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Incorporating tillage effects into a soybean model

A.A. Andales [a], W.D. Batchelor [b,*], C.E. Anderson [b], D.E. Farnham [c], D.K. Whigham [c]

[a]Institute of Agricultural Engineering, University of the Phillipines at Los Baños, 4031 College, Laguna, Philippines
[b]Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50011, USA
[c]Department of Agronomy, Iowa State University, Ames, IA 50011, USA

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Abstract

Crop growth models can be useful tools in evaluating the impacts of different tillage systems on the growth and final yield of crops. A tillage model was incorporated into CROPGRO-Soybean and tested for conditions in Ames, IA, USA. Predictions of changes in surface residue, bulk density, hydraulic conductivity, runoff curve number, and surface albedo were consistent with expected behaviors of these parameters as described in the literature. For conditions at Ames, IA, the model gave good predictions of soil temperature at 6 cm depth under moldboard ($R^2=0.81$), chisel plow ($R^2=0.72$), and no-till ($R^2=0.81$) for 1997 and was able to simulate cooler soil temperatures and delayed emergence under no-till in early spring. However, measured differences in soil temperature under the three tillage treatments were not statistically significant. Excellent predictions of soybean phenology and biomass accumulation (e.g. $R^2=0.98$, 0.97, and 0.95 for pod weight predictions under moldboard, chisel plow, and no-till, respectively) were obtained in 1997. More importantly, the model satisfactorily predicted relative differences in soybean growth components (canopy height, leaf weight, stem weight, canopy weight, pod weight, and number of nodes) among tillage treatments for critical vegetative and reproductive stages in one season. The tillage model was further tested using weather and soybean yield data from 1995 to 1997 at Nashua, IA. Tillage systems considered were no-till, disk-chisel + field cultivator, and moldboard plow + field cultivator. Predicted yields for the 1996 calibration year were within 1.3% of the measured yields for all three tillage treatments. The model gave adequate yield predictions for the no-till (−0.2–3.9% errors), disk-chisel (5.8–6.9% errors), and moldboard (5.5–6.1%

* Corresponding author. Fax: +1-515-294-2552.
E-mail address: bbatch@iastate.edu (W.D. Batchelor).

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errors) tillage treatments for the two years of validation. A sensitivity analysis showed that predicted soybean yield and canopy weight were only slightly sensitive to the tillage parameters (less than 3% change with 30% change in tillage parameters). The model predicted lower yields under no-till for nine out of 10 years of weather at Ames, IA, primarily due to delayed emergence. Yield under no-till was higher for one of the years (a drought year) when no-till had better water conservation and negligible delays in emergence.

Keywords: Tillage; Soybeans; Modeling

1. Introduction

Tillage practices can significantly influence the soil environment of a crop and can be a major factor in determining final yield. With the advent of herbicides, reduced tillage and no-till management systems have become economically viable alternatives to conventional tillage. The greatest advantage of reduced tillage is the reduction of adverse environmental impacts of crop production (e.g. less soil erosion, lower energy requirement). However, a major concern among producers is the possible yield penalties associated with reduced tillage compared to conventional tillage. In this regard, crop growth models can be useful tools in evaluating the impacts of different tillage systems on the growth and final yield of crops. Compared to field experimentation, the use of crop models to evaluate crop responses to a wide range of management and environmental scenarios can give more timely answers to many management questions at a fraction of the cost of conducting extensive field trials. However, a major barrier to their widespread use is the lack of information required to run the models as well as the complexities of calibrating and validating them for different locations.

The CROPGRO-Soybean model (Hoogenboom et al., 1994) was developed to compute growth, development, and yield on homogeneous units and has been demonstrated to adequately simulate soybean growth at the field or research plot scale. The model requires inputs including management practices (variety, row spacing, plant population, and fertilizer and irrigation application dates and amounts) and environmental conditions (soil type, daily maximum and minimum temperature, rainfall, and solar radiation) (Paz et al., 1998). From this information, daily growth of vegetative, reproductive, and root components is computed as a function of daily photosynthesis, growth stage, and water and nitrogen stress. Soil water and nitrogen balance models are used to compute water and nitrate levels in the soil as a function of rainfall and soil water-holding properties.

CROPGRO-Soybean does not have a tillage component. The objectives of this research were to: (1) adapt an existing tillage component for CROPGRO-Soybean; (2) collect field data of soybean response under different tillage systems; and (3) demonstrate the model's functionality in predicting effects of tillage on soybean growth and yield.

2. Procedures

2.1. Tillage model

CROPGRO-Soybean accounts for residue incorporation and its effects on the soil nutrient balance. However, it does not account for effects of surface residue on the water balance and on soil temperature — two important factors affected by tillage and residue management. The model also has provisions for the input of tillage date, tillage implement, and tillage depth but does not account for changes in soil physical properties (bulk density, hydraulic conductivity, porosity, surface residues, soil temperature) caused by tillage. Therefore, a more comprehensive tillage model was incorporated into CROPGRO-Soybean.

The tillage model adapted for this study was based on CERES-Till (Dadoun, 1993) — a model used to predict the influence of crop residue cover and tillage on soil surface properties and plant development. CERES-Till was tested for maize and demonstrated the ability to simulate differences in soil properties and maize yield under several tillage systems. The following section describes the theory adapted from Dadoun (1993) and modifications made to incorporate it into CROPGRO-Soybean. Table 1 has definitions for the variables.

2.1.1. Residue coverage

During a tillage operation, a fraction of the surface residue is incorporated into the soil depending on the tillage implement used. The amount of residue remaining on the soil surface after tillage is calculated by:

$$\mathrm{MULCH} = \mathrm{RESAMT} \times (1.0 - \mathrm{RINP}/100) \tag{1}$$

where MULCH is amount of surface residue remaining (kg ha^{-1}), RESAMT is the amount of surface residue before tillage (kg ha^{-1}), and RINP is percent of surface residue incorporated by the tillage operation. Buckingham and Pauli (1993) give residue incorporation percentages after specific field operations. Table 2 shows sample values of RINP for some common field operations. The fraction of the soil surface covered by the remaining residue (FC) is calculated by:

$$\mathrm{FC} = 1.0 - \mathrm{EXP}(-\mathrm{AM} \times \mathrm{MULCH}) \tag{2}$$

where AM is the area covered per unit dry weight of residue (ha kg^{-1}) and is dependent on residue type (e.g. crop, density). The equation is based on the probability of each piece of residue falling on a bare soil surface. Dadoun (1993) gives AM values for common crops (Table 3). FC is used in subsequent calculations for surface albedo and the effect of rainfall kinetic energy on surface soil properties.

Residue thickness is important in determining the reduction of soil evaporation due to surface residue. The algorithm for estimating average residue thickness assumes that the residues are arranged in layers, each layer one residue thick, with the coverage of each layer described by Eq. (2). The mass of residue (XMASS$_i$, kg ha^{-1}) overlying

Table 1
Definitions of variables in the tillage model

Variable	Definition	Units
ALBEDO	Aggregate surface albedo of the field surface	Unitless
AM	Area covered per unit dry weight of residue	ha kg^{-1}
AS	Soil aggregate stability (0–1)	Unitless
ATHICK	Average thickness of a residue layer with 100% coverage	cm
BD(L)	Bulk density of soil layer L	g cm^{-3}
CANCOV	Fraction of the ground surface covered by the crop canopy	Unitless
$CRAIN_t$	Cumulative rain from the start of simulation to time t	mm
DEPTH	Depth of layer L	cm
DUL(1)	Drained upper limit of the top 5 cm soil layer	cm^3 cm^{-3}
EOS	Soil potential evaporation	mm
FC	Fraction of soil surface covered by remaining residue	Unitless
FF	Saturation ratio	Unitless
LL(1)	Lower limit of plant-available soil water in the top 5 cm soil layer	cm^3 cm^{-3}
MULCH	Amount of surface residue remaining after tillage	kg ha^{-1}
MULCHALB	Albedo of surface residues	Unitless
MULCHSAT	Maximum amount of water that can be retained by surface residues	mm
MULCHSW	Amount of water currently held by surface residues	mm
MULCHTHICK	Total thickness of the surface residues	cm
NRAIN	Net amount of precipitation reaching the soil surface after some is intercepted by surface residues	mm
OC(L)	Organic carbon content of layer L	% mass basis
RAIN	Total daily precipitation before interception by residues	mm
R_{cov}	Reduction factor for soil potential evaporation due to partial coverage by residues relative to bare soil	Unitless
RESAMT	Amount of residue before tillage	kg ha^{-1}
RINP	Residue incorporation percentage	%
RSTL	Rate of change of the dynamic soil property	cm^2 J^{-1}
R_{thick}	Reduction factor for soil potential evaporation due to the thickness of the residues fully covering the ground	Unitless
SALB	Albedo of dry bare soil	Unitless
SALBEDO	Albedo of bare soil	Unitless
SAT(L)	Saturation water content for soil layer L	cm^3 cm^{-3}
S_i	Residue needed to cover the underlying residue in layer $i-1$	ha residue ha^{-1} ground surface
SOILCOV	Fraction of the soil surface covered by the canopy and surface residues	ha ha^{-1}
$SUMKE_t$	Cumulative rainfall kinetic energy from start of simulation to time t	J cm^{-2}

Table 1 (*continued*)

Variable	Definition	Units
SUMKE(L)	Effective kinetic energy for layer L	J cm^{-2}
SW(1)	Volumetric water content of the top 5 cm soil layer	cm^3 cm^{-3}
XHLAI	Leaf area index	m^2 m^{-2}
$XMASS_i$	Mass of residues in residue layer *i*	kg ha^{-1}
Xstl	Settled value of the soil property	Same as units of soil property
Xtill	Value of the soil property just after a tillage operation	Same as units of soil property
Xvar	Dynamic soil property	Same as units of soil property

an adjacent lower layer $i-1$ is the difference between the overlying biomass from the previous calculation step ($XMASS_{i-1}$, kg ha^{-1}) and the biomass needed to cover the underlying residue layer (S_{i-1}, ha residue per ha ground surface):

$$\mathrm{XMASS}_i = \mathrm{XMASS}_{i-1} - S_{i-1}/\mathrm{AM} \tag{3}$$

The portion of the underlying layer that the remaining biomass would cover (S_i, ha residue per ha ground surface) is then calculated:

$$S_i = S_{i-1} \times (1.0 - \mathrm{EXP}(-\mathrm{AM} \times \mathrm{XMASS}_i/S_{i-1})) \tag{4}$$

and the total thickness of the surface residues (MULCHTHICK, cm) is calculated by summing the area-weighted thickness of each layer once all of the total residue biomass is accounted for:

$$\mathrm{MULCHTHICK} = \sum_{i=1}^{n} S_i \times \mathrm{ATHICK} \tag{5}$$

where ATHICK is the observed average thickness of a residue layer with 100% coverage (cm) and n is the number of layers.

2.1.2. Water balance effects

The presence of crop residues affects the soil water balance through rainfall interception and reduction in soil evaporation. The maximum amount of water that can be retained by crop residues (MULCHSAT, mm) is proportional to the mass of the residues. Dadoun (1993) noted that residues were shown to hold water up to 3.8 times their weight. The transformation from mass of water to equivalent depth gives:

$$\mathrm{MULCHSAT} = 3.8 \times 10^{-4} \times \mathrm{MULCH} \tag{6}$$

where MULCH is the amount of surface residue remaining after tillage (kg ha^{-1}) and 3.8×10^{-4} is a factor for converting kg ha^{-1} to mm of water (mm ha kg^{-1}). The

Table 2
Residue incorporation percentage (RINP) during common field operations (adapted from Buckingham and Pauli, 1993)

Operation	Type of residue[a]	
	Non-fragile	Fragile
Plows		
Moldboard plow	90–100	95–100
Disk plow	80–90	85–95
Chisel plows with:		
Sweeps	15–30	40–50
Straight spike points	20–40	40–60
Twisted points or shovels	30–50	60–70
Combination chisel plows		
Coulter-chisel plow with:		
Sweeps	20–40	50–60
Straight spike points	30–50	60–70
Twisted points or shovels	40–60	70–80
Disk-chisel plow with:		
Sweeps	30–40	50–70
Straight spike points	40–50	60–70
Twisted points or shovels	50–70	70–80
Field cultivators (including leveling attachments)		
Field cultivator as primary tillage operation:		
Sweeps 12–30 inches (30–50 cm)	20–40	25–45
Sweeps or shovels 6–12 inches (15–30 cm)	25–65	30–50
Duckfoot points	40–65	45–70
Field cultivator as secondary tillage operation:		
Sweeps 12–20 inches (30–50 cm) wide	10–20	25–40
Sweeps or shovels 6–12 inches (15–30 cm)	20–30	40–50
Duckfoot points	30–40	50–65
Row cultivators: 30 inches (76 cm) wide rows or wider		
Single sweep per row	10–25	30–45
Mutliple sweeps per row	15–25	35–45
Finger wheel cultivator	25–35	40–50
Rolling disk cultivator	45–55	50–60
Ridge–till cultivator	60–80	75–95
Row planters		
Conventional planters with:		
Runner openers	5–15	10–20
Staggered disk openers	5–10	5–15
Double disk openers	5–15	15–25

Table 2 (*continued*)

Operation	Type of residue[a]	
	Non-fragile	Fragile
No-till planters with:		
Smooth coulters	5–15	10–25
Ripple coulters	10–25	15–30
Fluted coulters	15–35	20–45

[a] Non-fragile residues are generally more difficult to incorporate due to their large size, greater resistance to breakage and decomposition (e.g. corn, wheat) in contrast to fragile residues that are relatively small and easily incorporated (e.g. soybeans, peanuts).

Table 3
Values of average mass to area conversion (AM) for residues (from Dadoun, 1993)

Crop	AM[a] (ha kg^{-1})
Maize	0.00032; 0.00040 (two sources)
Wheat	0.00054; 0.00045 (two sources)
Winter wheat stem	0.00027
Soybean	0.00032
Grain sorghum stems	0.00006
Sunflower	0.00020

[a] Dadoun (1993) obtained values from various sources.

amount of precipitation intercepted is a function of the amount of water currently held (MULCHSW, mm) and the maximum amount that can be retained by the residues:

$$\mathrm{NRAIN} = \mathrm{RAIN} - (\mathrm{MULCHSAT} - \mathrm{MULCHSW}) \quad (7)$$

where NRAIN is the net amount of precipitation reaching the soil surface (mm), and RAIN is the total precipitation before interception (mm). All of the water held by residues is assumed to be available for evaporation.

The energy available for soil evaporation (i.e. soil potential evaporation) is budgeted for two processes: evaporation of water from residue; and evaporation of water from the soil. The soil potential evaporation (EOS, mm) is decreased by the amount of water evaporating from the residues and the residue water content is updated:

$$\text{if } \mathrm{EOS} < \mathrm{MULCHSW_i}: \ \mathrm{MULCHSW_f} = \mathrm{MULCHSW_i} - \mathrm{EOS_i} \text{ and } \mathrm{EOS_f} = 0 \quad (8)$$

$$\text{if } \mathrm{EOS} \geqslant \mathrm{MULCHSW_i}: \ \mathrm{MULCHSW_f} = 0 \text{ and } \mathrm{EOS_f} = \mathrm{EOS_i} - \mathrm{MULCHSW_i} \quad (9)$$

where the subscripts i and f designate initial and final values (before and after evaporation from residues), respectively. Surface residues also reduce soil potential evaporation. The following equation is used to calculate the decrease (R_{cov}) in soil potential evaporation from a surface partially covered by residues (relative to bare soil):

$$R_{cov} = 1 - 0.807 \times FC. \tag{10}$$

When residue provides a full cover, thickness of the layer is used to predict the relative decrease in soil evaporation (R_{thick}):

$$R_{thick} = EXP(-0.5 \times MULCHTHICK) \tag{11}$$

The minimum of the two coefficients is then used to calculate the reduced soil potential evaporation:

$$EOS_f = MIN(R_{cov},\ R_{thick}) \times EOS_i \tag{12}$$

where subscripts i and f indicate values before and after reduction due to residue barriers, respectively.

2.1.3. Soil properties

Crop residues generally increase the surface albedo and can cause the temperature of upper soil layers to be cooler than bare soils. Also, the albedo of bare soil (SALBEDO) varies with soil volumetric water content:

$$SALBEDO = SALB \times (1-0.45 \times FF) \tag{13}$$

$$\frac{FF = (SW(1) - LL(1))}{(SAT(1) - LL(1))} \tag{14}$$

where SALB is the albedo of dry bare soil (fraction), FF is saturation ratio, SW(1) is water content of the top 5-cm soil layer ($cm^3\ cm^{-3}$), SAT(1) is the saturation water content of the top 5-cm soil layer ($cm^3\ cm^{-3}$), and LL(1) is the lower limit of plant-available water in the top 5-cm soil layer ($cm^3\ cm^{-3}$). The aggregate surface albedo (ALBEDO, fraction) is then calculated by:

$$\begin{aligned} ALBEDO = CANCOV \times 0.23 + FC \times (1 - CANCOV) \\ \times MULCHALB + (1 - FC) \times (1 - CANCOV) \times SALBEDO \end{aligned} \tag{15}$$

$$CANCOV = 1.0 - EXP(-0.75 \times XHLAI) \tag{16}$$

where CANCOV is the fraction of the surface covered by the canopy, XHLAI is the leaf area index, and the rest of the variables are as previously defined.

2.1.4. Effects on soil parameters

Dadoun (1993) modified the soil temperature model of CERES to account for the presence of crop residues. In this work we adapted an energy balance approach for soil temperature. The component gave improved soil temperature and emergence date predictions during cool, wet weather in early spring and gave better predictions for deeper layers compared to the original CROPGRO-Soybean model (Andales et al., 2000).

The four soil properties in the model that vary with tillage are bulk density (g cm^{-3}), saturated hydraulic conductivity (cm day^{-1}), SCS runoff curve number, and water content at saturation (cm^3 cm^{-3}). Soil conditions after tillage are inputs and dynamically changed when precipitation occurs. Only properties in the top 30 cm of soil are assumed to be subject to change by tillage. However, the actual depth of the changes depends on the tillage implement used and may not go as deep as 30 cm. The process of change in bulk density, saturated hydraulic conductivity, and curve number follows the same pattern: the parameter changes from an initial value to a settled value following an exponential curve that is a function of cumulative rainfall kinetic energy since the last tillage operation:

$$\mathrm{Xvar} = \mathrm{Xstl} + (\mathrm{Xtill} - \mathrm{Xstl}) \times \mathrm{EXP}(-\mathrm{RSTL} \times \mathrm{SUMKE}) \tag{17}$$

where Xvar represents the dynamic soil property, Xtill is its value just after a tillage operation, Xstl is the settled value of the property, RSTL is the rate of change of the soil property (per J cm^{-2} of rainfall kinetic energy), and SUMKE is the cumulative rainfall kinetic energy since the last tillage operation (J cm^{-2}). The rate of change of the soil property is assumed to be a function of soil water aggregate stability (AS, 0.0−1.0):

$$\mathrm{AS} = 0.205 \times \mathrm{OC(L)} \tag{18}$$

$$\mathrm{RSTL} = 5.0 \times (1 - \mathrm{AS}) \tag{19}$$

where OC(L) is the percentage organic carbon content of soil layer L. Aggregate stability is not measurable in absolute terms. It expresses the resistance of aggregates to breakdown when subjected to disruptive processes such as intermittent rainfall (Hillel, 1982). Eq. (18) normalizes the value of aggregate stability such that a value of 1.0 represents the greatest stability while a value of 0.0 represents soil aggregates that have absolutely no resistance to destructive forces.

A regression relationship was used to estimate cumulative rainfall kinetic energy from cumulative precipitation:

$$\mathrm{SUMKE}_t = 0.00217 \times \mathrm{CRAIN}_t \tag{20}$$

where SUMKE_t is cumulative rainfall kinetic energy from the start of simulation to time t (J cm^{-2}) and CRAIN_t is cumulative growing-season rain (mm). The regression equation ($R^2 = 0.993$) was derived from 23 years (1964–1986) of breakpoint rainfall data obtained from a rain gauge station at Treynor in southwest Iowa. For any day the cumulative kinetic energy since the last tillage operation is the difference between the current value of cumulative kinetic energy ($\mathrm{SUMKE}_{t=\mathrm{today}}$) and the value at the time of the latest tillage operation ($\mathrm{SUMKE}_{t=\mathrm{last\ tillage\ date}}$):

$$SUMKE = SUMKE_t - SUMKE_{t=\text{last tillage date}} \tag{21}$$

The effect of rainfall kinetic energy diminishes with depth and with coverage by the crop canopy and crop residues such that:

$$SUMKE(L) = (1.0 - SOILCOV) \times SUMKE \times EXP(-0.15 \times DEPTH) \tag{22}$$

$$SOILCOV = CANCOV + FC \times (1.0 - CANCOV) \tag{23}$$

where SUMKE(L) is the effective kinetic energy for soil layer L (J cm^{-2}), SOILCOV is the fraction of the soil surface covered, SUMKE is the cumulative kinetic energy from Eq. (21), and DEPTH is the depth of soil layer L (cm).

Every time bulk density changes, the saturation water content for each layer L (SAT(L)) is updated using the equation relating porosity and density:

$$SAT(L) = 0.85 \times (1.0 - BD(L)/2.66) \tag{24}$$

where BD(L) is the bulk density of layer L (g cm^{-3}), soil particle density is assumed to be 2.66 g cm^{-3}, and only 85% of the total porosity is assumed to be effective due to air entrapment (Dadoun, 1993).

2.2. New inputs

In addition to the inputs required by CROPGRO-Soybean, the tillage model requires a tillage parameter file named 'SOIL.TIL'. This file contains the treatment name (should be identical to the treatment name given in the CROPGRO experiment file), a user-defined output filename (used to save the time series values of the dynamic soil properties), values for area covered per unit dry weight of residue and initial residue amount, the tillage dates, and values of the tillage parameters corresponding to each tillage operation. A maximum of 10 tillage operations may be specified for each treatment, and any number of treatments may be included in the file. The values of BD, SWCN, and CN2 given in the soil file of CROPGRO (SOIL.SOL) are then used as the settled values. Table 4 is a list of definitions of the tillage input parameters.

2.3. 1997 Central Iowa study

A tillage study was conducted at the Iowa State University Agronomy and Agricultural Engineering Research Center near Ames, IA, during the 1997 planting season. The soil is predominantly Clarion loam (Fine-loamy, mixed, mesic Typic Hapludolls) with 2–5% slope. The experimental plots were arranged according to a randomized complete block design with two blocks containing three tillage treatments (CP = fall chisel plow, MB = fall moldboard plow, NT = no-till). Each plot was 30.5×14.5 m planted to 20 rows of soybean cultivar Stine 2250 with 76-cm row spacing. The soybeans were planted on 29 April 1997 at a planting density of 49 plants m^{-2}.

Table 4
Definitions of parameters required as inputs in the tillage component

Parameter	Definition	Units
AM	average surface coverage of residues (Table 3)	ha kg^{-1}
CN2TILL(*I*)	SCS curve number immediately after the *I*th tillage operation (0 = no runoff; 100 = all precipitation runs off)	Unitless
NTILL	Total number of tillage operations	Unitless
RESAMT	Amount of surface residues at the start of simulation	kg ha^{-1}
RINP(*I*)	Residue incorporation percentage during the *I*th tillage operation	%
STLBD(L)[a]	Settled bulk density of layer L	g cm^{-3}
STLCN2[a]	Settled SCS curve number	Unitless
STLSWCN(L)[a]	Settled saturated hydraulic conductivity of layer L	cm day^{-1}
TDEP(*I*)	Depth of the *I*th tillage operation	cm
TILLBD(*I*,L)	Bulk density of layer L immediately after the Ith tillage operation (layers within 0–30 cm depth only)	g cm^{-3}
TILLSWCN(*I*,L)	Saturated hydraulic conductivity of layer L immediately after the *I*th tillage operation (layers within 0–30 cm depth only)	cm day^{-1}
TYRDOY(*I*)	Date of the *I*th tillage operation (e.g. 97135)	yydoy

[a] Specified in the soil input file of CROPGRO (SOIL.SOL).

The field operations performed during the 1997 tillage study are summarized in Table 5. The fall moldboard and fall chisel plow plots were field cultivated prior to planting while the no-till plots were undisturbed. The same tillage operations were applied on all the plots after planting.

At the center of each plot, two thermistor cables, each attached to a StowAway XTI temperature logger (Onset Computer Corporation), were installed in the row: one at 6 cm and the other at 30 cm depth to monitor soil temperature during the season. Biweekly sampling of aboveground biomass and gravimetric soil moisture was done on all plots throughout the season. Vegetative and reproductive stages also were recorded at the time of sampling.

The tillage model was calibrated for each tillage treatment using the 1997 data set. The tillage parameters were adjusted to get the best visual fit for measured soil moisture, soil temperature, pod weight, total canopy weight, and final yield. The

Table 5
Field operations performed during the 1997 tillage study

Date	Operation
4/24/97	Treflan applied 2.72 l ha^{-1}
4/28/97	Moldboard and chisel plow plots field cultivated
4/29/97	Planted Stine 2250; 49 plants m^{-2}
6/13/97	All plots cultivated
6/24/97	All plots cultivated
9/20/97	Yield samples taken

relative differences in soil properties under the three tillage treatments were estimated based on a survey of experts done by Mankin et al. (1996).

We tested model sensitivity to weather by running the calibrated model for Ames using 10 years of weather data (i.e. 1982–1990, 1995). Weather years 1991–1994 were intentionally skipped due to incomplete weather records for those years. The same tillage treatments as in the 1997 calibration were used in the simulations. The sensitivity of the model to tillage parameters also was evaluated using the 1997 tillage data set. Each tillage parameter was changed by 10 and 30% (both positive and negative changes) in order to see the effect on predicted final yield.

2.4. 1995–1997 northeast Iowa studies

Whigham et al. (1998) conducted a study to evaluate soybean row spacing and tillage effects on yield and related parameters in northeast Iowa. Three years (1995–1997) of soybean yield data under three different tillage systems were available from Iowa State University's Northeast Research and Demonstration Center (NERC) near Nashua, IA. Planting dates, harvest dates, and final yields from this study were used in testing the tillage model. Soybean cultivar Asgrow A2242, an early maturity group II variety adapted to northern Iowa, was planted at a targeted stand level of 40 plants m^{-2}. The planting dates for the three years were 25 May 1995, 22 May 1996, and 22 May 1997. The harvest dates were 13 October 1995, 7 October 1996, and 4 October 1997. Default values of genetic coefficients for maturity group II early variety provided in CROPGRO-Soybean were used in the simulations. The tillage treatments included no-till (soybeans planted directly into standing corn stalks), disk chisel (disk chisel followed by field cultivator tillage of corn stalks), and moldboard (moldboard plow followed by field cultivator tillage of corn stalks) (Whigham et al., 1998). The data from the 30-inch row spacing treatments were used for model testing.

The soils at NERC are predominantly Kenyon (fine-loamy, mixed, mesic Typic Hapludoll). Average measured values of bulk density, saturated hydraulic conductivity, particle size distribution, and organic carbon percentages from Singh (1994) were used in testing the tillage model. Lower limit, drained upper limit, and saturated water content values were obtained from Shen et al. (1998) for the same location. The plots at NERC are drained with tiles installed 120 cm deep at 28.5-m spacing (Singh, 1994). Daily solar radiation, maximum and minimum air temperature, and precipitation measurements from NERC were used as weather inputs to the model.

Planting date, harvest date, and final yield were available from the studies. Tillage operations were specified: field cultivation before planting (disk chisel and moldboard systems only), row planting on the actual planting dates, and two post-emergence cultivation operations for weed control (all three tillage systems). In the simulations, field cultivation was assumed to occur the day before planting while the post-emergence cultivation operations were done when soil conditions were favorable (e.g. soil was well drained, no rainfall 2 days prior to cultivation).

The 1996 data set was selected for model calibration because this was the data set that had significant differences in yield between tillage treatments. Differences in tillage parameters were presumed to have caused differences in yield. Specifically, the yield from no-till was significantly lower than from moldboard (LSD = 129 kg ha^{-1}, $P = 0.05$). The yield from disk chisel was not significantly different from the two other treatments in 1996. The soybeans in the 1995 field experiment were damaged by hail. Thus, it was difficult to judge if the measured differences were due to tillage treatment or due to variable hail damage. Hail damage estimates were based on work by Allen (1996). The 1997 data set did not show significant yield differences between tillage systems. The soil hospitality factor, saturated hydraulic conductivity of the bottom layer, effective drain spacing, and initial residue amount were adjusted during the calibration such that the predicted yield for each tillage system approached measured yields for 1996. The calibrated tillage parameters were then used for the model in 1995 and 1997 to compare measured and simulated yields.

3. Results and discussion

3.1. Simulation results

3.1.1. 1997 Central Iowa study

Tables 6 and 7 show the estimated settled and tilled values of the soil properties affected by tillage, respectively (Eq. (17)). Figs. 1 and 2 show the simulated behavior of soil properties as affected by tillage operations in 1997. Reductions in surface residue (Fig. 1A) were due to residue incorporation at the times of field cultivation (for moldboard and chisel plow only), planting (all three tillage treatments), and row cultivation (all three tillage treatments). Predicted changes in bulk density (Fig. 1B), saturated hydraulic conductivity (Fig. 1C), and runoff curve number (Fig. 1D) were due to tillage operations or rainfall kinetic energy. The behaviors of the surface properties, as depicted by the model, were consistent with general expectations described by Mankin et al. (1996). Bulk density of the top soil layer decreased after

Table 6
Estimated soil physical properties of Clarion loam under three tillage systems in 1997 at Ames, IA (settled values)

Soil property[a]	Tillage system		
	No-till	Chisel plow	Moldboard plow
STLCN2	72	76	78
STLBD(1), g cm^{-3}	1.40	1.30	1.25
STLBD(2), g cm^{-3}	1.40	1.40	1.35
STLBD(3), g cm^{-3}	1.40	1.40	1.40
STLSWCN(1), cm day^{-1}	94	108	115
STLSWCN(2), cm day^{-1}	94	94	101
STLSWCN(3), cm day^{-1}	94	94	94

[a] See Table 4 for definitions. The index for STLBD and STLSWCN indicates the soil layer number: layer 1 = 0–5 cm; layer 2 = 5–15 cm; layer 3 = 15–30 cm.

Table 7
Tillage input parameters used for three tillage treatments in 1997 at Ames, IA

Parameter[a]	No-till	Chisel plow	Moldboard plow
AM, ha kg^{-1}	0.00032	0.00032	0.00032
NTILL	3	4	4
RESAMT, kg ha^{-1}	3097	2000	877
Field cultivation (CP and MP only)			
CN2TILL	NA[b]	72	74
TDEP, cm	NA	12.7	12.7
RINP,%	NA	30	30
TILLBD(*I*,1), g cm^{-3}	NA	1.20	1.20
TILLBD(*I*,2), g cm^{-3}	NA	1.20	1.20
TILLBD(*I*,3), g cm^{-3}	NA	1.35	1.35
TILLSWCN(*I*,1), cm day^{-1}	NA	122	122
TILLSWCN(*I*,2), cm day^{-1}	NA	122	122
TILLSWCN(*I*,3), cm day^{-1}	NA	101	101
Planting			
CN2TILL	71	73	75
TDEP, cm	3.0	3.0	3.0
RINP,%	10	10	10
TILLBD(*I*,1), g cm^{-3}	1.35	1.21	1.21
TILLBD(*I*,2), g cm^{-3}	1.35	1.21	1.21
TILLBD(*I*,3), g cm^{-3}	1.38	1.35	1.35
TILLSWCN(*I*,1), cm day^{-1}	101	120	120
TILLSWCN(*I*,2), cm day^{-1}	101	120	120
TILLSWCN(*I*,3), cm day^{-1}	97	101	101
Row cultivation			
CN2TILL	70	72	74
TDEP, cm	12.7	12.7	12.7
RINP,%	15	15	15
TILLBD(*I*,1), g cm^{-3}	1.30	1.20	1.20
TILLBD(*I*,2), g cm^{-3}	1.30	1.20	1.20
TILLBD(*I*,3), g cm^{-3}	1.40	1.35	1.35
TILLSWCN(*I*,1), cm day^{-1}	108	122	122
TILLSWCN(*I*,2), cm day^{-1}	108	122	122
TILLSWCN(*I*,3), cm day^{-1}	94	101	101

[a] Table 4 for definitions. The first index for TILLBD and TILLSWCN indicates the tillage operation number while the second index indicates the layer number: layer 1 = 0–5 cm; layer 2 = 5–15 cm; layer 3 = 15–30 cm.
[b] Settled values for no-till are used instead (Table 6).

every tillage due to loosening of the soil, while it increased thereafter due to compaction brought about by rainfall. Saturated hydraulic conductivity was inversely related to bulk density. Runoff curve number decreased (less runoff) after a tillage operation and gradually increased with the occurrence of rainfall. The decrease in the runoff curve number after tillage is due to increased roughness and storage capacity of the soil surface. Predicted residue amounts for the three tillage treatments were consistent

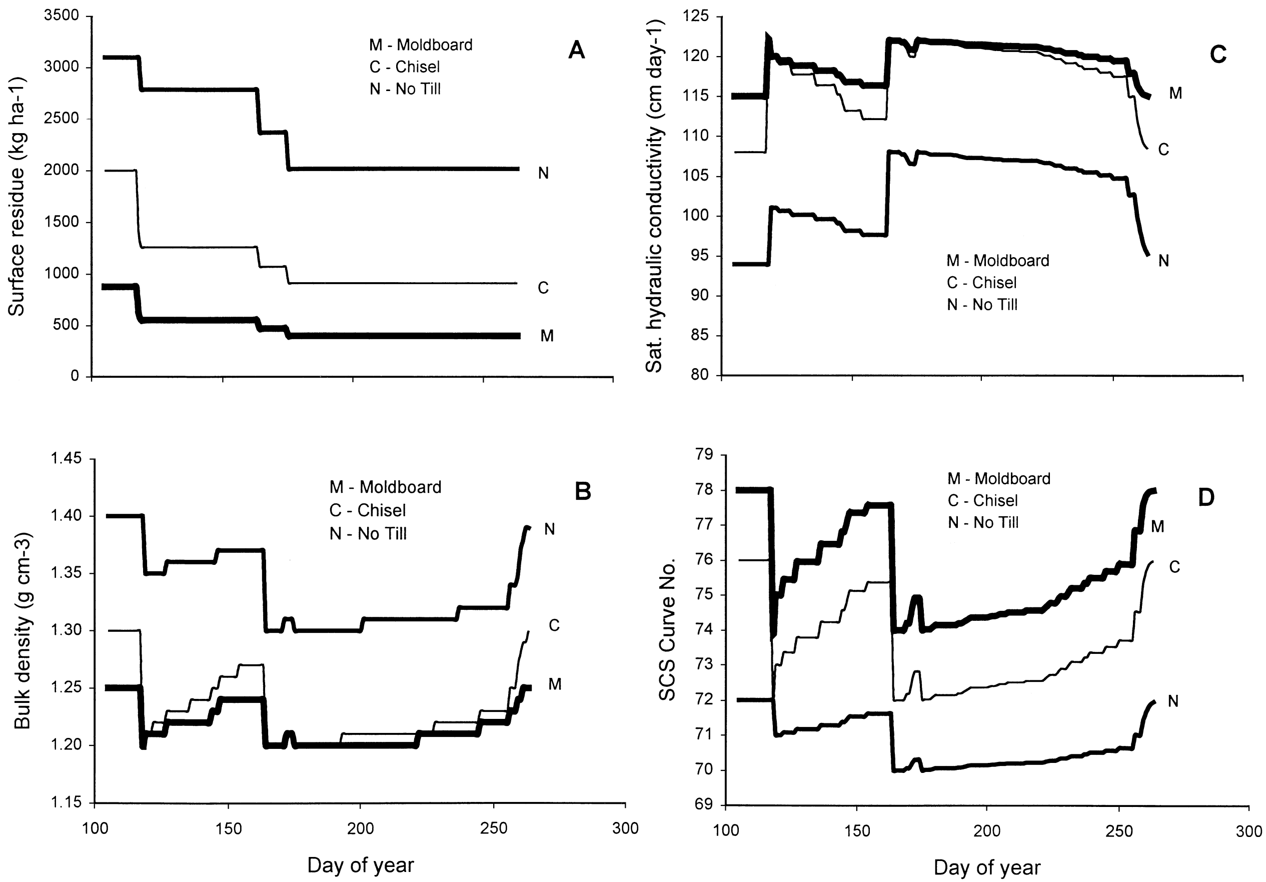


Fig. 1. Predicted changes in (A) surface residue, (B) bulk density, (C) saturated hydraulic conductivity, and (D) runoff curve number in the top 5 cm under three tillage systems in Ames, IA, 1997.

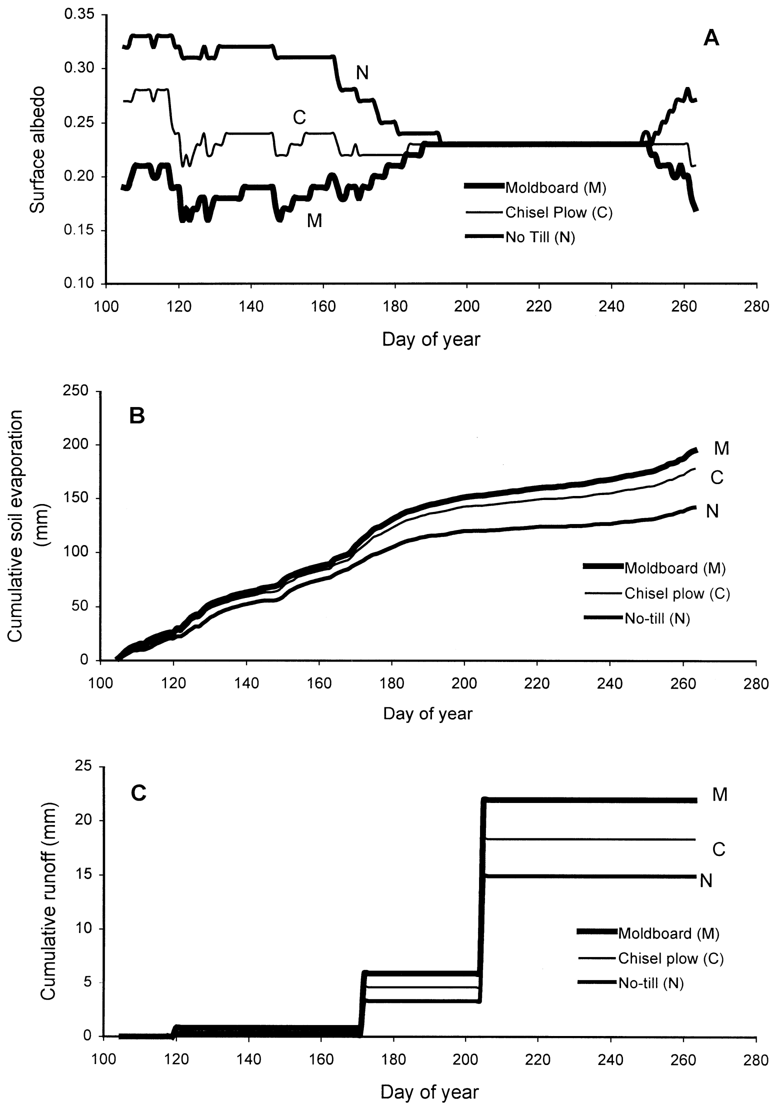


Fig. 2. Predicted (A) surface albedo, (B) cumulative soil evaporation, and (C) cumulative runoff under three tillage systems in Ames, IA, 1997.

with estimates obtained from residue cover measurements done in late June and early July 1997. No field measurements were available to verify the predicted changes in bulk density, hydraulic conductivity, and runoff curve number.

Predicted surface albedo (Fig. 2A) was least for the moldboard treatment due to low amount of residues compared to chisel plow and no-till. The values for the three tillage treatments converged to 0.23 (albedo of crop canopy) in the middle of the season. The reduction in soil evaporation was clearly evident under no-till (Fig. 2B) and chisel plow relative to moldboard. Consistent with the values of the runoff curve number under the three tillage treatments (Fig. 1D), cumulative runoff was greatest under moldboard and least under no-till (Fig. 2C). Most of the differences in soil water content between tillage treatments are reflected in the top soil layer (Fig. 3). The water content of the top layer is the most difficult to predict because of rapid changes brought about by infiltration and evapotranspiration. The root mean square errors (RMSEs) of soil water predictions for the 0–5 cm layer were 0.035, 0.047, and 0.051 for chisel plow, no-till, and moldboard, respectively. The predicted soil water contents were within one standard deviation of half of all the measured values taken in the season for all tillage treatments. Possible sources of error in predicted soil water content were inaccurate estimates of: bulk density, water holding capacity, hydraulic conductivity, amount of surface residues, and runoff curve number. During most of the season, measured soil water content in the top 15 cm was greater in no-till compared to moldboard and chisel plow. However, the differences in soil water content between tillage treatments were not statistically significant at the 5% level.

The good agreement ($R^2=0.81$, 0.72, and 0.81 for moldboard, chisel plow, and no-till, respectively) between predicted and measured soil temperatures for the 5–15 cm soil layer (Fig. 4A, B, C) under all three tillage treatments verified that the model was adequately simulating changes in residue cover and consequent changes in surface albedo. Early in the season, predicted soil temperature was greatest under moldboard and lowest under no-till (Fig. 4D). However, canopy closure towards the middle of the season in all tillage treatments resulted in similar amounts of solar energy reaching the soil surface, thus causing the predicted soil temperatures to be similar from mid-season onwards. The same was true for the measured soil temperatures under the three tillage treatments. The lower soil temperatures under no-till early in the season delayed predicted emergence to 21 days after planting compared to soybeans planted under moldboard (17 days) and chisel plow (19 days). These differences in emergence dates caused part of the differences in predicted soybean growth and yield in 1997. However, the differences in measured soil temperatures before canopy closure were not statistically significant at the 5% level.

The results of Duncan's multiple range test (DMRT) performed on measured growth components are summarized in Table 8. Model predictions are given in parentheses for comparison. Significant differences were observed for mean canopy height, mean leaf weight, and mean canopy weight during early to mid-vegetative stage (50–65 days after planting). Generally, soybeans under moldboard treatment, and under chisel plow to a lesser degree, had more biomass than those under no-till. The model predicted the same relative differences. Delayed emergence under no-till may have been a major factor. Weed competition was also more prevalent under no-till, although hand weeding was regularly performed for all tillage treatments. At flowering (79 days after planting), significant differences in canopy height, leaf weight, stem weight, and canopy weight were observed among tillage treatments. The tillage treatments ranked according to decreasing biomass as moldboard plow > chisel plow > no-till. Again, the model predicted the same relative differences at flowering. Significant differences in pod weight and leaf number per stem (nodes)

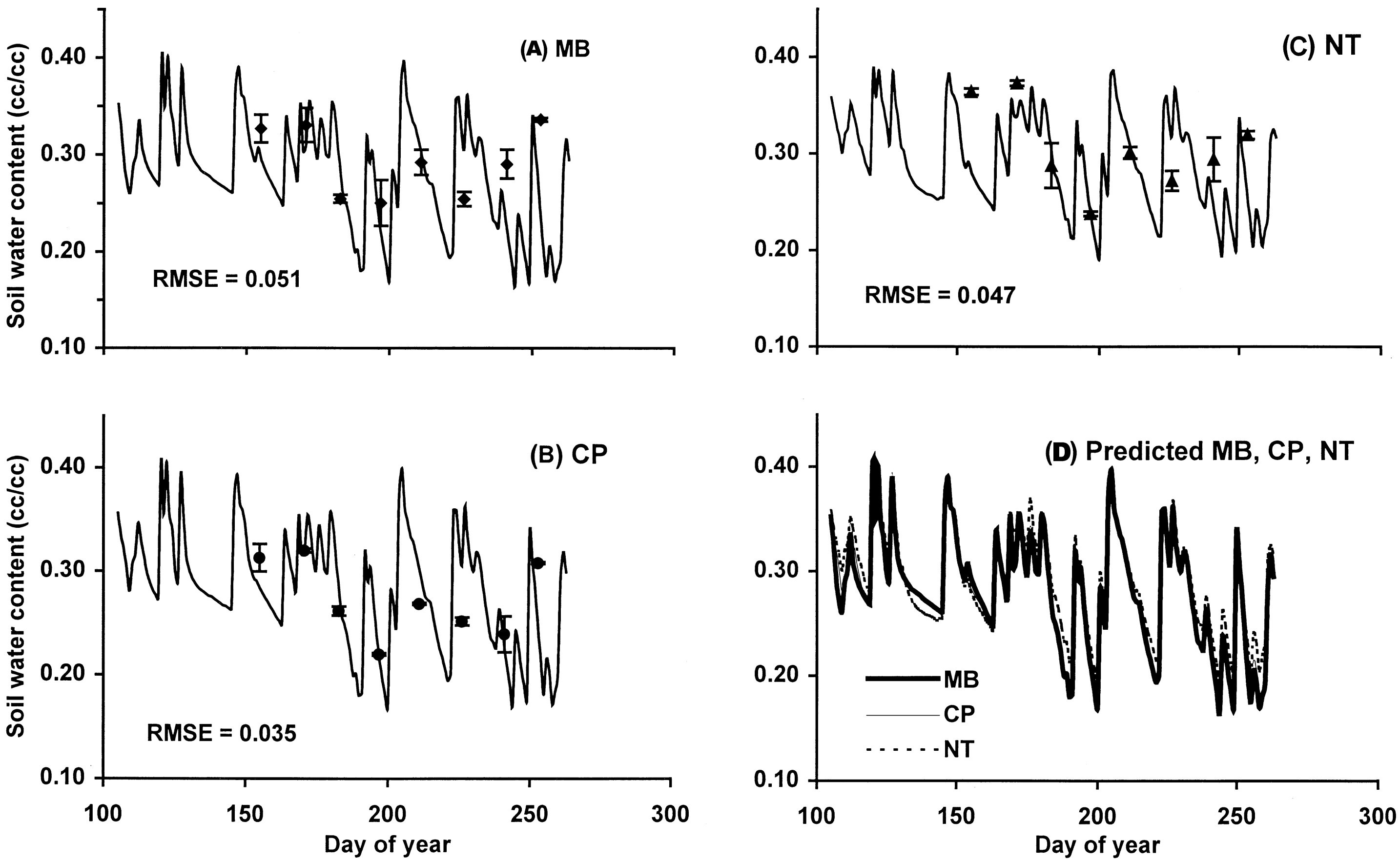


Fig. 3. Soil water in the top 5 cm under (A) moldboard (MB), (B) chisel plow (CP), (C) no-till (NT), and (D) all three tillage systems. The lines denote predicted values while the points denote measured values. The error bars represent one standard deviation above and below the mean of two measurements.

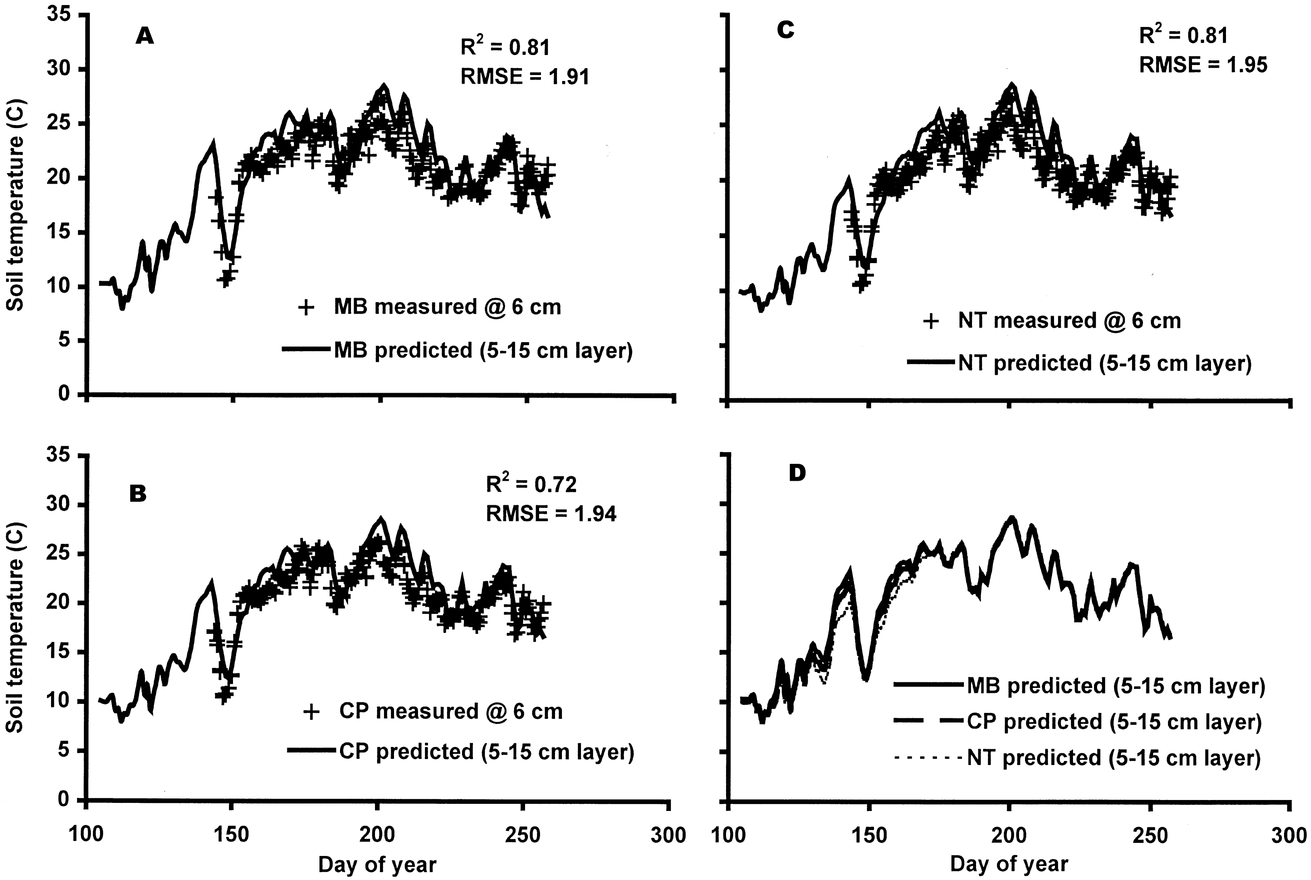


Fig. 4. Soil temperature for (A) moldboard (MB), (B) chisel plow (CP), (C) no-till (NT), and (D) predictions for all three in 1997. Measurements were taken at 6 cm while predictions were for the 5–15 cm soil layer.

Table 8
Duncan's multiple range test (DMRT) for comparing measured soybean development under three tillage treatments on eight dates in 1997 (values in parentheses are model predictions)[a]

Trt.[b]	Days after planting							
	36	50	65	79	92	106	122	134
Mean canopy height (m)								
CP	0.08 a	0.19 b	0.42 ab	0.65 a	0.82 a	0.91 a	0.93 a	0.82 a
	(0.06)	(0.19)	(0.40)	(0.55)	(0.77)	(0.89)	(0.95)	(0.95)
MB	0.09 a	0.21 a	0.43 a	0.67 a	0.79 a	0.93 a	0.93 a	0.83 a
	(0.07)	(0.20)	(0.41)	(0.57)	(0.80)	(0.91)	(0.96)	(0.96)
NT	0.08 a	0.18 b	0.39 b	0.58 b	0.74 a	0.84 a	0.84 b	0.79 a
	(0.05)	(0.18)	(0.39)	(0.54)	(0.76)	(0.88)	(0.94)	(0.94)
Mean leaf weight (kg ha^{-1})								
CP	88 a	241 a	611 a	1140 b	1298 a	1530 ab	1171 a	62 a
	(39)	(181)	(780)	(1622)	(2019)	(1874)	(1407)	(622)
MB	91 a	229 a	601 a	1343 a	1273 a	1576 a	1098 a	134 a
	(50)	(213)	(863)	(1705)	(2057)	(1875)	(1408)	(502)
NT	82 a	162 b	472 a	869 c	1198 a	1391 b	918 a	6 a
	(36)	(165)	(722)	(1553)	(2003)	(1910)	(1426)	(626)
Mean stem weight (kg ha^{-1})								
CP	31 a	144 a	598 a	1513 b	2051 a	2807 ab	2506 ab	1833 a
	(19)	(117)	(675)	(1687)	(2433)	(2520)	(2181)	(1699)
MB	31 a	151 a	604 a	1787 a	1847 a	2910 a	2579 a	1796 a
	(23)	(150)	(775)	(1824)	(2538)	(2573)	(2230)	(1679)
NT	27 a	116 a	450 a	1127 c	1740 a	2453 b	1965 b	1514 a
	(16)	(100)	(620)	(1602)	(2408)	(2581)	(2200)	(1711)
Mean canopy weight (kg ha^{-1})								
CP	119 a	386 a	1209 a	2690 b	3860 a	6428 a	7931 a	7094 a
	(59)	(298)	(1456)	(3311)	(5039)	(6304)	(7337)	(7124)
MB	122 a	380 a	1205 a	3180 a	3671 a	6711 a	8404 a	6963 a
	(73)	(363)	(1638)	(3538)	(5254)	(6489)	(7520)	(7073)
NT	108 a	277 b	921 a	1998 c	3218 a	5732 b	6644 a	5982 a
	(52)	(264)	(1342)	(3155)	(4885)	(6186)	(7181)	(6991)
Mean pod weight (kg ha^{-1})								
CP	0	0	0	37 a	511 a	2091 b	4254 a	5199 a
	(0)	(0)	(0)	(1)	(586)	(1910)	(3749)	(4803)
MB	0	0	0	51 a	551 a	2225 a	4728 a	5161 a
	(0)	(0)	(0)	(9)	(659)	(2041)	(3882)	(4892)
NT	0	0	0	2 a	280 b	1888 c	3761 a	4335 a
	(0)	(0)	(0)	(0)	(474)	(1695)	(3555)	(4654)
Mean leaf number per stem (nodes)								
CP	1.0 a	3.0 a	7.5 a	9.5 a	12.5 ab	14.2 b	14.2 a	13.7 a
	(0.9)	(3.8)	(7.5)	(10.4)	(13.8)	(16.1)	(16.7)	(16.7)

Table 8 (*continued*)

Trt.[b]	Days after planting							
	36	50	65	79	92	106	122	134
MB	1.0 a	3.5 a	7.3 a	9.8 a	13.0 a	14.8 a	14.2 a	15.0 a
	(1.3)	(4.2)	(7.9)	(10.7)	(14.2)	(16.4)	(17.0)	(17.0)
NT	1.0 a	2.5 a	6.3 a	9.0 a	11.2 b	12.8 c	13.0 a	13.0 a
	(0.9)	(3.6)	(7.3)	(10.2)	(13.5)	(15.9)	(16.7)	(16.7)

[a] In a column, means followed by a common letter are not significantly different at 5% level.
[b] Tillage treatments: CP, fall chisel plow; MB, fall moldboard plow; NT, no-till.

occurred during mid to late reproductive stages (92–106 days after planting). The model also predicted similar differences (Table 8). Overall, the model satisfactorily predicted the relative differences in soybean growth among tillage treatments. Errors in the predicted magnitudes of the biomass components may have been due to the use of default (uncalibrated) genetic coefficients. Weed competition, which is not included in the model, may have affected growth, especially under no-till, even though considerable efforts were made in hand-weeding all plots. Other possible sources of error were incorrect estimates of soil properties and various model limitations.

Biomass accumulation for the three tillage treatments is shown in Fig. 5. For all three treatments, the model matched the first two measurements of canopy weights, which indicated that predicted emergence was reasonable, but overpredicted canopy weights primarily due to overestimation of leaf biomass. The measured canopy weights indicated possible stress during a mid-season warm period, especially on day 211 when all treatments were beginning seed development. The overall model fit for canopy weight was good ($R^2=0.94$, 0.94, and 0.92 for moldboard, chisel plow, and no-till, respectively).

Fig. 6 shows biomass accumulation in the pods. The onset of pod development as well as the increase in pod weight was simulated well by the model ($R^2=0.98$, 0.97, and 0.95 for moldboard, chisel plow, and no-till, respectively). Predicted total pod weight was highest for moldboard and lowest for no-till. The measured average yields were 4013 kg ha^{-1} for moldboard, 3353 kg ha^{-1} for chisel plow, and 3567 kg ha^{-1} for no-till. The measured differences in yield between treatments were not significant ($F=6.17<F_{\alpha=0.05}=19.00$). Predicted yields were 3638 kg ha^{-1} (−9.3% error) for moldboard, 3602 kg ha^{-1} (7.4% error) for chisel plow, and 3463 kg ha^{-1} (−2.9% error) for no-till. Default values of genetic coefficients for Stine 2250 (maturity group 2) were used without calibration and may have contributed to the negative error in predicted yield for moldboard. The measured yield of 4013 kg ha^{-1} could not be simulated even when water stress was completely removed.

3.1.2. 1995–1997 northeast Iowa studies

The yield predictions for the 1996-calibration year at Nashua are given in Table 9. The percentage errors were intentionally made to be the same (−1.3%) for all treatments in order to preserve the relative differences in yield between tillage treatments.

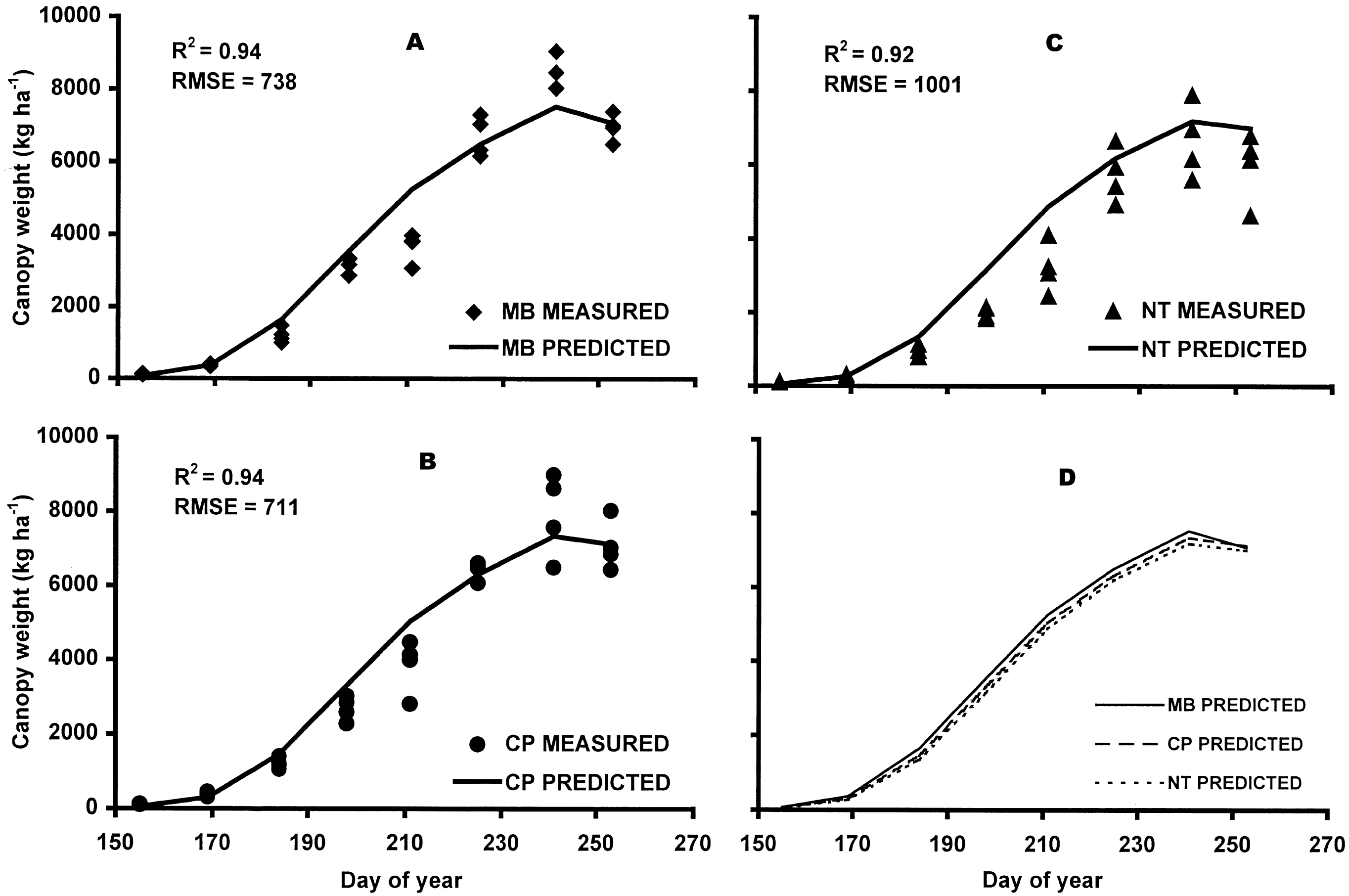


Fig. 5. Canopy weights for (A) moldboard (MB), (B) chisel plow (CP), (C) no-till (NT), and (D) predictions for all three tillage systems in 1997.

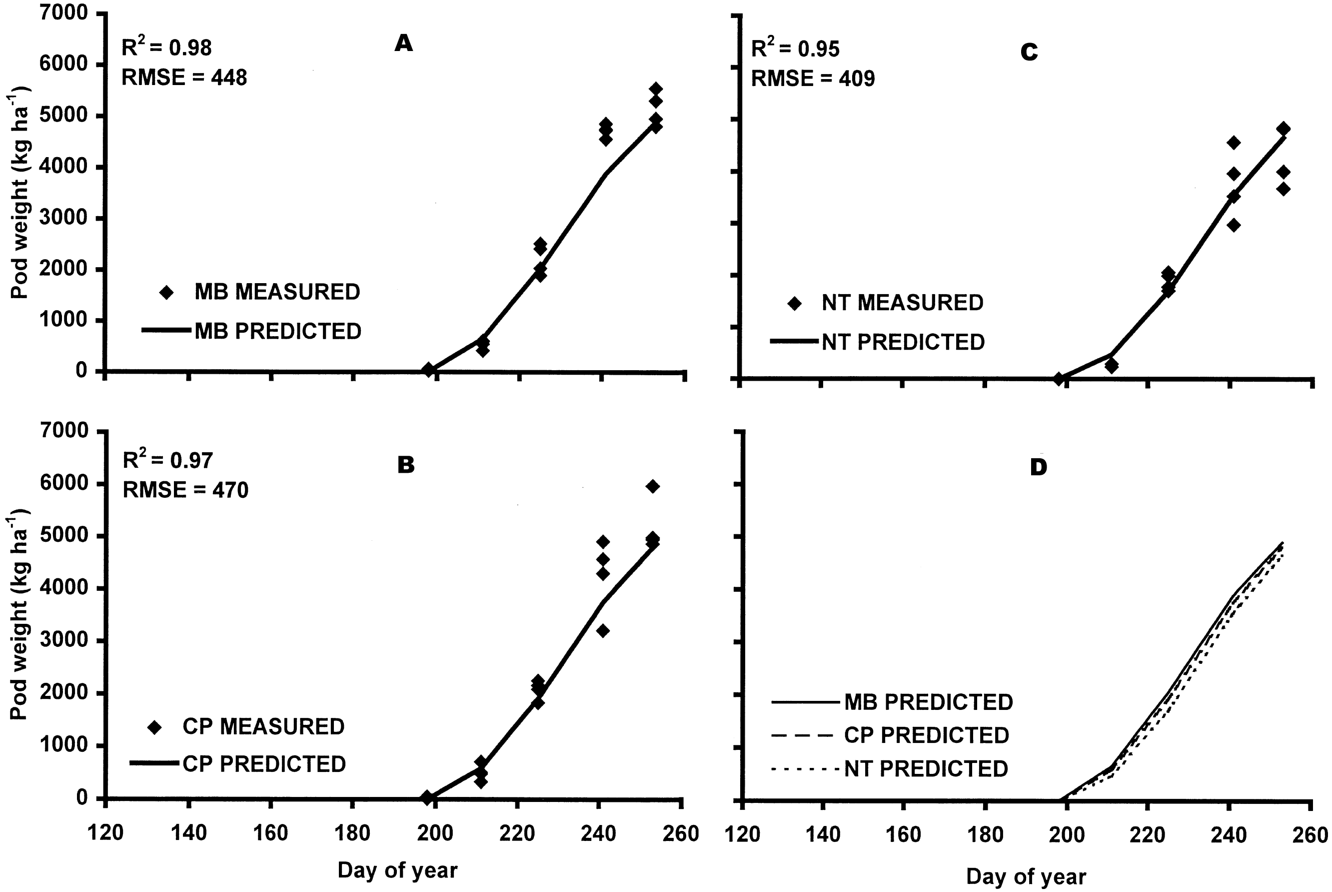


Fig. 6. Pod weights for (A) moldboard (MB), (B) chisel plow (CP), (C) no-till (NT), and (D) predictions for all three tillage systems in 1997.

Table 9
Results of the tillage model simulations for 1995–1997 at Nashua, IA

Tillage system	Measured yield (kg ha^{-1})	Model predictions			
		Yield[a] (kg ha^{-1})		Emergence[b] (days)	Average water stress[c] (0–1)
1995 (Validation)					
No-till	2404	2400	(−0.2)	10	0.169
Disk chisel	2281	2413	(5.8)	9	0.164
Moldboard	2240	2363	(5.5)	9	0.171
1996 (Calibration)[d]					
No-till	3529 b	3484	(−1.3)	15	0.134
Disk chisel	3571 ab	3524	(−1.3)	15	0.123
Moldboard	3688 a	3641	(−1.3)	15	0.063
1997 (Validation)					
No-till	2844	2954	(3.9)	12	0.104
Disk chisel	2873	3072	(6.9)	11	0.076
Moldboard	2849	3024	(6.1)	10	0.077

[a] Values in parentheses are percent errors.
[b] Days from planting to emergence.
[c] First seed to physiological maturity; 0.0 = minimum stress, 1.0 = maximum stress.
[d] 1996 measured yields followed by different letters are statistically different (LSD = 129, P = 0.05).

There were no predicted differences in emergence dates. Predicted soybean yield was related inversely to water stress during the period from first seed to physiological maturity (Table 9). No-till had the lowest while moldboard had the highest yield. Although no-till had less predicted runoff and soil evaporation compared to disk chisel and moldboard, less effective rainfall (due to interception by surface residues) and more tile drainage were predicted under no-till. Greater water stress in no-till was primarily due to rapid root senescence predicted during periods of temporary waterlogging, especially in the deeper layers (60–120 cm depth). This root senescence resulted in less total root mass for extracting water during the water stress periods that occurred in the seed-filling stage.

In 1997, the model predicted the same relative responses as was observed in the field experiments. However tillage treatment yield differences were not statistically significant. The highest yield was from disk chisel while the lowest was from no-till. The predicted yield differences were due to a combined effect of delayed emergence (no-till and disk chisel) and water stress. The model gave better yield predictions for no-till (3.9% error) than for disk chisel (6.9% error) and moldboard (6.1% error). The water balance predictions in 1997 were similar to those in 1996 in terms of relative differences between tillage systems.

The 1995 measured yields were relatively low because of hail damage. In order to account for this in the model, we imposed a 67% reduction in leaf mass (Allen, 1996) on 22 July (actual date of hail occurrence) for all three tillage treatments while still using the same calibrated set of soil parameters obtained from 1996. This assumption generally gave adequate yield predictions for all three tillage systems (Table 9). Excellent yield prediction was achieved for no-till (−0.2% error), which suggested that the calibrated soil parameters as well as the simulated hail damage described the actual field conditions very well. Acceptable but less accurate yield predictions were obtained for disk chisel (5.8% error) and moldboard (5.5% error). Three possible explanations can be given for this: the calibrated soil properties for disk chisel and moldboard were incorrect; soybeans under disk chisel and moldboard treatments incurred more hail damage than was simulated (i.e. >67% reduction in leaf mass); or a combination of both. Again, the predicted yields were inversely related to water stress (Table 9).

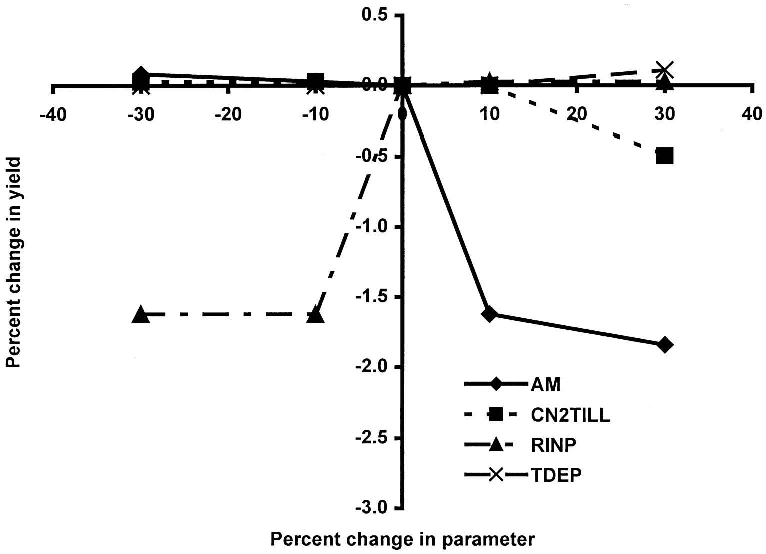
In general, the model gave the best yield predictions for no-till (−0.2–3.9% errors) and less accurate predictions for disk chisel (−1.3–6.9% errors) and moldboard (−1.3–6.1% errors) for the 1995–1997 simulations. This suggested that the model was calibrated better for no-till than for the other two tillage treatments. In the model, the effects of tillage on water stress explained most of the variations in yield that occurred under the different tillage systems. Delays in emergence, especially under no-till, also affected yield variability, especially when planting during cool periods.

3.2. Model sensitivity

Fig. 7 shows changes in soybean yield versus changes in tillage parameters using 1997 weather and experiment conditions. Predicted yield was only slightly sensitive to tillage parameters. Soybean yield was most sensitive to high bulk density (TILLBD), high residue amount (RESAMT), high area coverage per unit residue weight (AM), low residue incorporation (RINP), and high curve number (CN2TILL). Predicted soybean yield was relatively insensitive to saturated hydraulic conductivity (TILLSWCN), and tillage depth (TDEP).

Predicted canopy weight was only slightly sensitive to tillage parameters (Fig. 8). In order of decreasing sensitivity, canopy weight was most sensitive to low soil hospitality factor, high bulk density, high curve number, high area coverage per unit residue weight, and high residue amount. Predicted canopy weight was insensitive to residue incorporation, tillage depth, and saturated hydraulic conductivity.

The tillage model was sensitive to weather and tillage treatment for conditions at Ames, IA, depending on temperature and degree of moisture stress. The model predicted no water stress for soybeans in all tillage treatments for six years: 1982, 1986, 1987, 1989, 1990, and 1995. On the other hand, the model predicted water stress during 1983, 1984, 1985, and 1988. In nine out of the 10 years, no-till yielded lower than moldboard and chisel plow (Fig. 9). During these years, the yield penalty for no-till, and to a lesser degree for chisel plow, was primarily due to delayed emergence (1984, 1985, 1986, 1988, 1989, and 1990) or greater water stress (1983–1985). Predicted soybean yield for no-till was more than for moldboard or chisel plow only in 1988, which was a drought year. During this year, no-till had better water conservation and negligible delays in emergence due to warm conditions at planting.



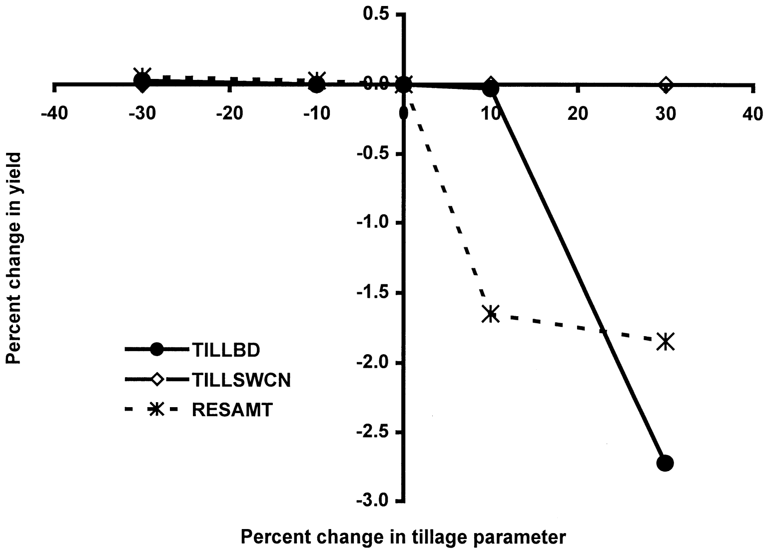


Fig. 7. Sensitivity of predicted soybean yield to tillage parameters.

4. Conclusions and recommendations

A tillage model was integrated into CROPGRO-Soybean and tested for conditions in Central and northeast Iowa. Predictions of changes in surface residue, bulk density, hydraulic conductivity, runoff curve number, and surface albedo were consistent with expected behaviors of these parameters as described in the literature. The tillage

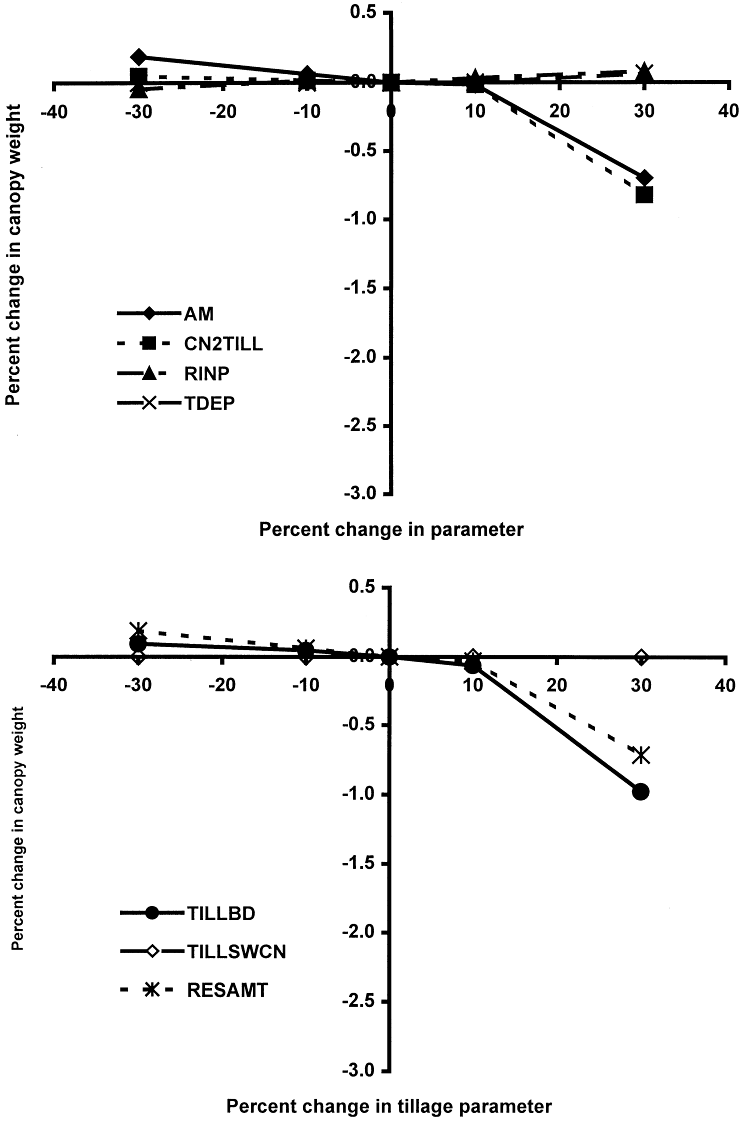


Fig. 8. Sensitivity of predicted soybean canopy weight to tillage parameters.

model was able to show differences in runoff and soil evaporation amounts among the moldboard, chisel plow, and no-till treatments. The model gave good predictions of soil temperature for one season. However, measured soil temperatures under the three tillage treatments were not significantly different. The model was able to simulate cooler soil temperatures under no-till in early spring and demonstrated the ability to simulate delays in emergence. Adequate predictions of soybean (cultivar Stine 2250) phenology and biomass accumulation (canopy weight and pod weight)

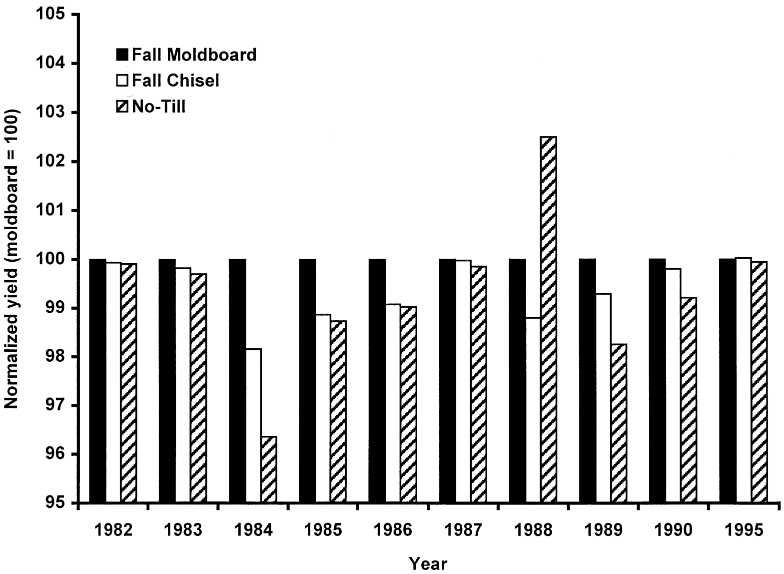


Fig. 9. Normalized yields for 10 years of weather data under three tillage systems in Ames, IA.

were obtained for the three tillage treatments in 1997. More importantly, the model satisfactorily predicted relative differences in soybean growth components (canopy height, leaf weight, stem weight, canopy weight, pod weight, and number of nodes) among moldboard, chisel plow, and no-till treatments for critical vegetative and reproductive stages in one season. However, the model must be tested under a wider range of conditions and for other soybean cultivars.

The tillage model showed differences in predicted soybean yield based on the effects of surface residue cover (delayed emergence, intercepted rainfall, and reduced soil evaporation) and on soil properties (runoff curve number, bulk density, saturated hydraulic conductivity) affected by tillage. The model further showed that predicted soybean yield was inversely related to water stress. This study demonstrated that the tillage model could be used for tile-drained locations such as northeast Iowa.

Model predictions indicated that the no-till system had the advantage of better water conservation (less runoff and soil evaporation) compared to the chisel plow and the moldboard plow systems. This advantage, however, may occasionally be offset by delayed emergence, less effective rainfall (due to rainfall interception by surface residues), less soil porosity and saturated water content (due to higher bulk density), and temporary waterlogging that limits root proliferation. Better water conservation with no-till may be more advantageous during drought years and in well-drained soils.

Predicted soybean yield and canopy weight were only slightly sensitive to the tillage parameters. Calibration of the tillage model should be focused on adjustment of bulk density, residue amount, area coverage per unit residue weight, and percentage residue incorporation by a tillage operation. The tillage model was sensitive to weather and gave varying yields for a given tillage treatment, depending on temperature and degree of moisture stress. The yield penalty for no-till was primarily due to delayed emergence. On the other hand, the yield from no-till was higher when no-till had better water conservation and negligible delays in emergence compared to moldboard plow and chisel plow.

Additional data on the changes of surface soil properties throughout the season under different tillage treatments are needed to validate the tillage model. Residue decomposition and weed competition may be included in the model for improved simulations. The tillage model used in this study did not consider nitrogen and organic matter contributions to the soil from surface crop residues. This feature may also be added to improve the predictions of the soil nitrogen balance.

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