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Modelling the Growth and Yield of Choy Sum (*Brassica chinensis* Var. *Parachinensis*) to Include the Effects of Nitrogen and Water Stress

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ABSTRACT

The response of choy sum (*Brassica chinensis* var. *parachinensis*) to water and nitrogen (N) stress is still uncertain and no growth and yield model exists specifically for this crop. Consequently, this study conducted a field experiment to determine the growth and yield of choy sum grown under several watering frequencies and N application rates. Measured crop parameters were then used to aid in the crop model development and in model validation. Choy sum growing under the once-a-day and once-a-week watering treatments did not experience water stress unlike the water-stressed choy sum grown under the once-every-two-weeks watering treatment. The optimal volumetric soil water content level and N application rate for maximum yield were determined to be 40% and between 30 to 40 kg N ha^{-1}, respectively. Model validation showed that the choy sum model had an overall mean estimation error of 7.3% for leaves dry weight, 28.9% for stem dry weight, 28.9% for roots dry weight, 41.7% for leaf area index, and -0.8% for plant height. The model errors could be due to the assumption of an open-field energy balance growing environment and the lack of accuracy on the leaf area index estimation.

Keywords: Brassica, choy sum, drought, model, nitrogen fertilizer, water stress

INTRODUCTION

Choy sum (*Brassica chinensis* var. *parachinensis*) is one of the most widely planted leafy vegetables in Asia, including in Malaysia (Tin *et al*. 2000). Choy sum is planted for its leaves which are rich in glucosinolates that are claimed to have anti-aging, antioxidants, and anti-cancer effects (Halkier and Gershenzon 2006). Choy sum varies in height between 20 to 30 cm and has a short life cycle enabling the plant to be harvested within a month (Edward 2009). Since choy sum is a leafy plant and has a succulent stem, choy sum is sensitive to nitrogen (N) and water stress (Nobel 2009).

Although the effects of N and water stress on plant growth have been widely reported for many crops (Clay *et al*. 2012; Sun *et al*. 2011; Pandey *et*

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al. 2000), much less is known specifically on the response of choy sum to these two stresses. Different Brassica species can respond differently to water stress. For example, caisin (*Brassica rapa* subsp. *parachinensis*) was observed to be more tolerant to waterlogging and water deficiency than Chinese kale (*Brassica oleracea* var. *alboglabra*) (Issarakraisila *et al.* 2007). Nonetheless, both these two Brassica species still experienced reduced total leaf area and leaf weight, delayed flowering, and increased tissue N concentration under 14 days of water deficit conditions.

N uptake by plants is influenced by soil-water status (Shangguan *et al.* 2000). Plants experiencing water stress and simultaneously fertilized with the highest N rate (140 mg N L^{-1}), for instance, were found to experience high stress levels (Scagel et al. 2011). Fertilization under more well-watered conditions can reduce plant stress, but fertilization under water-stressed conditions can aggravate plant stress (Sun *et al*. 2011). The decomposition of granular fertilizers to ionic forms such as urea $CH(NH_2)_2$ decomposition to nitrate NO_3^- can occur in the presence of soil moisture, urease enzyme, and nitrifying soil bacteria. But fertilizers that dissolve under drought condition can instead increase the concentration of ions around the root system and at the same time decrease the availability of soil water. In the other words, fertilization during drought condition would have a greater deleterious effect on plant growth than the effect of drought alone. Furthermore, shortage of water supply can cause the concentration of N within plant tissues to increase, along with a suppression of yield.

Water stress experienced by plants fertilized with high N rates can be reduced by watering the plants more frequently. However, over-irrigation could instead decrease efficiency of plant N uptake (N uptake per N applied) and alter the biomass allocation in the plants (Scagel *et al.* 2011). The plants maintain a dynamic balance in biomass allocation. Root growth is typically less affected by drought stress than shoot growth (Franco 2011; Alam 1999), and the shoot: roots ratio is usually used to indicate the effect of drought stress on plant growth and biomass allocation (Franco 2011).

Plants require a certain amount of glucose for the production of the six major biochemical groups (carbohydrate, protein, lipid, lignin, organic acid and mineral) to synthesise a new material in plant tissues. Consequently, determining the glucose content in the various plant parts is important. According to Vertregt and Penning de Vries (1987), glucose content in a plant can be calculated from total carbon and total nitrogen. This calculation method is inexpensive and more rapid and practical compared to measurements of glucose content (Teh 2006). Glucose is needed for plant maintenance and growth respiration, with the former being needed to sustain the survival of existing plant tissues, and the latter to synthesise new structural materials for plant growth. However, maintenance and growth respiration can vary between plant species, varieties, and even between plant parts (Teh 2006).

Nitrogen concentration in a plant varies at each development stage because N is mobile within the plant. For instance, N moves from old to young leaves

when the plant faces N deficiency. N concentration is usually higher in the early stages of plant growth compared to the later stages. Hence, the age of plant tissues is also an important factor that determines N content within the various plant parts.

Water loss from the soil is through soil evaporation and plant transpiration. The simultaneous occurrence of these two processes is called evapotranspiration (ET) (Teh 2006). The ratio between actual and potential evapotranspiration is often used to quantify water stress (Vertregt and Penning de Vries 1987) in crop models. Some of the crop models calculate the daily crop water stress as 1 – AT/PT where AT is the daily actual water uptake and PT is the daily potential transpiration (Doorenbos and Kassam 1979).

Considering choy sum's response to the simultaneous effects of water and N stresses are still uncertain, this study aimed to develop and validate a mathematical growth and yield model that included the effects of water and N stresses. The aim was also to use this model for estimation of the impact of climate change (such as increases in water deficit levels) on the growth and yield of choy sum in Malaysia. The model could additionally be used to study ways to offset the detrimental climate change effects on the plant (for example, could higher N rate application offset the decrease in choy sum yield due to higher air temperatures?).To help achieve these goals, a field experiment was conducted to gauge choy sum's response to five rates of N fertilizer and three watering levels. Data collected from the field experiment were used to aid in model development as well as serve as model parameters to validate the model's simulation results.

MATERIALS AND METHODS

Field Experiment

The field experiment has been described in great detail by Kamarudin (2012), soonly the necessary details are outlined here. Choy sum was grown in polyethylene bags under a rain shelter in March 2011 at the Agronomy Research Farm (2° 59.47' N and 101° 42.882' E), Universiti Putra Malaysia, Serdang, Selangor. Choy sum were exposed to three watering frequencies (once-a-day, once-a-week, and once-every-two-weeks), and five N fertilizer application rates (0, 34, 68, 136, and 272 kg N ha^{-1}). Plant parameters (such as plant height, leaf number, total leaf area, plant part dry weights such as leaves including petiole, stem, and roots, and total C and N in various plant parts tissues) were collected weekly (0, 7, 14, 21, and 28 days after transplanting) for four weeks. The soil properties used to grow the choy sum in the polyethylene bags are shown in Table 1.

Four meteorological parameters (wind speed, relative humidity, solar irradiance, and air temperature) were measured using a portable weather station (WatchDog Model 2600) set at 30-minute recording intervals.

TABLE 1

The soil properties at study site

Parameters	Value
Soil series	Munchong (Typic Hapludox)
pH	6.8
EC (dS m^{-1})	0.62
Particle size distribution (%)	
Clay (2-50µm)	65.41
Silt (< 2µm)	7.63
Sand (> 50 µm)	26.74
Texture class (USDA)	Clay
Total carbon (%)	0.99
Total nitrogen (%)	0.15
Bulk density (Mg m^{-3})	1.08
Volumetric soil water content, Θ (%)	
Saturation	74.97
Field capacity	44.55
Permanent wilting point	25.32

Crop Model Development

The choy sum growth model was modified from the generic crop growth model developed by Teh (2006). Here we describe the essential key model calculations, in particular what we altered in the generic crop model, to enable model application specifically to choy sum.

The study model was written in Microsoft Excel with the modelling add-in called BuildIt (Teh 2011). The model consisted of four core components: weather, photosynthesis, evapotranspiration, and maintenance and growth respiration. The model run consisted of nine main steps (*Figure 1*). The model run started with the reading of model parameters; subsequently growth development stage (ξ_s) was checked to determine if the model run should continue or stop. The growth stage for choy sum was set to have three important growth stages (milestones): 0 for transplanting, 1 for maturity, and 2 for harvesting which occurred 28 days after transplanting (DAT).

Model run would stop if the growth stage reached the harvesting stage (ξ_s=2); otherwise, the model would run for weather, photosynthesis, evapotranspiration, and maintenance and growth respiration components, after which the crop's growth stage would be updated by the growth development rate (ξ_r):

$$\xi_{(s,t+1)}=\xi_{(s,t)}+\xi_{(r,t)}\,\Delta t \qquad (1)$$

where $\xi_{(s,t)}$ and $\xi_{(s,t+1)}$ are the growth development stage at time t and subsequent time step t+1, respectively; Δt is the time step (taken as 1 day); and $\xi_{(r,t)}$ (≥0)is the growth development rate (days^{-1}) at time t, determined by:

$$\xi_{(r,t)} = \alpha(T_{avg} - T_b) \quad (2)$$

where T_{avg} is the mean of the minimum and maximum daily air temperature (°C); T_b is the base temperature (°C), below which crop growth stops; and α is a crop-dependent coefficient (°C^{-1} day^{-1}). For Brassica species like choy sum, T_b is approximately 0°C and α is 0.00102 °C^{-1} day^{-1} (Dixon 2006).

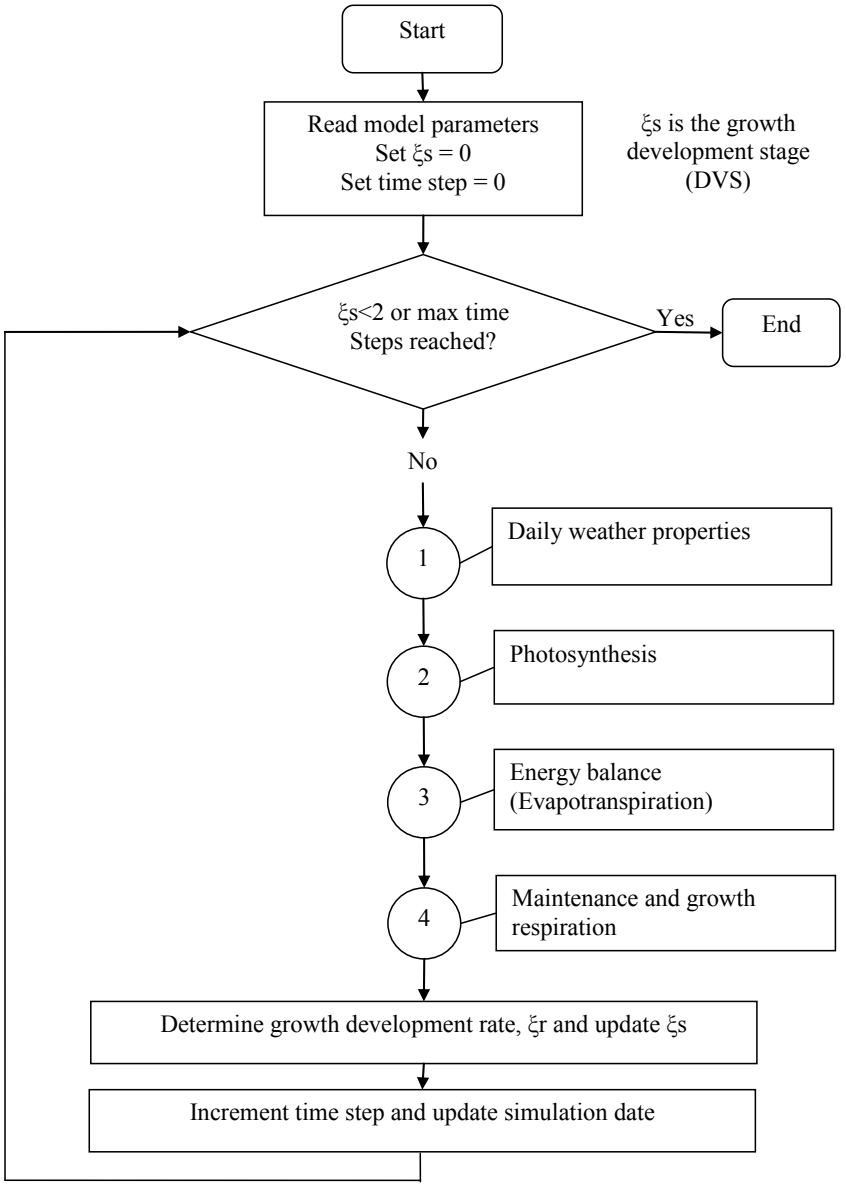


Figure 1: Main program flow of the choy sum growth and yield model.

Leaf area index (LAI) was calculated as:

$$LAI = W_{greenleaves} \cdot SLA \quad (3)$$

where $W_{greenleaves}$ is the weight of green leaves (g dry matter m^{-2} total ground area); and SLA is the specific leaf area (m^2 leaf area g^{-1} dry matter leaf) (Teh *et al*. 2004).

Meteorological data collected from the weather station were used to determine the potential transpiration (ET_c; W m^{-2}) based on the energy balance by Shuttleworth and Wallace (1985). ET_c was scaled down to actual transpiration ($ET_{c,\alpha}$; W m^{-2}) by a reduction factor of α

$$ET_{c\alpha} = R_D \times ET_c \quad (4)$$

where R_D is the reduction factor (0 to 1) due to water stress, calculated based on the amount of water in the soil as

$$R_D = (\theta_v - \theta_{pwp}) / (\theta_{cr} - \theta_{pwp}) \quad (5)$$

where θ_v is the volumetric soil water content (m^3 m^{-3}); θ_{pwp} is the volumetric soil water content at permanent wilting point (m^3 m^{-3}); and θ_{cr} is the critical volumetric soil water content (m^3 m^{-3}), below which the plant experiences water stress. θ_{cr} is calculated from:

$$\theta_{cr} = \theta_{pwp} + p(\theta_{sat} - \theta_{pwp}) \quad (6)$$

where θ_{pwp} is the volumetric soil water content at saturation point (m^3 m^{-3}); and p is 0.5 for C3 plants like choy sum (Doorenbos and Kassam 1979).

The photosynthesis model component calculated the canopy photosynthetic rate (A'_{canopy}; g CH_2O m^{-2} total ground area day^{-1}) following the semi-mechanistic photosynthesis model from Collatz *et al*. (1991).The assimilates produced from photosynthesis was scaled down due to water and N stress, if any, by:

$$A_{canopy} = A'_{canopy} \times R_D \times N_D \quad (7)$$

where N_D is the reduction factor (0 to 1) due to N stress where N_D is determined by

$$N_D = a + bN_{rate} \quad (8)$$

where coefficients a and b were determined empirically for choy sum by Edward (2009) as 0.6 and 0.00118, respectively. Consequently, A_{canopy} (g CH_2O m^{-2} total ground area day^{-1}) was the reduced assimilates due to water stress and N stress.

These assimilates were then used for maintenance and growth respiration. Growth respiration required a certain amount of glucose to synthesise new structural compounds, and the total glucose requirement (G) was calculated from

Goudriaan and van Laar (1994) as:

$$G = \sum_{i=plant\ parts} F_i G_i \tag{9}$$

where G_i is the glucose requirement for plant part i (green leaves, stem, and roots) in g CH_2O g^{-1} dry matter; and F_i is the fraction of dry matter of plant part i.The glucose requirement for each plant part was calculated separately and expressed as a function of the carbon (C) and nitrogen (N) content of the tissues following the calculation by Vertregt and Penning de Vries (1987):

$$G_i = 5.4C_i + 6N_i - 1.1 \tag{10}$$

where the total carbon (C_i; %) and total nitrogen (N_i; %) for plant part i were measured using the combustion (LECO-CR 412 Carbon Analyser) and wet ashing methods (Jones, 1991; Auto-Analyzer, 2000 Series), respectively.

Maintenance respiration (R_M) rate, corrected for air temperature, was calculated as:

$$R_M = R'_M \times 2^{(T_{avg} - 25)/10} \tag{11}$$

where R'_M(g CH_2O m^{-2} total ground area day^{-1})was calculated as:

$$R'_M = \sum_{i=plant\ parts} k_{M,i} W_i \tag{12}$$

where W_i is the weight (g dry matter m^{-2} ground area) for plant part i; and $k_{M,i}$ is the maintenance respiration coefficient (g CH_2O g^{-1} dry matter day^{-1}), calculated from Goudriaan and van Laar (1994) as:

$$k_{M,i} = 0.04(N_i/0.16)+0.01 \tag{13}$$

where N_i is the N concentration (%) in plant part i (green leaves, stem, and roots).

Knowing the rates of canopy photosynthesis, maintenance respiration, and growth respiration, the dry weight of plant part i at time t ($W_{i,t}$) could then be increased to its new dry weight at the next time step t+1 ($W_{i,t+1}$) as follows:

$$W_{i,t+1} = W_{i,t} + F_i \left(\frac{A_{canopy} - R_M}{G} \right) \Delta t \tag{14}$$

Once the weight of all plant parts are increased, the model runs the next time step by repeating the above calculations until crop growth development stage reaches harvesting time (ξ_s=2).

Among the collected field parameters needed for crop model parameters were (i) the initial plant part weights of the stem, leaves, and roots and initial total leaf area (both at time of transplanting);(ii) volumetric soil water content at permanent wilting and saturation points;(iii) daily meteorological properties (air

temperature, solar irradiance, and wind speed); and (iv) the C and N contents in the various plant parts.

Crop Model Validation

The accuracy of the model was tested by comparing model simulations with the measured crop properties via two methods. The first method was by plotting model estimations with measured values in charts to determine, via visual inspection, how closely their corresponding values agree with each other. The second method was by determining the average estimation error, calculated as the mean difference between the predicted and measured values:

$$Error\ (\%) = \sum_{i=1}^{N} \frac{(P_i - O_i)}{O_i} \Big/ N \times 100 \qquad (15)$$

where P_i and O_i are the predicted (estimated or simulated) and measured (actual) values, respectively; and N is the number of observations. A large positive and negative error indicates a strong tendency for the model estimates to be larger (model overestimation) and smaller (model underestimation) than measured values, respectively. A preferable error is a value nearer 0 which indicates little model bias and a small mean difference between predicted and measured values.

RESULTS AND DISCUSSION

Results from the field experiment have been reported in detail by Kamarudin (2012), so we will only state the relevant field experiment results here for this part of the study. Based on Eq. 6 and values from Table 1, the critical soil water content below which C4 plants like choy sum would begin to experience water stress was determined as 0.35 $m^3\ m^{-3}$. The average (±standard error) soil water content under once-a-day and once-a-week watering treatments were 42% (±0.34) and 35% (±0.76), respectively, where both values were above the soil critical water level. However, the least frequent watering treatment (once-every-two-weeks) had an average soil water content of 29% (±1.15), which was below the critical water level. This meant that choy sum growing under the once-a-day and once-a-week watering treatments did not experience water stress, but the choy sum under the once-every-two-weeks watering treatment suffered water stress. This was why field results indicated that, at the same N rate applied, there were generally no differences in the measured growth and yield parameters between the once-a-day and once-a-week watering treatments, but the once-every-two-weeks watering treatment gave the lowest growth and yield parameters due to the water stress effects.

Measured specific leaf area (SLA), which is the ratio between leaf area and leaf dry weight, was related to *DAT* (days after transplanting) and N_{rate} (N fertiliser applied, kg N ha^{-1}) by using multiple linear regression, and the following equation was developed:

$$SLA = 0.02473 + 0.0008724DAT - 0.00004012N_{rate} \quad (16)$$

with R^2=0.52 and all regression coefficients significant at 5% level. Eq. 16 was used to estimate the LAI, as indicated in Eq. 3.

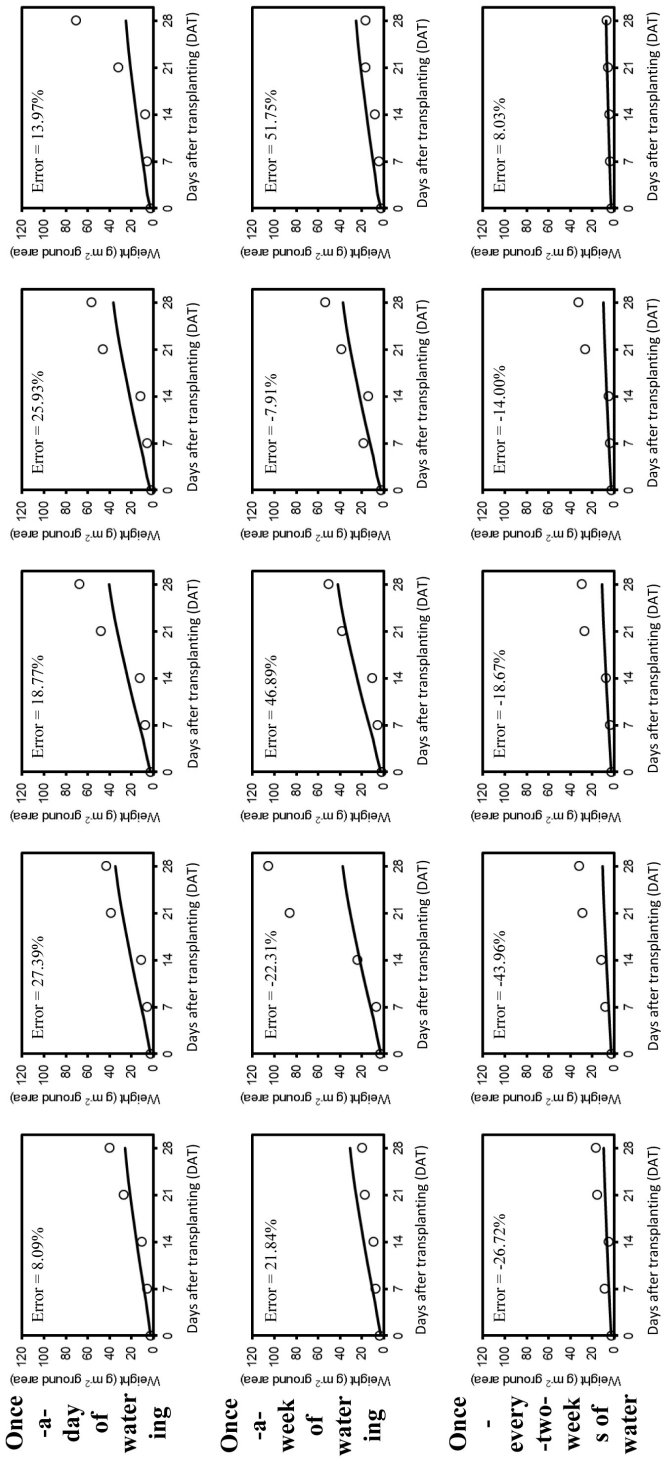
Field experiment results (Kamarudin 2012) also indicated that the optimal volumetric soil water content level and N application rate for maximum yield parameters (in terms of highest total leaf area, leaf dry weight, and leaf number) were 40% and between 30 to 40 kg N ha^{-1}, respectively. This is evident in *Figures 2* to *6* which show that maximum growth and yield parameters were generally obtained for treatments having once-a-day or once-every-week watering frequency and with N application rate of 34 kg N ha^{-1}.

Also shown in *Figures 2* to 6 are the results of model validation, where the model simulations are compared against field measurements. Errors of model estimation (their values are indicated in the charts) were calculated as the mean difference between the predicted and measured values (Eq. 15).

There was overall tendency for the model to overestimate the growth and yield parameters for once-a-day and once-a-week watering treatments. For once-every-two-weeks watering treatment, the model, in contrast, tended to underestimate these crop parameters. However, modelling the once-every-two-weeks watering treatment tended to produce smaller estimation errors than the errors for the more frequent watering treatments. The model estimation errors ranged between 33% to 163%. For the leaf dry weight, the overall mean estimation error was 7.3%, stem dry weight 28.9%, roots dry weight 27.3%, leaf area index (LAI) 41.7%, and plant height was -0.8%.

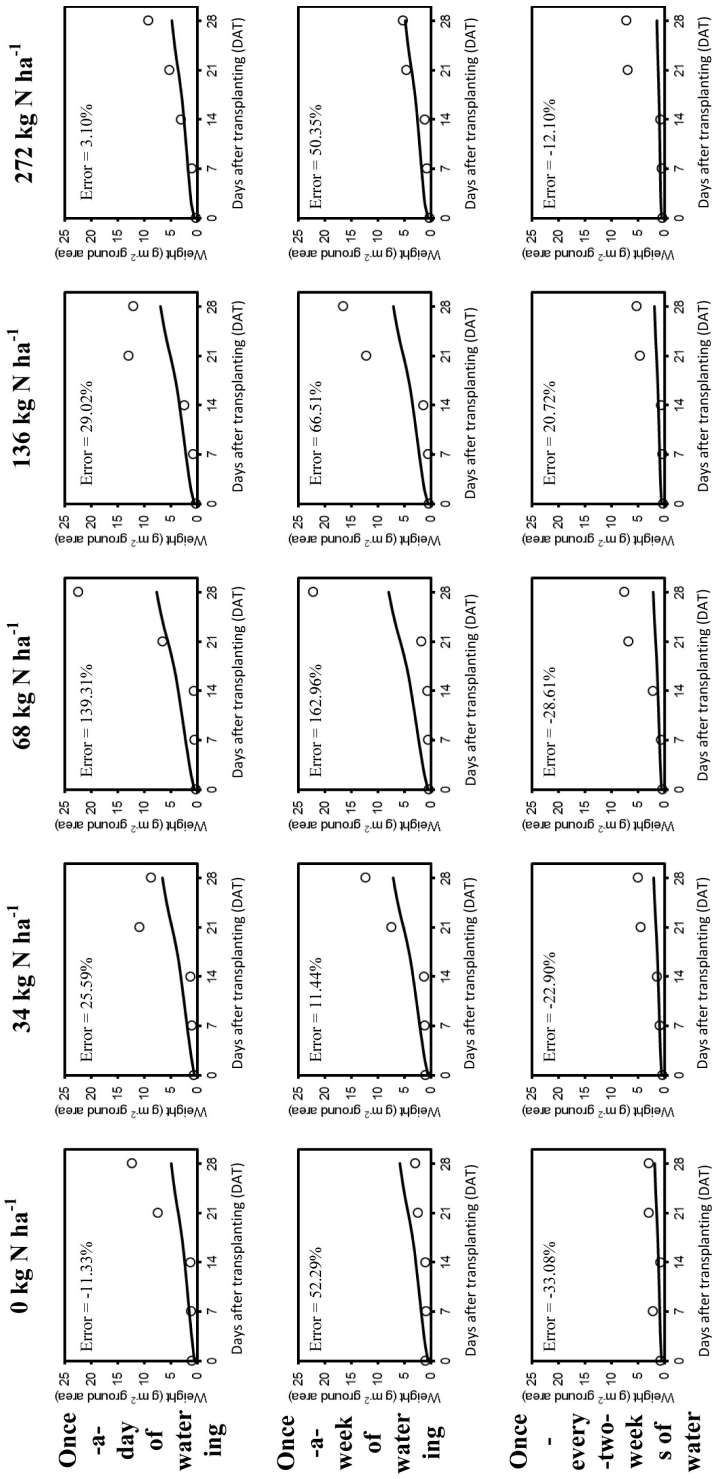
One particular source of error in this study was the use of the open-field energy balance equation by Shuttleworth and Wallace (1985). Choy sum in this study was grown in soil in polyethylene bags under a rain shelter, not in the open field. The energy balance from this kind of partially sheltered environment would be different from that in the open field. Consequently, evapotranspiration rate from both environments could be different from each other. Another important source of error in this study was the estimation of SLA using *DAT and* N_{rate} (Eq. 16). The multiple linear regression for SLA only accounted about half of the total variance. A more accurate estimation of SLA would be needed, to enable a more accurate estimation of LAI. An accurate LAI estimation would lead to more accurate estimation of the photosynthetic rate of the crop and ultimately the crop yield. As stated earlier, the overall mean error of LAI was 41.7%, the highest of all the measured crop parameters. Sensitivity analysis (results not shown) revealed that a ±50% change in SLA resulted in a mean change in choy sum yield by about 18%.

Nonetheless, this study model is the first developed specifically for choy sum, and should serve as a useful tool to estimate the response of choy sum, a popular leafy vegetable in Malaysia, to various growing conditions such as drought and N stresses and increased air temperatures.



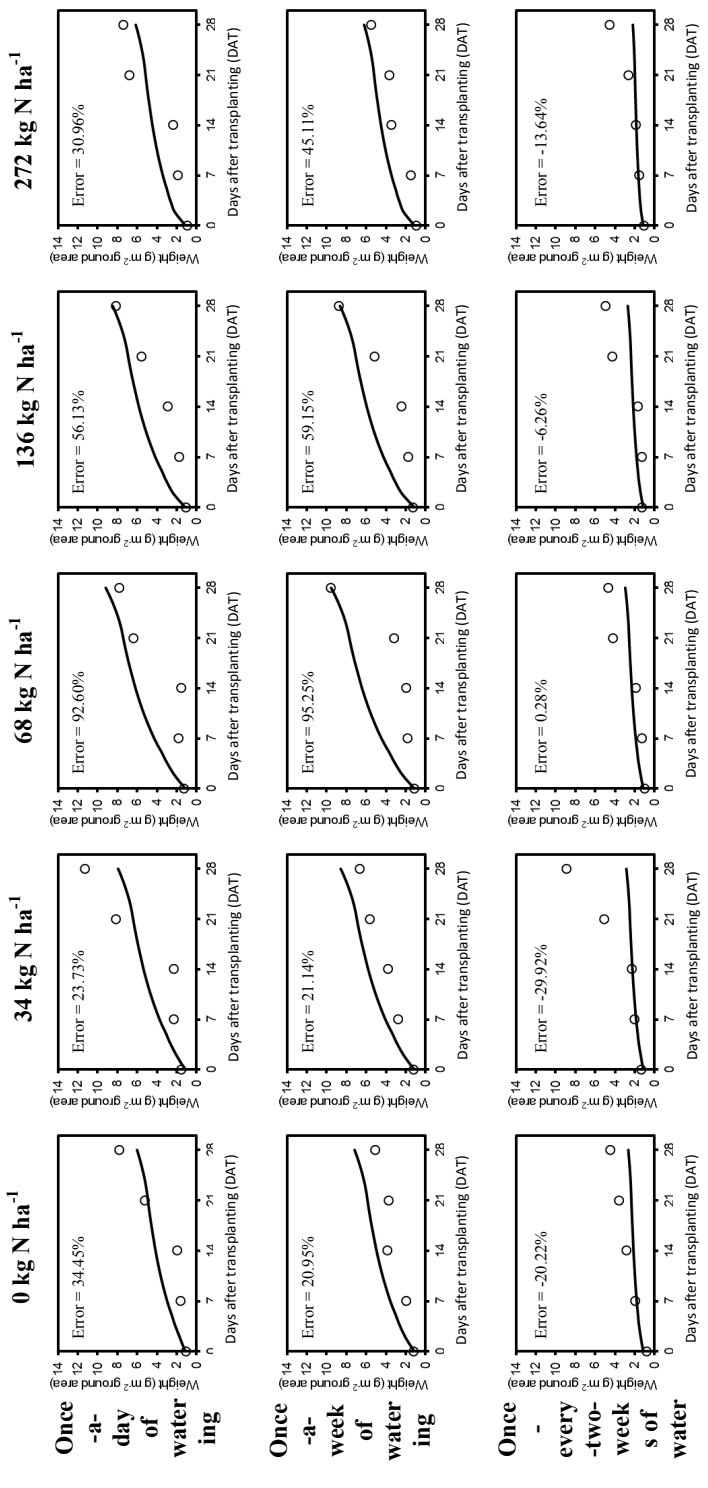
Note: The errors shown are the average weekly percentage of the difference between observed and simulated values.

Figure 2: Observed (o) and simulated (---) leaves dry weight of choy sum



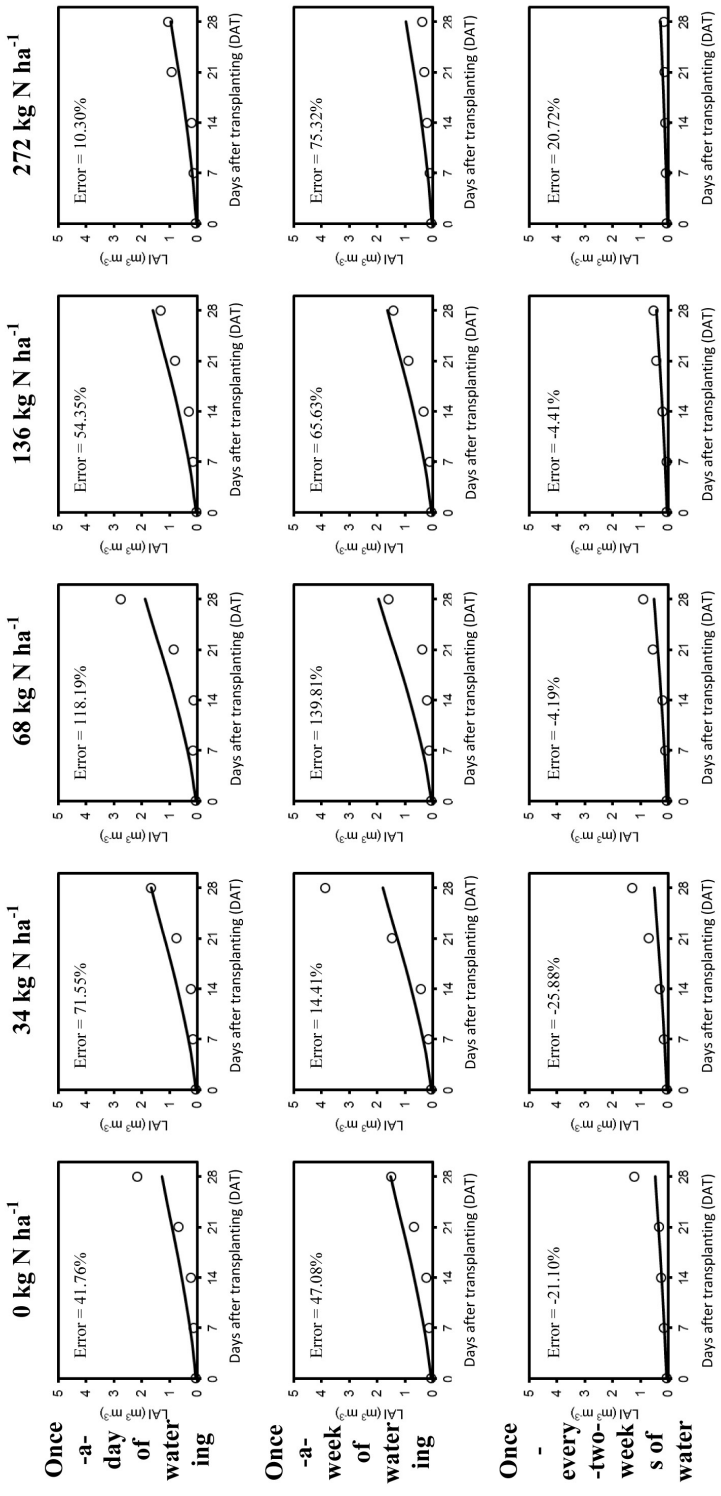
Note: The errors shown are the average weekly percentage of the difference between observed and simulated values.

Figure3: Observed (o) and simulated (---) stem dry weight of choy sum



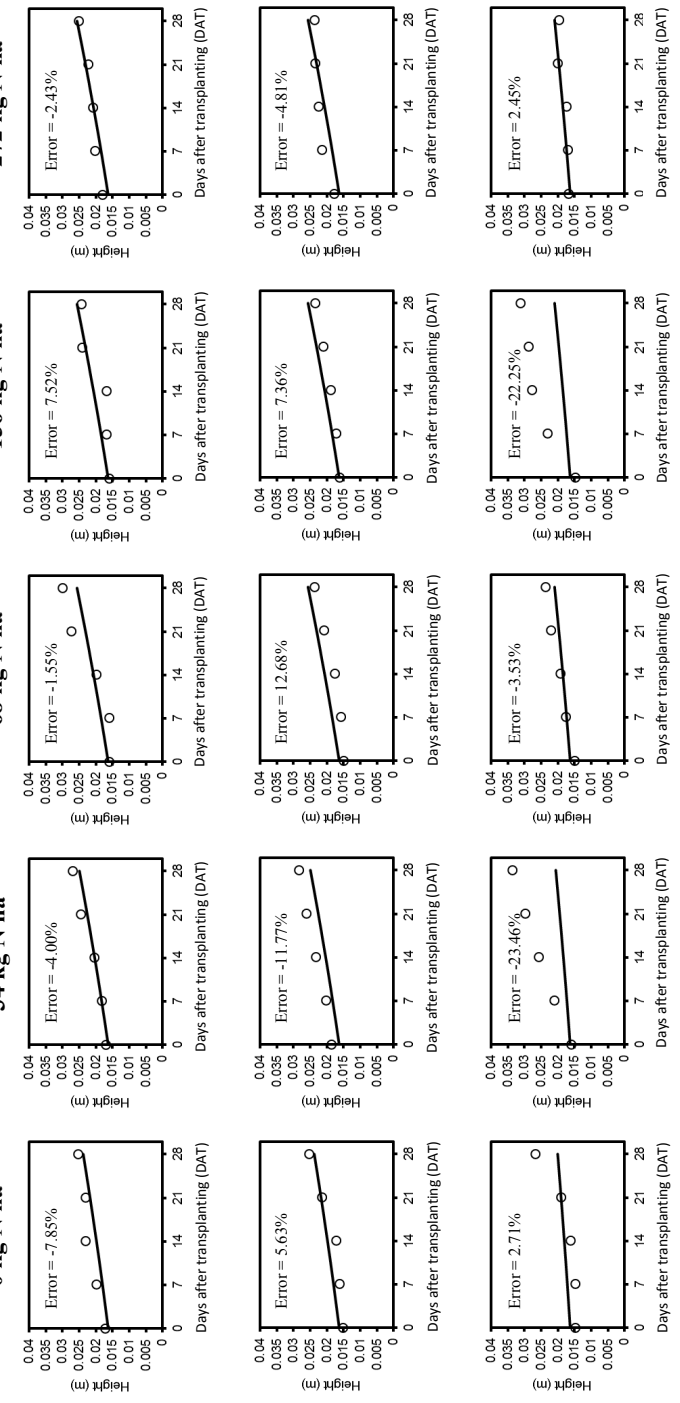
Note: The errors shown are the average weekly percentage of the difference between observed and simulated values.

Figure 4: Observed (o) and simulated (---) roots dry weight of choy sum.



Note: The errors shown are the average weekly percentage of the difference between observed and simulated values.

Figure 5: Observed (o) and simulated (---) leaf area index (LAI) of choy sum.



Note: The errors shown are the average weekly percentage of the difference between observed and simulated values

Figure 6: Observed (o) and simulated (---) plant height of choy sum.

CONCLUSION

A choy sum growth and yield model was successfully developed with an overall mean estimation error of 7.3% for leaf dry weight, 28.9% for stem dry weight, 28.9% for roots dry weight, 41.7% for leaf area index, and -0.8% for plant height. Future work is being planned to improve the model's accuracy because the current model tended to overestimate crop parameters in non-water stressed conditions but underestimate in water stressed conditions. This could be because the model assumed an open-field energy balance growing environment and the lack of accurate leaf area index estimation.

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