



CropSyst, a Cropping Systems Simulation Model: Water/Nitrogen Budgets and Crop Yield*

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ABSTRACT

In agriculture, water and nitrogen are two critical resources for growing a crop. However, their management cannot be analyzed independently of weather, soil characteristics, field hydrology, crop characteristics, crop rotation, and management factors. This paper describes the water, nitrogen, and crop growth components of CropSyst, a comprehensive cropping systems simulation model, and provides preliminary verification of these components. The water budget of the model properly describes crop water use. Predicted nitrogen contents throughout the soil profile did not exactly match the measured values from leaching experiments, but they did follow the general trends of the data. The agreement between simulated and observed biomass and yield of corn, winter wheat and spring wheat grown in two locations with a total of 77 data points was good as shown by several statistical indicators. Based on this preliminary validation, CropSyst appears promising as a tool to analyze management practices for water and nitrogen. Additional validation of model components, including a wide range of crops and conditions, should be conducted in the future.

INTRODUCTION

In order to develop best management practices (BMPs), water and nitrogen management cannot be analyzed independently of weather, soil

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characteristics, field hydrology, crop characteristics, crop rotation, residue levels, crop management and other factors of the complex soil-plant-atmosphere system. Thus, it is useful to integrate these factors into a comprehensive cropping systems approach. A successful method of evaluating BMPs should provide information regarding the ability of given management practices to increase productivity while minimizing the environmental impact.

Cropping systems models, which are able to simulate many possible scenarios from only a few experiments for calibration, appear to be a cost effective approach for evaluating BMPs. Once developed, many simulations could be performed to determine appropriate water and nitrogen management. The work reported here is part of a larger effort aimed at developing CropSyst (Stockle *et al.*, 1991, 1993; Campbell & Stockle, 1992), a daily time step, multiyear, multicrop simulation model designed to predict crop growth and development, crop yield, daily residue loss, nitrogen leaching, and erosion in response to soil conditions, weather, and management (irrigation, fertilization, residue, and tillage).

Although many models for single crops are available, comprehensive, management-oriented cropping systems models are virtually non-existent. One example is the Erosion-Productivity Impact Calculator, EPIC (Sharpley & Williams, 1990), which was originally developed for erosion prediction but has also been applied for the analysis of cropping systems (e.g. Stockle *et al.*, 1992). CropSyst was developed with a focus on crop processes and has fundamental differences with the approach adopted by EPIC. The water budget in CropSyst presents distinctive features which are not found in other management-oriented crop models. This paper describes the water, nitrogen and crop growth components of CropSyst and provides preliminary validation of these components, particularly regarding predictions of crop growth responses to water and nitrogen availability.

A simple flow diagram of CropSyst is presented in Fig. 1. Three essential components of the model are the water balance, the nitrogen balance, and crop growth. These components are described in detail in following sections. Other components of CropSyst include calculation of soil erosion and residue accumulation and decomposition. Details of these components, and details on the use, parameterization, and execution of the model are given in the model user's manual (Stockle *et al.*, 1993).

MODELING THE WATER BUDGET

The water budget in CropSyst includes irrigation and precipitation, interception and runoff, infiltration and redistribution, potential and actual evaporation, and water uptake. The amount and dates of irrigation and

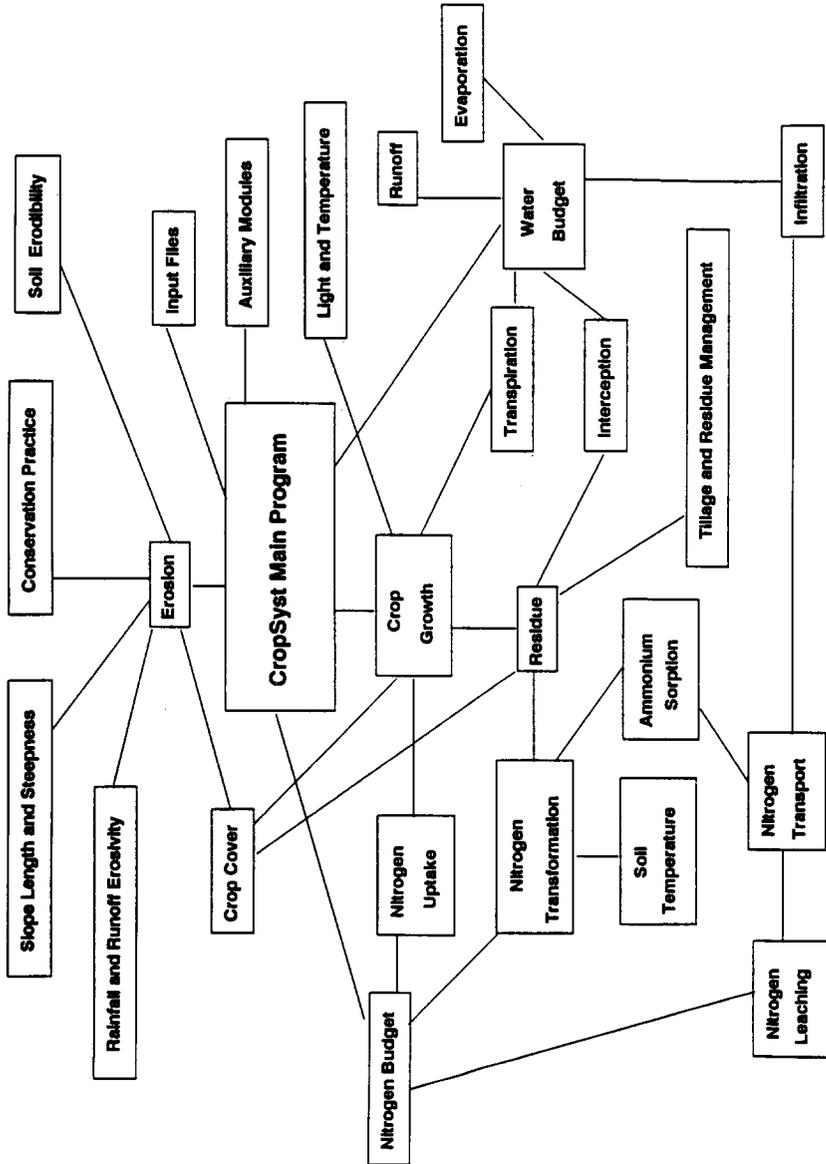


Fig. 1. Flow diagram of CropSyst.

precipitation are assigned in input files. Other components of the water budget are calculated as follows.

Interception

A fraction of the precipitation that falls on the crop is intercepted by and evaporated from the canopy. Another fraction is intercepted by surface residues. The remainder of the water reaches the soil. Canopy interception is modeled following Campbell & Diaz (1988), who proposed that the fractional interception of precipitation by the canopy is the same as the fractional interception of radiation ($FRACTCOVER_{canopy}$), to be discussed later. This is multiplied by the storage capacity of the canopy, assumed to be 1 mm, to determine total canopy interception. This intercepted water is evaporated the same day of the rainfall. Interception by surface residues is a function of the residue mass, the current water content, and the maximum water holding capacity of the residue (assumed to be 4 kg H₂O kg⁻¹ residue). When precipitation occurs, and after canopy interception is subtracted, the residue layer is filled to its maximum water content and then passes the water on to the soil layers. Residue evaporation proceeds at the potential residue evaporation rate, unless limited by residue water content.

Runoff, infiltration and redistribution

Runoff, after a precipitation event, is calculated using the USDA-SCS curve number approach (USDA-ARS, 1972). The remaining water after interception and runoff is assumed to infiltrate into the soil. The water redistribution in the soil profile is calculated using a cascading approach, where each soil layer is filled to field capacity before water flows into the next layer. The field capacity, initial water content, and the depth of water reaching the current layer determines if the water front moves to the next layer.

Crop potential evapotranspiration

CropSyst calculates crop potential evapotranspiration (ET_{cp}) based on the Priestley-Taylor equation (Priestley & Taylor, 1972):

$$ET_{cp} = \frac{K_c \alpha s RAD_{net}}{(\gamma + s)\lambda} \quad (1)$$

where ET_{cp} is crop potential evapotranspiration (kg m⁻² day⁻¹), K_c is a full-canopy cover crop coefficient, α is the Priestley-Taylor constant, λ is

the latent heat of vaporization (MJ kg^{-1}), λ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), s is the slope of the saturation vapor pressure function ($\text{kPa } ^\circ\text{C}^{-1}$), and RAD_{net} is the isothermal net radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$). The values of s , γ and λ are functions of temperature and/or pressure. Equations for these are given by Jensen *et al.* (1990).

RAD_{net} is:

$$RAD_{net} = (1 - ALBEDO) SOLAR - LN_i \quad (2)$$

where $ALBEDO$ is the albedo of the crop or the soil surface, $SOLAR$ is the solar radiation, ($\text{MJ m}^{-2} \text{ day}^{-1}$), and LN_i is the isothermal long-wave net radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$).

If solar radiation data is not available, CropSyst estimates solar radiation from temperature data:

$$SOLAR = (TRANSMIT) RAD_{pot} \quad (3)$$

where $TRANSMIT$ is the daily average atmospheric transmissivity, and RAD_{pot} is the estimated daily potential solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$).

The atmospheric transmissivity is given by Bristow & Campbell (1984) as:

$$TRANSMIT = A[1 - \exp(-B \Delta T^C)] \quad (4)$$

where A , B and C are empirical constants, derived from measured solar radiation data and ΔT is the range in daily temperature ($T_{max} - T_{min}$), with T_{min} taken as the average of the current and previous day minimum temperature. Typical values are $A = 0.7-0.8$ (clear sky transmission coefficient), $B = 0.006-0.014$ depending on location, and $C = 2$. The potential solar radiation is calculated as suggested by Campbell & Diaz (1988).

The isothermal long-wave net radiation is given by (Campbell & Stockle, in press):

$$LN_i = [1.0 - 1/(1 + 0.034 e^{(7.9 * TRANSMIT)})](0.026 T_{avg} - 9.2) \quad (5)$$

Another available option to determine potential evapotranspiration is based on the use of the Penman-Monteith equation. The implementation of this option follows the procedure outlined by Jensen *et al.* (1990).

The CropSyst water budget and determination of crop growth require separate estimates of crop potential transpiration (PT) and potential soil evaporation (PE). This is calculated as a function of the fraction of incident radiation intercepted by the canopy ($FRACTCOVER_{CANOPY}$) (Stockle & Campbell, 1985):

$$PT = ET_{cp} FRACTCOVER_{canopy} \quad (6)$$

$$PE = ET_{cp}(1 - FRACTCOVER_{canopy}) \quad (7)$$

where $FRACTCOVER_{CANOPY}$ is an exponential function of leaf area index (LAI):

$$FRACTCOVER_{CANOPY} = 1 - EXP(-K LAI) \quad (8)$$

Actual crop transpiration (crop water uptake)

In CropSyst, crop water uptake and actual crop transpiration are considered equal, i.e. crop water storage is assumed negligible. For calculation of crop water uptake, the soil profile is divided into layers, and the water uptake from each layer is calculated from the water potential difference between the soil and the plant xylem, multiplied by plant conductance (mainly determined by root conductance). The soil conductance is assumed to be large compared to root conductance so that water uptake is not limited by water movement toward the roots. The water uptake from each soil layer is given by:

$$U_{wi} = KC_i(\psi_{si} - \psi_x) \quad (9)$$

where U_{wi} is the layer water uptake ($\text{kg m}^{-2} \text{ day}^{-1}$), ψ_{si} and ψ_x are, respectively, soil layer and xylem water potential (J kg^{-1}) or ($\text{m}^2 \text{ s}^{-2}$), C_i is root conductance for layer i (kg s m^{-4}), and K is a unit conversion constant (86 400). ψ_{si} is computed from the layer soil water content (θ_i) as follows:

$$\psi_{si} = a\theta_i^{-b} \quad (10)$$

where a and b are parameters obtained by simultaneous solution of eqn (10) for two points: field capacity and wilting point.

The total water uptake (U_{wt}) is equal to the sum of the uptake from each soil layer.

$$U_{wt} = \sum_{i=1}^{i=n} U_{wi} \quad (11)$$

The layer root conductance is determined from the current total root conductance (C_{Tc}) and the fraction of total root length in each layer (f_i):

$$C_i = f_i C_{Tc} \quad (12)$$

The xylem water potential is calculated from the following expression:

$$\psi_x = \overline{\psi_s} - \frac{PT}{C_{Tc}K} \quad (13)$$

where ψ_s is the average soil water potential and K is a unit conversion constant (86 400). The value of $\overline{\psi_s}$ depends on the soil water potential and the fraction of total root length in each soil layer (Stockle & Campbell, 1985).

If ψ_x from eqn (13) is less than the xylem water potential just before the beginning of stomatal closure ($\psi_{x,sc}$), then ψ_x is recalculated as:

$$\psi_x = \bar{\psi}_s - \frac{PT \frac{\psi_x - \psi_{x,wilt}}{\psi_{x,sc} - \psi_{x,wilt}}}{C_{Tc} K} \quad (14)$$

Because ψ_x is on both sides of eqn (14), its value is calculated by solving for ψ_x as follows:

$$\psi_x = \frac{\bar{\psi} C_{Tc} K (\psi_{x,sc} - \psi_{x,wilt}) + PT \psi_{x,wilt}}{C_{Tc} K (\psi_{x,sc} - \psi_{x,wilt}) + PT} \quad (15)$$

where $\psi_{x,wilt}$ is the plant wilting point xylem potential. If the value of ψ_x from eqn (15) is less than $\psi_{x,wilt}$ then ψ_x is set equal to $\psi_{x,wilt}$.

The value of the total root conductance (C_T) can be estimated if a maximum uptake rate (U_{wmax}) is assumed for a fully developed and unstressed crop, with unrestricted root penetration, and under environmental conditions providing large atmospheric evaporative demand. Under this set of conditions, any evaporative demand larger than the maximum uptake rate will induce stomatal closure.

$$C_T = \frac{U_{wmax}}{(\psi_{fc} - \psi_{x,sc})K} \quad (16)$$

where C_T is in kg s m^{-4} , U_{wmax} is in $\text{kg m}^{-2} \text{day}^{-1}$, K is a unit conversion constant (86400), $\psi_{fc} = -30 \text{ J kg}^{-1}$, and $\psi_{x,sc}$ is the xylem potential (J kg^{-1}) just before the beginning of stomatal closure due to water deficit. C_T corresponds to the maximum root conductance at full vegetative development. The root conductance (C_{Tc}) at any given time before reaching the maximum is calculated as:

$$C_{Tc} = C_T \text{ FRACTCOVER}_{canopy} \quad (17)$$

The fraction of total root length in each soil layer is calculated assuming a linear decrease of root length as a function of soil depth, with a maximum at the top of the soil profile and a value of zero at the tip of the current root depth (Stockle & Campbell, 1985; Campbell & Stockle, 1992).

Soil evaporation

Soil evaporation is modeled by assuming that the evaporation rate E ($\text{kg m}^{-2} \text{day}$) is equal to potential evaporation (PE) if the water content of the top 10 cm of soil (evaporative layer) is above the permanent wilting

point. Below this point, soil evaporation is equal to a fraction of PE as given by (Campbell & Diaz, 1988):

$$E = PE \left[\frac{WC - WC_d}{PWP - WC_d} \right]^2 \quad (18)$$

where WC_d is the air-dry soil water content, estimated as a third of the volumetric permanent wilting point (PWP).

MODELING THE NITROGEN BUDGET

The components of the nitrogen balance in CropSyst include nitrogen transport, nitrogen transformations, ammonium sorption, and crop nitrogen uptake.

Nitrogen transport

Nitrogen transport through the soil profile has been modeled in many different ways. Complex methods using numerical solutions such as the one described by Murali & Aylmore (1981), the SHAW model (Flerchinger, 1987), or the LEACHM model (Wagenet & Hutson, 1989) are useful in groundwater studies. However, they are not practical when used within a cropping systems model which simulates many other processes for a large number of crop rotation cycles. Simple approaches are then preferable. The method developed for CropSyst is similar to that described by Corwin *et al.* (1991). This method transports the nitrogen in the soil in one daily time step on days when water infiltrates into the soil. The approach includes a bypass coefficient (BC) to describe the fraction of water in a soil layer that does not interact with a new water input, while $(1-BC)$ represents the fraction of the soil water subject to piston-type displacement. The bypass coefficient simplistically accounts for flow through cracks and macropores that bypasses small and dead-end pores, the flow of a mobile water phase independent of an immobile phase of water, and the phenomenon of dispersion-diffusion (Corwin *et al.*, 1991).

The nitrogen concentration remaining within and leaving a layer can be calculated three ways, depending upon the initial water content and the amount of water to reach a layer. As water enters a layer, it first fills the layer to field capacity if enough water is available. Once the layer is at field capacity, the incoming water begins to replace the existing water (excluding immobile water) and the existing water is moved out of the layer. The incoming water continues to replace the existing water until all

the existing water is replaced and then the incoming water begins to move out of the layer.

If the amount of water to reach a layer is enough to fill the layer to field capacity and replace the existing mobile water, then the nitrogen concentration out of the layer is:

$$C_{out} = \frac{W_{in}C_{in} - LTH(FC - BC WC_{bi})C_{in} + (1 - BC)LTH WC_{bi} C_{bi}}{W_{out}} \quad (19)$$

and the layer nitrogen concentration after the water input event is:

$$C_{ai} = \frac{(FC - BC WC_{bi})C_{in} + BC WC_{bi} C_{bi}}{FC} \quad (20)$$

where C_{out} is the nitrogen concentration of the water leaving the layer (kg N m⁻³ of water), C_{ai} is the nitrogen concentration of the water within the layer after a water input event (kg N m⁻³ of water), C_{bi} is the nitrogen concentration of the water within the layer before a water input event (kg N m⁻³ of water), C_{in} is the nitrogen concentration of the water that enters the layer (kg N m⁻³ water), BC is the bypass coefficient (dimensionless, ranging from 0 to 1), LTH is the layer thickness (m), WC_{bi} is the volumetric water content before water input (m³ m⁻³), FC is the volumetric field capacity (m³ m⁻³), W_{in} is the water depth entering the layer (m) or m³ water m⁻² soil), and W_{out} is the water depth leaving the layer (m or m³ water m⁻² soil).

If the amount of water to reach a layer is not enough to completely replace the existing mobile water but is greater than the amount required to fill the layer to field capacity, then

$$C_{out} = C_{bi} \quad (21)$$

$$C_{ai} = \frac{(LTH FC - W_{in})C_{bi} + W_{in} C_{in}}{LTH FC} \quad (22)$$

If the amount of water to reach a layer is less than the amount required to fill the layer to field capacity, then

$$C_{out} = 0 \quad (23)$$

$$C_{ai} = \frac{LTH WC_{bi} C_{bi} + W_{in} C_{in}}{LTH WC_{bi} + W_{in}} \quad (24)$$

Nitrogen transformations

The nitrogen transformations developed for CropSyst include net mineralization, nitrification and denitrification, which are simulated using first

order kinetics (Stockle & Campbell, 1989) and are assumed to occur in the top 30–50 cm of the soil profile. Because these transformations are temperature-dependent, soil temperature simulation is included in the model using a method similar to that proposed by Sharpley & Williams (1990). Stockle & Campbell (1989) give details on the nitrogen transformation model.

Ammonium sorption

Ammonium in the soil is either sorbed to the soil solid phase or in solution in the soil water. A Langmuir relationship is used to relate ammonium in solution and ammonium in the soil matrix. Further details for ammonium sorption simulation are presented elsewhere (Stockle & Campbell, 1989).

Crop nitrogen uptake

Crop nitrogen uptake was modeled by modifying the approach of Godwin & Jones (1991). Crop nitrogen uptake is determined as the minimum of crop nitrogen demand and potential nitrogen uptake. Crop nitrogen demand is the amount of nitrogen the crop needs to meet its potential growth, as limited by light, temperature and water, plus its deficiency demand. The deficiency demand is the difference between the crop maximum and actual nitrogen concentration before new growth.

$$ND = (NC_{max} - NCONC_b)(TM + RM) + NC_{max}(PRG + PTG) \quad (25)$$

where ND is the crop nitrogen demand (kg ha^{-1}), NC_{max} is the crop maximum nitrogen concentration (kg N kg^{-1} biomass), $NCONC_b$ is the crop nitrogen concentration before new growth (kg ha^{-1}), TM is the cumulative top biomass (kg ha^{-1}), RM is the cumulative root biomass (kg ha^{-1}), PRG is the potential new root growth (kg ha^{-1}), and PTG is the potential new top growth (kg ha^{-1}). The first term on the right-hand side of eqn (25) represents the deficiency demand, and the second term represents the nitrogen demand for new growth.

The potential nitrogen uptake is calculated for each soil layer and summed for the soil profile. For each layer, it is calculated as follows:

$$N_{upt} = U_{max} RL N_{avail} SWF^2 \quad (26)$$

where N_{upt} is the potential nitrogen uptake ($\text{kg N ha}^{-1} \text{ day}^{-1}$), U_{max} is the maximum nitrogen uptake per unit length of root ($\text{kg N day}^{-1} \text{ m}^{-1}$), RL is the root length (m ha^{-1}), N_{avail} is a nitrogen availability factor (dimensionless, 0–1), and SWF is a soil water availability factor (dimensionless,

0–1). The functional form of these availability factors is given by Godwin & Jones (1991).

Crop growth

Crop growth is modeled to depend on three factors: transpiration (water-limited), carbon fixation (radiation-limited), and nitrogen uptake (nitrogen-limited). Each one of these factors is capable of limiting growth.

Water-limited growth (G_w) follows the approach suggested by Tanner & Sinclair (1983):

$$G_w = \frac{T_{act} BT}{VPD} \quad (27)$$

where G_w is in $\text{kg m}^{-2} \text{day}^{-1}$, T_{act} is actual transpiration ($\text{kg m}^{-2} \text{day}^{-1}$), BT is the above-ground biomass/water transpired ratio ($\text{kg biomass kPa kg}^{-1} \text{water}$), and VPD is the daytime mean vapor pressure deficit (kPa).

Radiation-limited growth (G_R) is calculated following Monteith (1977):

$$G_R = e(SOLAR) FRACTCOVER_{canopy} T_{lim} \quad (28)$$

where G_R is in ($\text{kg m}^{-2} \text{day}^{-1}$, e is the radiation conversion to above-ground biomass (kg MJ^{-1}), $SOLAR$ is total solar irradiance above the crop canopy ($\text{MJ m}^{-2} \text{day}^{-1}$), $FRACTCOVER_{canopy}$ is the fraction of incident radiation intercepted by the canopy, and T_{lim} is a temperature limitation factor which may be applied when air temperature is near the base temperature. It is assumed that the core of the temperature response during active growth is accounted for by the empirically derived radiation conversion to above ground biomass parameter. T_{lim} increases linearly (from 0 to 1), with a minimum at air temperature equal to base temperature and a maximum at and above a specified optimum temperature for growth threshold.

The values of G_R and G_w are compared, and the minimum is used as potential new growth (PNG) to determine nitrogen-dependent growth. The nitrogen-dependent growth is a function of PNG , the critical and minimum crop nitrogen concentrations, and the crop nitrogen concentration expected after growth:

$$G_N = PNG \left(1 - \frac{NC_{crit} - NCONC_a}{NC_{crit} - NC_{min}} \right) \quad (29)$$

where G_N is the nitrogen-dependent growth ($\text{kg m}^{-2} \text{day}^{-1}$), PNG is potential growth after other limiting factors have been accounted for ($\text{kg m}^{-2} \text{day}^{-1}$), $NCONC_a$ is the crop nitrogen concentration after new growth (kg kg^{-1}), NC_{crit} is the critical nitrogen concentration required by the crop to

grow at potential rate (kg kg^{-1}), and NC_{min} is the crop minimum nitrogen concentration at which growth stops (kg kg^{-1}).

The crop nitrogen concentration after new growth is equal to the ratio of cumulative nitrogen uptake to total crop biomass (including new growth):

$$NCONC_a = \frac{CNU}{TM + RM + PNG \left(1 - \frac{NC_{crit} - NCONC_a}{NC_{crit} - NC_{min}}\right)} \quad (30)$$

where CNU is cumulative nitrogen uptake (kg m^{-2}), TM and RM are top and root cumulative biomass (kg m^{-2}), and the third term in the denominator is the nitrogen-dependent new growth (kg m^{-2}). To solve for $NCONC_a$, eqn (30) must be arranged into a quadratic.

VALIDATION OF THE MODEL

Validation consisted of evaluating the model's ability to describe crop ET and water uptake, nitrogen transport, crop growth response to water, and crop growth response to water and nitrogen.

Water budget

As an example of the model's ability to predict components of the water budget, Fig. 2 shows a comparison of measured ET for corn grown in a lysimeter at Davis, California and predicted ET using the Priestley-Taylor equation (Eqn (1)). In addition, Fig. 3 shows a comparison of measured and simulated water distribution in the soil profile at three times during the growing season for a spring wheat crop at Davenport, Washington State. These results show the model performing satisfactorily,

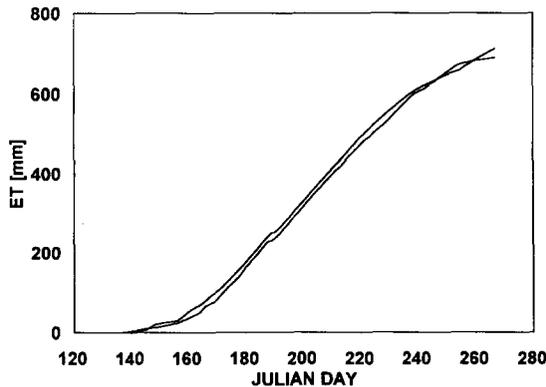


Fig. 2. Comparison of predicted evapotranspiration (ET) versus observed ET determined with a lysimeter at Davis, California, 1974.

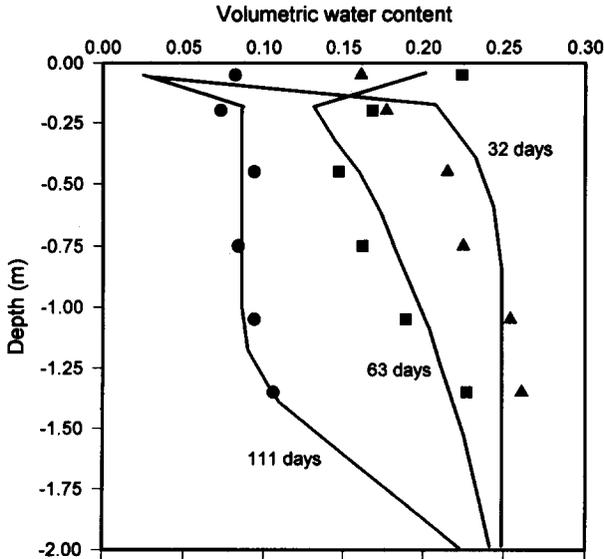


Fig. 3. Predicted (lines) and observed (symbols) soil water distribution on days 32, 63 and 111 after sowing. The crop is spring wheat grown at Davenport, Washington State, 1983.

with the agreement between measurement and predictions being adequate for most applications.

Crop water use predictions were tested for crop rotations without reinitializing the model. Figure 4 shows predicted and observed crop seasonal water use for 12 crop-years within 6-year crop rotation and management

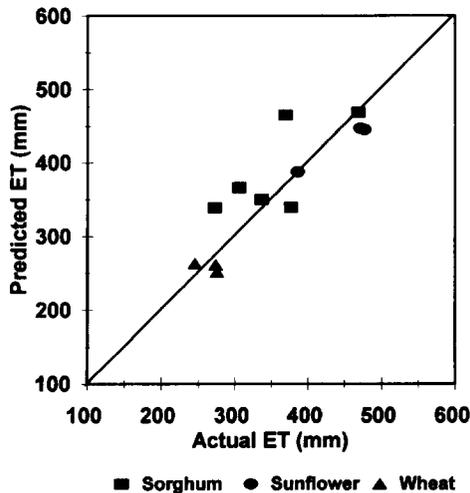


Fig. 4. Predicted and observed evapotranspiration (ET) for 12 crop-years in 6-year long crop rotation experiments at Foggia, Italy (Rizzo *et al.*, 1990).

experiments at Foggia, Italy (Rizzo *et al.*, 1990), for which gravimetric soil moisture measurements were available. Half of the simulation years were run on predicted radiation. Considering the uncertainty associated with the measurements, the interaction between the prediction of crop growth and water use (i.e. water use cannot be properly predicted if crop growth is not represented adequately and vice versa), the agreement between predicted and observed crop water use appears reasonable.

Nitrogen transport

Field experimental data from two published papers were used to provide some validation of nitrogen transport predictions. It is important to consider that there is significant uncertainty associated with these kind of data. In addition, the model LEACHM was also run and compared to CropSyst. LEACHM is a mechanistic model that calculates nitrogen transport using a numerical solution to the diffusion-convection equation (Wagenet & Hutson, 1989).

The first data set was found in a paper by Kanwar *et al.* (1985), which included nitrate content within the soil profile for a moldboard plowed plot with nitrogen incorporated into the soil. The experiment was conducted over 2 days with two simulated rains in each day of 12.7 (Fig. 5(a)) and 6.4 cm (Fig. 5(b)), respectively. Nitrate distributions by soil depth produced by the two models (CropSyst and LEACHM) were similar. Neither model predicted as much movement as shown by the data. This type of experiment, with large inputs of water over short time periods, results in maximum bypass flow, whereas natural rain may not produce such rapid transport.

The second data set used (Cassel, 1971) included chloride concentrations within the soil profile for plots covered with a tarp to eliminate evaporation. The experiment was conducted over a continuous period of 64 days, during which seven irrigations were applied. Because nitrogen concentrations reported could not be converted from soil solution to total soil concentration, comparisons were made of the shapes of the chloride distribution in the soil profile. No chloride content measurements in the upper 30 cm were given. Figures 6(a), 6(b), and 6(c) show observed and predicted chloride distributions in the soil profile after 10.2, 22.4, and 38.9 cm of applied water. LEACHM matched the data better than the simple transport model included in CropSyst. The general shape of the graphs of LEACHM more closely follow the data, but overall CropSyst and LEACHM were fairly close, and as in the first data set, the peaks and valleys of nitrogen content occurred at the same depths.

Prediction of solute movement under field conditions is not an easy

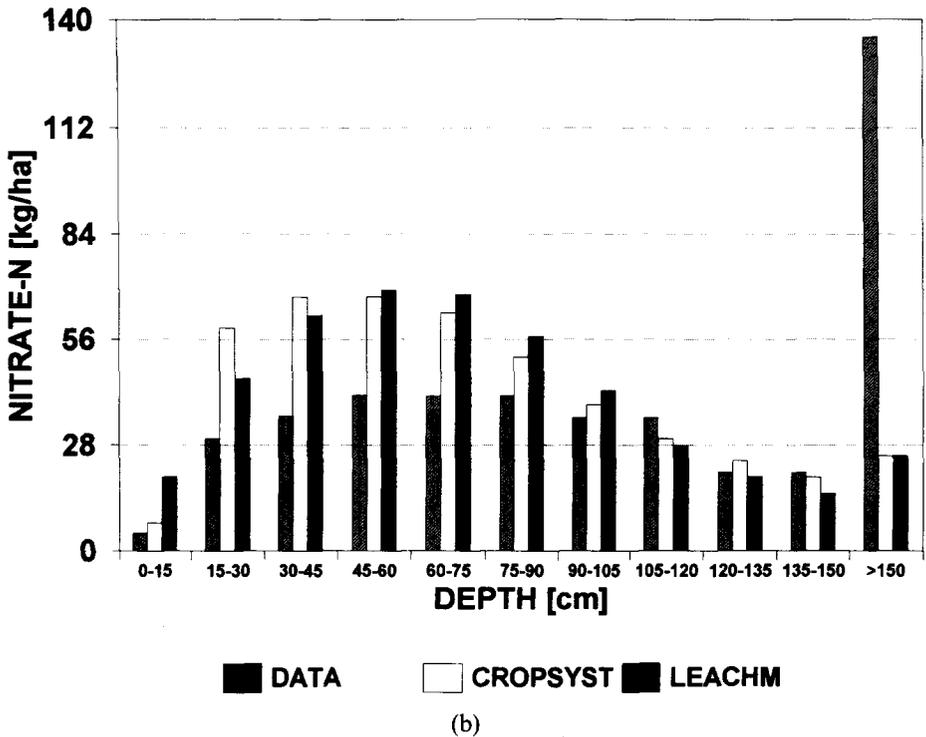
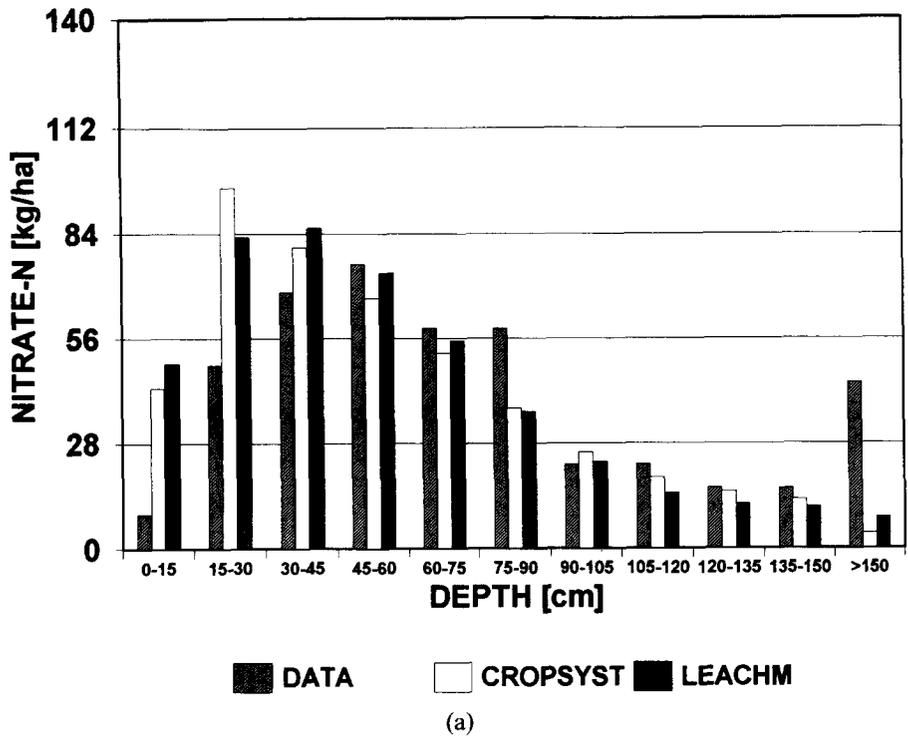
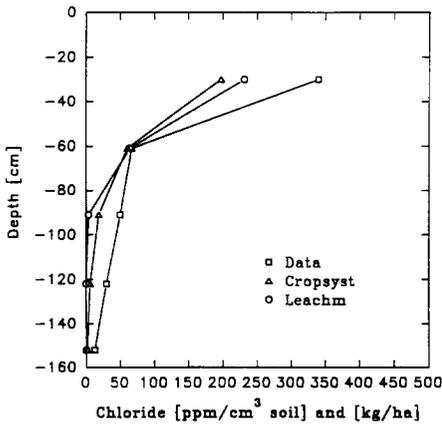
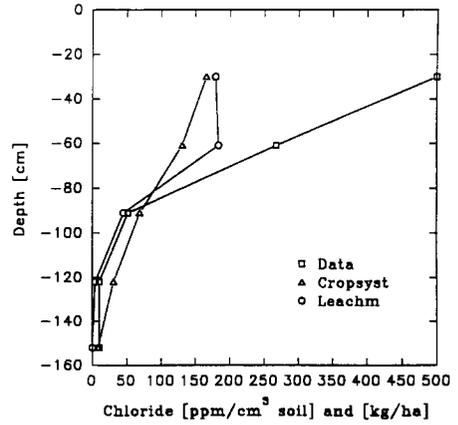


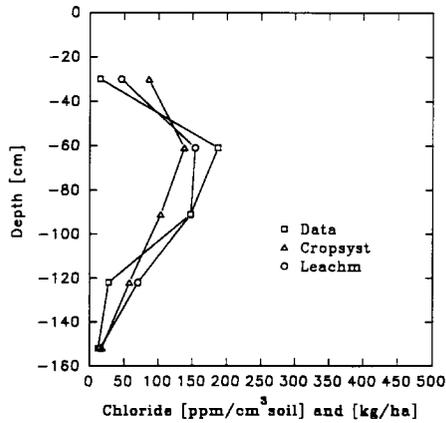
Fig. 5. Predicted and observed nitrate-N distribution (a) after 12.7 cm of water applied and (b) after 19 cm of water applied. Data is from Kanwar *et al.* (1985).



(a)



(b)



(c)

Fig. 6. Predicted and observed chloride distribution (a) after 10.2 cm of water applied, (b) after 22.4 cm of water applied, and (c) after 38.9 cm of water applied. Data is from Cassel (1971).

task. Variability of soil properties and experimental difficulties in measuring the solute concentration are elements of uncertainty. Mechanisms other than those included in conventional diffusion-convection equations participate in the transport process, which are difficult to define and account for in models. Additional testing of the nitrogen transport in CropSyst is needed.

Grain yield and above-ground biomass response to water

Validation of above-ground biomass and grain yield responses to water management was done for corn, winter wheat and spring wheat. All

experiments used a line source sprinkler system to apply water, producing a gradient of water application from full irrigation to near dryland (Hanks *et al.*, 1974).

The corn data were from Stewart *et al.* (1977), including data from Davis, California, and Fort Collins, Colorado for the 1974 growing season. In these experiments, the growing season was divided into three growing stages: (1) vegetative period; (2) pollination period; and (3) maturation period. Water was applied during every period (III), the 2nd and 3rd period (OII), the 1st and 3rd period (IOI), or only the last period (OOI). The following subset was used for simulation: all irrigation schedules and application rates at Davis (24 total), and the III schedule for all application rates at Fort Collins (6 total).

The wheat data were from Logan, Utah, in experiments reported by Hanks *et al.* (1981). This included winter wheat grown in 1978–79 and two spring wheat cultivars (Fielder and Fremont) grown in 1979. In these experiments, there was only one irrigation schedule with six application rates. While the winter wheat data included an irrigation schedule indicating amount and date of water applications (Hubbard, 1981), the spring wheat data only had the season total amount of water applied and it was mentioned that water was applied weekly.

CropSyst crop parameters used in the validation are presented in Table 1. The calibrated parameters were adjusted, within reasonable boundaries of fluctuation, using a high and a low irrigation/yield treatments for each data set so as to obtain a good match between predicted and observed biomass, grain yield, and seasonal ET. Data points used for calibration were not included in the statistical analysis. Soil parameters including field capacity, permanent wilting point, and bulk density were set as reported for the corresponding soils.

Predicted grain yield and above-ground biomass are plotted against observed values in Figs 7(a) and 7(b) for corn, and Figs 9(a) and 9(b) for wheat. In addition, a comparison between predicted and observed seasonal ET for corn at Davis is shown in Fig. 8. The statistical analysis of predicted versus observed biomass and grain yield is presented in Table 2. For this analysis, all the corn data (corn/water) and all the wheat data (wheat/water) were pooled together. Average predicted and observed grain yield and biomass compared well. RMSE values were less than 10% of the observed average in the case of corn, and 11–14% of the observed average in the case of wheat. The values of the index of agreement, d (Willmott, 1982), were high (a value of one implies perfect agreement), particularly for wheat, while the normalized mean square error (NMSE) values (Hanna, 1988) were low (a value of zero implies perfect agreement). Generally, a model with NMSE of 0.4 or lower is

TABLE 1
Crop Parameters

<i>Parameter</i>	<i>C, Ft.</i> <i>Collins,</i> <i>1974</i>	<i>SW,</i> <i>Logan,</i> <i>1982</i>	<i>WW,</i> <i>Logan,</i> <i>1978-79</i>	<i>SW,</i> <i>Fielder</i> <i>Logan,</i> <i>1979</i>	<i>SW,</i> <i>Fremont</i> <i>Logan</i> <i>1979</i>	
Determined from data:						
Max. root depth (m)	2.9	2.1	1.30	1.50	1.30	1.20
Unstressed harvest index	0.54	0.52	0.48	0.52	0.57	0.50
GDD emergence (°C-day)	55	40	80	80	60	60
GDD flowering (°C-day)	690	670	760	1500	970	970
GDD grain filling (°C-day)	1090	870	940	1700	1170	1170
GDD maturity (°C-day)	1620	1190	1660	2500	1900	1900
Base temperature (°C)	8	8	3	0	3	3
Standard values (from manual):						
<i>LAI</i> maximum	5	5	5	4	4	4
Light to biomass conversion (g MJ ⁻¹)	4	4	3	3	3	3
Light extinction coefficient	0.45	0.45	0.45	0.45	0.45	0.45
Calibrated:						
Biomass/transpiration coefficient	8.7	8.7	6.5	5.8	4.7	4.9
ET crop coefficient	1.17	1.17	1.1	1.05	1.15	1.15
AT/PT that limits expansion	0.8	0.8	0.9	0.95	0.95	0.95
Critical xylem water potential (J kg ⁻¹)	-1100	-1100	-1150	-1150	-1150	-950
Wilting xylem water potential (J kg ⁻¹)	-1600	-1600	-2200	-2200	-2200	-1600
Max. water uptake (mm day ⁻¹)	14	14	14	14	14	11
Max. N conc. during early growth	N/A	N/A	0.047	N/A	N/A	N/A
Min. N conc. during early growth (kg kg ⁻¹)	N/A	N/A	0.024	N/A	N/A	N/A
Max. B conc. at maturity (kg kg ⁻¹)	N/A	N/A	0.025	N/A	N/A	N/A

SW = Spring wheat. Experiments in 1979 (Fielder and Fremont) corresponded to early planting.
 WW = Winter wheat.
 C = Corn.

considered good (Hanna, 1988). Figures 7-9 and the statistical analysis (Table 2) indicate a reasonable performance of the model in the prediction of biomass and grain yield under a wide range of irrigation application levels.

Grain yield and above-ground biomass response to water and nitrogen

Model validation regarding the prediction of yield response to water and nitrogen management was done for spring wheat using data from an experiment conducted at Logan, Utah (Baiden, 1983). A line source sprinkler set-up (Hanks *et al.*, 1974) was also used in this experiment. There were six water application rates ranging from 0 to 315 mm, and five nitrogen application levels ranging from 0 to 228 kg N⁻¹ ha, for a

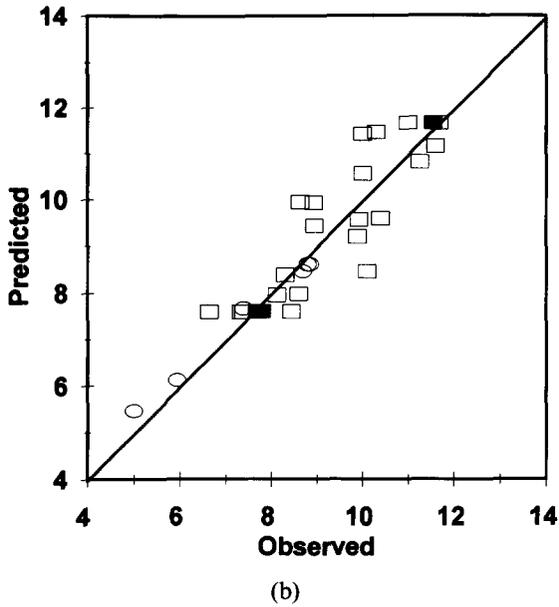
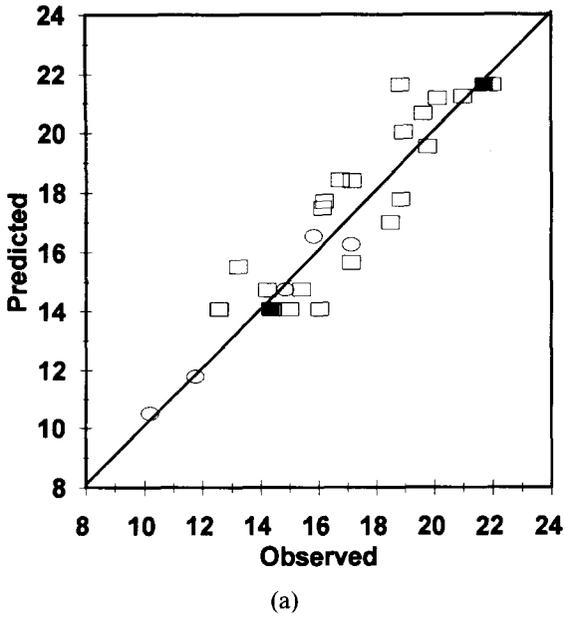


Fig. 7. Predicted and observed (a) corn biomass and (b) corn grain yield, at Davis, California (squares) and Fort Collins, Colorado (circles) in 1974. Dark symbols represent calibration points.

TABLE 2

Statistical Comparison of Predicted and Observed Values of Grain Yield (G) and Total Above Ground Biomass (B)^a

		\bar{O} (Mg ha ⁻¹)	\bar{P} (Mg ha ⁻²)	RMSE (Mg ha ⁻¹)	RMSE \bar{O}	<i>d</i>	NMSE
Corn/Water	G	8.931	9.026	0.724	0.081	0.950	0.0065
	B	16.460	16.808	1.246	0.076	0.954	0.0056
Wheat/water	G	4.1	4.261	0.443	0.108	0.979	0.0113
	B	8.033	8.460	1.121	0.140	0.961	0.0185
Wheat/Water/N	G	4.946	4.963	0.383	0.077	0.975	0.0058
	B	10.293	10.339	0.786	0.076	0.996	0.0058

^a Calibration data not included.

\bar{O} = average observed.

\bar{P} = average predicted.

RMSE = root mean square error.

d = index of agreement (Willmott, 1982).

NMSE = normalized mean square error (Hanna, 1988).

total of 30 different managements. Crop parameters used for these simulations are presented in Table 1. Calibrated parameters were adjusted using three points in the data set (no N/high water, high N/no water, high N/high water). Because initial soil nitrate concentrations were not determined, reasonable values were chosen to match measured biomass and yield for the treatment with high water content and no nitrogen. Pre-

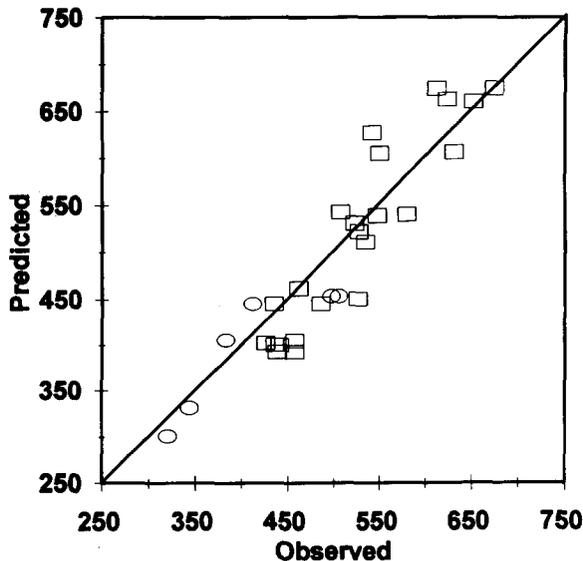


Fig. 8. Predicted and observed seasonal ET for corn at Davis, California (squares) and Fort Collins Colorado (circles) in 1974.

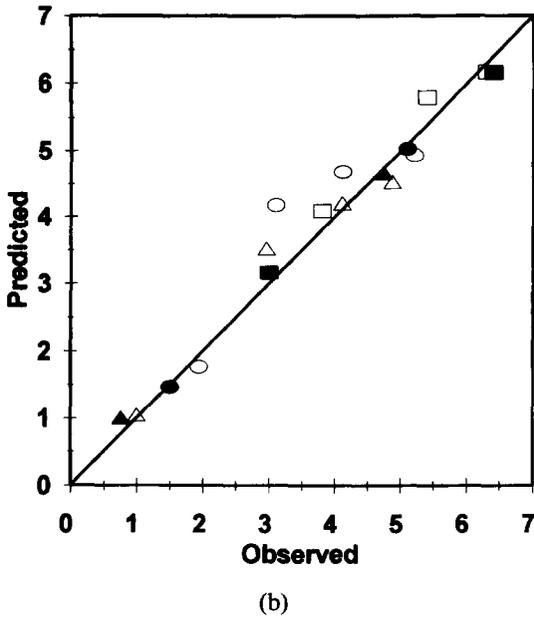
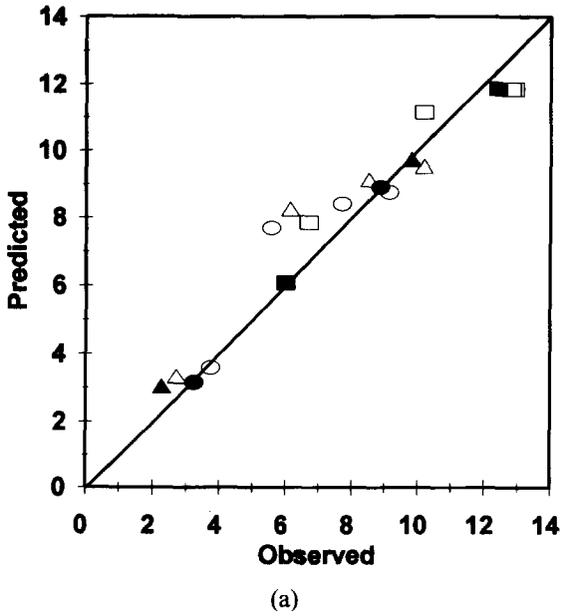


Fig. 9. Predicted and observed (a) winter and spring wheat biomass and (b) winter and spring wheat grain yield at Logan, Utah in 1979. Symbols: winter wheat (squares), Fielder spring wheat (circles), Fremont spring wheat (triangles). Dark symbols represent calibration points.

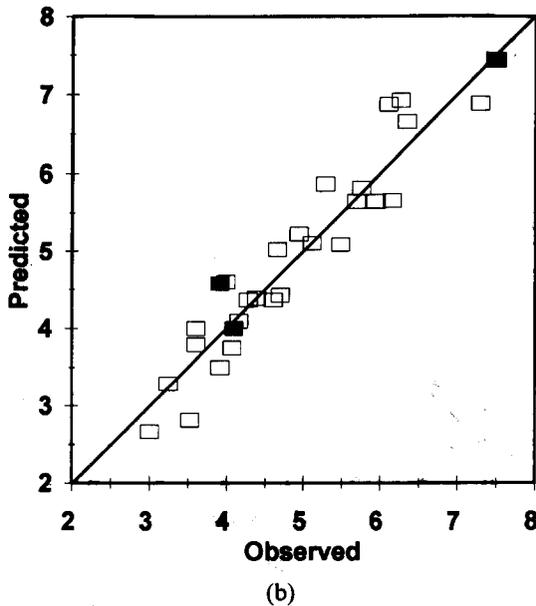
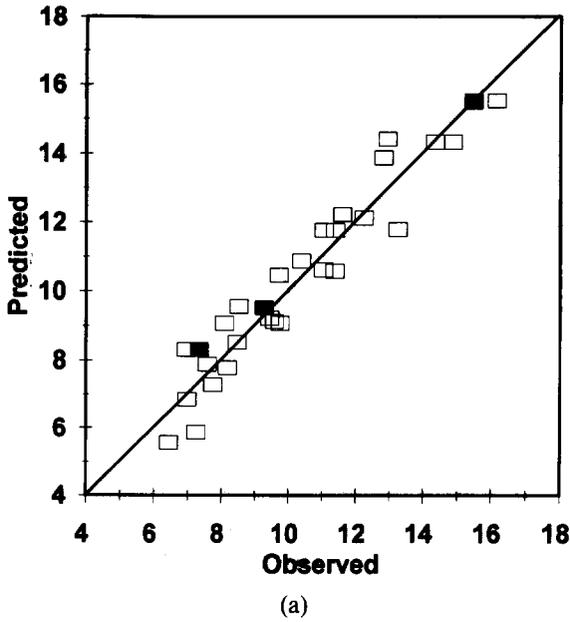


Fig. 10. Predicted and observed (a) spring wheat biomass and (b) spring wheat grain yield in response to water and nitrogen treatments at Logan Utah in 1982. Dark symbols represent calibration points.

dicted and measured grain yield and above-ground biomass compared quite satisfactorily (Figs 10(a) and 10(b)). Table 2 includes the statistical analysis for these comparisons (wheat/water/N). As given by all indicators, the performance of the model was good.

CONCLUSION

The water budget component of the model properly described crop water use, an important element in predicting crop response to water management. The nitrogen transport subcomponent of the model is simple, yet performed similarly to LEACHM, a more complex model with greater input data requirement and longer execution time. The predicted nitrogen content throughout the soil profile did not exactly match the measured values from leaching experiments, but it did follow the general trends of the data. Adequate field data sets to verify solute transport are not easy to find, and they include large uncertainty in the reported distribution of solutes in the soil profile. Additional verification of CropSyst prediction for nitrogen transport will be necessary.

CropSyst, as any other model attempting to predict crop responses to the environment, is not a universal model. It requires some field data for calibration so as to represent a particular crop or cultivar, although typical values for various crops are already known. From two extreme management conditions, CropSyst was calibrated for corn at Davis and then successfully predicted yield and biomass for 22 other water management treatments. The model also showed good performance in predicting yield and biomass in response to water management for corn grown in Fort Collins, Colorado. Similarly, grain yield and above-ground biomass of winter wheat and two spring wheat cultivars grown in Logan, Utah were well predicted for a wide range of irrigation application rates. Using data from three extreme management situations for calibration, grain yield and above-ground biomass of spring wheat grown in Logan, Utah were successfully predicted for 26 other instances of water and nitrogen management including a wide range of irrigation and nitrogen application rates. Based on this preliminary validation, CropSyst appears promising as a tool to analyze best management practices for water and nitrogen. Additional validation, including a wider range of crops and conditions, should be conducted.

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