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Evaluation of the Crop Growth Component of the Root Zone Water Quality Model for Corn in Ohio

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EVALUATION OF THE CROP GROWTH COMPONENT OF THE ROOT ZONE WATER QUALITY MODEL FOR CORN IN OHIO

S. E. Nokes, F. M. Landa, J. D. Hanson

ABSTRACT. The Root Zone Water Quality Model (RZWQM) is a computer model developed to simulate water, chemical, and biological processes in the root zone of agricultural management systems. As of this writing RZWQM is in the beta-testing phase of development. This article reports on a parameterization and evaluation study performed in Ohio on field corn for the crop growth component of RZWQM. The generic crop growth model in RZWQM had not previously been parameterized or tested on field corn. This article reports the results of such a study. One year of data was used to calibrate RZWQM, and two additional years of data from the same site were used to check the predictions of the model once it was calibrated. Crop growth, soil water content, and soil nitrate concentration predictions were compared to observed values collected throughout the growing season at the Ohio Management System Evaluation Area in Piketon, Ohio. The simulation results performed consistently with our expectations of the physical system. Since the generic crop growth model had not previously been tested on simulated field corn growth, we were unsure of its capabilities. For our site, the model was capable of being parameterized with one year's data, and reliably simulated the soil water content, nitrate in the root zone, corn growth, and yield for two other years. Keywords. Crop growth model, Biomass, Soil water, Nitrate, Simulation.

The principal objective of the Root Zone Water Quality Model (RZWQM) is to simulate water, chemical, and biological processes in the root zone (DeCoursey et al., 1992). The primary use of RZWQM is as a tool for assessing the environmental impact of alternative agricultural management strategies on a field-by-field basis. RZWQM is intended primarily for comparative purposes as opposed to rigorous quantitative predictions.

RZWQM, version 2.1, simulates the movement of water, nutrients, and pesticides through the root zone portion of the soil profile. It is primarily a one-dimensional model, designed to simulate conditions at a representative point in a field. Therefore, agricultural practices which are two-dimensional in nature, such as ridge-tillage, banded chemical application, or subsurface drainage are not considered in this version of the model. The generic crop growth model simulates plant size and yield as affected by daily temperature, water, and nutrient stress. RZWQM 2.1 simulates on a single year basis, with a daily time step for plant growth, and on a breakpoint basis for water redistribution.

A large number of interrelated hydrologic processes are simulated including: Green and Ampt infiltration; chemical transport with infiltration; transfer of chemicals to runoff during rainfall; water and chemical flow through macropore channels and their absorption by the soil matrix; evapotranspiration, root water uptake, soil water redistribution; and chemical transport during water redistribution.

The soil inorganic chemical environment is simulated to support the prediction of nutrient processes, chemical transport, and pesticide fate and transport. The model is capable of predicting soil solution chemistry across a wide range of soil pH. The nutrient submodel defines carbon and nitrogen transformations within the soil profile. The model simulates mineralization, nitrification, immobilization, denitrification, and volatilization of appropriate nitrogen based on initial levels of soil humus, crop residues, other organics, and nitrate and ammonium concentrations.

PLANT MODEL STRUCTURE

The RZWQM plant growth submodel is a generic plant model, which can be parameterized to simulate a specific crop. The basic equations will be described here mainly to give the reader a sense of the plant model’s strengths and limitations. It is not the authors’ intent to fully describe the plant model. Additional information can be found in Hanson and Hodges (1992). A listing of symbols, definitions, and units used in the article is included in the Nomenclature section.
Environmental fitness (EVP) is used in the plant model as a measure of the suitability of the environment for providing for the needs of the plant. Environmental fitness is determined as the product of the current temperature fitness (ETP, dimensionless) and the minimum of the current water (EWP, dimensionless) and nitrogen fitness (ENP, dimensionless). All factors are scaled between 0 and 1, with 1 representing ideal conditions. Thus, environmental fitness is computed as:

\[ \text{EVP} = \text{ETP} \times \min(\text{ENP}, \text{EWP}) \]  
(1)

Temperature fitness is an empirical function that includes air temperature, maximum, optimum, and minimum temperatures at which vegetative and reproductive growth occurs for each crop being simulated, and an empirical shape parameter for this curve.

Nitrogen is passively taken into the plant daily in proportion to the predicted plant transpiration rate and in quantities necessary to satisfy the present N demand. Since water uptake affects the passive uptake of nitrogen, the water uptake equations will affect the nitrogen stress (ENP) predictions. ENP is computed by:

\[ \text{ENP} = 1 - e^{\text{EFFN}} \times \text{SPCTN}, \text{ if SPCTN} > 0 \]
\[ 0, \text{ otherwise} \]  
(2)

where EFFN is the nitrogen-use coefficient and SPCTN is the difference between the current predicted leaf nitrogen and the lower limit of leaf N.

The water fitness factor EWP is defined as ratio of actual water uptake, \( T_r \), to transpiration demand, \( T_a \):

\[ \text{EWP} = \frac{\int_0^T T_r \, dz}{T_a} \]  
(3)

Water uptake \( T_r \) in cm d\(^{-1}\) soil layer\(^{-1}\) is computed using the equation derived by Nimah and Hanks (1973a, b):

\[ T_r = \sum_{t=1}^{24} \left[ P_r + P_{res} \times z - h(z,t) - s(z,t) \right] \times RDF(z) \times K(\Theta) \]  
(4)

where

\( t \) = hour of the day
\( P_{res} \) = root resistance term which accounts for the gravity and friction loss terms in the root water potential (cm)
\( P_r \) = effective water potential in the root at the soil surface (cm)
\( z_0 \) = root zone depth (cm)
\( h(z,t) \) = soil water pressure head (cm)
\( s(z,t) \) = osmotic potential (cm)
\( dx \) = distance between roots at depth z (cm)
\( RDF(z) \) = proportion of the total roots active in the depth increment dz

\( K(\Theta) \) = soil hydraulic conductivity (cm h\(^{-1}\))

Transpiration demand is calculated by the Penman-Montieth equation modified to account for a sparse crop (Shuttleworth and Wallace, 1985).

Growth stage in RZWQM 2.1 is a theoretical index of plant development and ranges from 0 (seeds) to 1 (totally mature plant). Growth stage (GS) is defined as the development rate for the predominant vegetative or reproductive growth class \( j \), modified by the current environmental fitness:

\[ \text{GS} = \sum_{i=1}^{t} \text{DEV RAT}_j \times \text{FACT}_j(\text{EVP}_j) \]  
(5)

where DEV RAT\(_j\) is the inverse of the minimum time required to pass through the current average phenological stage under optimal environmental conditions and FACT\(_j(\text{EVP}_j)\) is an empirical function of the environmental fitness at time \( i \) which allows for acceleration or deceleration of crop growth rate depending on the stage at which stress occurs.

A modified Leslie probability matrix is used to track the phenological development of the crop. At the end of the time step, which is equal to the age-class length, the plant either remains in the present class, progresses to the next age class, or dies. Environmental fitness controls the plant development rate by reducing the probability of progressing to the next stage as follows:

\[ p'(j + 1, j) = p(j + 1, j) \times \text{EVP} \]  
(6)

where \( p'(j + 1, j) \) is the probability of progressing to the next class under the current environmental stress, and \( p(j + 1, j) \) is the probability of progressing to the next class under no environmental stress.

The net carbon assimilation rate is computed from the daily solar radiation incident at the top of the canopy as follows:

\[ \text{PNCA} = \frac{\text{ALPHA} \times \text{RAD} \times \text{P.MAX}}{\text{ALPHA} \times \text{RAD} + \text{P.MAX}} \]  
(7)

where

\( \text{PNCA} \) = net carbon assimilation rate (mole C J\(^{-1}\))
\( \text{RAD} \) = daily solar radiation incident at the top of the canopy (W m\(^{-2}\))
\( \text{ALPHA} \) = light-use efficiency coefficient (mole C J\(^{-1}\))
\( \text{P.MAX} \) = theoretical maximum net assimilation rate (mole C m\(^{-2}\) day\(^{-1}\))

Whole-plant respiration rate is calculated in the RZWQM as a function of plant weight and current day photosynthetic rate based on McCree (1970).

\[ \text{W.PRESP} = \text{BETA} \times \text{PNCA} + \text{GAMMA} \times \text{BIOPLT} \]  
(8)

where

\( \text{W.PRESP} \) = whole-plant respiration (mole C m\(^{-2}\) day\(^{-1}\))
\( \text{BETA} \) = proportion of the photosynthate respired for general plant maintenance (dimensionless)
evaluating the impact of alachlor, atrazine, and metribuzin on the 260-ha VanMeter farm in Pike County, Ohio (39°02'N, 83°02'W), which overlies the Scioto River Buried Valley Aquifer. The site is located on primarily Huntington soils (fine-silty, mixed, mesic fluventic hapludoll). Below the soils are sands that grade into gravelly sand at a depth of 2 m.

The MSEA project was primarily interested in evaluating the impact of alachlor, atrazine, and metribuzin on the water quality of agricultural systems. Management systems and rotations were selected by a team of scientists to represent existing and innovative practices for Ohio, within the constraints of the chemicals of interest. The three management systems under evaluation at the Ohio MSEA were a conventional corn/soybean rotation, a "high chemical input" corn/soybean/wheat rotation with a winter cover crop of hairy vetch following the wheat. Data from each of the plots. The cores were collected biweekly during the growing season and monthly during the nongrowing season. Undisturbed soil cores with a diameter of 9 mm were encased in an acetate liner which extended from the soil surface to a depth of 0.9 m. In 1991 the cores were collected from between the corn rows, and in 1992 and 1993 the cores were collected from within the crop row. The cores were sectioned into segments corresponding to 0.0 to 0.15, 0.15 to 0.3, 0.45 to 0.6, and 0.75 to 0.9 m and analyzed for nitrate, atrazine, alachlor, metribuzin, and gravimetric soil water content at the National Soil Tilth Laboratory in Ames, Iowa.

Two automatic Campbell weather stations collected climatic data. One station was located adjacent to the plot area, and the other station was located to the southwest of the leased area. The weather stations recorded required by a label change. Alachlor was applied at the rate of 2.8 kg a.i. ha⁻¹ each year.

The management systems were established on 0.4-ha plots, which were replicated three times in a randomized complete block arrangement. Above-ground plant biomass measurements were obtained 6 to 10 times throughout the growing season from three, 1-m strips of row. The corn was separated into leaf, stem, and seeds, oven-dried at 40°C overnight, then weighed. Phenology data were collected weekly by observing the plots and recording the stage displayed in at least 50% of the plants. The stages used for classification are defined in table 2 and are from the IBSNAT data standardization system for crop growth models (Beinroth et al., 1986; J. W. Jones, personal communication, 1991). Yields were determined by weighing the grain removed from each plot, and recording the water content of the grain at the time of weighing. All yields were adjusted to 15.5% water content for corn, and 13.5% water content for soybeans and wheat.

Soil cores for chemical analysis were collected from each of the plots. The cores were collected biweekly during the growing season and monthly during the nongrowing season. Undisturbed soil cores with a diameter of 9 mm were encased in an acetate liner which extended from the soil surface to a depth of 0.9 m. In 1991 the cores were collected from between the corn rows, and in 1992 and 1993 the cores were collected from within the crop row. The cores were sectioned into segments corresponding to 0.0 to 0.15, 0.15 to 0.3, 0.45 to 0.6, and 0.75 to 0.9 m and analyzed for nitrate, atrazine, alachlor, metribuzin, and gravimetric soil water content at the National Soil Tilth Laboratory in Ames, Iowa.

Table 2. Crop growth and development categories used in recording phenology for the Ohio MSEA project

<table>
<thead>
<tr>
<th>Code</th>
<th>Definition</th>
<th>Code</th>
<th>Definition</th>
<th>Code</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBL1</td>
<td>1st leaf on main stem fully expanded</td>
<td>IBD1</td>
<td>Germination</td>
<td>IBS1</td>
<td>Storage organ initiation</td>
</tr>
<tr>
<td>IBL2</td>
<td>2nd leaf on main stem fully expanded</td>
<td>IBD2</td>
<td>End of the juvenile phase</td>
<td>IBS2</td>
<td>First evidence of leaf yellowing or loss of leaf area</td>
</tr>
<tr>
<td>IBL3</td>
<td>3rd leaf on main stem fully expanded</td>
<td>IBD3</td>
<td>Tassel initiation</td>
<td>IBS3</td>
<td>Obvious leaf yellowing or loss of leaf area</td>
</tr>
<tr>
<td>IBL4</td>
<td>4th leaf on main stem fully expanded</td>
<td>IBD4</td>
<td>One open tassel</td>
<td>IBS4</td>
<td>Leaves golden yellow; only 2-3 active leaves remaining</td>
</tr>
<tr>
<td>IBL5</td>
<td>5th leaf on main stem fully expanded</td>
<td>IBD4F</td>
<td>Beginning silking</td>
<td>IBS5</td>
<td>Above-ground parts dead, stalks dry</td>
</tr>
<tr>
<td>IBL6</td>
<td>6th leaf on main stem fully expanded</td>
<td>IBD5</td>
<td>Beginning to set ears</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBL(n)</td>
<td>nth leaf on main stem fully expanded</td>
<td>IBD5F</td>
<td>Beginning to set ears</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBD6</td>
<td>One fully expanded ear</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBD7</td>
<td>Ear at dough stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBD8</td>
<td>Ear at dent stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBD8D</td>
<td>Ear at dent stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBD8F</td>
<td>Ear with black layer</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IBD9</td>
<td>Harvest maturity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
precipitation, air temperature, relative humidity, solar
radiation, wind speed and direction, and soil temperature.
Weather conditions were sampled every minute, then
averaged, and recorded hourly.

**PARAMETERIZATION**

RZWQM 2.1 requires several types of parameters in the
input data files. The simplest to determine are those which
describe the site or agricultural management system, such
as the area of the field, the number of soil horizons, and the
rate of chemical application. These are known with a
reasonable degree of accuracy and were not involved in the
calibration process.

Another type of input needed for RZWQM is a
measurable parameter which is specific to a geographic
location (site-specific) such as the bulk density of the soil.
These parameters were measured at the Ohio MSEA site
and were assumed to be correct and were not changed in
the parameterization process. The soil profile depth used
was 140 cm. Actual on-site measurements for bulk density,
soil texture, field capacity, and saturated hydraulic
capacity were used. The soil physical properties used
in the simulations are shown in Table 3. Estimates of the
initial surface residue cover and soil incorporated residue
were determined from previous end-of-season biomass
measurements.

RZWQM requires estimates of the fast, medium, and
slow soil organic carbon pools. The fast and medium
fractions were obtained using the C:N ratio and estimates
of potentially mineralizable nitrogen (PMN). PMN values
were obtained from the GLEAMS nitrogen database
(Knisel et al., 1993) and labile N measurements from
autoclaved soil samples removed from unfertilized on-site
areas in 1993. The slow organic carbon pool was
determined as the difference between the measured on-site
total soil organic carbon measurements, and the fast and
medium pool estimates (Ferguson et al., 1991; Saint-
Fort et al., 1990).

Some parameters in RZWQM are empirical coefficients
which are not easily measured nor are they available in the
literature. These parameters need to be calibrated or fit to
observed data. Parameters of this type can be further
categorized as those parameters which are site-specific and
those which are not (regional parameters). The RZWQM
development team parameterized the regional parameters
including parameters to describe the growth of field corn
using data sets from each of the five MSEA sites. Some of
the regional parameters include the stem diameter and stem
height of the mature plant cylinder, stem biomass at which
height is 1/2 maximum height, stem biomass of a mature
plant, and biomass of plant at four-leaf stage. Also included
in the regional parameterization are plant nitrogen
management and nitrogen content limits, carbon
conversions, and photosynthesis constants (DeCoursey,
1992). The results reported in this article were obtained
using default regional parameters developed during this
project for field corn, and adjusting the site specific
parameters.

The obvious problem when attempting to calibrate a
complex model like RZWQM is that each process depends
on the proper prediction of other processes. For example,
plant growth predictions depend on the nutrient and
hydrology submodels performing correctly. The calibration
procedure used was iterative, first focusing on the
hydrology submodel, then the nitrogen, plant, and
phenology submodels. One parameter was adjusted at a
time, and the predictions were visually compared to
observed values. Using our knowledge of the system
dynamics (for example, if leaf area index is too low, then
evapotranspiration will be low, and the soil water content
will be too high) educated guesses were used to select the
parameter to be adjusted. During the first phase of the
parameterization procedure the plants were assumed to
have adequate nitrogen, and the nitrogen stress prediction
algorithm was bypassed. In the second phase of the
calibration process, the nitrogen stress prediction algorithm
was operational, and predicted nitrogen stress was allowed
to occur if the model determined that field conditions were
favorable for nitrogen deficits.

The adjusted parameters are shown in Table 4. The dry
and wet soil albedo parameters affect evaporation
predictions, which in turn affect predictions of water stress
(eqs. 4, 3, and 1). Water stress predictions are assimilated
into the environmental fitness factor (eq. 1), which affects
plant growth and development (eqs. 5 and 6).

The minimum time to a certain growth stage parameters
shown in Table 4 are phenology parameters (DEVRAIj in
eq. 5), and these were adjusted to shift the growth stage.
CARBO is the biomass of a plant with leaf area index of 1
and was set to 9.0. The minimum root:shoot ratio was set to
0.3, and the leaf:shoot ratio was adjusted to 0.8. The
CARBO, root:shoot, and leaf:shoot parameters change the
slope of the biomass curves, and are used in carbon
partitioning. The maximum N uptake is used to compute
the active N uptake rate through a Michaelis-Menten rate
equation (Shuler and Kargi, 1992).

**EVALUATION**

Once the parameter set was determined for the 1992
data, no other changes were made to the parameter set
during the evaluation simulations. Weather data input files
for 1991 and 1993 were used in the simulations, and the

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>Sand Fraction</th>
<th>Silt Fraction</th>
<th>Clay Fraction</th>
<th>Bulk Density (g cm⁻³)</th>
<th>Organic Matter Content (%)</th>
<th>Field Capacity (cm³ cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-25</td>
<td>0.2</td>
<td>0.55</td>
<td>0.24</td>
<td>1.43</td>
<td>1.58</td>
<td>0.34</td>
</tr>
<tr>
<td>25-50</td>
<td>0.2</td>
<td>0.56</td>
<td>0.25</td>
<td>1.53</td>
<td>1.37</td>
<td>0.28</td>
</tr>
<tr>
<td>50-75</td>
<td>0.6</td>
<td>0.26</td>
<td>0.13</td>
<td>1.63</td>
<td>0.92</td>
<td>0.19</td>
</tr>
<tr>
<td>75-140</td>
<td>0.6</td>
<td>0.26</td>
<td>0.13</td>
<td>1.63</td>
<td>0.33</td>
<td>0.19</td>
</tr>
</tbody>
</table>

* The soil type was Huntington.
Figure 1—Predicted and observed soil water content for 0 to 15 cm (left column) and 45 to 60 cm (right column) depths for 1991, 1992, and 1993 at Piketon, Ohio. The 1992 data were used in calibration; 1991 and 1993 were used for evaluation.

Figure 2—Predicted and observed soil nitrate concentrations for 0 to 15 cm (left column) and 45 to 60 cm (right column) depths for 1991, 1992, and 1993 at Piketon, Ohio. The 1992 data were used for calibration; 1991 and 1993 were used for evaluation.
season, even though leaf biomass predictions were fairly good in September and October. Seed biomass predictions were reasonable at the end of the season, but it is noteworthy that the predicted curve is lagging the observed data, especially when predicted soil water and leaf biomass were well above the observed data early in the season. The observed early seed formation may be the result of water deficit stress-induced maturation (Hodges, 1991) that the model did not predict because of the adequate soil water that was predicted. The 1991 observed phenology data can be interpreted as exhibiting signs of an early mild stress which potentially caused early maturation. The model predicted the plant would reach the fourth leaf stage seven days earlier than the corn actually did. The model also predicted the corn would silk six days later than the observed silking date, although the differences in time predictions are within the variation seen in the field.

Predicted nitrate concentrations for 1991 were low after the anhydrous ammonia application (mid-June) for the 0 to 15 cm depth. This reflects the field sampling technique. In 1991, the starter fertilizer was broadcast with the herbicides. A soil core taken between corn rows would have similar nitrate concentrations as cores taken within the row before sidedressing of nitrogen occurred. Anhydrous ammonia was injected between the rows in

<table>
<thead>
<tr>
<th>Year</th>
<th>IBL4 – Fourth Leaf Stage</th>
<th>IBD4F – Silking</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>Observed 6/20/91</td>
<td>Predicted 6/13/91</td>
</tr>
<tr>
<td>1992</td>
<td>Observed 6/10/92</td>
<td>Predicted 6/12/92</td>
</tr>
<tr>
<td>1993</td>
<td>Observed 6/5/93</td>
<td>Predicted 6/12/93</td>
</tr>
</tbody>
</table>

Table 6. Root mean square errors between predicted and observed data from figures 1, 2, and 3

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil water content</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-15 cm depth (%)</td>
<td>6.8</td>
<td>4.5</td>
<td>4.7</td>
</tr>
<tr>
<td>45-60 cm depth (%)</td>
<td>4.2</td>
<td>5.1</td>
<td>4.7</td>
</tr>
<tr>
<td>NO₃-N (ppm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-15 cm depth (ppm)</td>
<td>24.8</td>
<td>2.2</td>
<td>3.4</td>
</tr>
<tr>
<td>45-60 cm depth (ppm)</td>
<td>2.9</td>
<td>2.3</td>
<td>6.2</td>
</tr>
<tr>
<td>Biomass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaf (g plant⁻¹)</td>
<td>17.7</td>
<td>13.3</td>
<td>9.0</td>
</tr>
<tr>
<td>Stem (g plant⁻¹)</td>
<td>17.8</td>
<td>36.8</td>
<td>21.7</td>
</tr>
<tr>
<td>Seed (g plant⁻¹)</td>
<td>49.1</td>
<td>17.6</td>
<td>17.3</td>
</tr>
</tbody>
</table>
mid-June. Soil samples taken between the rows resulted in NO$_3$-N levels that were much higher than expected within the row. The model simulated within the row conditions, but the observed data were collected between the rows. In 1992 and 1993 soil cores were taken from within the row, thereby eliminating this problem.

Predicted soil water content is within one standard deviation for most of the 1993 season for the 0 to 15 cm soil depth, except for the July and August sample. Interestingly, the biomass was overpredicted for July and August, so one would expect the soil water content to be underpredicted during that period. The 45 to 60 cm depth soil water content was predicted well through harvest (27 October 1993). Simulated leaf biomass was better in 1993 than the other two years, however, stem biomass was not predicted well. Seed biomass was predicted well in all experiments. The good leaf and seed predictions in 1993 may reflect the good NO$_3$-N predictions. The model predicted the fourth leaf stage a week after it occurred, and the silking stage about three days after it occurred. The difficulty of pinpointing the dates of phenological events in the field precludes much comment on a difference of a week. Typically plants within the same field may exhibit at least a week's difference in development.

Probably the most widely accepted measure of a crop growth model's value is its ability to predict the final yield. Table 7 presents the predicted versus observed end of season seed mass for all three years. The model overpredicted final yield by 8.0, 6.3, and 10.8% for 1991, 1992, and 1993, respectively.

**SUMMARY AND CONCLUSIONS**

The RZWQM was parameterized for 1992 data for field corn in Ohio, and evaluated for two other years at the same site. The model predictions were reasonable, however, less consistent than desired. The least well-simulated output variable that we examined was stem biomass. Several more years and geographic locations should be used to evaluate RZWQM field corn simulation to gain confidence in the model's ability to simulate diverse conditions. Yield predictions were in error 8.6, 3.3, and 10.8% for the three years investigated. From this investigation it has been shown that RZWQM is capable of being calibrated to a particular site, then adequately predicting corn growth, soil water content, and nitrate concentrations in the 0 to 15 cm soil layer for other years.

**REFERENCES**


**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHA</td>
<td>albedo – proportion of sunlight reflected (proportion)</td>
</tr>
<tr>
<td>BETA</td>
<td>light-use efficiency coefficient (mol C J$^{-1}$)</td>
</tr>
<tr>
<td>BIOPLT</td>
<td>photosynthate respired for plant maintenance (proportion)</td>
</tr>
<tr>
<td>CARBO</td>
<td>plant biomass (grams C plant$^{-1}$)</td>
</tr>
<tr>
<td>C</td>
<td>carbon (gram)</td>
</tr>
<tr>
<td>CARBO</td>
<td>biomass of a plant with LAI of 1 (grams C plant$^{-1}$ LAI$^{-1}$)</td>
</tr>
</tbody>
</table>

Figure 4—Monthly rainfall totals for 1991, 1992, 1993, and the 30-year historical average for Piketon, Ohio.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEVRAT&lt;sub&gt;j&lt;/sub&gt;</td>
<td>inverse of minimum time required to pass through the current phenological stage under ideal environmental conditions (days&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>dx</td>
<td>distance between roots at soil depth z (cm)</td>
</tr>
<tr>
<td>dz</td>
<td>depth increment (cm)</td>
</tr>
<tr>
<td>EFFN</td>
<td>nitrogen-use coefficient (dimensionless)</td>
</tr>
<tr>
<td>ENP</td>
<td>nitrogen fitness (dimensionless)</td>
</tr>
<tr>
<td>ETP</td>
<td>temperature fitness (dimensionless)</td>
</tr>
<tr>
<td>EVP</td>
<td>environmental fitness (dimensionless)</td>
</tr>
<tr>
<td>EWP</td>
<td>water fitness (dimensionless)</td>
</tr>
<tr>
<td>FACT&lt;sub&gt;j&lt;/sub&gt;(EVP)</td>
<td>empirical function of environmental fitness for changing rate of crop development (dimensionless)</td>
</tr>
<tr>
<td>GAMMA</td>
<td>temperature dependent respiration parameter (dimensionless)</td>
</tr>
<tr>
<td>GS</td>
<td>growth stage index (dimensionless)</td>
</tr>
<tr>
<td>h(z, t)</td>
<td>soil water pressure head (cm)</td>
</tr>
<tr>
<td>i</td>
<td>time (day)</td>
</tr>
<tr>
<td>K(θ)</td>
<td>soil hydraulic conductivity (cm h&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>LAI</td>
<td>surface area of leaves per surface area of ground (dimensionless)</td>
</tr>
<tr>
<td>Pr</td>
<td>effective water potential in the root at the soil surface (cm)</td>
</tr>
<tr>
<td>P&lt;sub&gt;res&lt;/sub&gt;</td>
<td>root resistance term (cm)</td>
</tr>
<tr>
<td>p'(&lt;i&gt;j&lt;/i&gt;+1, j)</td>
<td>probability of progressing to the next developmental class under current EVP (dimensionless)</td>
</tr>
<tr>
<td>p(&lt;i&gt;j&lt;/i&gt;+1, j)</td>
<td>probability of progressing to the next developmental class under no stress (dimensionless)</td>
</tr>
<tr>
<td>PNCA</td>
<td>net carbon assimilation rate (mol C m&lt;sup&gt;-2&lt;/sup&gt; day&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>PMAX</td>
<td>theoretical maximum net assimilation rate (mol C m&lt;sup&gt;-2&lt;/sup&gt; day&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>RAD</td>
<td>solar radiation incident at the top of the canopy (W m&lt;sup&gt;-2&lt;/sup&gt;)</td>
</tr>
<tr>
<td>RDF(z)</td>
<td>proportion or roots active in the depth increment (dimensionless)</td>
</tr>
<tr>
<td>s(z, t)</td>
<td>osmotic potential (cm)</td>
</tr>
<tr>
<td>SPCTN</td>
<td>difference between current % leaf N and the lower limit of % leaf N (%)</td>
</tr>
<tr>
<td>t</td>
<td>time (variable)</td>
</tr>
<tr>
<td>Tr</td>
<td>actual water uptake (cm day&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Ta</td>
<td>transpiration demand (cm day&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>WRESP</td>
<td>whole plant respiration (mol C m&lt;sup&gt;-2&lt;/sup&gt; day&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>z&lt;sub&gt;0&lt;/sub&gt;</td>
<td>total root zone depth (cm)</td>
</tr>
</tbody>
</table>