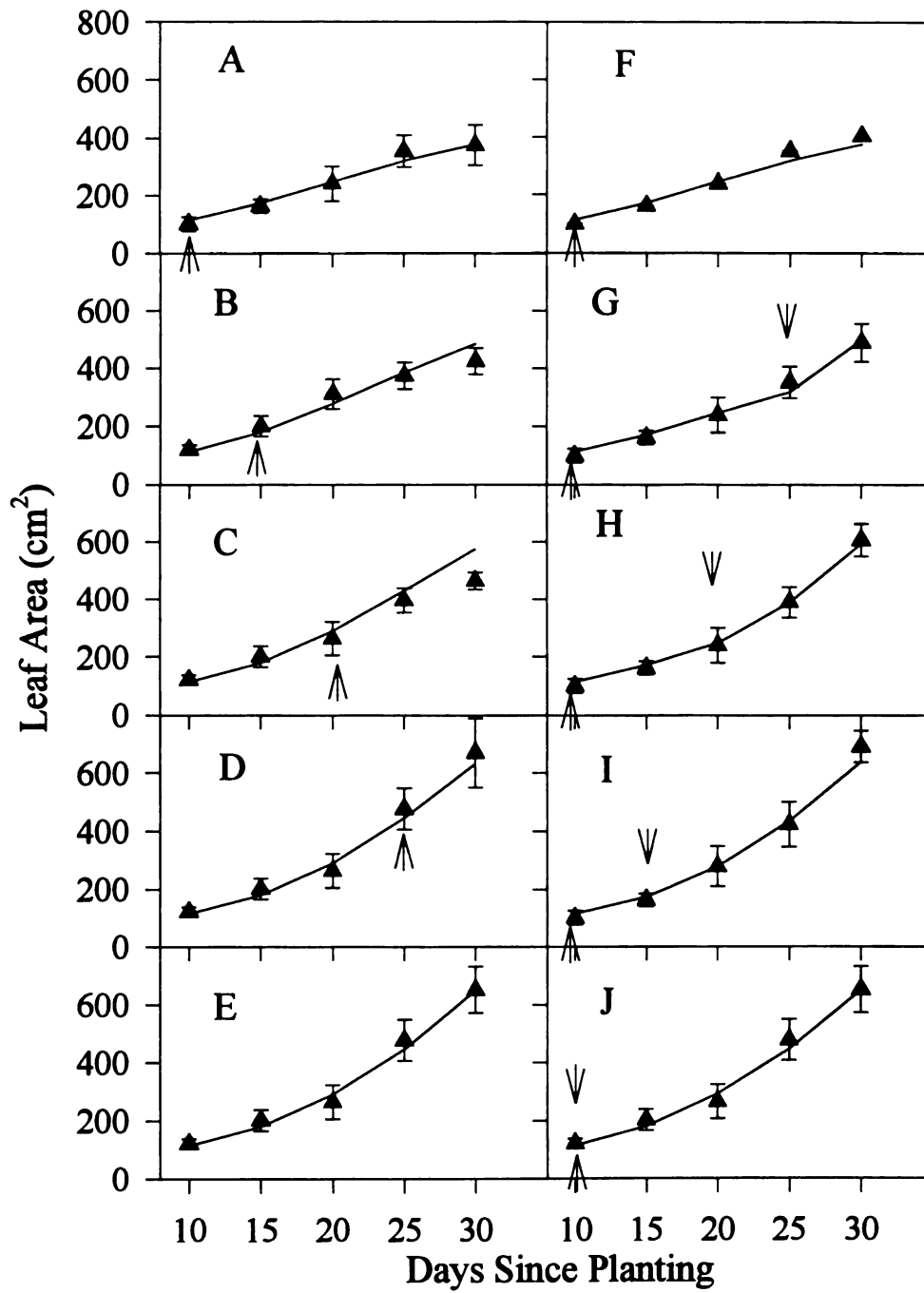


Figure 2. Predicted (lines) and actual (triangles) leaf area at different times since planting.

The actual leaf area is the mean of 5 replicates with the bars above and below the points indicating the standard deviation of the mean. The arrows pointing upwards indicate when the N was removed and withheld. The downward pointing arrows indicate the time when the N supply was replenished.



SECTION III

**A MODEL TO PREDICT THE MOVEMENT OF NITRATE
AND AMMONIUM IN A PEAT-BASED ROOT-MEDIUM.**

A Model To Predict The Movement Of Nitrate And Ammonium In A Peat-based Root-medium.

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Received for publication____. Acknowledgment is made to the Michigan State Agriculture Experiment Station. The use of trade names in this publication does not imply endorsement by the MSAES of the products named, nor criticism of similar ones not mentioned.

A model to predict the movement of nitrate and ammonium in a peat-based root-medium.

Additional index words: Dendranthemum morifolium, mathematical model, peat-based medium, salt stratification.

Abstract

A model was constructed to predict the movement of nitrate and ammonium out of the root zone and into the top layer from the root-medium of subirrigated pots. The movement of nitrate and ammonium was modeled to occur due to the rapid movement of salts during a fertilization and due to the slower movement of salts in the mass flow of water. To quantify the rates of movements of N the concentration of nitrate and ammonium was determined in fallow pots before and after sub-irrigation with fertilizer over 4 wetting and drying cycles. The $\text{NO}_3\text{-N}$ content in the root zone was reduced on average by 46% between irrigations. The amount of N removed from the root zone during an irrigation was 3.4 mg for $\text{NO}_3\text{-N}$ and 1.8 mg for $\text{NH}_4\text{-N}$ average over the four fertilizations, accounting for a loss of from 26 to 40% of the $\text{NO}_3\text{-N}$ and 27% to 94% of the $\text{NH}_4\text{-N}$ was initially present before the irrigation. The predicted rate of movement out of the root zone averaged over the 27 day period was $1.2 \text{ mg} \cdot \text{day}^{-1}$ for $\text{NO}_3\text{-N}$ (range 0.5 to $2.0 \text{ mg} \cdot \text{day}^{-1}$) and $0.5 \text{ mg} \cdot \text{day}^{-1}$ $\text{NH}_4\text{-N}$ (range 0.2 to $0.8 \text{ mg} \cdot \text{day}^{-1}$).

High concentrations of nutrients occur in the upper layer of peat-based root-media of both top watered and subirrigated container-grown plants (Guttormsen 1969; Argo, 1993; Argo and Biernbaum, 1994). Nutrients in the upper layer of the media are less available to the plant than nutrients in the root zone due to low water contents, low root infiltration or excessive salt concentration and therefore constitute a significant loss of nutrients from the root zone (Biernbaum et al. 1993). The root-medium of container-grown plants can be partitioned into two layers (Argo, 1993). The *root zone* is the layer where the majority of a plants roots would be found. The *top layer* is the upper most volume of medium and where few roots grow. In experiments reported by Argo (1993) and Argo and Biernbaum (1994), when the surface of a medium was covered with an evaporative barrier, the concentration of salt in the top layer of the medium was reduced.

The chemical potential of the system, having activity, pressure, electrical and gravity components is the driving force for ion movement (Nobel, 1991). While considerable concentration gradients have been reported to exist between the top layer and root zone, (i.e. a driving force for the activity and electrical components), the diffusion coefficients for ions are too low (e.g. $1.9 \times 10^{-9} \text{ m}^2 \cdot \text{sec}^{-1}$ for K^+) to explain the formation of the top layer over the distance from the bottom to the top of growing container. Also when the pot is first filled with a homogenous medium, the gradients between the top layer and root zone would be very small or non existent. The gravitational potential would also be fairly small due to the relatively small distances involved and would be a driving force moving the ions from the top layer into the root zone. This leaves the pressure potential,

driven by the mass flow of water, $d\text{Wat}_{\text{Evap}}/dt$, as the dominant driving force for salt movement. An equation describing this phenomena is,

$$\frac{d\text{NRZ}_{\text{OUTe}}}{dt} = \frac{d\text{Wat}_{\text{Evap}}}{dt} * \frac{\text{NRZ}}{\text{WatRZ}}, \quad [1]$$

where $d\text{NRZ}_{\text{OUTe}}/dt$ is the rate of N movement out of the root zone and into the top layer ($\text{mg} \cdot \text{day}^{-1}$), $d\text{Wat}_{\text{Evap}}/dt$ is rate of evaporation from the medium surface ($\text{liter} \cdot \text{day}^{-1}$) and NRZ/WatRZ is the root zone nutrient concentration ($\text{mg} \cdot \text{liter}^{-1}$).

Equation [1] would predict that if evaporation was reduced, the formation of a top layer of salts would be reduced. However, in an experiment by Yelanich and Biernbaum (1994) poinsettias were grown with and without an evaporative barrier on the medium and were given the same quantity of fertilizer, the top layer of salt was reduced but not eliminated for covered medium. Plants grown in covered medium received 38% less water than uncovered controls. One hypothesis to explain why evaporation was reduced and top layer formation still occurred is that nutrient salts must also be moving into the top layer with the mass movement of water during an irrigation. The salts probably accumulate in the top layer since few roots form near the surface of the medium (Chen and Lieth, 1993; Guttormsen, 1969).

During fertilization by subirrigation, it is hypothesized that the applied N moving through the root zone to the top layer of the medium will mix with the N currently in the root zone. This would be analogous to mixing which occurs during leaching that occurs during top watering (Wagenet, 1983). A proposed equation to describe this is,

$$\frac{dNRZ_{OUTi}}{dt} = \frac{dWat_{TL}}{dt} * \frac{NRZ}{WatRZ} * f_{MixA} \quad [2]$$

where $dNRZ_{OUTi}/dt$ ($\text{mg} \cdot \text{day}^{-1}$) is the rate of N entering the top layer from the root zone with the irrigation water and $dWat_{TL}/dt$ ($\text{liter} \cdot \text{day}^{-1}$) is the volume of water passing through the root zone and entering the top layer after an irrigation. The function f_{MixA} predicts the amount of root zone N available for removal during an irrigation and would probably be influenced by the initial water content and medium physical and chemical properties (Kerr and Hanan, 1985). Under the conditions of this experiment it is simplified to a constant since one media was used and irrigations occurred at a uniform water content. A model predicting removal of N out of the root zone and into the top layer would incorporate both of these concepts presented,

$$\frac{dNRZ_{out}}{dt} = \frac{dNRZ_{OUTe}}{dt} + \frac{dNRZ_{OUTi}}{dt} \quad [3]$$

The objective of this paper was to test the ability of equations [1], [2] and [3] to predict the rate of movement of nitrate and ammonium N out of the root zone of a subirrigated container medium.

Materials and Methods

To determine the values of f_{MixA} , fallow pots of medium with three initial root zone N concentrations were subirrigated with a fertilizer solution and the root zone medium concentration was determined before and after the irrigation. Nine cm tall by 12.5 cm wide pots (total pot volume 754 cm^3) were filled with a 100% sphagnum peat medium with a common starting base charge of MgSO_4 ($0.03 \text{ kg} \cdot \text{m}^{-3}$), CaSO_4 ($0.06 \text{ kg} \cdot \text{m}^{-3}$),

CaHPO₄ (0.06 kg·m⁻³), hydrated lime (0.21 kg·m⁻³), and a micronutrient mix (FTE 111 0.01 kg·m⁻³). The three initial medium N concentrations were obtained by incorporating both KNO₃ and Ca(NO₃)₂ at the same rate of 0.03, 0.06 or 0.12 kg·m⁻³. After filling the pots, the conducting pores in the medium were allowed to stabilize by allowing the medium to go through one wetting and drying cycle. The pots of medium were kept in individual shallow water tight trays and all irrigations were made by pouring 0.2 liters of solution into the tray, a volume of solution taken up by capillarity within 0.5 hr of the application. The pots of medium were subirrigated with water and allowed to dry until the pots achieved a mass of 250 grams when the experiment was started. This weight corresponded to approximately 45% of the total water holding capacity. The pots of medium were then irrigated with a nutrient solution consisting of 9.5 mol·m⁻³ (133 mg·liter⁻¹) NO₃-N, 4.5 mol·m⁻³ (63 mg·liter⁻¹) NH₄-N, 0.5 mol·m⁻³ (15.5 mg·liter⁻¹) P, 5 mol·m⁻³ (195 mg·liter⁻¹) K, and 50 mg·liter⁻¹ Compound 111 (Scotts, Marysville, Ohio). Macronutrient sources were KNO₃, NH₄NO₃, and H₃PO₄.

Before and after irrigation, five pots per treatment were cut into a top layer and root zone by slicing the medium into two sections at a height 5 cm from the bottom and allowed for a adequate sample size for extraction and analysis using the saturated medium extraction method (Warncke, 1986). The extract was analyzed for nitrate N, nitrite N and ammonium N using colormetric methods (Diamond, 1986a and Diamond, 1986b). The concentration of nitrite N was considered negligible (< 0.07 mol·m⁻³) and will not be reported. A sub-sample of the saturated medium paste was weighed before and after

Results and Discussion

Values of 0.68 for $\text{NO}_3\text{-N}$ and 1.08 for $\text{NH}_4\text{-N}$ were determined for f_{MixA} and provided good predictions of the root zone N content after an irrigation (Figures 1). A higher value of f_{MixA} would indicate that more of the initial solution is available for transport to the upper layer during an irrigation. It was surprising that the value of f_{MixA} was lower for $\text{NO}_3\text{-N}$ than for $\text{NH}_4\text{-N}$ since there is little anion exchange in peat-based medium as compared with cation exchange. The term f_{MixA} probably has similar attributes to equations used in predicting leaching of salts from medium (Wagenet, 1983). The medium physical could influence capillarity and water movement in the medium as well as the mixing occurring between the applied and medium solutions. The medium chemical properties could influence retention of salts by the exchange sites and could influence the quantity of salts moving towards the medium surface. However at this stage of development attributing chemical and physical basis to f_{MixA} is probably not advisable.

The model worked well in predicting the rates of water loss from the root zone and the amount of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ removed after an irrigation (Figure 2). The model predicted that the rate of movement out of the root zone averaged over the 27 day period was $1.2 \text{ mg} \cdot \text{day}^{-1}$ for $\text{NO}_3\text{-N}$ (range 0.5 to $2.0 \text{ mg} \cdot \text{day}^{-1}$) and $0.5 \text{ mg} \cdot \text{day}^{-1}$ $\text{NH}_4\text{-N}$ (range 0.2 to $0.8 \text{ mg} \cdot \text{day}^{-1}$). The $\text{NO}_3\text{-N}$ content in the root zone was reduced on average by 46% between irrigations, demonstrating the large influence the outflow rate of N would have on the N status of the root zone. The rate of N applied to the root zone, averaged over the 27 day period, was $1.3 \text{ mg} \cdot \text{day}^{-1}$ for $\text{NO}_3\text{-N}$ and $0.64 \text{ mg} \cdot \text{day}^{-1}$ $\text{NH}_4\text{-N}$. The

values presented in this paper are higher than would be observed if there was a plant growing in the pot, since the plant canopy would reduce the amount of water evaporation and upward movement of water, therefore reducing the upward movement of N (Yelanich, 1995). The amount of N lost during an irrigation was 3.4 mg for $\text{NO}_3\text{-N}$ and 1.8 mg for $\text{NH}_4\text{-N}$ average over the four fertilizations, accounting for a loss of from 26 to 40% of the $\text{NO}_3\text{-N}$ and 27% to 94% of the $\text{NH}_4\text{-N}$ initially present before the irrigation.

The movement of salts out of the root zone can be reduced by placing an evaporative barrier over the surface of the medium (Argo and Biernbaum, 1995). Over the 30 day period of this experiment, an average of 39 mg of $\text{NO}_3\text{-N}$ was applied with 36 mg of this moving into the top layer. If the evaporation water lost was eliminated the movement out of the root zone would have been reduced 89% (32 mg) for the 30 day time period (assuming 1 irrigation). If a plant was added to this system the movement of N into the top layer would probably be greater since more irrigations would be necessary due to transpirational water loss.

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Figure 1. Before subirrigation (no fill), after subirrigation (bottom to top lines) and model (top to bottom lines) nitrate N contents (top graph) or ammonium N (lower graph) in the root zone of fallow pots filled with 100% peat. Bars over data are the standard deviation of the mean ($n = 5$). Nitrogen was incorporated into the medium prior to filling at rates of 0.03, 0.06 and 0.12 $\text{kg} \cdot \text{m}^{-3}$. The N concentration in the nutrient solution was 133 $\text{mg} \cdot \text{liter}^{-1}$ $\text{NO}_3\text{-N}$ and 63 $\text{mg} \cdot \text{liter}^{-1}$ $\text{NH}_4\text{-N}$.

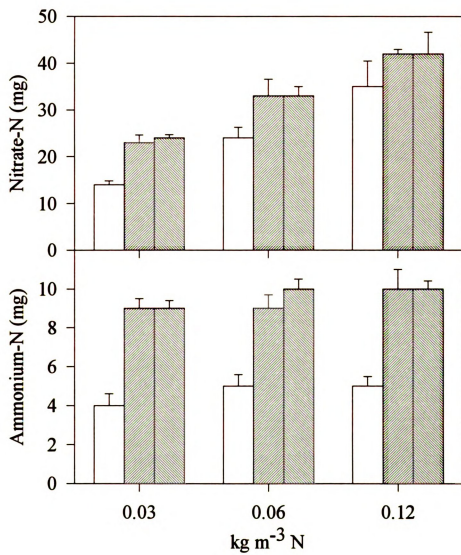
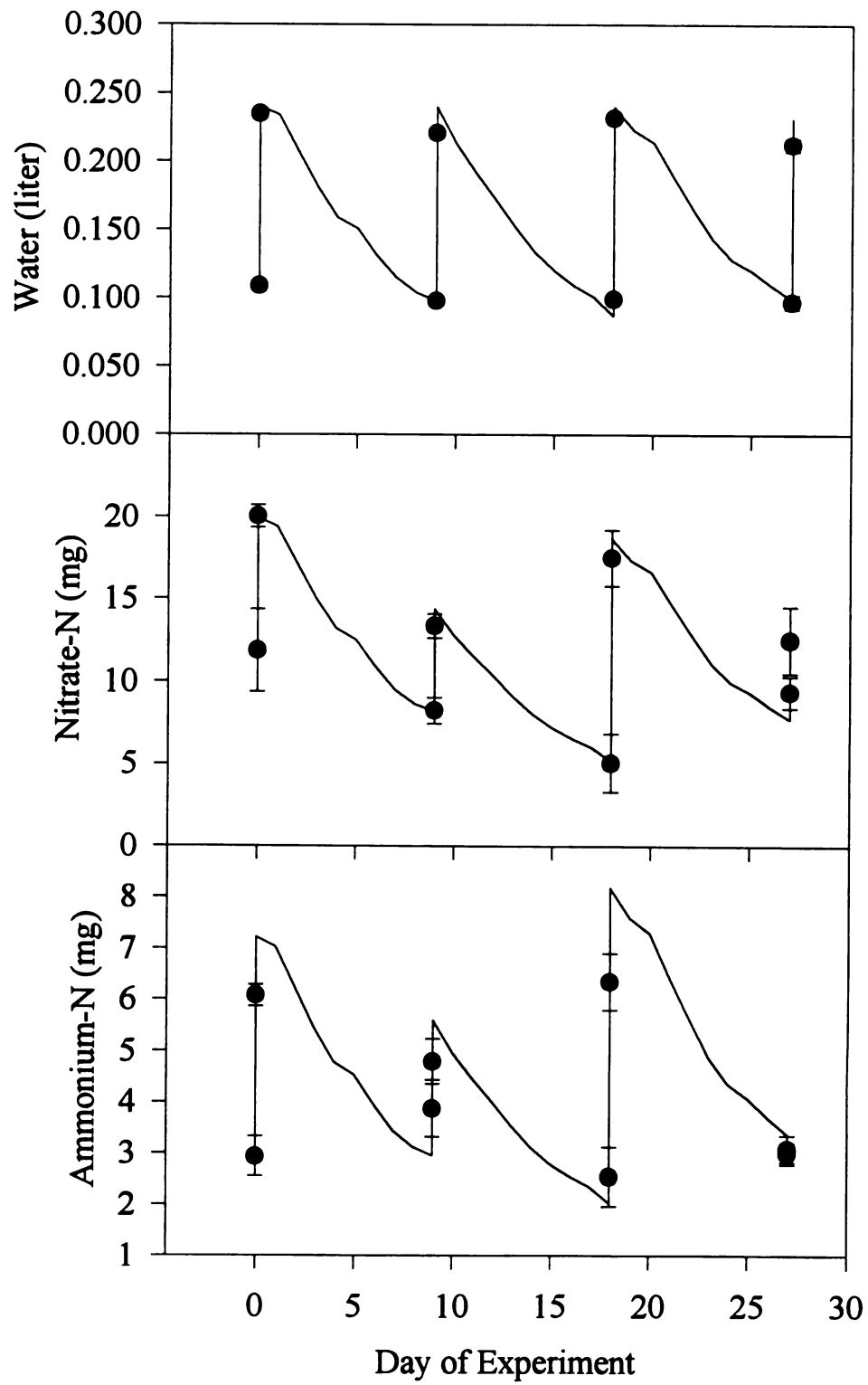


Figure 2. Model (lines) and actual (●) water volumes (top graph), nitrate N content (middle graph) or ammonium N content (lower graph) for the root zone of a fallow pot filled with 100% peat . Bars over data points are the standard deviation of the mean ($n = 5$). The volume of water applied to the medium was 0.2 liters on days 0, 9, 18 and 27. The concentration of nitrate-N applied to the medium was $102 \text{ mg} \cdot \text{liter}^{-1}$ on days 0 and 18 and $33 \text{ mg} \cdot \text{liter}^{-1}$ on days 9 and 27. The concentration of ammonium-N applied to the medium was $48 \text{ mg} \cdot \text{liter}^{-1}$ on days 0 and 18 and $17 \text{ mg} \cdot \text{liter}^{-1}$ on days 9 and 27.



SECTION IV

A MODEL TO PREDICT THE RATE OF WHOLE PLANT NITROGEN ACCUMULATION IN SUBIRRIGATED CONTAINER-GROWN CHRYSANTHEMUM 'BRIGHT GOLDEN ANNE'

**A Model To Predict The Rate Of Whole Plant Nitrogen Accumulation In
Subirrigated Container-grown Chrysanthemum 'Bright Golden Anne'**

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Soils, Nutrition and Fertilizers

A model to predict the rate of whole plant nitrogen accumulation in subirrigated container-grown chrysanthemum ‘Bright Golden Anne’

Additional index words: Dendranthemum morifolium, mathematical model, peat-based medium, nutrition.

Abstract

The rate of whole plant N accumulation by chrysanthemum ‘Bright Golden Anne’ was modeled based on the dry mass accumulation rate of the plant. The model was based on demands of N needed for new growth and for maintenance of the standing dry mass. The new growth demand was modeled as a function of a critical plant N concentration (N_{critical}) and the rate of dry mass. The maintenance demand was modeled as a function of the total dry mass, the current plant N concentration and N_{critical} . To calibrate the model and estimate a value for N_{critical} three growth rates were created by growing plants in a growth chamber using fluence rates of 4, 7 and 11 mol • day⁻¹ PPF and weekly harvesting 4 plants per treatment. The least squares estimate of N_{critical} was determined to be 3.4%. Using this value of N_{critical} , the R^2 for the predicted plant N content was 97%, indicating the N demand model was a good approach for predicting chrysanthemum N accumulation.

Nitrogen fertilization of container-grown plants needs to be reduced to minimum levels required for adequate growth to prevent N runoff from greenhouses and nurseries (Birnbaum, 1992). The rate of N accumulation by a plant is influenced by factors such as medium N concentration (Siddiqi et al, 1990.), N form (Cox and Reisenauer, 1973; Elliot and Nelson, 1983), and root activity (Raper et al, 1978). It has been possible to predict the rate of N accumulation based on the dry mass accumulation rate of the plant (Raper et al., 1977) implying that there is a constant relationship between dry mass accumulation and N accumulation.

Willits et al. (1992) found a 1:1 relationship between relative growth rate (RGR) and the relative accumulation rate (RAR) of N for hydroponically grown chrysanthemums but had to make corrections for the age of the plants. RAR was found to decrease with respect to RGR as the plant progressed toward flowering, with a more rapid decrease as flower formation began to occur. There was also a decrease in the total concentration of N in the plant with most of this decrease occurring in the stems. Woodson and Boodley (1983) also found that as container-grown chrysanthemum aged there was a decrease in the rate of N accumulation and that at flower formation there was a loss of N from the leaves and stems and an increase of N in the flower. While there has been much work on the N nutrition of chrysanthemum, a usable model has not been developed for the prediction of N uptake.

The rate of N uptake has been modeled for other field grown crop plants using the concept of maintenance and new growth demands with the form of,

$$\frac{d N_p}{dt} = \frac{d N_{pm}}{dt} + \frac{d N_{pn}}{dt}, \quad [1]$$

where N_{pm} is equal the maintenance demand for N and N_{pn} is equal to the new growth demand for N (Goodwin and Jones, 1991). The rate of N_{pm} has been modeled as a function of the standing dry mass (DM) of the plant and the concentration of N in the shoot and is described by

$$\frac{d N_{pm}}{dt} = \frac{(N_{critical} - N_{actual})}{100} * DM \quad [2]$$

where $N_{critical}$ is the critical percent N in the dry matter necessary for normal functioning, and N_{actual} is the current percent N of the plant. N_{pn} is the N uptake needed to support the new dry mass of the plant and is described by,

$$\frac{d N_{pn}}{dt} = \frac{N_{critical}}{100} * \frac{dDM}{dt}. \quad [3]$$

Our objective was to test the validity of using equations [1], [2] and [3] to predict N accumulation by container-grown chrysanthemum. Our intent is to incorporate this model into a larger model to predict the N content in the root zone of container-grown chrysanthemum.

Materials and Methods

One rooted cutting of chrysanthemum 'Bright Golden Anne' was placed in a 10 cm pot filled with a 100% peat medium. Prior to planting KNO_3 ($0.06 \text{ kg} \cdot \text{m}^{-3}$), $Ca(NO_3)_2$ ($0.06 \text{ kg} \cdot \text{m}^{-3}$), $MgSO_4$ ($0.03 \text{ kg} \cdot \text{m}^{-3}$), $CaSO_4$ ($0.06 \text{ kg} \cdot \text{m}^{-3}$), $CaHPO_4$ ($0.06 \text{ kg} \cdot \text{m}^{-3}$), hydrated lime ($0.21 \text{ kg} \cdot \text{m}^{-3}$) and a micronutrient mix (FTE 555 $0.01 \text{ kg} \cdot \text{m}^{-3}$) were

incorporated into the medium. Plants were placed in a 1.3 m by 2.5 m growth chamber with day and night temperature set points of 20 C. Plants were exposed to a day-length of 16 hours for the first 7 days, after when they were pinched to 6 nodes and placed under a day-length of 10 hours. Plants were pruned to 3 shoots per plant when the shoots were large enough to handle. Irradiance in the chambers was supplied by cool-white fluorescent tubes (Philips VHO F96712/CW/VHO) and incandescent bulbs (Sylvania 60-W) with an input wattage of 77% and 22%, respectively. Plants in the highest light treatment were exposed to a PPF of $11 \text{ mol} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$. Two other fluence treatments were obtained by placing 1 or 2 layers of shade cloth beneath the lamps resulting in fluence rates of 7 or 4 $\text{mol} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$. Plants were fertilized at every irrigation with $9.5 \text{ mol} \cdot \text{m}^{-3}$ ($133 \text{ mg} \cdot \text{liter}^{-1}$) $\text{NO}_3\text{-N}$, $4.5 \text{ mol} \cdot \text{m}^{-3}$ ($63 \text{ mg} \cdot \text{liter}^{-1}$) $\text{NH}_4\text{-N}$, $0.5 \text{ mol} \cdot \text{m}^{-3}$ ($16 \text{ mg} \cdot \text{liter}^{-1}$) P, $5 \text{ mol} \cdot \text{m}^{-3}$ ($195 \text{ mg} \cdot \text{liter}^{-1}$) K and with micronutrients supplied from $50 \text{ mg} \cdot \text{liter}^{-1}$ of Compound 111 (Scotts, Marysville, Ohio). Water used to make the nutrient solution had an initial alkalinity of $1.7 \text{ mol} \cdot \text{m}^{-3}$ ($170 \text{ mg} \cdot \text{liter}^{-1}$) CaCO_3 , pH of 6.4 and an electrical conductivity (EC) of $0.3 \text{ dS} \cdot \text{m}^{-1}$. Plants were weighed daily and irrigated when the mass of the plant, pot and medium was less than 350 grams. Plants were kept in individual water tight trays and were subirrigated by pouring 0.2 liters of solution into the tray, a volume of solution absorbed by the medium within 0.5 hr of application. Five plants per treatment were randomly selected for evaluation weekly. The root-medium in the pots selected for sampling was first sliced into two vertical halves, one half was used to collect the roots for dry mass and the other half was used for medium N determination. The half used for the root dry mass determination was rinsed with water over a mesh screen to remove the media

particles from the roots. Primary and secondary leaf area, shoot and root dry mass, shoot and root Kjeldahl N (Diamond, 1992) and medium $\text{NO}_3\text{-N}$, $\text{NO}_2\text{-N}$ (Diamond, 1986a) and $\text{NH}_4\text{-N}$ (Diamond, 1986b) concentrations as well as pH and electrical conductivity of a saturated media extract (Warncke, 1986) were determined at each sampling date.

The two main inputs into equations [2] and [3], DM and $d\text{DM}/dt$, were modeled as functions of time and the average photosynthetic flux intercepted by the plant. Dry mass was modeled using an exponential equation and is described by,

$$\text{DM} = b_0 + (1 - e^{(b_1 \cdot t)}) * (f_{\text{ppf}}) \quad [4]$$

where b_0 is the initial DM, b_1 is a parameter to be estimated, and t is the day of the experiment (days) (Causton, 1983). The function f_{ppf} is described by,

$$f_{\text{ppf}} = c_1 * \text{PPF} , \quad [5]$$

where PPF is photosynthetic photon flux ($\text{mol} \cdot \text{day}^{-1}$) and c_1 is a constant. Least squares estimates were determined for b_1 and c_1 using the weekly total dry mass data (NLIN procedure, SAS, 1990). The first derivative of equation [4] is the rate of dry mass accumulation, $d\text{DM}/dt$ and is described by,

$$\frac{d\text{DM}}{dt} = b_1 * (-e^{(b_1 \cdot t)}) * (f_{\text{ppf}}) . \quad [6]$$

Equation [6] was used as an input into equation [3] to determine the nonlinear least squares estimate of N_{critical} using the weekly total plant N contents (mg N) (NLIN procedure, SAS institute, 1990). N_p and DM were determined by numerical integration using the form,

$$N_p(t + \Delta) = N_p(t) + \Delta * \left(\frac{dN_p}{dt} \right) \quad [7]$$

$$DM(t + \Delta) = DM(t) + \Delta * \left(\frac{dDM}{dt} \right) \quad [8]$$

where Δ is the time step of integration.

Results and Discussion

Values of $N_p(t=0)$ of 19 mg and $DM(t=0)$ of 0.75 g were used to initialize the model and are based on the mean actual data from the initial harvest. The root medium concentration of nitrate and ammonium N was 68 and 15 mg • liter⁻¹, respectively, averaged over PPF and samples (Figure 1). The medium NO₃-N concentrations fell near the lower end of the 40-200 mg • liter⁻¹ NO₃-N acceptable range for the SME (Warncke and Krauskopf, 1983). Total plant dry mass and plant N increased as a function of time since the start of short days (Figures 2 and 3). There were significant, linear increases in dry mass and plant N in response to the PPF treatments for the plants from the day 70 sample.

The parameters determined for equations [4] and [5] are found in Table 1. The equation relating predicted dry mass to actual dry mass was $DM_{actual} = DM * 1.0$ with an $R^2 = 0.95$ ($n = 132$). Equation [5], relating PPF to the rate of dry mass accumulation simulating net photosynthesis, is limited to plants grown at the constant 20 C. Equation [5] predicts a linear relationship between PPF and the rate of dry mass accumulation. Holcomb et al.(1988) found that chrysanthemum single leaf photosynthesis rates were asymptotically related to irradiance rates in the range of 0 to 1200 $\mu\text{mol} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$, with the

plateau, for plants grown at greater than $325 \mu\text{mol} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$, in the range of 900-1200 $\mu\text{mol} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$. The maximum irradiance rate in this experiment was $305 \mu\text{mol} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ is well below the $900 \mu\text{mol} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ plateau value. A more complicated function would have been necessary for f_{ppf} if fluence levels greater than $900 \mu\text{mol} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ would have been used in this experiment.

The R^2 (sum of square residual divided by sum of square total) for the predicted plant N was 97% ($N = 132$) indicating that the model was working very well. A value of 0.034 was predicted for N_{critical} (Table 1). N_{critical} is not related to the plant N concentration where deficiency symptoms would begin to occur, but is the concentration the plant N concentration maintains under non-limiting N conditions. There are only limited reports of whole plant chrysanthemum N concentrations since leaf N concentrations are typically reported. In the most recent report by Willits et al. (1992), whole plant N ranged from 5% early in the crop to 3.5% later in the crop for solution grown chrysanthemum. In this experiment values of whole plant N concentrations for plants were in the range of 2 to 5% indicating that medium grown plants may have a lower value of N_{critical} than solution grown plants.

There are many possible improvements to the model excluded in favor of simplicity. One improvement is to incorporate root parameters such as length to determine a maximum rate of N accumulation (Goodwin and Jones; 1991). This is especially important earlier in the crop when both the root density and medium

concentrations are low. This would also allow for prediction of conditions when roots become damaged and N accumulation is reduced.

Another possible improvement would be to simulate the movement of N within the plant. Currently the model simulates the N in the plant as one pool, when realistically there is movement between the roots, stems, leaves and flowers (Woodson and Boodley, 1983). While under the conditions of this experiment treating the N as one pool worked, this method may not work under conditions of plant stress where remobilization of N from one plant part to another would become important.

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Table 1. Parameter estimates for the nonlinear models describing plant dry mass (Eq [4] and [5]) and plant N content (Eq [2]).

b_1	c_1	N_{critical} (%)
Eq.[4]	Eq.[5]	Eq.[2]
0.02	-0.507	3.4

Figure 1. Mean nitrate (left figures) and ammonium (right figures) N concentrations from the medium of chrysanthemums grown at 4 mol•day⁻¹ (top figures), 7 mol•day⁻¹ (middle figures) or 11 mol•day⁻¹ (bottom figures) PAR. Concentrations were determined from saturated medium extracts. Bars around triangles are the standard deviation of the means (n=4).

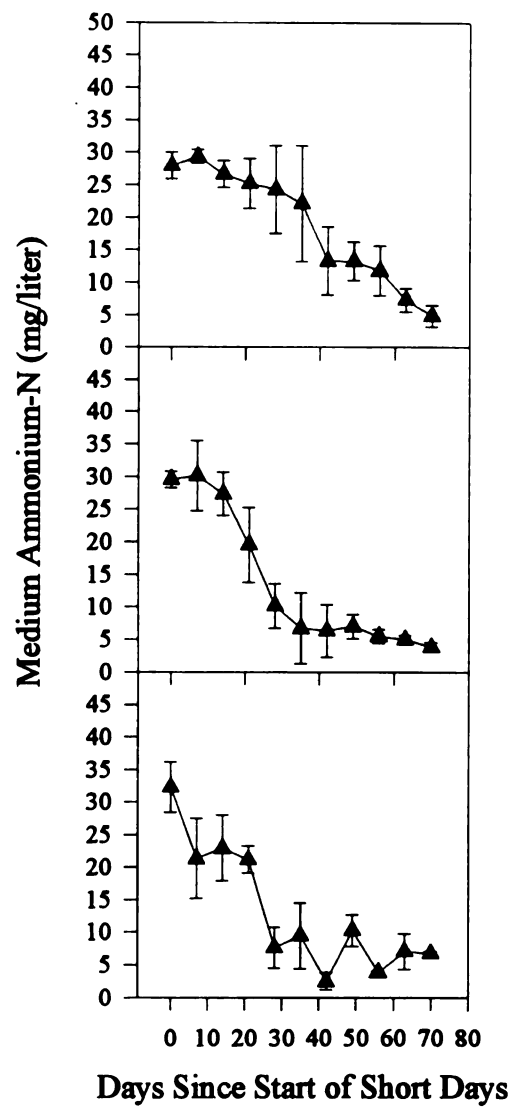
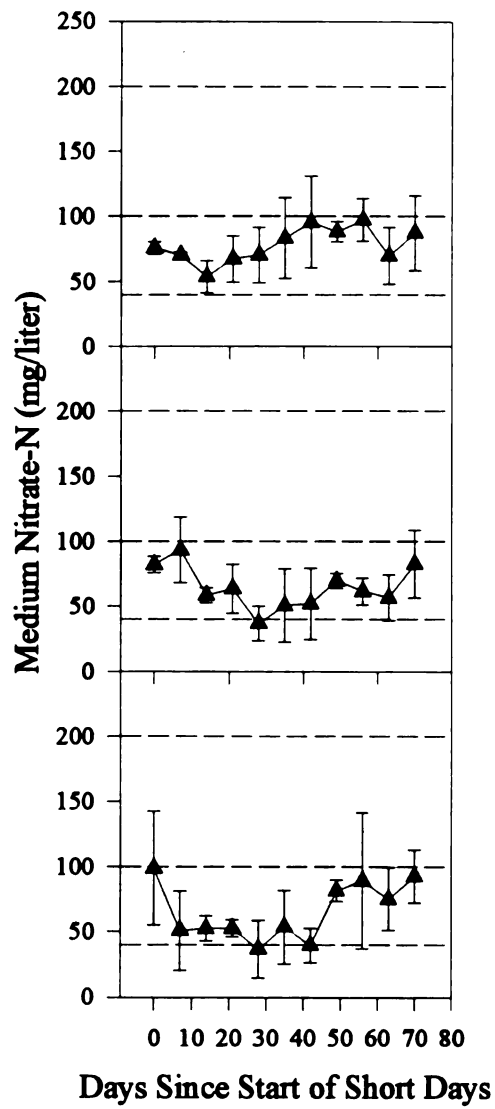


Figure 2. Actual (triangles) and model predicted (lines) dry mass over time since the start of short days for chrysanthemums grown at $4 \text{ mol} \cdot \text{day}^{-1}$ (top figure), $7 \text{ mol} \cdot \text{day}^{-1}$ (middle figure) or $11 \text{ mol} \cdot \text{day}^{-1}$ (bottom figure) PPF. Bars around triangles are the standard deviation of the mean dry mass ($n=4$).

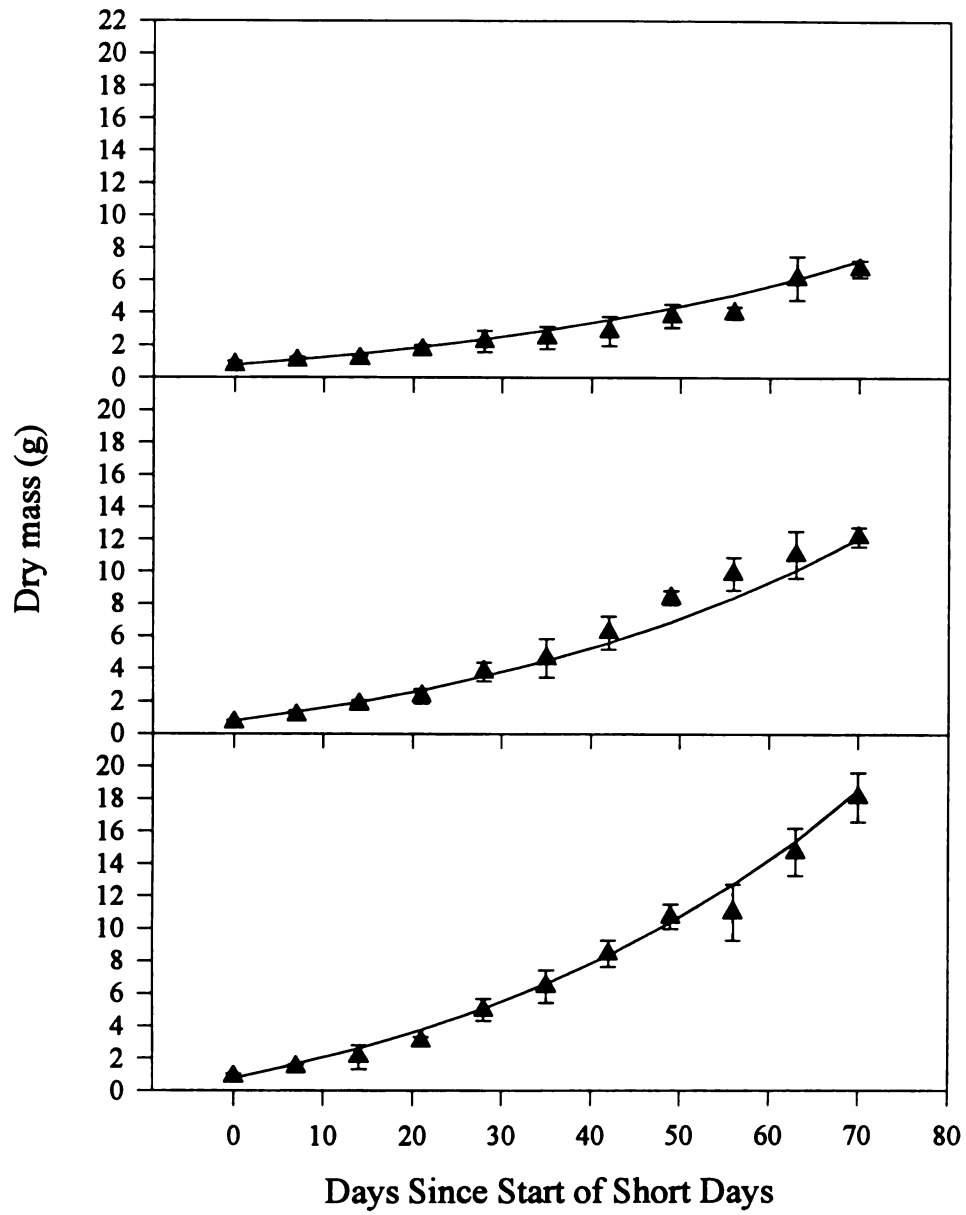
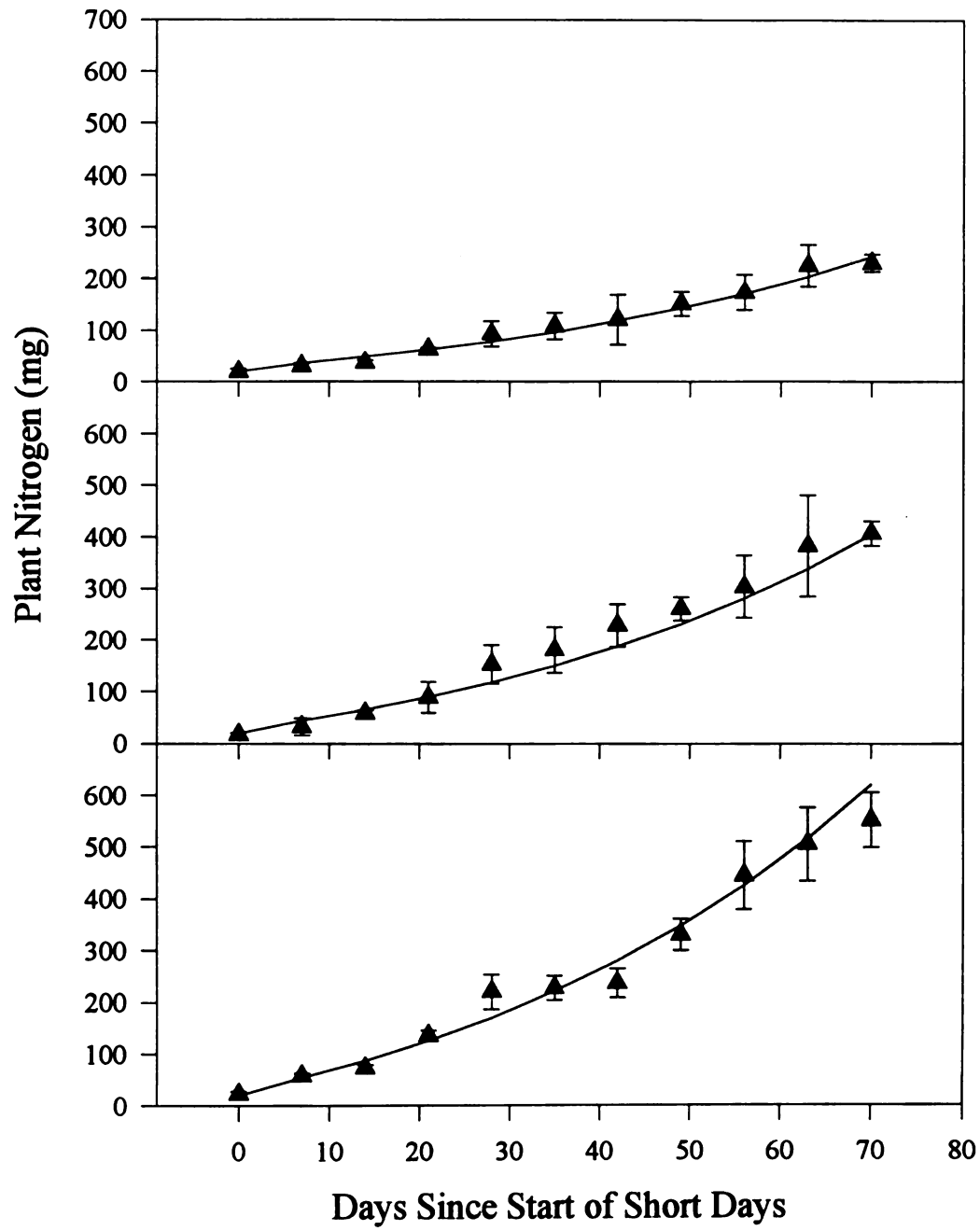


Figure 3. Actual (triangles) and model predicted (lines) plant N content (mg) over time since start of short days for chrysanthemums grown at $4 \text{ mol} \cdot \text{day}^{-1}$ (top figure), $7 \text{ mol} \cdot \text{day}^{-1}$ (middle figure) or $11 \text{ mol} \cdot \text{day}^{-1}$ (bottom figure) PPF. Bars around triangles are the standard deviation of the mean plant N content ($n=4$).



SECTION V

**VALIDATION OF A MODEL TO PREDICT THE NITROGEN
CONTENT IN THE ROOT ZONE OF CONTAINER-GROWN
CHRYSANTHEMUM 'BRIGHT GOLDEN ANNE'.**

**Validation Of A Model To Predict The Nitrogen Content In The Root Zone Of
Container-Grown Chrysanthemum ‘Bright Golden Anne’.**

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Soils, Nutrition and Fertilizers

Validation of a model to predict the nitrogen content in the root zone of container-grown chrysanthemum 'Bright Golden Anne'.

Additional index words: Dendranthemum morifolium, mathematical model, peat-based medium, nutrition.

Abstract

A model was constructed to describe the dynamics of N in the root zone of subirrigated container-grown chrysanthemum. The daily root zone content N content was determined by numerical integration of the rates of N applied, plant uptake and top layer formation. The root zone N concentration at any time period was based on the root zone water volume, determined by numerical integration of the rates of evaporation, transpiration and application. To validate the model, chrysanthemum 'Bright Golden Anne' was produced at two times of the year (winter and spring), with three fluence levels (70% shade, ambient and HPS) and with three N fertilizer concentration (3.5, 7, 10.5 mol • m⁻³ N). Leaf area, total plant dry mass, plant Kjeldahl N, root zone NO₃-N content and NH₄-N content were determined biweekly. Water loss was evaluated daily by weighing the pot, medium and plant. The model was able to predict the general trends of leaf area, dry mass and plant N as well as root zone NO₃-N and NH₄-N contents. The model was used to develop fertilization strategies to more efficiently apply N.

With a move towards management strategies limiting leaching and reducing the applied fertilizer concentration, a better understanding of the processes influencing the medium nutrient concentration becomes more critical (Biernbaum, 1992). Nutrients in the medium of container-grown plants are maintained by the frequent application of water soluble nutrients with the irrigation water. To ensure that the correct concentration of fertilizer is being applied, the nutrient concentration of the medium is evaluated on a periodic basis (Nelson, 1994). The results from the medium evaluation are interpreted using recommended guidelines giving upper and lower values selected to supply plants with the nutrient concentrations required for optimal growth (Warncke and Krauskopf, 1983). If the medium nutrient concentration is outside of the acceptable range, the typical course of action is to make a change in the concentration of the applied water soluble fertilizer concentration. The magnitude of the change in fertilizer concentration is based on grower experience interpreting the medium tests and growing the crop. If insufficient fertilizer is applied then crop failure could result. If excess fertilizer applied leaching may be necessary resulting in fertilizer being wasted and entering the environment (Yelanich and Biernbaum, 1993;1994). A better understanding of the processes influencing the medium nutrient concentration would allow growers to apply the correct quantity of fertilizer to the pot so that less fertilizer is wasted or lost to the environment. One way of achieving this understanding is through the use of models. Models development has the advantage over conventional research methods in that models allow the real time evaluation of various strategies on long time frame processes (Ritchie, 1986). Our objective was to develop and validate a simulation model of the root zone N concentration of container-grown

chrysanthemum using a limited set of environmental inputs. Once validated the model was then used to develop strategies limiting the quantity of N applied while maintaining the nutrients at desired levels.

Materials and Methods

Model Development. Chrysanthemum was chosen as the model crop plant because of the large amount of information available on its growth and development. The system used in this project is based on the root-medium being divided into two layers. The *root zone* is where the majority of a plants roots would be found. The *top layer* is the upper most volume of the container where few roots grow. The majority of the N is supplied to the pot in the irrigation water, applied by subirrigation. The model predicts the rate of N inflow and outflow for the root zone, and through integration of these rates predicts the N content in the root zone at any time period and is illustrated in Figure 1.

The rate of N flow in the root zone of a chrysanthemum pot is described by,

$$dNRZ/dt = dNRZ_{AP}/dt + dPN/dt + dNRZ_{TL}/dt \quad [1]$$

where $dNRZ/dt$ is the rate of N content change in the root zone ($\text{mg} \cdot \text{day}^{-1}$), $dNRZ_{AP}/dt$ is the rate of N applied ($\text{mg} \cdot \text{day}^{-1}$), dPN/dt is the rate of plant accumulation of N ($\text{mg} \cdot \text{day}^{-1}$) and $dNRZ_{TL}/dt$ is the rate of N moving to the top layer ($\text{mg} \cdot \text{day}^{-1}$). The term $dNRZ_{AP}/dt$ is a function of the rate of water loss and can be described by,

$$\frac{dNRZ_{AP}}{dt} = \begin{cases} dWRZ_{AP} * N\text{conc} & \text{if } WRZ < WRZ_{\min} \\ 0 & \text{if } WRZ > WRZ_{\min} \end{cases} \quad [2]$$

where is the volume of solution applied ($\text{liter} \cdot \text{day}^{-1}$) remaining in the root zone, WRZ is the current volume of water in the root zone (liter), $\text{WRZ}_{\min}$ is the volume of water in pot triggering an irrigation (liter) and N_{conc} is the concentration of N applied ($\text{mg} \cdot \text{liter}^{-1}$). The integral of $d\text{NRZ}_{\text{AP}}/dt$ is the content of N applied to the root zone over the time period of integration.

The rate of PN is modeled as a function of the dry mass accumulation of the plant and separates N accumulation as N needed by the plant for maintenance of the standing dry mass and N needed for new growth (Yelanich and Biernbaum, 1995a). The equation describing plant uptake is,

$$\frac{d\text{PN}}{dt} = \left[\frac{d\text{DM}}{dt} * \frac{N_{\text{critical}}}{100} \right] + \left[\frac{(N_{\text{critical}} - N_{\text{actual}})}{100} * \text{DM} \right], \quad [3]$$

where $d\text{DM}/dt$ is the rate of dry mass accumulation ($\text{mg} \cdot \text{day}^{-1}$), DM is the total dry mass of the plant (mg), N_{critical} is the critical percent plant N, and N_{actual} is the current plant percent N. A value of 3.4% was used for N_{critical} based on Yelanich and Biernbaum (1995).

The rate of NRZ_{TL} is modeled based on the medium evaporation of water as well as mixing of the irrigation and medium solution (Yelanich and Biernbaum, 1994c). The equation describing $d\text{NRZ}_{\text{TL}}/dt$ is,

$$d\text{NRZ}_{\text{TL}}/dt = (\text{NRZ} / \text{WRZ}) * f_{\text{mix}} * d\text{WTL}_{\text{AP}}/dt + d\text{WRZ}_{\text{EVAP}}/dt * (\text{NRZ} / \text{WRZ}). \quad [4]$$

The term $d\text{WRZ}_{\text{EVAP}}/dt$ is the rate of evaporation of water from the medium surface (liters/day), $d\text{WTL}_{\text{AP}}/dt$ is the volume of the water entering the top layer during an irrigation (liter/day), and f_{mix} is an empirically determined mixing function. The model of $d\text{WRZ}_{\text{AP}}/dt$ is based upon the maximum water holding capacity of the root zone $\text{WRZ}_{\max}$ and is described by,

$$dWRZ_{AP} / dt = \begin{cases} WRZ_{max} - WRZ & \text{if } (WRZ_{max} - WRZ) < W_{tot} \\ W_{tot} & \text{if } (WRZ_{max} - WRZ) > W_{tot} \end{cases} \quad [5]$$

$$dWTL_{AP}/dt = W_{tot} - dWRZ_{AP}/dt \quad [6]$$

where W_{tot} is the total volume of water applied. The rate of water change in the root zone, $dWRZ/dt$ is described by,

$$dWRZ/dt = dWRZ_{AP}/dt + dWRZ_{EVAP}/dt + dWRZ_{PLANT}/dt \quad [7]$$

where $dWRZ_{PLANT}/dt$ is the rate of transpiration from the canopy. The terms $dWRZ_{EVAP}/dt$ and $dWRZ_{PLANT}/dt$ are modeled using the combination equation (Penman, 1942) and incorporates equations found in Yelanich and Biernbaum (1994d) and Chen and Lieth (1994) and are described by,

$$\frac{dWRZ_{plant}}{dt} = \frac{\Delta \cdot Rn_{plant} + \gamma \cdot 6.43 \cdot f(u) \cdot (e_s - e_d)}{\Delta + \gamma} * LA * 0.69 \quad [8]$$

$$\frac{dWRZ_{medium}}{dt} = \frac{\Delta \cdot Rn_{medium} + \gamma \cdot 6.43 \cdot f(u) \cdot (e_s - e_d)}{\Delta + \gamma} * MA * 0.62 \quad [9]$$

where Δ is the slope of the saturation vapor pressure function, γ is the psychometric constant, Rn_{plant} is the plant net radiation ($MJ \cdot m^{-2} \cdot d^{-1}$), Rn_{medium} is the medium net radiation ($MJ \cdot m^{-2} \cdot d^{-1}$), e_s is the saturated vapor pressure (KPa), e_d is the saturation vapor pressure at the dew point temperature (KPa), LA is the plant leaf area (m^2), MA is the media surface area (m^2) and $f(u)$ is the empirical wind function (Allen et al. 1989). The terms Rn_{plant} and Rn_{medium} are modeled using empirical equations (Jensen et al. 1989) and are described by,

$$Rn_{plant} = \frac{\left[(1 - \alpha_{plant}) * R_{S_{plant}} - \sigma * (ADT + 273)^4 * (0.39 - 0.158\sqrt{e_d}) * \left(\frac{R_s}{R_{so}} \right) \right]}{2.45 \text{ liter} \cdot \text{MJ}^{-1}} \quad [10]$$

$$Rn_{medium} = \frac{\left[(1 - \alpha_{medium}) * R_{S_{medium}} - \sigma * (ADT + 273)^4 * (0.39 - 0.158\sqrt{e_d}) * \left(\frac{R_s}{R_{so}} \right) \right]}{2.45 \text{ liter} \cdot \text{MJ}^{-1}} \quad [11]$$

were α_{plant} is the crop albedo, α_{medium} is the medium albedo, σ is the Stephan-Boltzman constant ($4.903 \times 10^{-9} \text{ MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1} \cdot \text{K}^{-4}$) e_d is the saturation vapor pressure at the dew point temperature (KPa), R_{so} is the clear sky solar radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), R_s is the actual solar radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), $R_{S_{plant}}$ is the short wave radiation reaching the plant canopy ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), $R_{S_{medium}}$ is the short wave radiation reaching the medium surface ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$). $R_{S_{medium}}$ was modeled as a function of the incoming R_s , the plant leaf area index (LAI), and the albedo of the medium (α_{medium}) (Chen and Leith, 1992) and is described by,

$$R_{S_{medium}} = \alpha_{medium} * R_s * e^{(-.22 * LAI)}. \quad [12]$$

Chen and Leith found values of 0.25 for chrysanthemum α_{plant} and 0.2 for peat medium α_{medium} . R_s was not directly measured but was converted from PAR measurement based on values found in Thimijan and Heins (1983). The empirical wind function $f(u)$ was set to a constant value of 1.4 based upon Chen and Lieth (1992) and Yelanich and Biernbaum (1995).

The plant portion of the model consists of the leaf area (LA) and dry mass (DM). The plant response to N deficiency in the medium is modeled by a reduction in concentration of N in the shoot, leading to a reduction in the rate of leaf area expansion. The response of the rate

of leaf area expansion to the N concentration of the plant is modeled by defining a plant critical N concentration, $N_{\max LA}$, where there is no improvement in the rate of leaf expansion and a minimum N concentration, $N_{\min LA}$, where there is no leaf area expansion (Goodwin and Jones, 1991). The equations describing this are,

$$f_{LA} = \begin{cases} 0 & \text{for } N_{\text{shoot}} < N_{\min LA} \\ (N_{\text{shoot}} - N_{\min LA}) / (N_{\max LA} - N_{\min LA}) & \text{for } N_{\min LA} < N_{\text{shoot}} < N_{\max LA} \\ 1 & \text{for } N_{\text{shoot}} > N_{\max LA} \end{cases} \quad [13]$$

where f_{LA} is a 0 to 1 function limiting the rate of leaf expansion in response to the current shoot N. Values of 0.0135 and 0.034 were used for $N_{\min LA}$ and $N_{\max LA}$ based upon Yelanich and Biernbaum (1995). The rate of leaf expansion, is described by the equation,

$$dLA/dt = (c_1 + 2 \cdot c_2 \cdot t) \cdot f_{LA} \quad [14]$$

where dLA/dt is the rate of leaf expansion in m^2/day , and c_1 and c_2 are constants. The rate of dry mass accumulation was modeled as a function of the photosynthetic active radiation (PAR) and the total leaf area and is described by,

$$dDM/dt = (PAR \cdot d_1 + PAR^2 \cdot d_2 + d_3) \cdot LA \quad [15]$$

where dDM/dt is the rate of dry mass accumulation in gm/day , d_1, d_2 and d_3 are constants.

The model was run using a one day time step. The various parameters were determined from the rates using numerical integration using the form,

$$Z(t + dt) = Z(t) + dt \cdot (dZ/dt). \quad [16]$$

Validation. To validate the model chrysanthemums were grown at two times of the year (winter, 7 January to 25 March; spring, 14 April to 30 June), with three fertilizer concentrations (3.6, 7.1, 10.7 $\text{mol} \cdot \text{m}^{-3}$ N), and at three fluence levels (30% shade,

ambient or supplemented with high pressure sodium, HPS 6 ($\text{mol}\cdot\text{day}^{-1}$). One rooted cutting of chrysanthemum 'Bright Golden Anne' was placed in a 10 cm pot filled with a 75% peat, 25% perlite (winter experiment) or 100% peat (spring) medium (Table 1). The amendments KNO_3 ($0.06 \text{ kg}\cdot\text{m}^{-3}$), $\text{Ca}(\text{NO}_3)_2$ ($0.06 \text{ kg}\cdot\text{m}^{-3}$), MgSO_4 ($0.03 \text{ kg}\cdot\text{m}^{-3}$) CaSO_4 ($0.06 \text{ kg}\cdot\text{m}^{-3}$), CaHPO_4 ($0.06 \text{ kg}\cdot\text{m}^{-3}$), hydrated lime ($0.21 \text{ kg}\cdot\text{m}^{-3}$) and a micronutrient mix (FTE 555, $0.01 \text{ kg}\cdot\text{m}^{-3}$) were incorporated into the medium prior to planting.

Plants were placed in a 3 m by 4 m glass greenhouse with day and night temperature set points of 20 C and were exposed to day-lengths of 16 HR for the first 7 days, after when the shoots were pinched to 6 nodes and placed under day-lengths of 10 hours per day. Plants were pruned to 3 shoots per plant when the laterals were large enough to handle. Water used to make the nutrient solution had an initial alkalinity of $170 \text{ mg}\cdot\text{liter}^{-1} \text{ CaCO}_3$, pH of 6.4 and an EC of $0.30 \text{ dS}\cdot\text{m}^{-1}$. The three fertilizer treatments were made from KNO_3 and NH_4NO_3 in a ratio to provide 64% $\text{NO}_3\text{-N}$ and 36% $\text{NH}_4\text{-N}$. All fertilizer treatments also had $0.5 \text{ mol}\cdot\text{m}^{-3} \text{ P}$ from H_3PO_4 and $50 \text{ mg}\cdot\text{liter}^{-1}$ of a chelated micronutrient mix (Compound 111, Scotts, Marysville, Ohio). Plants were weighed daily and irrigated when the mass of the plant, pot and medium was less than 250 grams. Pots were kept in individual water tight trays and were subirrigated by pouring 0.2 liters of solution into the tray, a volume of solution absorbed by the medium 0.5 hr after an irrigation. Three plants per treatment were randomly selected for evaluation biweekly. Leaf area, plant dry mass, and shoot and root Kjeldahl N (Diamond, 1992) were determined at each sampling date. The root-medium selected for sampling was first sliced into vertical

halves, one half was used to collect the roots for dry mass and the other half was used for medium N determination. The half used for medium N analysis was cut into top and root zone layers, at a height 5 cm from the bottom. The top layer and root zone, were extracted using the saturated medium extraction method (Warncke, 1986). Only the root zone data are reported. The extract was analyzed for nitrate N, nitrite N and ammonium N using colormetric methods (Diamond, 1986a and Diamond, 1986b). The concentration of nitrite N was less than 1 mg•liter⁻¹ and will not be reported. A sub-sample of the saturated medium paste was weighed before and after saturation, oven dried for 4 days at 60 C and weighed again, to determine the water content of the paste. Nitrogen contents were determined using the following formula,

$$N(\text{mg}) = N(\text{mg} / \text{liter}) * \frac{\text{Sample Water Mass}}{\text{Sample Mass}} * \frac{\text{Bulk Density}}{\text{Density of Water}} * \text{Layer Volume} \quad [17]$$

(Hillel, 1982). Bulk density was determined in a separate experiment and was found to be 0.0786 and 0.0580 g•liter⁻¹ for the 75% and 100% peat media, respectively and the volume of the root zone was 440 cm³ for the winter experiment and 366 cm³ for the spring experiment (Table 1). The LA parameters in equation [14] (c_1 and c_2) were determined using the supplemented light and high fertilizer treatments. The DM parameters in equation [15] (d_1, d_2 and d_3) were determined using the entire data set and the measured daily PAR values .

Optimization. Five fertilization strategies (FS) were developed and calibrated using the SAS PROC NLIN algorithm (SAS institute, 1995) and the ambient weather data from the winter and spring experiments. The first strategy was developed to determine what concentration of N

to apply to minimize the quantity of N applied while maintaining the saturated medium extract (SME) N concentration in the root zone in the reported optimal range of 7 to 14 mol•m⁻³ N.

A penalty function of the form

$$f_{\text{penalty}} = \begin{cases} (\text{NRZ} - 48)^2 & \text{NRZ} < 32 \\ 0 & 32 \leq \text{NRZ} \leq 64 \\ (\text{NRZ} - 64)^2 & \text{NRZ} > 64 \end{cases} \quad [18]$$

was used to constrain the model to maintain NRZ within the optimal range.

Four additional strategies were developed and calibrated using the concept of proportional integral derivative control (PID). PID control uses the output from a process as a means of determining a new input into that process. In this case the output from this system, NRZ, is used to determine the Nconc to apply to the system. After experimenting with the PID controller a PD controller was found to give the most stable over all response. The general equations used in the controller were,

$$\text{NRZ}_{\text{error}}(t) = (\text{NRZ}_{\text{setpoint}} - \text{NRZ}) \quad [19]$$

$$\frac{d\text{NRZ}_{\text{error}}(t)}{dt} = \text{NRZ}_{\text{error}}(t) - \text{NRZ}_{\text{error}}(t - dt) \quad [20]$$

$$\text{Nconc}(t + dt) = \text{Nconc}(t) + \left[\text{NRZ}_{\text{error}}(t) * P_1 + \frac{d\text{NRZ}_{\text{error}}(t)}{dt} * P_2 \right] \quad [21]$$

were $\text{NRZ}_{\text{setpoint}}$ is the desired root zone N content and $\text{NRZ}_{\text{error}}$ is the deviation from that setpoint. The parameters P_1 and P_2 determined how quickly the controller responds to deviations from the $\text{NRZ}_{\text{setpoint}}$. Strategies were developed based on daily (FS 2 and 4) or weekly (FS 3 and 5) determinations of NRZ and $\text{NRZ}_{\text{error}}$. A $\text{NRZ}_{\text{setpoint}}$ of 3.4 mmol (48 mg) N was used fertilization strategies 2 and 3 in the determinations of P_1 , P_2 and the initial applied

Nconc (t=0). The constraints placed upon this determination were to minimize the N applied while maintaining the N concentration within the optimal range using the penalty function in equation [16]. Fertilization strategies 4 and 5 involved determination of the $NRZ_{setpoint}$ in addition to determining P_1 , P_2 and the initial Nconc. These determinations had the constraint of minimizing the N applied while maintaining the N concentration in the plant at $N_{critical}$. A penalty function of the form

$$f_{penalty} = \begin{cases} (N_{actual} - N_{critical})^2 & N_{actual} < N_{critical} \\ 0 & NRZ > N_{critical} \end{cases} \quad [22]$$

was used to constrain the model to maintain N_{actual} above the critical concentration.

Results and Discussion

There was a significant response of LA to increased fertilizer concentration. The mean LA across light and experiments was 707, 960 or 1067 cm² when 3.6, 7.1 or 10.7 mol•m⁻³ N was applied respectively. There was less of a response to the light treatments in the spring experiment than in the winter experiment. The LA model, made up of equations [13] and [14], worked very well across the environments tested in this experiments with an R^2 of 0.95 (n=270) (Figure 2). The LA model could be further improved by basing the equation [14] on temperature rather than time since planting, however there was insufficient data to construct such a model from this experiment.

Plant dry mass followed a similar trend to LA, with increasing dry mass as the fertilizer concentration increased as well as the significant interaction between experiment and light treatments. The average across fertilizer treatment dry mass was 12, 19 and 19 g for the

shaded, ambient and HID treatment, respectively, indicating that there was little improvement of the supplemental lighting in the winter. In the spring experiment there was a benefit of the supplemental lighting, with the average across fertilizer treatment dry mass was 13, 16 and 24 g for the shaded, ambient and HID treatments, respectively. The R^2 for the predicted DM (Figure 3) was high at 0.91 ($n=270$), though the model could be improved with the incorporation of temperatures in equation [15] to better simulate plant respiration.

Plant N increased with increasing fertilizer concentration (321, 457, 545 mg for 3.6, 7.1 and 10.7 mol·m⁻³ N, respectively), with increasing light (321, 457 560 mg for shaded, ambient and HID, respectively) but decreased between winter and spring (463 and 420 mg respectively). The R^2 for the PN predictions were lower than DM or LA at 0.88 ($n=270$) and tended to over predict N accumulation at the end of the crop. The PN model could be improved by making $N_{critical}$ a function of the since $N_{critical}$ as been shown to vary with the age of the plant (Willits et al., 1992). The PN model could further be improved with the addition of sub-models separating nitrate and ammonium uptake and base N uptake as a function of concentration, pH and root activity. The over prediction of N accumulation at the end of the crop could be due to remobilization of the N from the leaves, stems and roots and into the flower. The current model predicts N for flower formation would come from the medium.

The water loss model worked well considering the simplicity of the equations used (Figure 5). The prediction of water loss could be improved with the addition of the relationship between water potential of the medium and water loss. The assumption that plant temperature was equal to air temperature, while necessary for simplification purposes, has been shown to be false (Faust, 1994), especially for plants grown using supplemental lighting.

The root zone N content increased as the concentration of fertilizer applied increased. At the final sampling, the medium N concentration was dependent on the fertilizer concentration applied but independent of light intensity (Table 5). The model simulated these general trends very well with the NRZ increasing as the fertilizer concentration applied but not changing as the light intensity increased from the shade to supplemented light treatments (Figure 6). The model predicted very rapid day to day changes in the medium N content. These rapid changes would indicate that the pool of N in the root zone is very labile, requiring frequent replenishment to maintain a set quantity of N. The large increase in the N concentration in the medium at the final sample was not predicted by the model and is probably due to the over prediction of plant N uptake discussed earlier.

The predicted optimal solution of FS 1 to maintain a root zone concentration of 7 to 14 mol•m⁻³ N was for an applied N concentration of 16.3 mol•m⁻³ (229 mg•liter⁻¹) (Table 5) is near the typically recommended concentration of N to apply for top watered plants. All five strategies tested were able to maintain the concentration of nutrients near the set point values (Figure 7). The medium N concentration data presented in Figure 7 are actually the concentration of saturated medium extracts (SME), the preferred test method for peat-based media (Warncke, 1988). To obtain concentration data, the model output and actual N content data were divided by the average volume of water (0.317 liters, corrected for volume) in a SME from the two experiments (Table 1). The setpoint values of 6.3 mol•m⁻³ (88 mg•liter⁻¹) determined for FS 4 is lower than the midpoint value of 10.7 mol•m⁻³ (150 mg•liter⁻¹) typically used, indicating that a lower optimal range could be used for

subirrigated chrysanthemum. The model predicted that using a lower setpoint value would result in less N being applied than if the standard setpoint values was used (FS 2 vs. FS4). The lower setpoint also resulted in less change in Nconc to compensate for changes in medium N content. There was no clear cut improvement in using daily medium testing as compared to weekly medium testing indicating that the weekly testing frequency is adequate. All FS tested predicted plants with comparable leaf area, dry mass and plant N.

Subirrigated plants have been reported to have a lower root zone concentration of N than top watered plants when fertilized with the same fertilizer N concentration (George, 1989). Paradoxically subirrigated plants are commercially fertilized with lower concentrations of N than top watered plants (Biernbaum, 1993). These two finding fit well with the optimization results since a higher than typically commercially applied N concentration was necessary (FS 1, $16.3 \text{ mol} \cdot \text{m}^{-3} \text{ N}$) to maintain the root zone N concentration within the 7 to $14 \text{ mol} \cdot \text{m}^{-3} \text{ N}$ accepted range, but a lower root zone N concentration could be maintained with little detrimental effect on plant growth (FS 3). It may be possible, at least for subirrigated chrysanthemums, to establish a lower range of acceptable medium test values and allow growers to apply less fertilizer to their crop.

The apparent simplicity of this container-grown plant system is deceiving, since there are many possible interactions influencing the medium N concentration. The model is based on the hypothesis that the N concentration in the medium is dependent on the rates of N application, uptake by the plant and movement into the top layer. The prediction of the rate of plant N uptake is in turn dependent on the prediction of dry mass.

Dry mass is dependent on the leaf area expansion and the PAR available. The rate of leaf area expansion is modulated by the N concentration of the shoot, and is ultimately dependent on the N concentration of the medium. Leaf area influences the rate of water loss and ultimately determines the frequency of N fertilizer application. With all these interactions, container-grown plants are typically produced using the simplest of all control strategies, that of a constant input of N, applied with every irrigation. One hypothesis has been that a single concentration of nutrients would be unable to compensate for variations in plant growth and that more elaborate control strategies are needed to handle these variations in growth (Fynn and Bauerle, 1988). This did not appear to be the case since a single concentration of applied N supplied sufficient N under both winter and spring conditions as well as under high (HID) and low (shade) irradiance conditions.

Using a control strategy where RZN was determined daily and used to determine the N concentration to apply did reduce the quantity of N applied by an average of 32% when compared with using a single concentration. The benefit of this reduction in N applied, at least in a subirrigated system, is limited since the fertilizer cost is a small cost of total production, and any extra N applied is lost to the top layer instead of entering the environment. In the future when reliable insitu N detectors are developed it will be possible to use this control strategy to better maintain the root zone N content.

There may be an implication based on the results from this model that medium testing is not a necessary requirement for maintaining the nutrient status in the root zone

of chrysanthemum. It appears, at least under the conditions of this experiment, that applying a constant concentration N of greater than $16.4 \text{ mol} \cdot \text{m}^{-3}$ ($229 \text{ mg} \cdot \text{liter}^{-1}$) will maintain the nutrients in a range needed for adequate growth. However, medium testing is necessary since it is used to determine when problems such as injector failure or misapplication of fertilizer have occurred. The rapid rate the medium N concentration changes would indicate that daily monitoring of the medium N levels are necessary to determine when problems occurs. Chrysanthemum has been shown to tolerate periods of N deprivation of a week or less (Yelanich and Biernbaum, 1995b) so that weekly monitoring is probably sufficient.

There are many possible improvements to the model with the most pressing need a model to predict the flower response to N deficit. While the model appears to adequately deal with the total dry mass and leaf area of the plant it does not deal with flower size and mass reductions expected when N deficiencies occur. The flower is the main selling feature of a chrysanthemum and little work has been done to quantify the flower size response to N deficiency. The general form of the flowering model would be probably similar to the leaf area N function, f_{LA} used in this paper.

Further work is needed to characterize the response of chrysanthemum to excess concentrations of N and other salts. Since the model is unable to handle excess N , efforts were made in the modeling process to exclude conditions where reductions in plant size could occur due to excess salts in the medium. The form of N also can cause differences in plant morphology and has not been addressed in this model.

The model presented in this paper demonstrates the dynamics of the N flow in the root zone of a chrysanthemum. A potential use of the model will be to link the model with a medium testing diagnosis and interpretation program, and will allow growers to better interpret and make logical choices in their fertilization program. The concepts presented here could be expanded to study the dynamics of N supply in top water situations as described by Argo and Biernbaum (1995) or be used to interpret simple N petiole sap testing results.

Abbreviations

1. ADT = average daily temperature (C).
2. α_{medium} = Medium albedo.
3. α_{plant} = Plant albedo.
4. DM = Total dry mass (mg).
5. Δ = Slope of the saturation vapor pressure function.
6. γ = Psychometric constant.
7. σ = Stephan-Boltzman constant ($4.903 \times 10^{-9} \text{ MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1} \cdot \text{K}^{-4}$).
8. Rn_{plant} = Plant net radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$).
9. Rn_{medium} = Medium net radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$).
10. e_a = Saturated vapor pressure (kPa).
11. e_d = Saturation vapor pressure at the dew point temperature (KPa).
12. f_{LA} = Function influences leaf area based on plant % N.
13. f_{mix} = Function influencing N movement into top layer.

14. LAI = leaf area index.
15. LA = leaf area (m^2).
16. MA = medium area (m^2).
17. N_{actual} = current plant percent N (%).
18. N_{conc} = N concentration applied ($\text{mg} \cdot \text{liter}^{-1}$).
19. N_{critical} = critical plant percent N (%).
20. N_{maxLa} = Maximum plant N concentration for leaf expansion (%).
21. N_{minLa} = Minimum critical plant N concentration for leaf expansion (%).
22. NRZ = N in the root zone (mg).
23. NRZ_{AP} = N applied to root zone (mg).
24. NRZ_{TL} = N moved from the root zone to the top layer formation (mg).
25. PAR = photosynthetic active radiation ($\text{mol} \cdot \text{day}^{-1}$).
26. PN = Plant N uptake (mg).
27. R_s = Actual solar radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$).
28. $R_{s_{\text{medium}}}$ = Short wave radiation reaching medium ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$).
29. R_{s0} = Clear sky solar radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$).
30. $R_{s_{\text{plant}}}$ = Short wave radiation reaching plant ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$).
31. WRZ = Root zone water volume (liter).
32. WRZ_{AP} = Water applied to the root zone (liter).
33. WRZ_{EVAP} = Water evaporated from medium surface (liter).
34. WRZ_{max} = Maximum water volume of root zone (liter).
35. WRZ_{min} = Water volume when an irrigation occurs (liter).

36. WRZ_{plant} = Water transpired by plant (liter).
37. WTL_{AP} = Water applied to the top layer (liter).
38. W_{tot} = Total water volume applied (liter).

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Table 1. Physical properties and saturated medium extraction (SME) parameters of the medium used in the validation experiments.

	Winter Experiment	Spring Experiment
Peat (%)	75%	100%
Perlite (%)	25%	0%
Pot Volume (cm ³)	725	754
Root Zone Vol. (cm ³)	440	366
Bulk Density (g/cm ³)	0.074	0.058
Water Volume (cm ³)	306	291
Air Space (cm ³)	73	56
Solid (cm ³)	62	21
Avg. .SME Volume (liters)	0.366	0.268
Max. .SME Volume (liters)	0.520	0.344
Min. .SME Volume (liters)	0.295	0.149
Std. .SME Volume (liters)	0.052	0.032

Table 2. Photosynthetic active radiation (PAR), dry and wet bulb temperatures and statistics from winter and spring weather data.

	PAR ($\text{mol}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$)	Dry Bulb (C)	Wet Bulb (C)	PAR ($\text{mol}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$)	Dry Bulb (C)	Wet Bulb (C)
	Winter			Spring		
Average	7.29	20.1	13.9	11.3	20.8	17.8
Std Dev	5.00	0.5	1.3	4.7	2.4	3.4
Maximum	20.50	21.8	17.1	22.8	27.7	25.9
Minimum	0.40	18.9	11.1	1.3	17.3	11.5

Table 3. Photosynthetic active radiation (PAR), dry and wet bulb temperatures and solar irradiation statistics from generated weather data.

	PAR ($\text{mol}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$)	Dry Bulb (C)	Wet Bulb (C)	Solar ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$)
Average	16.3	20.9	15.1	8.3
Std Dev.	7.5	0.8	4.3	3.8
Maximum	28.2	23.5	21.0	14.4
Minimum	5.0	20.3	7.2	2.6
Number	208	208	208	208

Table 4. Analysis of variance of leaf area, dry mass, plant N, total N applied and nitrate-N concentration and ammonium N concentration 70 days since the start of short days.

N Applied mol • m ⁻³	Dry Mass mg	Leaf Area m ²	Plant N mg	Root Zone N mg
Winter Experiment				
<i>Shade</i>				
3.6	11	824	278	15
7.1	12	934	330	50
10.7	14	1068	402	102
<i>Ambient</i>				
3.6	17	846	309	16
7.1	20	1050	513	46
10.7	21	1165	611	74
<i>Supplemented</i>				
3.6	15	528	408	6
7.1	18	932	629	50
10.7	25	992	684	91
Spring Experiment				
<i>Shade</i>				
3.6	13	613	277	5
7.1	13	952	269	29
10.7	14	1049	363	57
<i>Ambient</i>				
3.6	13	682	256	6
7.1	17	786	422	32
10.7	19	1005	548	40
<i>Supplemented</i>				
3.6	21	749	398	0
7.1	26	1103	580	17
10.7	26	1120	663	45
EXP	ns	ns	*	***
PPF	***	ns	***	ns
EXP*PPF	*	**	ns	ns
FERT	**	***	***	***
EXP*FERT	ns	ns	ns	**
PPF*FERT	ns	ns	*	ns
EXP*PPF*FERT	ns	ns	ns	ns

ns, *, **, *** Nonsignificant or significant at P=0.05, 0.01, or 0.001, respectively.

Table 5. Optimization parameters for the 5 fertilizer strategies (FS) evaluated.

	FS 1	FS 2	FS 3	FS 4	FS 5
Starting N ($\text{mg} \cdot \text{liter}^{-1}$)	228	253	139	192	200
PD ₁		1.98	-1.13	-0.49	-1.63
PD ₂		4.06	3.74	0.50	1.98
set point ($\text{mg} \cdot \text{liter}^{-1}$ SME)		150	150	87	44

Table 6. Optimized leaf area, plant N, dry mass, total N applied, medium top layer (TLN), medium root zone (RZN), and mean and standard deviation of root zone N at 70 days since start of short days of the 5 fertilization strategies (FS). Mean and standard deviations were calculated over the entire 70 day period.

	Leaf Area cm^2	Plant N mg	Dry mass g	N Applied mg	TLN mg	RZN mg	Initial N mg	Mean RZN mg	Std RZN mg
Winter Experiment									
FS 1	1072	768	22.2	968	237	43	80	149	45
FS 2	1072	768	22.2	1071	321	62	80	194	59
FS 3	1072	768	22.2	1058	324	47	80	193	55
FS 4	1072	754	22.2	844	138	32	80	104	37
FS 5	1072	754	22.2	760	74	13	80	80	36
Spring Experiment									
FS 1	1072	694	20.0	1263	607	42	80	224	76
FS 2	1072	694	20.0	1140	485	41	80	187	56
FS 3	1072	694	20.0	1180	536	30	80	200	58
FS 4	1072	694	20.0	962	335	12	80	144	41
FS 5	1072	689	20.0	759	145	6	80	81	30

Figure 1. Diagram representing the various components of a model to predict N content in the root zone of container-grown chrysanthemum. $\int$ represents integration of a rate.

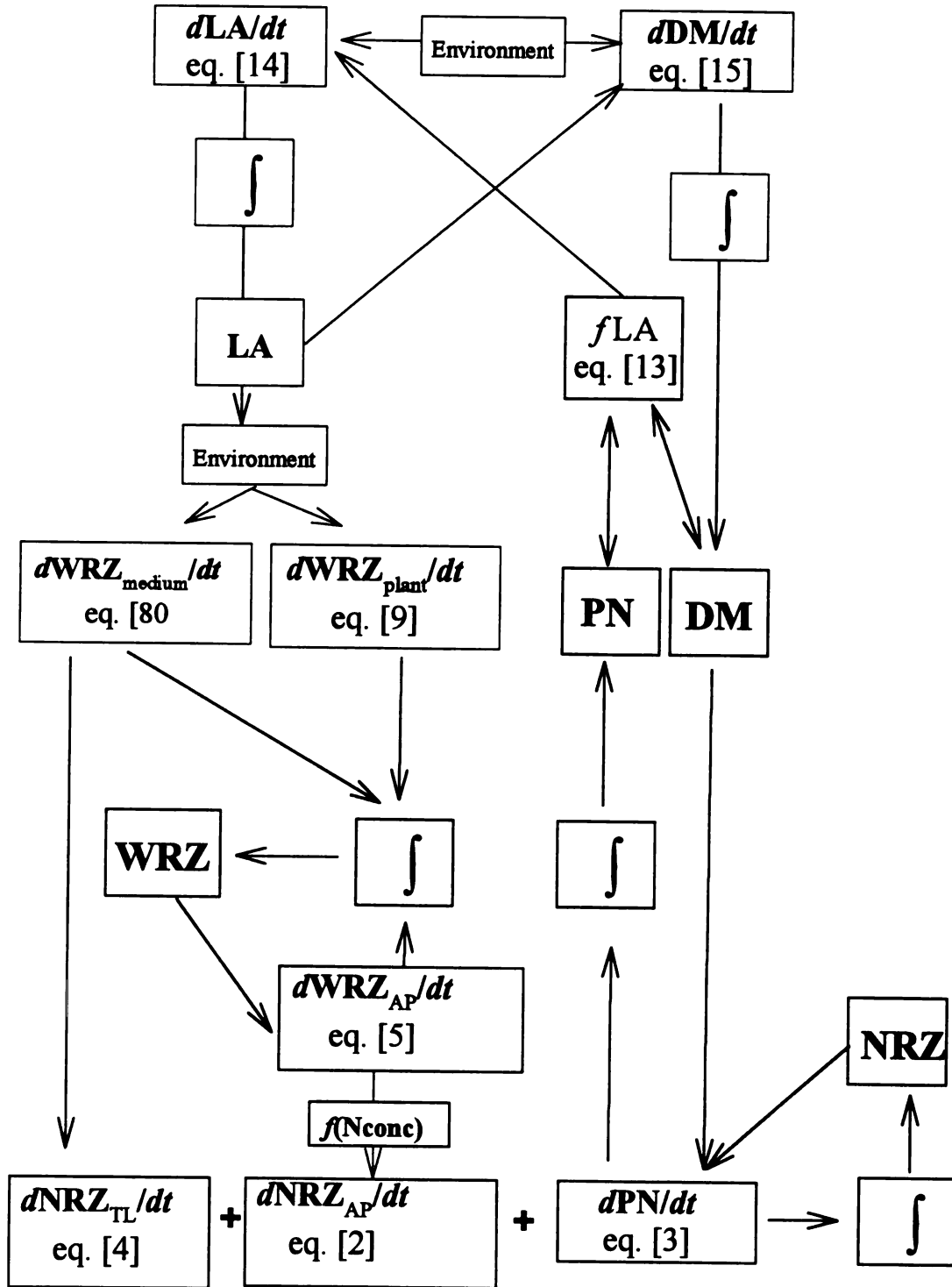


Figure 2. Leaf area over time since the start of short days under various light and fertilizer treatments. Graphs in left column are the leaf area of plants receiving $3.6 \text{ mol} \cdot \text{m}^{-3}$ ($50 \text{ mg} \cdot \text{liter}^{-1}$) N, graphs in the middle column are plants receiving $7.1 \text{ mol} \cdot \text{m}^{-3}$ ($100 \text{ mg} \cdot \text{liter}^{-1}$) N, and graphs in the right column are plants receiving $10.7 \text{ mol} \cdot \text{m}^{-3}$ ($150 \text{ mg} \cdot \text{liter}^{-1}$) N. The top three rows are plants from the winter experiment and the bottom three rows are from the spring experiment. Graphs in rows 1 and 4 are plants grown under 30% shade, 2 and 5 are plants grown under ambient light conditions and 3 and 6 were grown under supplemental HID lighting.

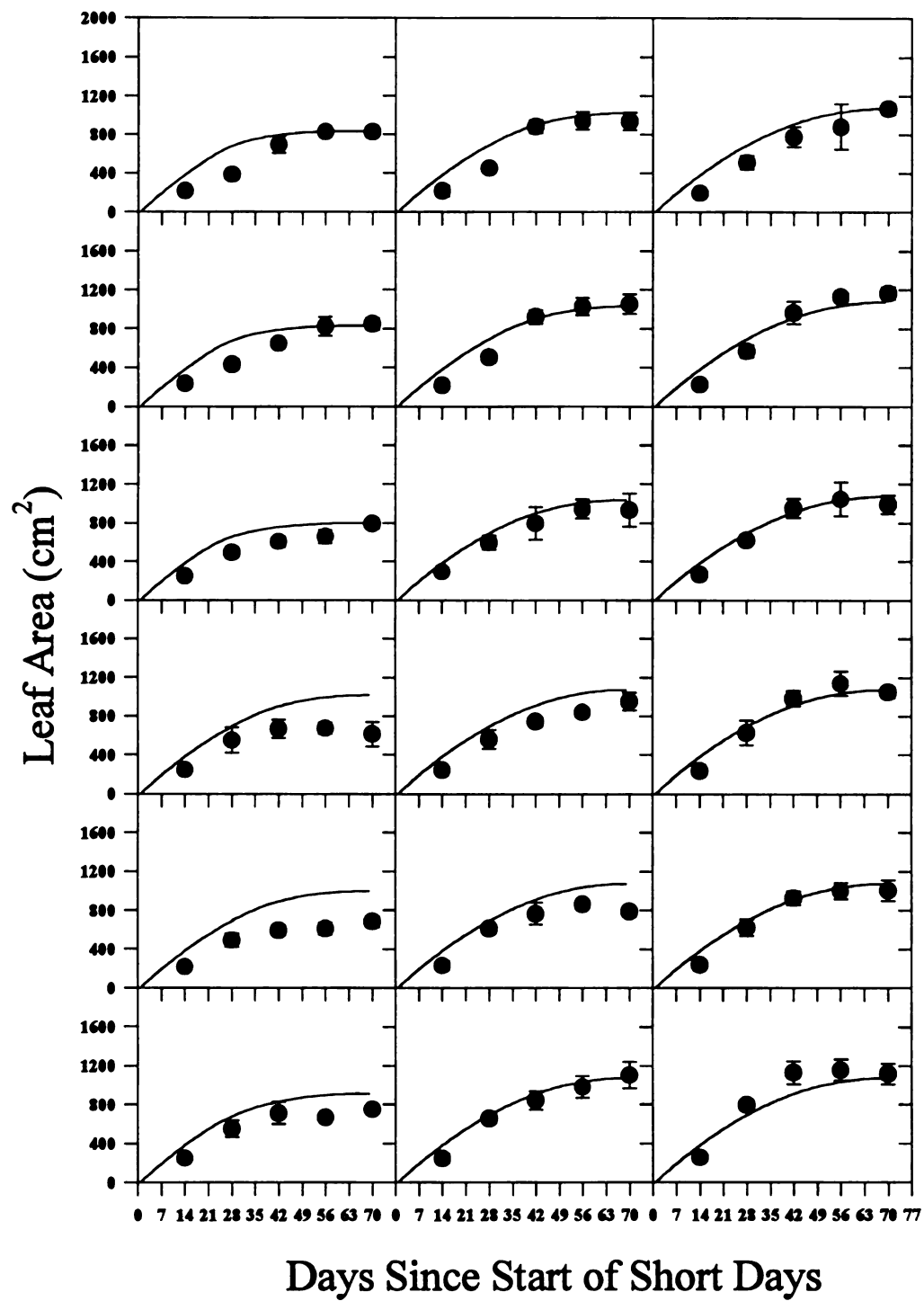


Figure 3. Dry mass over time since the start of short days under various light and fertilizer treatments. Graphs in left column are the dry mass of plants receiving $3.6 \text{ mol} \cdot \text{m}^{-3}$ ($50 \text{ mg} \cdot \text{liter}^{-1}$) N, graphs in the middle column are plants receiving $7.1 \text{ mol} \cdot \text{m}^{-3}$ ($100 \text{ mg} \cdot \text{liter}^{-1}$) N, and graphs in the right column are plants receiving $10.7 \text{ mol} \cdot \text{m}^{-3}$ ($150 \text{ mg} \cdot \text{liter}^{-1}$) N. The top three rows of graphs are plants from the winter experiment and the bottom three rows are from the spring experiment. Graphs in rows 1 and 4 are plants grown under 30% shade, 2 and 5 are plants grown under ambient light conditions and 3 and 6 were grown under supplemental HID lighting.

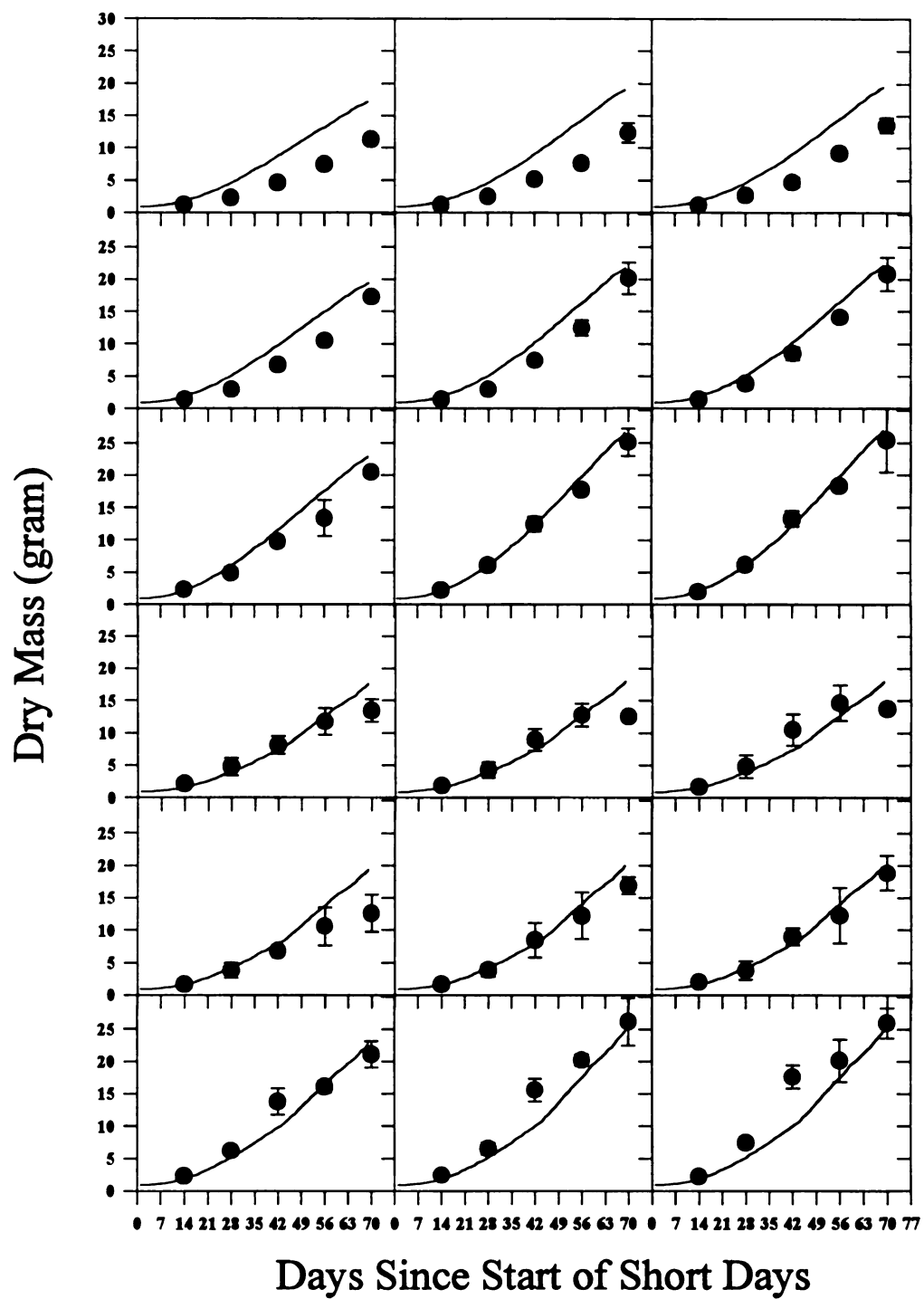


Figure 4. Plant N over time since the start of short days under various light and fertilizer treatments. Graphs in left column are the plant N of plants receiving $3.6 \text{ mol} \cdot \text{m}^{-3}$ ($50 \text{ mg} \cdot \text{liter}^{-1}$) N, graphs in the middle column are plants receiving $7.1 \text{ mol} \cdot \text{m}^{-3}$ ($100 \text{ mg} \cdot \text{liter}^{-1}$) N, and graphs in the right column are plants receiving $10.7 \text{ mol} \cdot \text{m}^{-3}$ ($150 \text{ mg} \cdot \text{liter}^{-1}$) N. The top three rows of graphs are plants from the winter experiment and the bottom three rows are from the spring experiment. Graphs in rows 1 and 4 are plants grown under 30% shade, 2 and 5 are plants grown under ambient light conditions and 3 and 6 were grown under supplemental HID lighting.

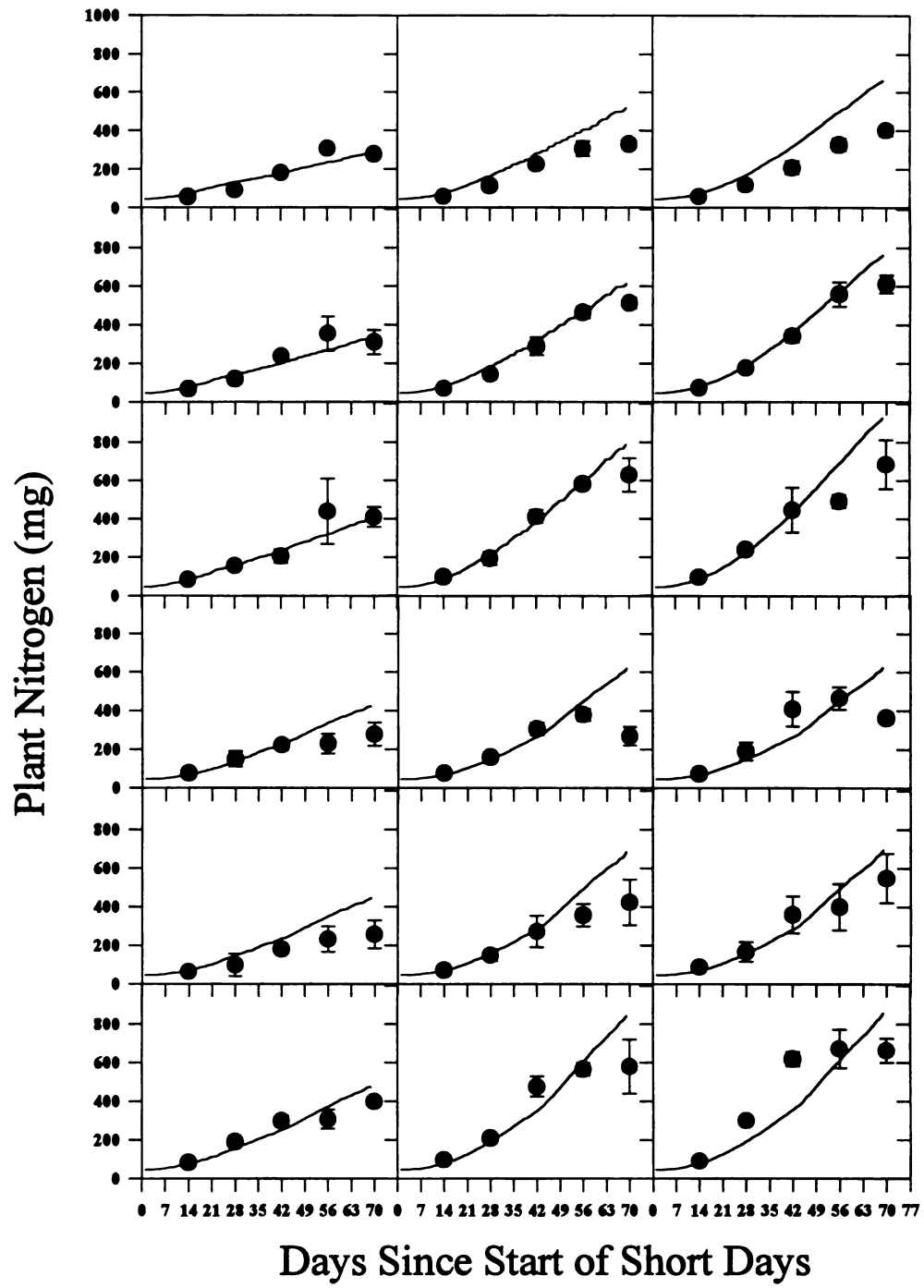


Figure 5. Water loss over time since the start of short days under various light and fertilizer treatments. Graphs in left column are the water loss of plants receiving $3.6 \text{ mol} \cdot \text{m}^{-3}$ ($50 \text{ mg} \cdot \text{liter}^{-1}$) N, graphs in the middle column are plants receiving $7.1 \text{ mol} \cdot \text{m}^{-3}$ ($100 \text{ mg} \cdot \text{liter}^{-1}$) N, and graphs in the right column are plants receiving $10.7 \text{ mol} \cdot \text{m}^{-3}$ ($150 \text{ mg} \cdot \text{liter}^{-1}$) N. The top three rows of graphs are plants from the winter experiment and the bottom three rows are from the spring experiment. Graphs in rows 1 and 4 are plants grown under 30% shade, 2 and 5 are plants grown under ambient light conditions and 3 and 6 were grown under supplemental HID lighting.

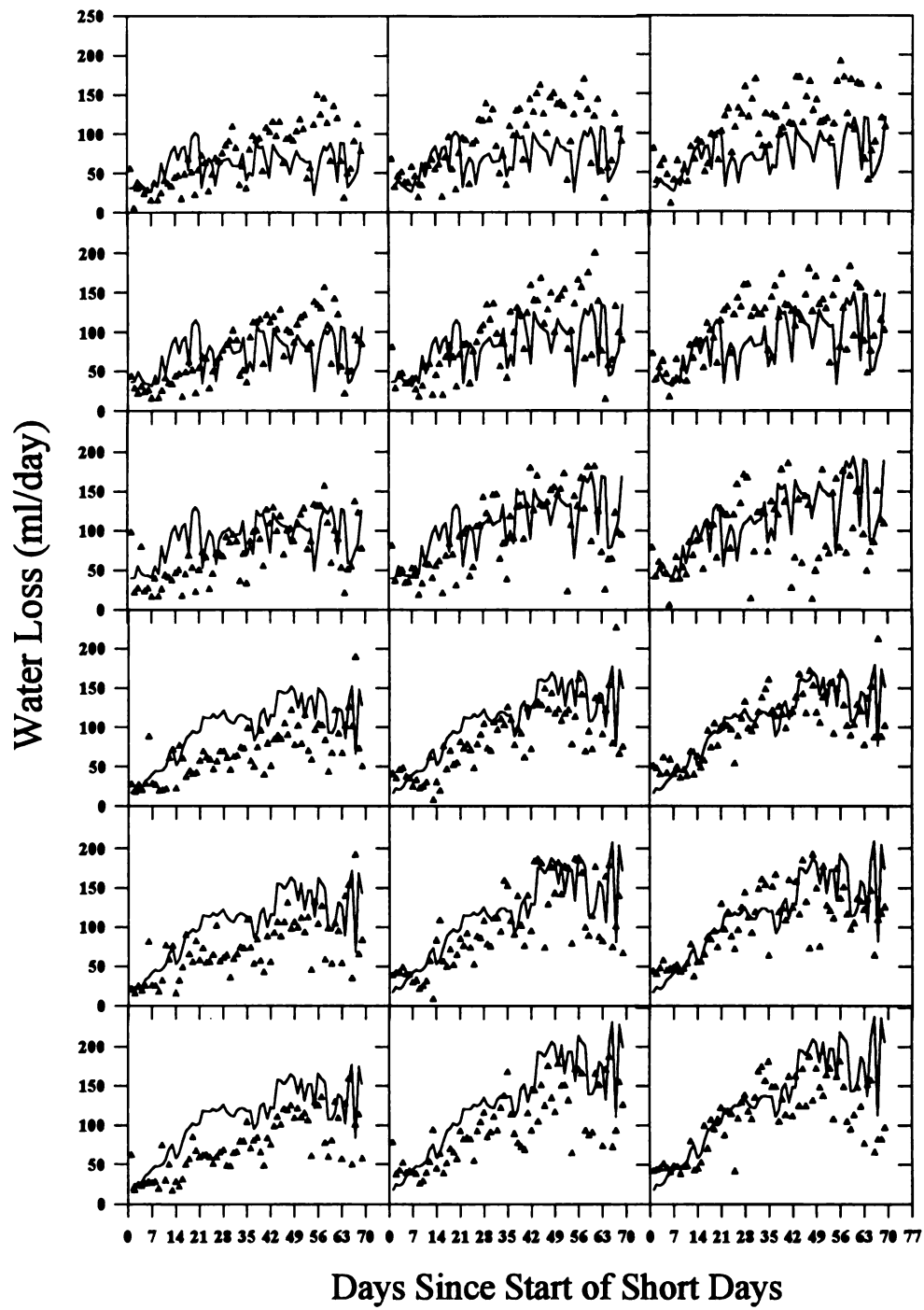


Figure 6. Root zone N content over time since the start of short days under various light and fertilizer treatments. Graphs in left column are the root zone N content of plants receiving $3.6 \text{ mol} \cdot \text{m}^{-3}$ ($50 \text{ mg} \cdot \text{liter}^{-1}$) N, graphs in the middle column are plants receiving $7.1 \text{ mol} \cdot \text{m}^{-3}$ ($100 \text{ mg} \cdot \text{liter}^{-1}$) N, and graphs in the right column are plants receiving $10.7 \text{ mol} \cdot \text{m}^{-3}$ ($150 \text{ mg} \cdot \text{liter}^{-1}$) N. The top three rows of graphs are plants from the winter experiment and the bottom three rows are from the spring experiment. Graphs in rows 1 and 4 are plants grown under 30% shade, 2 and 5 are plants grown under ambient light conditions and 3 and 6 were grown under supplemental HID lighting.

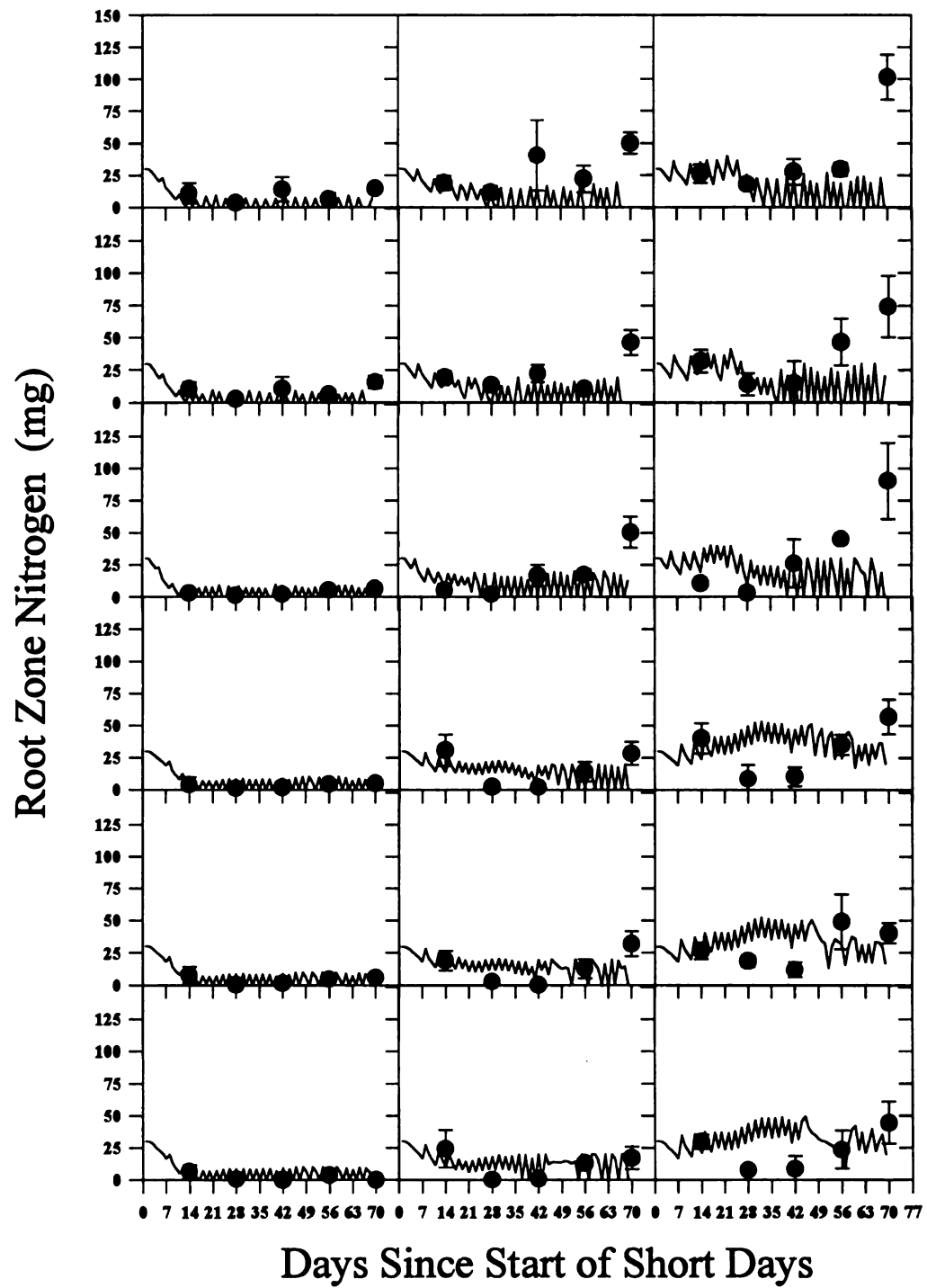
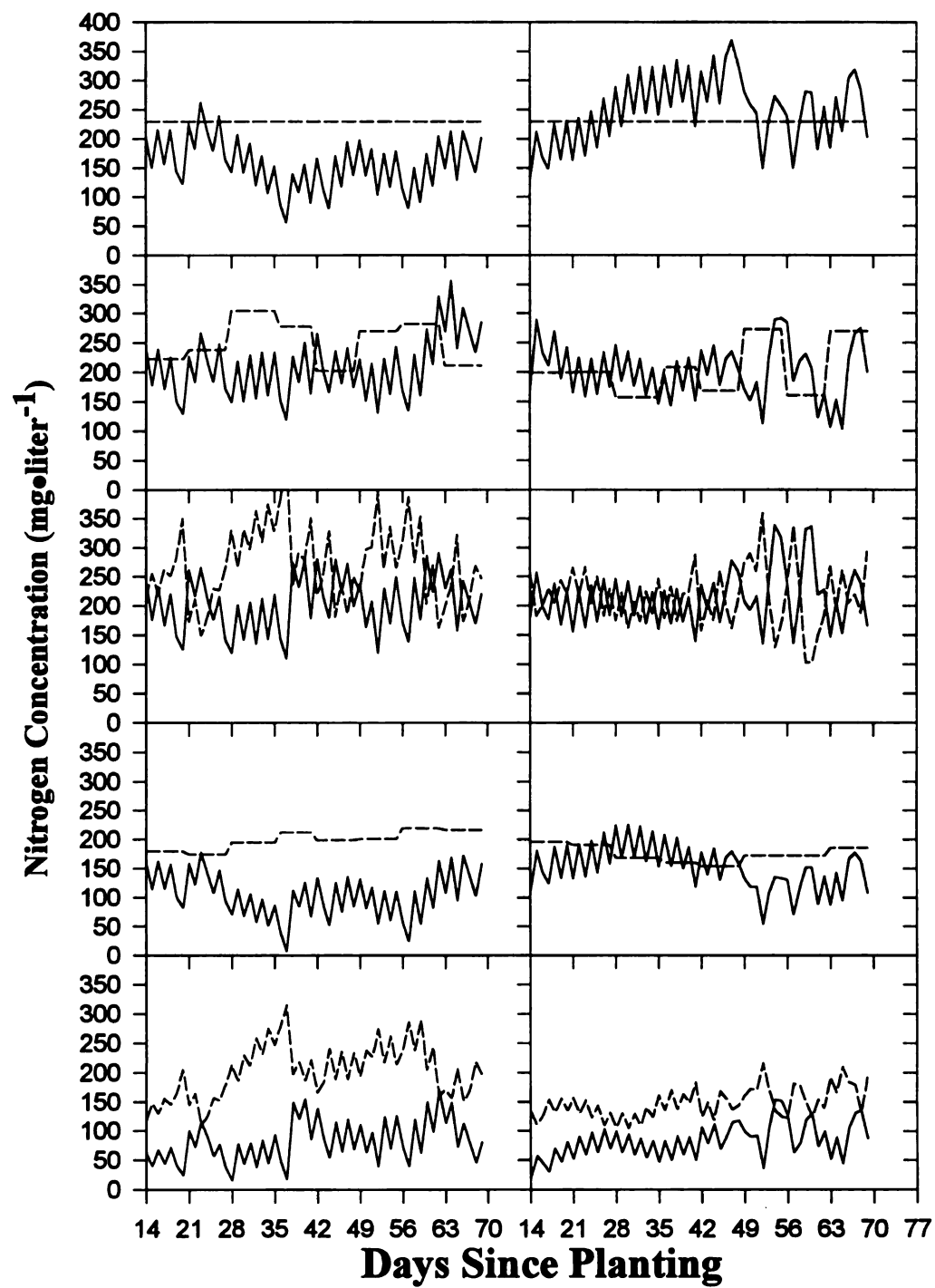


Figure 7. Predicted root zone N concentration of saturated medium extracts over time since the start of short days at two times of the year. Graphs in left column are the root zone N concentration of plants grown during the winter experiment and graphs in the right column are from the spring experiment. The graphs in row 1 (top) are predicted results for plants grown with a constant fertilizer concentration, row 2 through 4 are plants grown using a PD controller and with weekly medium sampling (row 2 and 4) or daily medium sampling (row 3 and 5). The graphs in rows 2 and 3 were from plants grown using a constant setpoint of 48 mg N where graphs 4 and 5 were based on plants grown with optimized setpoints.



APPENDIX

Appendix

/ SAS (version 6.04) for Windows 3.1 Code to run nitrogen model */*

LIBNAME 'H:\MVY\MODEL';

/ MODELOUT.XLS contains output data */*

/ DDE link to range in Microsoft EXCEL 6.0 spreadsheet */*

filename modout dde

'Excel|H:\MVY\MODEL\[MODELOUT.XLS]output!R3C1:R1244C14';

DATA MOD.RUNMOD;

/ Input weather file =mod.nlindata */*

set mod.nlindata;

file modout;

ARRAY DBTa{2,69} T1-T138;

ARRAY Rsa{2,69} TA1-TA138;

ARRAY RsMaxa{2,69} TB1-TB138;

ARRAY ESAIRa{2,69} TC1-TC138;

ARRAY GAMMAa{2,69} TD1-TD138;

ARRAY DELTAa{2,69} TE1-TE138;

ARRAY VPDa{2,69} TF1-TF138;

ARRAY PARa{2,69} TG1-TG138;

if Fert=1 then Ncnc=50;

if Fert=2 then Ncnc=100;

if Fert=3 then Ncnc=150;

/ Initialize rate and state variables */*

dLA=0;

dLAb=0;

dDM=0;

dPN=0;

dWL=0;

dWA=0;

dWA=0;

dNRZap=0;

dNRZtl=0;

PLA=12;

PLAb=12;

PDM=.903;

```
PPN=45;
PWRZ=300;
PNRZ=30;
```

```
LAI=(PLA/10000)/0.0113;
```

```
/*Contants for leaf area and dry mass models */
```

```
E0=2.495516413;
E1=0.177082945;
E2=-0.000576443;
```

```
B1=31.81604872;
B2=-0.23523788;
```

```
WRZmin=180;
WRZmax=300;
```

```
/****** Simulation Loop *****/
```

```
DO Cnt=1 to DOE BY 1;
```

```
DBT=DBTa{EXP,CNT};
Rs=Rsa{EXP,CNT};
RSMAX=RsMaxa{EXP,CNT};
ESAIR=ESAIRa{EXP,CNT};
Gamma=GAMMAa{EXP,CNT};
Delta=DELTAa{EXP,CNT};
VPD=VPDa{EXP,CNT};
PAR=PARA{EXP,CNT};
```

```
PLA=PLA+dLA;
PDM=PDM+dDM;
PPN=PPN+dPN;
```

```
PNRZ=PNRZ+(dNRZap-dPN-dNRZtl);
PNRZtest=PNRZ+dPN+dNRZtl;
PWRZ=PWRZ+(dWA-dWL);
```

```
PNcRZ=PNRZ/(PWRZ/1000);
PNsRZ=PNRZ/.25;
PNCact=PPN/(PDM*1000);
```

```
/* ***** Water Rates *****/
```

```
RsMedia=Rs* EXP(-.22*LAI)*(1-0.2);
RsShoot=Rs*(1-0.25);
```

FWIND=1.6636;

RB=(0.39-0.158*sqrt(esair))*(Rs/RsMax)*((DBT+273)**4)*(4.93E-9);
 RNMED=RsMedia-(RB);
 RNCAN=RsShoot-(RB);
 RNMED=RsMedia-RB;
 RNCAN=RsShoot-RB;
 EMED=(DELTA*RNMED+6.43*GAMMA*FWIND*VPD)/(DELTA+GAMMA)*.62;
 ECAN=(DELTA*RNCAN+6.43*GAMMA*FWIND*VPD)/(DELTA+GAMMA)*.69;

dWLmed=EMED*0.0133/2.45*1000;
 dWLplt=(ECAN*PLA/10000/2.45*1000)*.7;
 dWL=dWLmed+dWLplt;
 dWLb=dWLmed+dWLplt/.7;

if PWRZ<WRZmin then do;
 dWA=WRZmax-PWRZ;
 if dWA>200 then dWA=200;
 dNRZap=dWA/1000*Ncnc;
 dWAtl=200-dWA;
 end;
 else do;
 dWA=0;
 dNRZap=0;
 dWAtl=0;
 end;

/* ***** Plant Rates ***** */

if PNCact<.0135 then fLA=0;
 else if PNCact>.034 then fLA=1;
 else fLA=(PNCact-.0135)/(.034-.0135);

dLA=(b1+2*b2*cnt)*fLA;
 dDM=(PAR*e1+PAR**2*e2+e0)*PLA/10000;
 LAI=(PLA/10000)/0.0113;
 dPN=dDM*1000*(.034);
 if PNCact<.034 then
 do;
 dPN=dPN+PDM*1000*(.034-PNCact);
 end;

if (PNRZ+dNRZap)<=0 then dPN=0;
 else if (PNRZ+dNRZap-dPN)<0 then dPN=(PNRZ+dNRZap);


```

    if (PNRZ+dNRZap-dPN)<=0 then dNRZtl=(dWAtl/1000)*.68*PNcRZ; else
dNRZtl=dWLmed/1000*PNCrZ+(dWAtl/1000)*.68*PNcRZ;

```

```

    if (PNRZ+dNRZap-dPN-dNRZtl)<0 then dNRZtl=(PNRZ+dNRZap-dPN);

```

```

/* Outputs data to excel file */

```

```

IF REP=3 AND DOE=69 THEN DO;

```

```

    PUT PPF FERT EXP CNT PLA PPN PDM PNRZtest dWLb dNRZap dPN dNRZtl
PNRZ PNsRZ;

```

```

END;

```

```

end; /*DO LOOP*/

```

```

output;

```

```

RUN;

```

