An Experimental Validation of NICOLET B3 Mathematical Model for Lettuce Growth in the Southeast Region of Coahuila México by Dynamic Simulation

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Abstract — An experiment was developed to validate the NICOLET B3 model. This model has two state variables: carbon content in the vacuoles and carbon content in the cell structure. Carbon dioxide, temperature and radiation taken inside a greenhouse were used as inputs to the model; the model gave out fresh and dry matter of lettuce aerial part. The model dynamic simulation was carried out using Matlab Simulink R2009a. A lettuce crop growth was developed under greenhouse conditions in soilless system, with a set of data loggers to record data. Results have shown that the data obtained from experiment are accurately predicted with this model.

Keywords — Lettuce, dynamic simulation, crop, greenhouse.

I. INTRODUCTION

A model is a set of mathematical equations describing a physical system [1]. The crop model is a logical or quantificational expression of interactions between crop growth system and environmental factors [2].

A crop growth simulation is a computational recreation of the crop growing process [3]. The model simulates or imitates the behavior of a real crop by predicting the growth of its components, such as leaves, roots, stems and grains. Thus, a crop growth simulation model not only predicts the final state of total biomass or harvestable yield, but also contains quantitative information about major processes involved in the growth and development of a plant [1]. Simulation models have rapidly developed in the last years [3, 4, 5].

With development of the agricultural information technology, crop model study has come to a new stage. Researchers have proposed many kinds of crop growth simulating systems thus accelerating the development of automation and management of production systems [2].

A simple two state variables model was developed and tested in greenhouses of Northern Germany [6] to describe the nitrate concentration in lettuce when nitrate supply is unlimited. Later, the same model was modified to predict growth under limited nitrate conditions. The modified model includes a nitrate balance equation [7].

The NICOLET model has been able to reproduce seasonal variations of nitrate content, as well as the effects of drastic N-stress treatments. These results are illustrated by comparing measured data with model-simulations. Accurate prediction of nitrate concentration is difficult, due to its sensitivity to changes in the environment. Exact control of nitrate under commercial conditions may require transient corrective measures, such as N-interruption, in conjunction with a good plant-nitrate monitoring system [8].

Seginer modified the NICOLET model by adding a storage compartment for “excess” carbon, resulting in a model with three compartments [5]. The dynamic behavior of this model was examined, described and calibrated with data collected under severe N-stress conditions [9].

A sensitivity analysis of NICOLET B3 model was developed in Chapingo, Mexico. The sensitivity analysis showed that three parameters have a major effect on the model performance [4]. Also, a dynamic mechanistic model was developed to predict lettuce dry matter accumulation and nitrate concentration during growth. The model assumes that lettuce has three separate pools. At the same time, the model also simulates time-dependent water mass stored in lettuce [10].
The NICOLET model was studied for different climate zones of Europe within the scope of the EC NICOLET project [11]. The objective of the present work is to validate the NICOLET B3 model under the climate conditions of the southeast of Coahuila, Mexico.

II. METHODOLOGY

Description of the model

The NICOLET (Nitrate Control in Lettuce) model, proposed for lettuce crops [6], has two state variables: carbon content in the vacuoles and carbon content in the cell structure; the core of this model is a balance in carbon flows [4]. The outputs of the model, plant dry weight and fresh weight, are calculated from the states by means of algebraic equations [6]. The NICOLET B3 model is a modified version of original NICOLET [12].

The NICOLET B3 model [13] is defined by the following two ordinary differential equations:

\[
\frac{dM_{cv}}{dt} = F_{cv} - h_g F_{cm} - F_{cg} - F_{cvs} \tag{1}
\]

\[
\frac{dM_{cs}}{dt} = F_{cvs} - (1 - h_g)F_{cm} \tag{2}
\]

These equations represent carbon balances both in the vacuoles and in the cell structure. The terms \(M_{cv}\) and \(M_{cs}\) represent the carbon content in the vacuole and the carbon content in the cell structure. The terms \(F_{cv}, F_{cm}, F_{cg}\) and \(F_{cvs}\) denote the rates of photosynthesis, maintenance respiration, growth respiration and growth, respectively, \(h_g\) is a growth inhibition function. These terms are functions of the following states: \(M_{cs}\) [mol(C) m\(^{-2}\) (ground)], \(M_{cv}\) [mol(C) m\(^{-2}\) (ground)]. They are functions of the following variables: light, \(I\) (W m\(^{-2}\)), carbon dioxide, \(C\) (ppm) and temperature, \(T\) (°C). It is assumed that photosynthesis depends on light and carbon dioxide concentration but not on temperature, whereas growth and respiration hinges on temperature only. Appendix A shows all the functions of the model and they are thoroughly described in [4,14]. Table I shows all the values of the parameters of NICOLET B3 model [5, 11, 14].

### Experimental lettuce crop growth

An experiment about lettuce growth was carried out at the Universidad Autónoma Agraria Antonio Narro, Saltillo, Coahuila, México, coordinates 25° 22' N, 101° 00' W, altitude 1760 m, in a greenhouse of 200 m\(^2\), with a curved roof and polyethylene cover. A crop of lettuce (Lactuca sativa L.), “Great Lakes” variety, was cultivated from March 24\(^{th}\) 2010 to May 7\(^{th}\) 2010. Plants were transplanted to a perlite and peat moss (2:1 ratio) soilless system within 4 L bags. A density design of 19.6 plants per meter square was used. The model inputs were air temperature, radiation and carbon dioxide inside the greenhouse which were recorded every 15 minutes using different data loggers Fig. 3 shows the inputs as they were recorded during the elapsed time of 45 days of the experiment. A K33 ELG data logger (CO2 Meter) was used to measure carbon dioxide; a sensor Quantum Li-190 (LI-COR inc.) to measure PAR radiation and a sensor 1400-101 (LI-COR inc.) to measure temperature. The latter two sensors were connected to a unique data logger LI-1400 (LI-COR inc.). The sensors were placed in the center of the greenhouse at crop height. There was not control of greenhouse climate. The nutrient solution was a commercial solution (FertiDrip) with a pH of approximately 6.5 and electric conductivity of 1.4 mS. In order to get the necessary information to validate the model, 5 randomly selected plants were taken twice a week and the fresh weight of their aerial part was recorded. The dry weight was determined after drying the samples at 80 °C for 48 hours.

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**TABLE I.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>1.7</td>
<td>m(^{-2}) (ground) mol(^{-1}) (C)</td>
</tr>
<tr>
<td>(b_r)</td>
<td>0.2</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>(b_g)</td>
<td>0.8</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>(c)</td>
<td>0.0693</td>
<td>°C(^{-1})</td>
</tr>
<tr>
<td>(C_c)</td>
<td>0.0011</td>
<td>mol (C) m(^{-3})</td>
</tr>
<tr>
<td>(k)</td>
<td>0.26e-6</td>
<td>s(^{-1})</td>
</tr>
<tr>
<td>(T^*)</td>
<td>20</td>
<td>°C</td>
</tr>
<tr>
<td>(\beta)</td>
<td>6</td>
<td>m(^3)Pa mol(^{-1}) (N)</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>0.61</td>
<td>m(^3)Pa mol(^{-1}) (C)</td>
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<tr>
<td>(\epsilon)</td>
<td>0.04-0.07</td>
<td>mol (C) mol(^{-1}) (PAP)</td>
</tr>
<tr>
<td>(\theta)</td>
<td>0.3</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>1/1200</td>
<td>m(^3)mol(^{-1}) (C)</td>
</tr>
<tr>
<td>(\nu)</td>
<td>13</td>
<td>mol (C) mol(^{-2}) (suelo)</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>1.4e-3</td>
<td>m s(^{-1})</td>
</tr>
<tr>
<td>(s_p)</td>
<td>10</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>(s_s)</td>
<td>10</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>(P/dens)</td>
<td>19.6</td>
<td>Plants per meter square</td>
</tr>
<tr>
<td>(\eta)</td>
<td>580</td>
<td>Pa</td>
</tr>
<tr>
<td>(\eta_{DMC})</td>
<td>0.03</td>
<td>Kg (DM) mol(^{-1}) (C)</td>
</tr>
<tr>
<td>(\eta_{DMN})</td>
<td>0.148</td>
<td>Kg (DM) mol(^{-1}) (N)</td>
</tr>
<tr>
<td>(\eta_{NO})</td>
<td>0.062</td>
<td>Kg (NO(_3)) mol(^{-1}) (N)</td>
</tr>
</tbody>
</table>

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Experimental lettuce crop growth was carried out at the Universidad Autónoma Agraria Antonio Narro, Saltillo, Coahuila, México, coordinates 25° 22' N, 101° 00' W, altitude 1760 m, in a greenhouse of 200 m\(^2\), with a curved roof and polyethylene cover. A crop of lettuce (Lactuca sativa L.), “Great Lakes” variety, was cultivated from March 24\(^{th}\) 2010 to May 7\(^{th}\) 2010. Plants were transplanted to a perlite and peat moss (2:1 ratio) soilless system within 4 L bags. A density design of 19.6 plants per meter square was used. The model inputs were air temperature, radiation and carbon dioxide inside the greenhouse which were recorded every 15 minutes using different data loggers Fig. 3 shows the inputs as they were recorded during the elapsed time of 45 days of the experiment. A K33 ELG data logger (CO2 Meter) was used to measure carbon dioxide; a sensor Quantum Li-190 (LI-COR inc.) to measure PAR radiation and a sensor 1400-101 (LI-COR inc.) to measure temperature. The latter two sensors were connected to a unique data logger LI-1400 (LI-COR inc.). The sensors were placed in the center of the greenhouse at crop height. There was not control of greenhouse climate. The nutrient solution was a commercial solution (FertiDrip) with a pH of approximately 6.5 and electric conductivity of 1.4 mS. In order to get the necessary information to validate the model, 5 randomly selected plants were taken twice a week and the fresh weight of their aerial part was recorded. The dry weight was determined after drying the samples at 80 °C for 48 hours.
Model simulation

The model simulation was carried out using MatLab Simulink R2009a (MathWoks, inc.). A variable step-size solver was used (ode45). The initial values for $M_{cv}$ and $M_{cs}$ were 0.007 and 0.0671 respectively. The equations system were programmed in Simulink using radiation ($I$), temperature ($T$) and carbon dioxide concentration ($C$) as model inputs. This data was taken from experimental lettuce crop growth. The model outputs were fresh and dry matter variables.

In order to obtain the $R^2$ coefficient and the linear regression equation, Microsoft Excel 2010 (Beta) was used.

III. RESULTS

Fitting the model

Parameter tuning is one of the most important activities when testing a mathematical model. In our case a large number of parameters where found to integrate the model, nevertheless most of them are related to the specific crop being tested [5,11,14].

I. Lopez et al in [4] have shown that a small subset of these parameters has a major effect on both state and output variables through time, namely maintenance respiration coefficient ($k$), coefficient of radiation extinction through the canopy ($a$) and growth rate coefficient ($v$). Therefore, in order to adjust the model, several series of values were tested for each one of these parameters ($a$, $v$, $k$) until appropriate values were found (Table II).
Curve of lettuce growth

Lettuce crop does not develop to a complete plant before harvest mainly because it is consumed in its early stages. So, in order to measure lettuce crop growth, fresh and dry weights are used. These data were correlated to the model outputs in the validation process.

The data obtained from the experiment shows the lettuce growth curve under climatic greenhouse conditions of southeast Coahuila. Figure 1 shows the increment in fresh weight. The results are shown in kg m⁻² of aerial dry or fresh matter only (Figures 1, 2).

![Graph showing the relationship between real data of lettuce growth and those predicted by the model.](Image)

**Fig. 4.** The relationship between real data of the lettuce growth (Fresh matter kg/m²) and those predicted by the model, where R²=0.9975. The line represents the line of identity (1:1).

Model validation

The model was validated using the parameter values already mentioned [11, 14] (Table I) and those derived from the fitting of the model (k, a, v). The values predicted by the model fitted the collected data (Figures 4, 5). Regarding fresh matter weight, the correlation coefficient R²=0.9975 shows almost perfect relationship (Figure 4). Regarding dry matter weight the coefficient R²=0.974 shows in this case a little lower relationship, nevertheless it can be considered good (Figure 5). There was slight evidence for an over prediction of plant dry weight and fresh weight matter of the aerial part at higher values. Most of the error bars for individual points intersected the line of identity, suggesting a good fit for lettuce growth prediction.

### IV. DISCUSSION

This study has presented a validation of NICOLET B3 model in southeast of Coahuila for lettuce crop under greenhouse conditions and climate conditions of the region.

The NICOLET B3 model has been shown to imitate ‘normal’ responses to seasonal changes in the greenhouse environment, and the ontogenetic changes during the growing period (Figures 6, 7). The model was validated using data from one greenhouse without climate control. Nevertheless, the relationship was almost exact, with an R²=0.9975 for fresh matter weight and an R²=0.974 for dry matter weight. This is important because, generally speaking, there is temperature control in crop growth, even in research works [4].

Some variations were observed at the end of lettuce growth concerning the relationship between simulated data and real data, but this can be neglected because the average error is smaller than 3%. The reason of these discrepancies may be partly attributed to an error in the measured data.

It should be pointed out, however, that while very different treatments within a given data set can be simulated with a single set of parameters, each new set (new source) of data requires a re-adjustment of some (2 or 3) of the parameters [8]. Considering such a statement, we adjusted three parameters (a, k, v), as proposed by López-Cruz et al. [4]. This lack of robustness among data sets is partly the result of model shortcomings and partly due to differences in measurement techniques [8]. However, it can be seen that the simulation provided for the model is very exact, so it can be used under specific conditions for better results.

Particular attention should be paid to the equipment used to perform the experimental research. Sensors must stay outdoors and should be prepared to be functional throughout time. Data should be taken on a periodic basis as this information is essential for the

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**TABLE II. PARAMETERS SETTING.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.2</td>
<td>m² (ground) mol⁻¹(C)</td>
</tr>
<tr>
<td>k</td>
<td>0.4e-6</td>
<td>s⁻¹</td>
</tr>
<tr>
<td>v</td>
<td>22.1</td>
<td>mol (C) m² (ground)</td>
</tr>
</tbody>
</table>

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validation process. Dedicated software for model programming and simulation is needed. Greenhouse conditioning is necessary to carry out the experiment.

![Graph showing the relationship between real data of the lettuce growth (Dry matter Kg m\(^{-2}\)) and those predicted by the model, where \(R^2=0.974\). The line represents the line of identity (1:1).](image)

**Fig. 5.** The relationship between real data of the lettuce growth (Dry matter Kg m\(^{-2}\)) and those predicted by the model, where \(R^2=0.974\). The line represents the line of identity (1:1).

**Mathematical models are useful tools to reproduce or predict the behavior of crops throughout time. They can be used to optimize weather conditions needed to better crop yield, particularly under greenhouse conditions. Also, these models can be used to predict crop yield and to take decisions concerning mineral nutrient optimization, as well as seedtime and harvest date selection. So, this information can be used for prediction purposes and decision taking in greenhouse agriculture.**

**ACKNOWLEDGMENT**

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**REFERENCES**


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N. Yarkoni, P. McKeena, NICOLET simulation model B3, 2000, Agricultural Engineering Department, Technion-Israel Institute of Technology.


Appendix A: NICOLET B3 model equations

\[
\frac{dM_{CV}}{dt} = F_{Cav} - h_g F_{Cm} - F_{Cg} - F_{Cvs} \tag{1}
\]

\[
\frac{dM_{CV}}{dt} = F_{Cvs} - (1 - h_g)F_{Cm} \tag{2}
\]

\[
F_{Cav} = p\{I, C_{Ca}\}f\{M_{Cs}\}h_p\{C_{CV}\} \tag{3}
\]

\[
p\{I, C_{Ca}\} = \frac{e\sigma(C_{Ca} - C_{C})}{e\sigma(C_{Ca} - C_{C})} \tag{4}
\]

\[
f\{M_{Cs}\} = 1 - \exp\{-aM_{Cs}\} \tag{5}
\]

\[
h_p\{C_{CV}\} = \frac{1}{1 + \left(\frac{(1 - h\Pi_v)}{\Pi_v - \gamma C_{CV}}\right)} \tag{6}
\]

\[
\beta C_{NV} + \gamma C_{CV} = \Pi_v \tag{7}
\]

\[
F_{Cm} = M_{CV} e\{T\} \tag{8}
\]

\[
e\{T\} = K \exp\{c(T - T*)\} \tag{9}
\]

\[
F_{Cvs} = g\{T\}f\{M_{Cs}\}h_g\{C_{CV}\} \tag{10}
\]

\[
g\{T\} = v e\{T\} \tag{11}
\]

\[
h_g\{C_{CV}\} = \frac{1}{1 + \left(\frac{b_g \Pi_v}{\gamma C_{CV}}\right)} \tag{12}
\]

\[
F_{Cg} = \theta F_{Cvs} \tag{13}
\]

\[
C_{CV} = \frac{M_{CV}}{2M_{Cs}} \tag{14}
\]

\[
\Pi_v - \Pi_c = G_v \tag{15}
\]

\[
Y_{fm} = \frac{1000}{p \text{idens}} M_{fm} \tag{16}
\]

\[
M_{fm} = 1000 \lambda M_{Cs} + M_{DM} \tag{17}
\]

\[
C_{NO3} = 10^{6} \eta_{NO3} C_{NO3N} \tag{18}
\]

\[
C_{NO3N} = C_{NV} \frac{1 - DFR}{1000} \tag{19}
\]

\[
DFR = \frac{M_{DM}}{M_{fm}} \tag{20}
\]

\[
V_f = \lambda M_{Cs} \tag{21}
\]

\[
M_{DM} = \eta_{OMC}(M_{Cs} + M_{CS}) + \eta_{MIN}\left(\frac{\lambda \Pi_c}{\beta} M_{Cs} - \gamma M_{CV}\right) \tag{22}
\]