Simulation for Year-Round Nutrient Uptake of Greenhouse Roses over Flowering Cycles

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Abstract
The biomass of rose (*Rosa hybrida*) plants changes constantly during cut flower production cycles. This cyclical nature of productivity poses a challenge to optimization of the nutrient supply to the plants. This study aimed to develop a simulation model for year-round nutrient uptake of roses, coupled with a whole-plant growth model based on light use efficiency (LUE). The study consisted of three activities: (A) modeling plant growth including root growth (whole-plant growth model), (B) synchronization of a whole-plant growth model and a nutrient uptake model, and (C) development of a simulation model for year-round nutrient uptake and plant growth of cut roses over flowering cycles. A “short-cut” shoot growth model for cut rose plants was developed based on LUE and designed to respond to light and air temperature. To determine changes in root growth over a flowering cycle, self-rooted single-node cuttings of ‘Kardinal’ rose were grown in air-bubbled Hoagland solution of EC 1.0. Root biomass and root surface area were simultaneously measured weekly with shoot growth, shoot biomass, and leaf area. Root growth of rose plants followed a cyclic rhythm related to shoot growth over the flowering cycle. Through the correlation of root and shoot growth, the modules needed for the whole-plant growth model, including the root part, were made. The nutrient uptake model was developed by estimating coefficients of Michaelis-Menten function. The dynamic simulation model for year-round nutrient uptake of roses was developed by coupling the whole-plant growth model and the nutrient uptake model using root surface area (RSA) as a coupler. This model successively reflected the dynamic changes in year-round nutrient uptake of six macronutrients according to verified light and air temperature conditions.

INTRODUCTION
Intensive plant management systems involve the use of excessive fertilizers which eventually contributes to environmental pollution. Despite the reduction of irrigation water and fertilizer application in soilless plant growing systems, especially hydroponics, it can still contribute to pollution through the run-off of nutrient solution. Hydroponic recycling system was developed to address this concern.

Flush production of cut roses for particular seasons and dates are desirable. Most rose plants grown hydroponically produce flowers year-round in flushes. Flowering occurs when new buds develop after harvesting, pruning, or bending of the existing shoots. New flower shoots generally require 4-8 weeks to reach harvestable maturity depending on variety and growing conditions (Kim and Lee, 2002).

The cyclical nature of productivity observed in hydroponic rose plants served as basis in designing strategies to optimize nutrient supply to the plants. Nutrient uptake models for cut roses have been developed (Cabrera et al., 1995; Lorenzo et al., 2000). Bougoul et al. (2000) modeled ‘Sweet Promise’ transpiration and NO₃⁻ over four days at a given light and temperature, but not across a growth cycle. The mathematical model developed by Silberbush and Lieth (2004) which predicted NO₃⁻ and K⁺ uptake of hydroponically grown ‘Kardinal’ cut roses provides a logistic equation that describes the
growth of flower shoots assuming that they have constant dry weight (equilibrium between new growth and senescence).

The study was conducted to develop a simulation model for year-round nutrient uptake of roses coupled with a whole-plant growth model based on the light use efficiency (LUE) concept. It has three components, namely: a) modeling growth of plant including root (whole-plant growth model); b) synchronization of whole-plant growth model and nutrient uptake model; c) development of a simulation model for year-round nutrient uptake and plant growth of cut roses over flowering cycles.

MATERIALS AND METHODS

Plant Materials and Experiment Design

Self-rooted ‘Kardinal’ rose plants, with one five-leaflet leaf and no buds, were established in 8-L container with nutrient solution of 0.5 mM NH₄, 7.0 mmol NO₃, 0.5 mM H₂PO₄, 3.0 mM K, 2.0 mM Ca, 1 mM Mg, 1 mM SO₄, and micronutrients according to Hoagland and Arnon (1950). Aeration was done by continuously bubbling air into the solution. The set-up was placed in a chamber with controlled environment maintained at 25/18°C as day/night temperature and at 14-hour photoperiod through supplemental lighting of PAR about 700 µmol m⁻² s⁻¹. Nutrient solutions were replaced every week.

Data Collection

Ten plants from each group were collected weekly for root length and mean radius measurements following Tennant’s (1975) line intersect method. Root surface area (RSA) was calculated with the assumption that roots are cylindrical. Shoot length, dry mass, and leaf area were measured to indicate shoot growth. Nutrient solution samples were analyzed to determine macronutrient uptake rates per plant. The following methods of analysis were employed: NO₃-N and NH₄-N by the diffusion conductivity method; K, Ca and Mg by flame emission with an ion absorption spectrophotometer; and P by the stannous chloride colorimetric method with a Brinkman PL800 colorimeter.

Model Development

The whole-plant growth and nutrient uptake model involved a simplified conceptual system of nutrient uptake using several assumptions as follows: a) plants are “fully grown” following a pattern of shoot growth and flower harvest; b) dimensions and contents of static base (stems and leaves) are constant; and c) LUE decrease exponentially as it decreased at high light intensities based on light saturation of photosynthesis in the leaf and to a lesser extent in the crop (Heuvelink et al., 2002). Light and air temperature were factored in the three derived sub-models.

1. Shoot Growth. The flowering shoot light use efficiency (LUE in g DM MJ⁻¹) is the ratio of net dry mass (DM) produced per day to the amount of intercepted light L (photosynthetically active radiation: PAR, in MJ). It is written as:

\[
LUE = \frac{\text{dW}}{\text{dt}} \frac{1}{L(1-e^{-kLAI})} \tag{1}
\]

where \(\text{dW/dt}\) is growth rate of shoot dry mass, and \(L(1-e^{-kLAI})\) is light intercepted by the plant canopy. \(Q\) (MJ m⁻² per day) is calculated from daily sum of PAR \(L\) and leaf area index (LAI) (Monsi and Saeki, 1963): If

\[
Q = L(1-e^{-kLAI}) \tag{2}
\]

where \(k\) is extinction coefficient for \(L\), given as 0.65 then the daily shoot growth rate, \(\text{dW/dt}\) can be expressed as:
\[
\frac{dW}{dt} = LUE Q \tag{3}
\]

This equation may also be expanded to include a temperature factor, \( f_{\text{temp}} \):

\[
\frac{dW}{dt} = LUE Q f_{\text{temp}} \tag{4}
\]

Also, it can be assumed that LUE is a function of light, \( L \). This function may be exponentially decreased:

\[
LUE = LUE_{\max,0} e^{-aQ} \tag{5}
\]

where \( a \) is a coefficient and \( LUE_{\max,0} \) is the theoretical maximal value of LUE on \( I=0 \). Therefore, final shoot growth rate, \( \frac{dW}{dt} \) is finally described as follows:

\[
\frac{dW}{dt} = LUE_{\max,0} e^{-aQ} f_{\text{temp}} \tag{6}
\]

In the above equations, LUE was assumed to decrease exponentially because LUE is expected to decrease at high light intensities, based on light saturation of photosynthesis at leaf level, which also occurs, although to a much lesser extent, at crop level (Heuvelink et al., 2002).

2. Root Growth. Root growth was hypothesized to be dependent on shoot growth in terms of a sink for photosynthate. During harvest, flower shoot and root stopped growing for a certain period (delay period) then decreased dramatically (decay period). The root follows the same pattern of shoot growth so that it was assumed that root growth would cycle with three zones based on the events during shoot growth.

The root growth model applies the ‘Delay and Decay’ concept. In a shoot flowering cycle, root growth rate (g DM m\(^{-2}\) per day) was separated into three parts: (1) delay zone from shoot harvesting \( R_{\text{delay,0}} \) to end of delay \( R_{\text{delay, end}} \), (2) decay zone from end of delay \( R_{\text{delay, end}} \) or start of decay \( R_{\text{decay, 0}} \) to end of decay \( R_{\text{decay, end}} \), and (3) growth zone is from end of decay \( R_{\text{decay, end}} \) or start of root growth \( R_{\text{grow, 0}} \) to end of root growth \( R_{\text{grow, end}} \) or shoot harvest. “R” is a function of daily integrated temperature (degree hour, DH). DH was assumed to repeat cyclically from the previous harvest to the next harvest. Thus, root growth rate (g root DM per day) during delay zone, \( \frac{dR_{\text{delay}}}{dt} \), is described as follows:

\[
\frac{dR_{\text{delay}}}{dt} = a \tag{7}
\]

where \( a \) is constant, same as the root growth rate at shoot harvest. In the decay zone, root growth rate, \( \frac{dR_{\text{decay}}}{dt} \), is expressed as:

\[
\frac{dR_{\text{decay}}}{dt} = \frac{a}{DH_{R_{\text{delay, end}}} - DH_{R_{\text{delay, 0}}}} (DH_{R_{\text{delay, end}}} - DH_{R_{\text{delay, 0}}}) \tag{8}
\]

where \( DH_{R_{\text{delay, end}}} \) is daily integrated temperature at \( R_{\text{delay, end}} \) and \( DH_{R_{\text{delay, 0}}} \) is daily integrated temperature at \( R_{\text{delay, 0}} \). Root growth rate (g root DM per day) during growth zone, \( \frac{dR_{\text{growth}}}{dt} \), is expressed as:

\[
\frac{dR_{\text{growth}}}{dt} = f(dW/dt) \tag{9}
\]
where \(dR_{growth}/dt\) is a function of shoot growth rate, \(dW/dt\) (Eq. 6), and is calculated using an empirical relationship between shoot growth and root growth.

3. Nutrient Uptake Rate. Nutrient uptake by rose plants is predicted from the estimate of a modified Michaelis-Menten function using the data on the nutrient uptake rate per unit root surface area (RSA) (Barber, 1995). RSA changes according to root growth in relation to the growing stage of the flowering shoot. The nutrient uptake rate of rose plants is defined as:

\[
I(C) = \frac{I_{max}(C - C_m)}{K_m + (C - C_m)}
\]

where \(I\), \(I_{max}\), \(K_m\), and \(C_m\) are coefficients. \(I\) (mmol/L m\(^{-2}\) RSA per day) is nutrient uptake at current nutrient concentration \(C\), \(I_{max}\) (mmol/L m\(^{-2}\) RSA per day) is the maximum ion influx, \(K_m\) (mmol) is Michaelis constant as ion concentration at 1/2 \(I_{max}\), and \(C_m\) (mmol/L) is minimum concentration where influx becomes operational.

4. Dynamic Nutrient Uptake Model and Simulation. Using the above equations, a simple dynamic nutrient uptake model based on plant growth was developed by coupling nutrient uptake rate [Eq. (10)] with RSA and unit time:

\[
I(C) = \frac{I_{max}(C - C_m)}{K_m + (C - C_m)} \cdot RSA \Delta t
\]

where RSA is estimated using the function for root dry mass. Dry mass is predicted by estimating the relationship between root dry mass and shoot dry mass.

The developed model was simulated to allow rapid calculation of the nutrient status in hydroponic rose production over time using the parameter estimates derived during the model calibration. Initial conditions selected for simulation were similar or equal to the experimental plants. The number of flowering shoots was set as one. The base leaf area and dry mass were assumed to be 0.01 m\(^2\) (the approximate area of 4 mature five-leaflet leaves) and 0.088 g, respectively. The starting nutrient solution was assumed to have a two-strength (2S) recycled solution composed of 8.7 mM NO\(_3\)-N, 1.0 mM NH\(_4\)+N, 4.6 mM K, 2.2 mM Ca, 1.0 mM P, and 0.8 mM Mg. The flowering cycle was assumed to start at daily integrated temperature of 0 DH and end at 1,035 DH, which is also the start time for the next flowering cycle. It was also assumed that the “delay” period of root growth would be from 0 DH until 69 DH, which was harvest date for flowering shoot, and the “decay” period of root growth would be from 69 DH to 161 DH.

RESULTS AND DISCUSSION

Model Calibration

Leaf area index (LAI) over time in Eq. (1) was calculated based on leaf area data collected per shoot. There was a Michaelis-Menten kinetics (Barber, 1995) relationship between leaf area per shoot and flowering shoot dry mass. The equation was estimated using SAS procedure NLIN and the resulting equation was: leaf area (m\(^2\)) = 0.1211 (shoot dry mass - 0.1232) / [3.63 + (shoot dry mass - 0.1232)]. The value 0.1211 m\(^2\) was the maximum potential leaf area per shoot and 0.1232 g was the shoot dry mass when leaves began to unfold.

In Eq. (4), the temperature factor was calculated from the published data of Shin et al. (2000) as relative growth rate (RGR: range of 0 to 1) of cut rose plants and the resulting equation was: RGR = -0.0031T\(_{air}\)^2 + 0.1435T\(_{air}\) - 0.6429. The estimates of \(\text{LUE}_{max,o}\) and \(a\) were 2.0203 (g DM MJ\(^{-1}\)) and 0.1151, respectively, obtained by fitting the data published by Kim and Lee (2002) to Eq. (5) using non-linear regression routine NLIN in SAS procedure. The goodness of fit, \(R^2=0.85\), reflected homogeneity of the 32-plant group used in the calibration study. Air temperature (T\(_{air}\)) affects rose plant development more than crop growth (Kim and Lee, 2002).
The hypothesis that root growth was dependent on shoot growth was confirmed (Fig. 1, left). Measured RSA followed the same cyclical pattern exhibited by root dry mass over a crop cycle. RSA could be predicted by an empirical approach, indicated by the positive linear relationship between root dry mass and measured RSA (Fig. 1, right). RSA was described as a linear function of root dry mass with slope of 0.0747: RSA (m²) = 0.0747 × new root dry mass. Also root dry mass was estimated through an exponential function of shoot dry mass (Fig. 2). The ratio of root dry mass to shoot dry mass was 28.757e⁻₀.₀₆₃shoot dry mass, where 28.757 is theoretically the maximum ratio of root dry mass to shoot dry mass. Therefore, the growth rate of root growth zone, dR growth/dt in Eq. (9) can be estimated by this exponential function.

Plant root surface area was calculated using an empirical relationship between root growth and RSA as a function of root dry mass and the nutrient uptake model developed based on modified Michaelis-Menten function could be used to predict nutrient uptake of hydroponically grown cut roses (Kim et al., 2006). The model predicted highest uptake potential (per unit root surface area and day) for NO₃-N at 17.07 mmol m⁻² day⁻¹, followed by K (12.67 mmol m⁻² day⁻¹), NH₄-N (12.22 mmol m⁻² day⁻¹), Ca (4.39 mmol m⁻² day⁻¹), P (3.12 mmol m⁻² day⁻¹), and Mg (1.57 mmol m⁻² day⁻¹).

Model Simulation

The dynamic simulation model using RSA as a coupler successively simulated the dynamic changes in a year-round nutrient uptake of six macronutrients according to verified light and air temperature conditions. In addition, whole-plant growth including shoot and root dry mass, leaf area per shoot, and RSA was simulated corresponding to flowering cycles. Results of the simulation clearly showed that root growth emulates the whole plant growth and nutrient uptake pattern as illustrated in Fig. 3.

Simulation allowed simultaneous observation of growth responses of whole-plant and each plant part, identification of plant growth responses to environmental factors over flowering cycles, and prediction of dynamic nutrient uptake based on environmental factors and nutrient concentration. This simulation model would be useful to provide information for production management such as expected harvest time, flower quality, and nutrient requirements.

The model, in its current version, however, does not account for differences in other environmental conditions such as CO₂, root temperature, etc. Also, the nutrient uptake model was coupled only with RSA predicted by root growth and shoot growth. The model needs to convert some sub-models for successful simulation of abrupt nutrient uptake decreases in the middle of the flowering cycle. These effects may be introduced to the model in the future as variables.

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Literature Cited


Figures

Fig. 1. New roots and new root shoot area (left) and relationship between new root dry mass and RSA (right). $R^2=0.95$. Sample size =10.

Fig. 2. Ratio of root dry mass to shoot dry mass of cut rose plants, expressed by exponential decrease ($R^2=0.61$). Sample size =10.
Fig. 3. Simulation of whole-plant growth (shoot length and growth, leaf area, root growth, and whole plant growth) and macronutrient uptake for year-round production of cut roses based on driving environmental factors: irradiance and air temperature average.