Oper Res Int J
DOI 10.1007/s12351-009-0067-1

ORIGINAL PAPER

Issues of spatial and temporal scale in modeling the effects of field operations on soil properties

Jeffrey W. White · Jim W. Jones · Cheryl Porter · Gregory S. McMaster · Rolf Sommer

Received: 5 January 2009 / Revised: 30 July 2009 / Accepted: 14 September 2009

Abstract Tillage is an important procedure for modifying the soil environment to enhance crop growth and conserve soil and water resources. Process-based models of crop production are widely used in decision support, but few explicitly simulate tillage. The Cropping Systems Model (CSM) was modified to simulate tillage and related field operations for single seasons or multiple years. This paper provides an overview of how the new routines were implemented and discusses issues of spatial and temporal scaling that influenced the underlying strategy. The processes considered included effects of crop residues on the soil surface and on chemical and physical properties that vary with soil depth. Each event is described by date and implement used. The implement is characterized by its effects on soil properties, including mixing of soil layers and crop residues and changes in soil bulk density. The modeled responses are illustrated with a hypothetical case comparing effects of four implements (mold board plow, tandem disk, tine harrow, and planking) and a field experiment where winter wheat (*Triticum aestivum* L.) was grown with different tillage and residue management practices. From a modeling viewpoint, a key issue was how to manage different spatial and time scales. The soil is simulated as varying only with depth but in reality, the thickness of the soil is affected by tillage. This poses challenges for ensuring that the masses for water, nutrients, residues and

J. W. White (✉)
USALARC, USDA ARS, 21881 North Cardon Lane, Maricopa, AZ 85138, USA
e-mail: Jeffrey.white@ars.usda.gov

J. W. Jones · C. Porter
Department Agricultural and Biological Engineering, University Florida, Gainesville, FL, USA

G. S. McMaster
Agricultural Systems Research Unit, USDA ARS, Ft. Collins, CO, USA

R. Sommer
International Center for Agricultural Research in the Dry Areas (ICARDA),
P.O. Box 5466, Aleppo, Syria

Published online: 15 October 2009

the soil per se are conserved as soil layers are mixed and the density of each layer is altered. The model runs on a daily time step, but events such as tillage, application of residue, and irrigation can all happen within a single day and the sequence/timing can influence simulations. The new routines for field operations improve representation of tillage and residue management in the CSM model, but they are best viewed as providing a framework for future work that explicitly considers effects of residue type, soil type and distribution, and soil moisture on tillage effects and that deal with effects of rainfall kinetic energy in more detail.

Keywords Agriculture · Scale · Simulation · Soil · Tillage

Mathematics Subject Classification (2000) 90 · 92 · 93

1 Introduction

Agricultural fields are tilled for diverse reasons, including providing favorable conditions for planting and seedling establishment, controlling weeds, and incorporating crop residues and fertilizers. Leveling a field or forming furrows substantially alters field topography. Tillage can involve a diverse range of implements that often are designed and manufactured locally to match needs dictated by local farm practices and soil conditions. In addition to tillage operations, field operations such as planting and fertilizer applications also affect soil cover and physical conditions.

A field is tilled to benefit the current or future crops, but tillage can have numerous negative impacts and is often perceived as a major cause of environmental degradation (Lobb et al. 2007). Loosening of the soil surface and burial of surface residues increase the potential for soil erosion. Soil crusting and degradation of the natural structure of the soil can inhibit plant growth (Lipiec and Hatano 2003). Tillage also directly impacts scheduling of farm operations and of course, production costs. The need to conduct tillage when a field is neither too dry nor too wet can constrain planting and other operations, and long delays in tilling can prevent crops from being planted. Tillage and other operations are costly due to the large energy inputs and the costs of equipment and labor. Recognizing the multiple constraints and trade-offs, producers increasingly seek to minimize tillage (Knowler and Bradshaw 2007). Reduced and zero-tillage are usually combined with the practice of retaining crop residues. Such “conservation tillage” reduces production costs, conserves soil moisture, reduces erosion, and can improve soil health (Cannell and Hawes 1994; Hobbs et al. 2008). Producers thus face numerous, complex decisions relating to tillage, including which practices to apply (or withhold), when to till, and with what intensity. Beyond these are decisions to purchase, modify and maintain implements and tractors.

Process-based crop simulators are widely used to support decision making in agriculture. Applications include optimizing irrigation and nutrient management, precision farming, and assessing the potential impacts of climatic variation (as risk) and of climatic change. However, applications are often constrained because few models explicitly consider tillage or other field operations (see comparisons in Table

A. 1 of Sommer et al. 2007). The present paper describes new routines that allow field operations to be simulated in the Cropping Systems Model (CSM; Jones et al. 2003), which is distributed in the Decision Support System for Agrotechnology Transfer version 4.5 (DSSAT; Hoogenboom et al. 2009). Much of the description involves general principles that are relevant to other crop models. Two example applications illustrate features of the tillage routine. From an information systems perspective, programming the tillage routines is challenging due to the need to simulate processes occurring in a three dimensional space using a one dimensional representation of the soil and to consider events that involve different time scales. Variables referenced in the text are defined in Table 1.

2 Overview of tillage

Tillage alters the distribution of soil components and soil structure (the arrangement of aggregates of finer particles). These changes affect surface properties, the concentrations of particles, nutrients, organic matter and moisture within the profile, and the distribution and amount of pore spaces and channels.

Deep tillage such as with a moldboard plow is often performed to reduce compaction. Surface modifications include smoothing or loosening the soil surface in order to improve soil conditions for seed germination and seedling establishment. Larger changes may include leveling or formation of furrows or beds. When crops are well established, secondary tillage may be used to control weeds, hill soil around plants to stimulate root growth or reduce lodging, or seal soil cracks to reduce evaporation from deeper soil layers.

The potential for surface water runoff can be characterized using the runoff curve number (CN), which varies from 0 for no runoff to 100 for maximum runoff (Ritchie 1998). Surface residues affect infiltration and runoff, soil temperatures, and evaporation, so the portion of residue incorporated with tillage also needs to be tracked.

The mixing effect of tillage involves burial of residue and redistribution of soil particles. In actual field situations, this process largely involves bulk mixing where crop residues, soil particles and moisture are mixed in a similar manner somewhat independently of shape or density. It is mainly the type of farm implement and tillage intensity that determine the degree of mixing, the affected depth and the level of homogeneity of mixing (over depth). Soil type and wetness as well as the speed of tillage are further determining factors.

The soil loosening and compacting effects of tillage manifest themselves as changes in bulk density (the mass to volume ratio), which typically varies from 1.0 to 1.6 g cm^{-3} for dry soils differing in texture and structure. The bulk density of soil particles is approximately 2.66 g cm^{-3}. The lower values of soils mainly reflect the presence of air-filled pore spaces. Variation in pore space relates to packing of soil particles, differences in size of soil particles (particle size heterogeneity), as well as the structure provided by soil aggregates. Moderate tillage is often used to loosen the soil, i.e., decrease the bulk density, favoring root growth and water infiltration. Intensive tillage, however, can degrade the structure, thus in the long run increasing bulk density as compared to soils with intact aggregates.

Table 1 Definitions of variables used in the equations describing effects of tillage

Variable	Definition	Units	Name(s) in CSM
AS	Aggregate stability scaled from 0 to 1	Unitless	AS
$B_C(L)$	Current soil bulk density of a soil layer, *L*	g cm^{-3}	XBD
$B_T(L)$	Post-tillage event bulk density of a soil layer, *L*	g cm^{-3}	BDTEMP(*L*)
$B\%(M)$	Change in soil bulk density for a given implement and soil layer, *M*	%	SBDT, BDP(*I*, *M*)
CN	SCS soil runoff curve number	Unitless	CN
CN%	Change in SCS soil runoff curve number after a given tillage event	%	CN2T
F	Factor for change in soil properties due to effects of kinetic energy from rainfall and irrigations	cm^2 J^{-1}	RSTL
H%	Reduction in hard pan (if tillage depth is sufficient to reach pan)	%	HPAN
$K\%(M)$	Change in K_{SAT} for a given tillage implement and soil depth, *M*	%	SKST, SWCNP(*I*, *M*)
$K_0(L)$	Saturated hydraulic conductance of a soil layer, *L*, prior to tillage	cm h^{-1}	XSWCN(NS)
$K_T(L)$	Saturated hydraulic conductance of a soil layer, *L*, after tillage	cm h^{-1}	SCTEMP(*L*)
L	Index for a soil layer	Unitless	*L*
M	Index of soil layer used to define implement effects	Unitless	*M*
M%	Mixing efficiency of tillage event	%	MIXT, MIXPCT
N	Index for a soil layer	Unitless	NS
OC(*L*)	Soil organic carbon concentration	%	OC(*L*)
P	Total precipitation on a given day	mm	RAIN
R_0	Mass of residue which is on top of soil	kg ha^{-1}	MULCHMASS
R_T	Residue that is incorporated	kg ha^{-1}	RESINC
R%	Percent of surface residue that is incorporated by a tillage event	%	RINP, TILRESINC
S	Fraction of soil surface covered by residues	m^2 m^{-2}	SOILCOV
SS	Soil settling rate	cm^2 J^{-1}	Srate
S%	Percentage of soil surface is disturbed by a tillage event	%	SSDT
$U_S(L)$	Value of a soil parameter for layer *L* after modification by rainfall kinetic energy	(*v*)[a]	*X*
$U_T(L)$	Value of a soil parameter for layer *L* after tillage	(*v*)	X_t
$U_0(L)$	Value of a soil parameter for layer *L* prior to tillage	(*v*)	X_0
$X_M(L)$	Amount of a soil component available for mixing	(*v*)	AMT_2B_MIXED(*L*)
$X_0(L)$	Amount of a soil component to be partitioned between mixed and unmixed portions	(*v*)	VALUE_IN(*L*)
$X_T(L)$	Amount of soil component following tillage	(*v*)	VALUE_MIXED(*L*)
$X_U(L)$	Amount of soil component that is unmixed	(*v*)	AMT_UNMIXED(*L*)
$Y_L(L)$	Lower boundary of a soil layer, *L*	cm	SLB(*L*)
Y_T	Depth of tillage for a given tillage event	cm	TDEP
$\overline{Y}(L)$	Mean cumulative depth of a soil layer, *L*	cm	MCUMDEP
$Z(L)$	Thickness of a soil layer, *L*	cm	ZLAYER(*L*)

Table 1 continued

Variable	Definition	Units	Name(s) in CSM
ΣE_K	Cumulative kinetic energy since the last tillage event	J cm^{-2}	SUMKE
$\Sigma E_{K(t)}$	Cumulative kinetic energy through day t	J cm^{-2}	SUMKE
$\Sigma E_K(L)$	Cumulative kinetic energy on a given day that reaches a soil layer, L, with mean depth $\overline{Y}(L)$	J cm^{-2}	SUMKEL
ΣP_t	Cumulative (from previous days) precipitation or irrigation on day t	mm	$CRAIN_t$
ΣX_M	Total amount of a soil component to be mixed across all tilled soil layers	(v)	SUMMIXED
β	Proportional change in a soil property due kinetic energy effects of rainfall or irrigation	Unitless	KECHGE
$\theta(L)$	Volumetric soil water content	mm^3 mm^{-3}	SW(L)
$\theta_S(L)$	Saturated volumetric soil water content	mm^3 mm^{-3}	SAT(L), SATTEMP(L)
$\theta_U(L)$	Drained upper limit for soil water content	mm^3 mm^{-3}	DUL(L)
(na)[b]	Index for a tillage event	Unitless	*I*
(na)	Identifier used to link implement/operation from parameter file to field management file	Unitless	TIMPL
(na)	Day of a given tillage event	Date	TDATE
(na)	Whole profile soil drainage rate	mm day^{-1}	SWCON

The equivalent names used in the CSM parameter files and FORTRAN code are also given

[a] Units vary according to soil property

[b] Not applicable. Variable not used in equations in text

Severe compaction of soil below the tillage implement can result in formation of a plow pan, a layer of especially dense soil that roots cannot easily penetrate. To characterize effects of tillage, one thus needs to consider effects of a given operation on the bulk density, which varies by depth. Soils with similar bulk densities may differ in how easily water passes through a given layer, which is characterized by the hydraulic conductivity. The hydraulic conductivity of a soil is not a fixed value but changes with the water content of the soil. Still, for simplicity, water movement in soils is often simulated by considering only a whole profile drainage rate and/or a saturated hydraulic conductivity (K_{sat}). Thus, additional parameters are needed to characterize effects of tillage on drainage.

Effects of tillage on soil structure and other properties vary with implements used, the intensity of tillage, and soil conditions at the time of tillage. Four implements are compared qualitatively in Fig. 1, starting from a hypothetical soil that has three distinct sublayers. The mold board plow is assumed to penetrate to 30 cm soil depth. It mixes and loosens the soil, but leaves a rough surface. The tandem disk mixes and loosens to a lesser depth (approximately 15 cm), and it breaks large soil clumps, somewhat smoothing the soil surface. The tine harrow mixes and loosens only to about 8 cm but provides even more smoothing of the soil surface. Planking smoothes the surface with minimal mixing, but the smoothing operation increases the bulk density of the top layer (manifested as a decrease in thickness—here exaggerated).

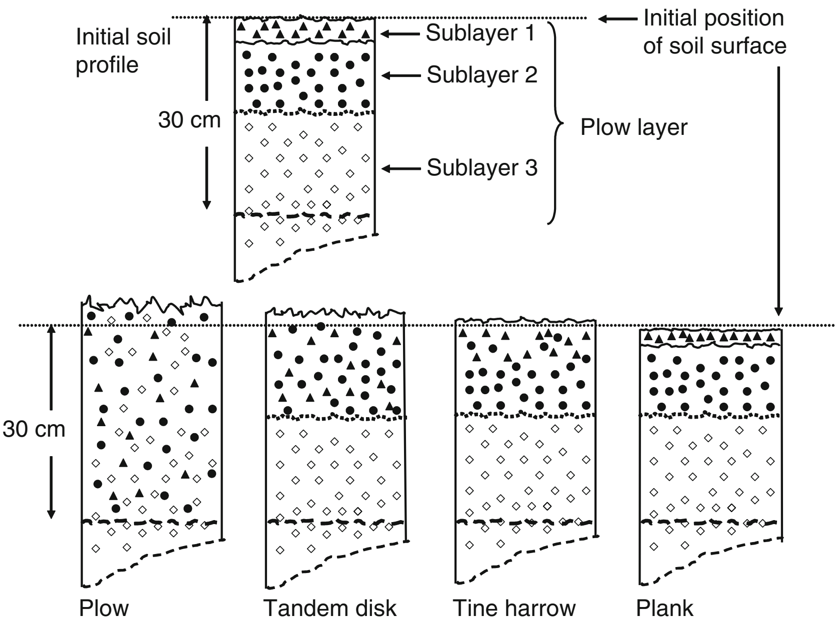

Fig. 1 Examples of a hypothetical soil profile showing effects of tillage with a plow, tandem disk, tine harrow, and planking. *Symbols* within profile layers indicate qualitative effects on soil mixing

Under actual field conditions, the impact of tillage varies with initial conditions of the soil, especially the moisture content, bulk density, and texture. Furthermore, the kinetic energy associated with precipitation or irrigation and the effect of water in reducing soil strength also affect the overall physical condition of the soil (tilth). The most notable effect of water is to increase the bulk density of soils loosened by tillage.

3 Implementation of tillage in CSM

The CSM model describes plant, atmospheric and soil processes and is implemented for over 20 crop species (Jones et al. 2003; Hoogenboom et al. 2009). The growth and development of a population of plants is simulated through routines that consider physiological processes such as phenological development, photosynthesis, and respiration. Partitioning rules allocate newly formed mass to different plant organs such as leaves, roots and stems. Leaves intercept solar radiation and are the site of uptake of CO_2 and loss (transpiration) of water vapor. Roots are the site of water and nutrient uptake from the soil. They grow downward in the soil in response to crop demand for water and nutrients, but growth is constrained by soil temperature and a root growth hospitality factor, which varies with soil depth.

The soil is described by surface properties and characteristics of soil layers and thus essentially has a one dimensional representation. Surface or whole profile properties are the albedo (the reflectance for incoming shortwave radiation), runoff potential, and a drainage factor. Soil layers are identified by depth increments (e.g., 0–5 cm, 5–15 cm). Key parameters for a layer are the water retention characteristics, bulk density, soil texture (portions of sand, silt, clay and coarse material), and water, soil carbon and nutrient levels.

Water from precipitation or irrigation either infiltrates into the soil or is lost through surface runoff. Once in the soil, moisture may evaporate from the soil surface, drain below the bottom of the profile, or be taken up by roots. Runoff varies with daily rainfall (including intensity), CN and the amount of soil moisture at the time of the rainfall event. Infiltration is the difference between precipitation and runoff. The infiltrated water is allocated from the upper layer down through other soil layers following the so-called 'cascade' or 'tipping bucket' approach (Ritchie 1998). For each given soil layer (L), water contents at saturation ($\theta_S(L)$) and drained upper limit ($\theta_U(L)$) are assigned. The difference between $\theta_S(L)$ and the current soil water content ($\theta(L)$) determines the capacity of the layer to hold additional water. If the volume of water to be infiltrated exceeds this amount, then the excess water is allocated to the next layer until all infiltrated water is distributed among soil layers. After infiltration events, a fraction of water in excess of $\theta_U(L)$ is drained based on a whole-profile drainage rate constant (SWCON). If the value of $\theta(L)$ for the lowest soil layer exceeds $\theta_U(L)$, that excess water is assumed to drain out of the profile. If the potential drainage for a layer is very large, the net drainage may be limited by K_{sat}. A more complete explanation is given by Ritchie (1998).

Additional soil processes involve nutrient availability and decomposition of organic matter (mainly from crop residues). These processes are affected by soil moisture and temperature, but the key effects of tillage are indirect, involving incorporation and mechanical degradation of surface crop and weed residues, mixing of soil layers, and changes in bulk density and K_{sat}.

The tillage routines used in CSM are based on procedures first developed by Dadoun (1993) as the CERES-Till model for maize and refined by Andales et al. (2000) for the CROPGRO-Soybean model. The timing and type of tillage are specified in a crop management input file, which also provides data on cultivars planted, the field environment, planting dates and arrangements, and irrigation and fertilizer regimes. This file can describe multiple treatments such as found in field experiments and has a relational architecture (Hunt et al. 2001). The tillage section (Table 2) of the crop management file specifies an identifier for the tillage event, the date of the event, an implement code to identify the implement used, the depth of tillage, and a name or description. The implement code links to a parameter file that specifies the effects of different implements. Multiple instances of a single operation are allowed, such as when a field is disked with multiple passes to achieve a desired tilth.

An input file describing implement effects provides two sets of parameters (Table 3). The first set mainly concerns tillage effects on the soil surface. The four most important parameters are the percent change in CN immediately after an operation (CN%), the percent of surface residue incorporated (R%), the percent of the soil surface area that is disturbed by the field operation (S%), and the mixing efficiency of tillage event (M%). A parameter to specify a reduction in the hard pan

Table 2 Example of the portion of a control file for the CSM model that specifies tillage or other field operations affecting soil properties

*TILLAGE AND ROTATIONS				
@T	TDATE	TIMPL	TDEP	TNAME
1978 Hypothetical tillage in bare fields at Gainesville, FL				
1	78182	TI042	25	Moldboard plow, 30 cm depth
1	78212	TI042	25	Moldboard plow, 30 cm depth
1	78242	TI042	25	Moldboard plow, 30 cm depth
1	78272	TI042	25	Moldboard plow, 30 cm depth
2	78182	TI009	15	Tandem disk
2	78212	TI009	15	Tandem disk
2	78242	TI009	15	Tandem disk
2	78272	TI009	15	Tandem disk
3	78182	TI015	10	Tine harrow
3	78212	TI015	10	Tine harrow
3	78242	TI015	10	Tine harrow
3	78272	TI015	10	Tine harrow
4	78182	TI023	4	Plank
4	78212	TI023	4	Plank
4	78242	TI023	4	Plank
4	78272	TI023	4	Plank
1996–1997 Tillage experiment at Ft. Collins, CO				
1	96289	TI031	7	No-till drill
2	96247	TI003	21	Moldboard plow
2	96252	TI039	10	Roller harrow
2	96289	TI031	7	No-till drill

The field *T* provides an identifier that links to a master table defining all combinations of treatments (e.g., cultivars, planting dates and fertilizer levels) to be simulated, TDATE is the date of the tillage event, TIMPL is a code to identify the field operations that allows linking treatments to a file containing parameters that describe effects of specific implements or operations (examples of values are given in Table 3), TDEP is the depth of tillage in centimeters, and TNAME is the name assigned to the specific tillage event

is also defined, but effects of a hard pan have not yet been implemented in the CSM model.

Two effects of tillage vary with depth, indicated by the lower boundary of the affected depth (Table 3). The first effect is the percent change in bulk density ($B\%(M)$) for soil layer M, and the second is the percent change in K_{sat} ($K\%(M)$). The effects for a given implement and depth may be positive or negative.

The implement file currently contains values for 36 implements or operations that range from moldboard plows to hand hoeing (Table 3). To simulate field operations such as planting that may also affect soil properties (e.g., through soil compaction), entries for seed drills and planters are included. Default values are provided for

Table 3 Examples of parameters provided as default settings to describe effects of different tillage practices or other field operations in the cropping systems model

Implement	Implement code[a]	Change in curve no.	Residue incorporated (%)	Soil surface disturbed (%)	Mixing efficiency (%)	Soil depth (cm)	Change in bulk density (%)	Change in K_{SAT} (%)
Moldboard plow, 30 cm depth	TI0042	−10	95	100	90	25.0	−10	10
						30.0	5	−5
Moldboard plow, 20 cm depth	TI003	−10	95	100	90	15.0	−10	10
						20.0	5	−5
Hand hoeing	TI040	−5	5	100	50	5.0	−5	5
No-till seed drill	TI034	0	20	20	5	5.0	5	0
Plank	TI023	5	20	100	20	4.0	10	−5
Planting stick	TI035	0	10	10	0	5.0	0	0
Roller harrow	TI039	−10	20	100	55	15.0	5	−5
Tandem disk	TI009	−10	50	100	20	7.5	−5	5
Tine harrow	TI015	−5	15	100	20	5.0	−5	5

The actual parameter file is TILOP045.SDA

[a] Corresponding variable names in the parameter file are: implement code, TIMPL; change in curve number, CN2T; residue incorporated, RINP; soil surface disturbed, SSDT; mixing efficiency, MIXT; soil depth, SLB; change in bulk density, SBDT; and change in K_{SAT}, SKST

testing, but users are expected to modify the values based on their tillage implements and soil conditions.

3.1 Effects of tillage via soil mixing

Individual soil components are mixed across soil layers based on the mixing value that corresponds to the tillage implement and the range of soil depths. The routine starts by comparing the depth of tillage specified for the tillage event (Y_T) with the cumulative soil depth to determine which layers (or portions of layers) require mixing. For each soil layer L and a given constituent $X_0(L)$ (e.g., soil moisture or nitrate), the constituent is apportioned into fractions to be mixed, $X_M(L)$, or left unmixed, $X_U(L)$, based on the mixing percentage, $M\%$ for the tillage practice. Thus,

$$X_M(L) = X_0(L) \times M\%/100$$

$X_U(L)$ is calculated as the remaining portion of $X_0(L)$, and $X_M(L)$ is added to the total amount to be mixed (over all layers affected by tillage), ΣX_M. The mixed portion is then added back into each layer to give $X_T(L)$, the amount of the soil component following tillage,

$$X_T(L) = \Sigma X_M \times Z(L)/Y_T + X_U(L)$$

where $Z(L)$ is the depth of the layer L. $Z(L)$ is reduced if only a portion of a layer is tilled.

Surface residues are incorporated separately in routines for soil organic matter, recognizing separate components of carbon, nitrogen and phosphorus. Thus for carbon, the incorporated residue carbon, R_T, is allocated from the total residue mass, R_0, as:

$$R_T = R_0 \times R\%/100$$

where $R\%$ is the portion of R_0 incorporated, as specified for the implement. R_T is then allocated uniformly through the soil layers up to Y_T. Currently, the model does not account for spatial variation in residue incorporation such as from strip tillage, although the implement parameter file allows for specifying the percent of the soil surface that is disturbed by a given field operation. For further information on simulation of soil organic matter dynamics in CSM see the paper by Porter et al. in this special issue (Porter et al. 2009).

3.2 Effects of tillage on soil properties exclusive of mixing effects

The primary effect of tillage on soil physical properties is on bulk density, which varies through the profile and affects the saturated water content, $\theta_S(L)$. Tillage can increase or decrease bulk density, which requires slightly different processing, but we discuss only the case of a decrease in soil bulk density.

To simulate the effects of tillage on bulk density, three soil depths indices are required. The soil depths for the effect of an implement are indexed by M. The depths in the field soil are indexed by N. The third index, L, is a combined index for depths of tillage and soil layers, which is required since the depths indexed by M and N seldom match.

For each soil layer, the current bulk density, $B_C(N)$, is reduced by the implement-specific tillage effect, $B\%(M)$,

$$B_T(L) = B_C(N) \times (1.0 + B\%(M)/100)$$

For tillage that reduces bulk density, values of $B\%(M)$ are negative.

The saturated water content for a soil layer L, $\theta_S(L)$, is calculated from the bulk density by assuming that soil particles have a density of 2.66 g cm^{-3} and that 95% of the air space can be occupied by water,

$$\theta_S(L) = 0.95 \times (1.0 - (B_T(L)/2.66)).$$

Effects of tillage on K_{SAT} are also specified as a percent change that varies with soil depth, $K\%(M)$. Thus, the value prior to tillage, $K_0(N)$, is adjusted accordingly to give the tilled value, $K_T(L)$.

$$K_T(L) = K_0(N) \times (1.0 + K\%(M)/100).$$

After calculating tillage effects on a given day, further processing is required to redistribute the soil properties, so that the post-tillage soil layers correspond to pre-tillage soil layers. Soil layer thicknesses are recomputed based on post-tillage bulk densities to preserve mass for all soil constituents.

3.3 Soil settling or loosening with rainfall (from SOILDYN.FOR)

When effects of tillage on bulk density are simulated, the processes of soil settling or loosening due to rainfall or irrigation also need to be considered. Settling and loosening of soil are assumed to be driven by the kinetic energy of water from rainfall and irrigation. Since the model uses a daily time step, these effects are simulated on a daily basis. A relation was estimated by regression analysis of rainfall data of Treynor, Iowa, by Andales et al. (2000) as:

$$\Sigma E_{\mathrm{K}(t)} = \Sigma E_{\mathrm{K}(t-1)} + 0.00217 \times \Sigma P_t$$

where $\Sigma E_{\mathrm{K}(t)}$ is the cumulative kinetic energy on day t, with units of J cm^{-2}, and ΣP_t is the cumulative daily rainfall in millimeters for the same period. Currently, irrigations are assumed to impart the same kinetic energy as rainfall, with the exception that drip irrigation imparts no energy.

In the routine for effects of kinetic energy, a flag indicating that tillage has occurred is set the first day that the current bulk density of any soil layer differs from the initial bulk density of that layer by more than 0.01 g cm^{-3}. The cumulative kinetic energy since the last tillage event, ΣE_{K}, is then reset to zero. Each day that there is rainfall (or an irrigation), the daily total, P in mm, is used to calculate the increase in kinetic energy. Soil cover (S, as a fraction from 0 to 1) is assumed to protect the soil, so the actual increment is

$$\Sigma E_{\mathrm{K}(t)} = \Sigma E_{\mathrm{K}(t-1)} + 0.00217 \times P \times (1 - S)$$

where t and $t-1$ denote the current and previous days, respectively.

The effective kinetic energy affecting a layer L, $\Sigma E_{\mathrm{K}}(L)$, is assumed to decrease exponentially with mean soil depth of the layer, $\overline{Y}(L)$,

$$\Sigma E_{\mathrm{K}}(L) = \Sigma E_{\mathrm{K}} \times \mathrm{e}^{-0.05\times\overline{Y}(L)}.$$

The proportional change in a given soil property, β, is determined by the product of $\Sigma E_{\mathrm{K}}(L)$ and a rate of change in the soil property, F, with units of cm^2 J^{-1},

$$\beta = \mathrm{e}^{-F\times\Sigma E}K^{(L)}$$

The value of F varies with the relative strength of the soil aggregates, AS (scaled from 0 to 1), which is assumed to increase with the organic content of the soil, OC(L) expressed as a percentage. Thus, AS is estimated as

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

and F as

$$F = \mathrm{SS} \times (1.0 - \mathrm{AS})$$

where SS is a soil settling rate, currently assigned a value of 30 cm^2 J^{-1} for all soils and soil parameters.

Paralleling the effects of tillage on soil properties, rainfall also affects bulk density, saturated hydraulic conductivity, saturated water content, and a root growth impedance factor. The same form of effect is assumed for all parameters,

$$U_S(L) = U_0(L) + ((U_T(L) - U_0(L)) \times \beta)$$

where $U_S(L)$ is the value of the parameter after settling or recovery from compaction. Note that β proportionally reduces the difference of the tilled value from the prior value, regardless of whether tillage resulted in a decrease (settling) or increase in a given soil parameter.

4 Evaluation of the model

To illustrate the response of the model to tillage, two cases were simulated. The first is a hypothetical case of a bare field tilled with four implements. The second is for a tillage and residue management study involving winter wheat (McMaster et al. 2002).

4.1 Sensitivity analysis with four implements

The simulations of a bare field used the four implements whose qualitative effects are presented in Fig. 1. The soil was a Millhopper fine sand. Weather data were used from Gainesville, Florida, USA. The field was tilled once every 30 days, starting on 1 July 1978 and continuing for four tillage dates. Three soil layers were considered: 0–5 cm, 5–15 cm and 15–30 cm.

The first series of simulations excluded rainfall and irrigations, so the effects on bulk density are due only to tillage. The deepest tillage effect was from the mold board plow, which was assumed to reach 25 cm deep, as specified in Tables 2 and 3. Between the soil surface and 5 cm depth, each plowing loosened the soil, reducing the bulk density (Fig. 2a). In the 5–15 cm layer (Fig. 3a), plowing still decreased bulk density, but for the 15–30 cm layer (Fig. 3b), there was little change in bulk density. The latter response reflects counterbalancing effects of tillage within the layer. For the upper portion of 15–30 cm, the parameters for plowing reduced bulk density, for the middle portions of the layer, bulk density increased, and for the lower portion, no change was expected because plowing only reached to 25 cm.

When an effect of rainfall was considered, the loosening effect of plowing was lost if there was sufficient rainfall. Thus, after the first tillage, bulk density returned to the initial value within 10 days, whereas after the third tillage, when there was much less rainfall, the change in bulk density was largely sustained (Fig. 2b).

Disking penetrated only to 7.5 cm, so most of the effects were in the top 5 cm of soil (Figs. 2a, 3a, b). Tine harrowing and planking only affected this top soil layer. Rather than loosening the soil, planking smoothed and compacted the soil (e.g., for improved seed-soil contact). The planking effect was largely offset by rainfall events (Fig. 2b).

Figure 4 shows additional effects of the plow, tandem disk and tine harrow on soil water content, excluding rainfall. With each tillage event, the uppermost soil layer briefly increased in moisture content due to soil mixing (Fig. 4a), mirrored as a decrease in soil moisture in the second layer (Fig. 4b). As for effects on bulk density, moisture effects in the 15–30 cm layer were minimal except with plowing (Fig. 4c).

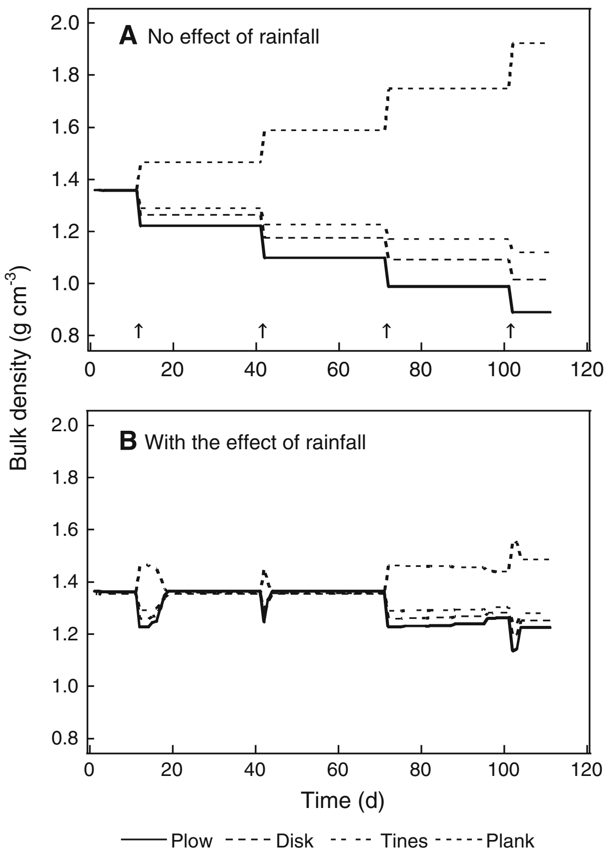

Fig. 2 Simulated changes in soil bulk density for the 0–5 cm soil layer for tillage every 30 days by a plow, tandem disk, tine harrow, and planking. **a** With no effect of rainfall to cause settling or to relieve compaction. **b** With the effect of rainfall. *Upward arrows* in **a** indicate dates of the four tillage events

4.2 Application to a winter wheat tillage experiment

Winter wheat in northern Colorado, USA, is normally grown under rainfed conditions, and water deficits usually limit grain yield. The crop is sown from mid-September to mid-October. The crop over-winters in a semi-dormant phase, resumes growth in the spring, and matures in July. McMaster et al. (2002) conducted an experiment over 7 years to compare effects of pre-planting tillage vs. no-till with three levels of crop residues (no residue, normal mass of residue from the previous wheat crop, and double the mass from a previous crop). No-till was expected to conserve soil moisture prior to planting, resulting in better seed germination and seedling growth. Improved crop establishment should also allow the crop to compete better with weeds. Early crop growth and residue are important in capturing more snow, so the enhanced growth from no-till plus benefits of the residue should further enhance spring growth. The conventional tillage consisted of moldboard plowing to 21 cm soil depth, followed about 1 week later by roller harrowing.

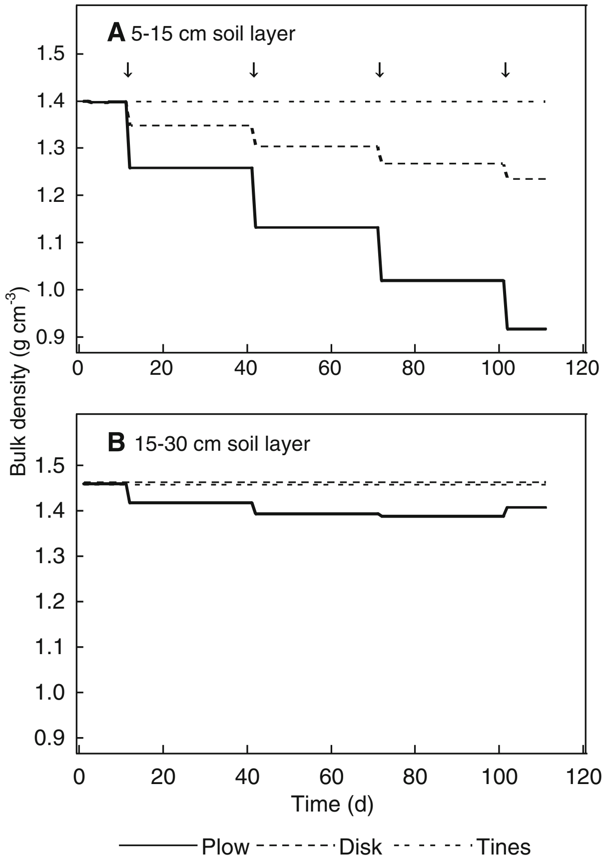

Fig. 3 Simulated changes in soil bulk density for the 5–15 cm and 15–30 cm soil layers for tillage every 30 days by a plow, tandem disk, and tine harrow. No effect of rainfall to cause settling or to relieve compaction was simulated. **a** 5–15 cm soil layer. **b** 15–30 cm soil layer. *Downward arrows* in **a** indicate dates of the four tillage events

Results are presented for the 1994–1995 and 1996–1997 seasons. The 1994–1995 season received over 100 mm more precipitation than the 1996–1997 season (Fig. 5a), but the two seasons had nearly identical patterns of potential demand for water, as indicated by potential evapotranspiration (Fig. 5b). Observed and simulated end-season above-ground dry matter was higher in 1994–1995 (Fig. 6). In part, the growth difference was likely due to the 1996–1997 crop being planted about a month later (14 Sept. 1994 vs. 15 Oct. 1996). In both seasons, the no-till treatments performed better than the plowed treatments, and this difference was reflected in the simulations. Subsequent discussion focuses on the no-till and plowed treatments, considering only the treatments with the normal residue level.

The soil layer that extends from 5 to 15 cm deep—this is a nominal range since the depth varies with tillage—best indicated the effects of tillage because responses in this layer were less dynamic than the surface layer and because the second layer

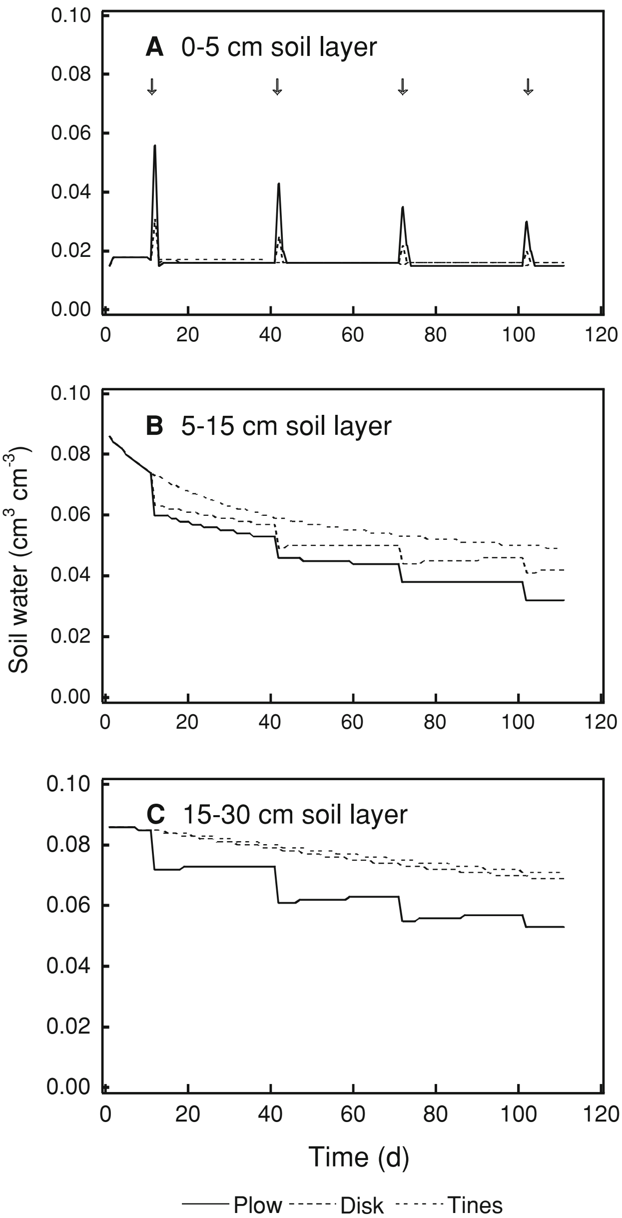

Fig. 4 Simulated changes in soil water content for three soil layers tilled every 30 days by a plow, tandem disk, and tine harrow. No effect of rainfall to cause settling or to relieve compaction was simulated. **a** 0–5 cm soil layer. **b** 5–15 cm. **c** 15–30 cm. *Downward arrows* in **a** indicate dates of the four tillage events

supplied an important portion of moisture to the crop, especially during early growth (data not shown). In both seasons, the bulk density decreased with plowing (Fig. 7a, b), but the return to a value around 1.3 g cm^{-3} was slower in 1994–1995

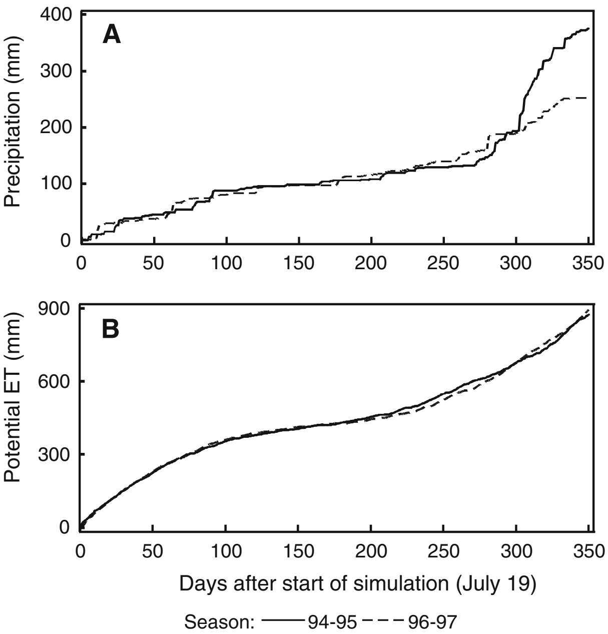

Fig. 5 Cumulative precipitation and potential evapotranspiration for the tillage experiments at Ft. Collins, CO for the 1994–1995 and 1996–1997 cropping seasons. **a** Precipitation. **b** Potential evapotranspiration

because there was less rainfall after the tillage event. The no-till treatment showed a negligible change in bulk density due to an effect of the seed drill.

The effect of soil mixing is seen in the large differences in soil moisture between the tillage treatments after plowing. Mixing of the 5–15 cm layer with drier soil from the top layer substantially decreased soil moisture. In 1994–1995, however, 20 mm of precipitation from day 88–92 partially replenished the soil. Since the no-till crop had access to more moisture during early growth, plants were larger and extracted a greater volume of water, causing the decline in moisture from day 90 to 150 in the no-till treatment. In 1996–1997, soil moisture started higher in the no-till crop, but the two treatments converged as the crop progressed.

Space limitation does not allow a more detailed discussion of how the simulated differences relate to field performance, including effects of crop residue on yield. However, the described results provide a qualitative view of the effects of tillage on soil bulk density and moisture over time.

5 Discussion

The implementation of tillage in CSM represents an important advance in allowing users to examine effects of tillage and residue management on crop production and soil resources. The qualitative responses appear realistic, and basic tests for

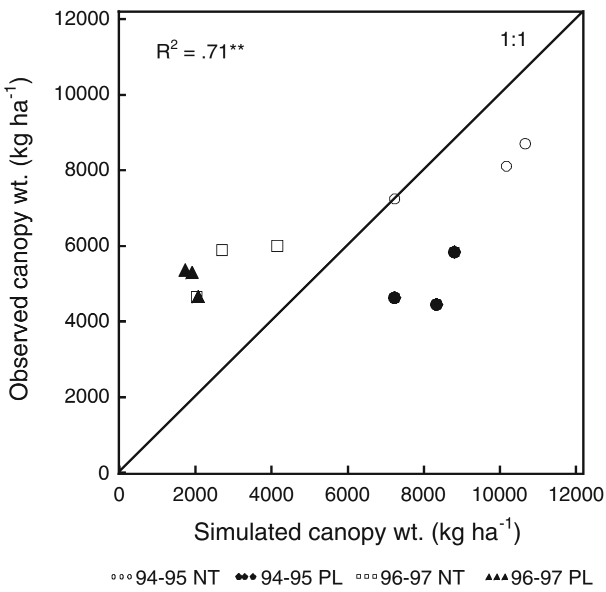

Fig. 6 Comparison of simulated versus observed effects of no-till (NT) and conventional tillage with a plow (PL) on winter wheat above ground (canopy) dry matter at Ft. Collins, CO for the 1994–1995 and 1996–1997 cropping seasons. Three values within each tillage and season combination are no residue, normal residue and 2× residue treatments

conservation of mass indicate that the complexities of soil mixing and changes in bulk density are properly implemented. Further testing is needed to refine the parameterization of different tillage practices, but the results from the wheat study suggest that the model already is suitable for exploring effects of various tillage practices. Among possible applications are assessing the potential for zero or reduced tillage to conserve soil moisture in different regions and estimating effects of residue incorporation on soil carbon.

The current implementation, however, is viewed largely as providing a framework for further evaluation and future improvement. Issues of spatial and temporal scale are discussed below. The effects of specific types of tillage also merit further study. Variation in crop residue types is ignored, but Buckingham et al. (2007) indicated that degree of incorporation varies with the texture of the residue. Effects of tillage also should vary with soil type and moisture content. The possibility of describing soil mixing by soil fauna, which is especially important in conservation tillage (Kladivko 2001), also merits study.

5.1 Problems of scale in modeling tillage

Among the challenges encountered in implementing the tillage effects were issues of spatial and temporal scales. Soils are represented in a single dimension using soil layer increments that usually are 5 cm or thicker. Unidimensionality constrains simulation of any management that involves furrows, hilling or horizontal

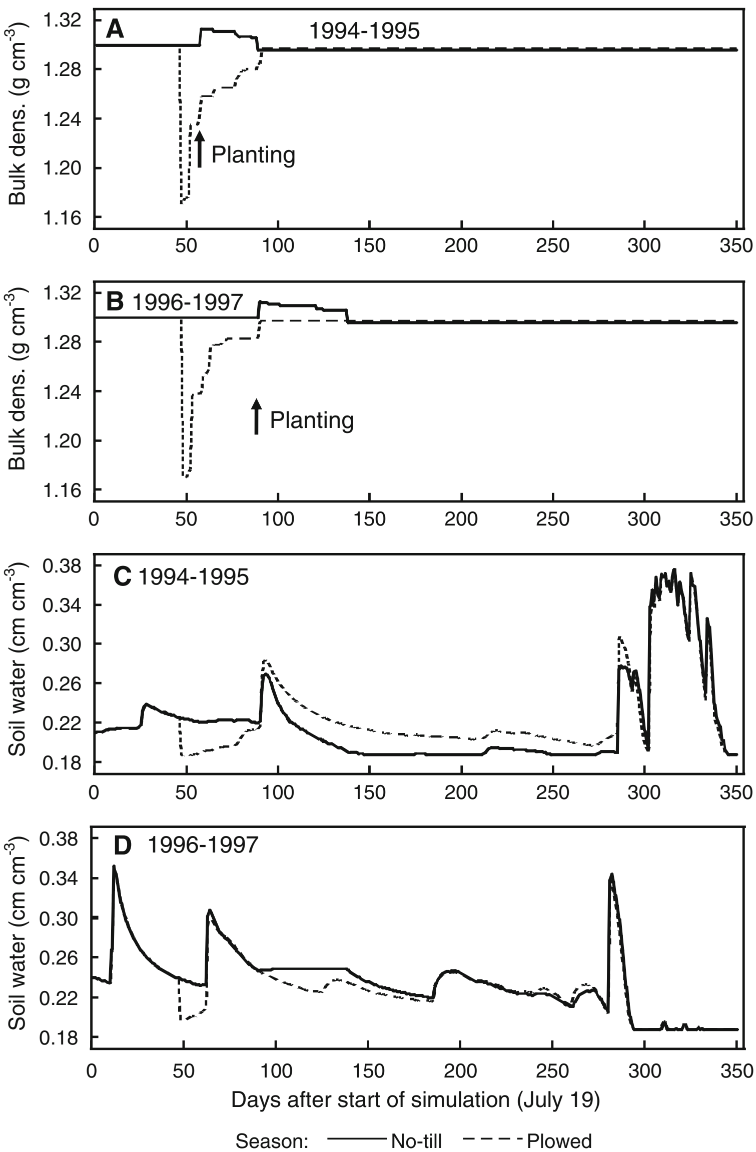

Fig. 7 Comparison of effects of no-till (NT) and conventional tillage with a plow (PL) on simulated bulk density and soil moisture for the 5–15 cm soil layer (nominal depth) at Ft. Collins, CO for the 1994–1995 and 1996–1997 cropping seasons and normal residue. **a** Soil bulk density for 1994–1995. **b** Soil bulk density for 1996–1997. **c** Soil water for 1994–1995. **d** Soil water for 1996–1997

distribution of crop residues on the soil surface. Temporal scale is an issue when dealing with events whose sequencing within a day would impact model outputs and in estimating the kinetic energy of rainfall. We examine these issues in the context of the CSM model.

Various tillage practices modify the topography of the soil surface. The passage of tractor wheels can be a major contributor to compaction as well as create ruts that become channels for runoff (Défossez et al. 2003). Furrows or beds are created to facilitate irrigation management or other operations. Furrows concentrate water in a limited portion of the soil, which can reduce the portion of the soil surface that becomes moist and thus has a large impact on soil evaporation. An extreme instance is with alternate row irrigation, where the wetted surface is limited to every other furrow. Depending on the orientation of the furrow to the slope of the field, furrows also may substantially increase or decrease potential for runoff. Strip-tillage involves tillage conducted parallel to crop rows and that disturbs less than the full width of a row. It is often performed to prepare a good seed-bed while otherwise limiting disturbance to soil and residues (Bolton and Booster 1981). Besides providing good tilth for seed germination, strip-tillage can result in a drier and warmer seed bed (Licht and Al-Kaisi 2005). Hilling involves heaping soil higher than the original base of the plant. Functions include protecting harvested materials (e.g., to prevent green skins in potato tubers), improving harvest quality (blanching of vegetables), stimulating growth, controlling weeds, and reforming furrows.

Some models consider a two dimensional soil, but they do not consider topography at sub-meter scales, which would be required to handle furrows, strip-tillage or effects of wheel tracks. A solution intermediate to a two or three dimensional representation of the soil surface with residues would be to define two zones, one as tilled and the other as undisturbed. Processes in these zones would only be simulated separately until partial canopy cover was achieved. For example, water balances and soil temperatures could be calculated for each zone. The approach seems best suited for models that estimate canopy width and track sunlit and shaded soil surfaces. Similarly, effects of furrows on runoff, infiltration and evaporation might be modeled either by partitioning the soil surface into zones or using empirical factors that adjust relevant processes based on the presence of furrows.

One difficulty with temporal scales concerns timing of management practices. For example, whether the soil is tilled prior to or after the fertilizer has been applied to the soil surface affects how the fertilizer is distributed in the soil. When events occur within a single day, CSM assumes a fixed order for management events based on expectations from the most common practices. Fertilizers and residues are applied first, followed by tillage, planting, and irrigation. Effects of rainfall on soil compaction are estimated at the same time as irrigations. Thus, for a given day, an ordinal time scale is assumed. While continuous scheduling with actual start and completion times could be implemented, this approach would substantially increase model complexity because of the need to consider simultaneous or overlapping processes. Irrigations often are conducted overnight and are sometimes used to deliver fertilizer. Tilling a large field may require multiple days, while "one pass" implements may perform strip-tillage, apply a fertilizer, and plant the crop in one operation. Relatively few users would require precise accounting of timing, and the additional net benefit to CSM users likely would be offset by the need to request detailed inputs, increasing the potential for errors. A compromise would be to allow users to input the order of a series of events and field operations within a single day.

Estimation of the kinetic energy from rainfall or irrigation also involves temporal scale. Rainfall intensity varies at scales of minutes, but CSM infers characteristics of intensity from daily rainfall. The review by van Dijk et al. (2002) noted that there is great uncertainty in estimating kinetic energy, even when the droplet size distribution is characterized. Where rainfall intensity data are available, daily totals of rainfall kinetic energy might be estimated and included as an additional input. Alternately, one might use rainfall disaggregation algorithms to infer the rainfall intensity (e.g., Kandel et al. 2004; Debele et al. 2007), and thence the intensity and kinetic energy. Most forms of irrigation are currently assumed to provide the same kinetic energy as rainfall, which is unrealistic. Analogous problems involving rainfall and irrigation intensity exist with estimation of runoff using daily totals, so better estimation of intensity or kinetic energy might improve estimation of runoff as well.

A common thread to the concerns over spatial and temporal scales is that for over 20 years, simple approaches for representing space and time have worked well in CSM and its predecessors. This simplicity undoubtedly contributed to the widespread adoption of the CSM model. As needs of users evolve, simplifications impose constraints. However, further modifications, such as subdividing the upper soil layer to accommodate strip-tillage, may be less expedient than they first seem. Introducing multiple approximations makes the code more complex and difficult to maintain and may require users to specify values for parameters that are not readily measured from basic physical or biological responses. The general expectation is that increasing the number of parameters can decrease model reliability due to propagation of parameter errors (Reynolds and Acock 1985). Thus, the question of appropriate temporal and spatial scales is also linked to long-discussed tradeoffs between models that provide accurate predictions for immediate decision support use vs. ones that attempt to fully integrate the known biological, chemical and physical processes (Nihoul 1994; Passioura 1996).

6 Conclusions

The ability of CSM to simulate effects of tillage increases the potential applications of the model, especially in relation to water, nutrient and soil organic matter management. The simple approach based mainly on consideration of soil mixing and changes in bulk density, runoff, and soil water holding capacity provides a framework for further improvements. However, as capabilities of the model are expanded, the number of parameters required increases, increasing the potential for errors in parameterization and as well as making the model more difficult to use correctly. For the CSM model, which uses a one dimensional soil profile and a daily time step, further enhancements to representation of tillage might require a more complex representation of the soil and use of finer time steps. Alternatively, judicious subdivision of the soil surface and chronological indexing of different management events might improve the robustness and applicability of the model.

References

Andales AA, Batchelor WD, Anderson CE (2000) Incorporating tillage effects into a soybean model. Agric Syst 66:69–98

Bolton FE, Booster DE (1981) Strip-till planting in dryland cereal production. Trans ASAE 24:59–62

Buckingham F et al (2007) Tillage. Deere & Company, Moline

Cannell RQ, Hawes JD (1994) Trends in tillage practices in relation to sustainable crop production with special reference to temperate climates. Soil Till Res 30:245–282

Dadoun FA (1993) Modeling tillage effects on soil physical properties and maize (*Zea mays* L.) development and growth. Unpublished Ph.D. thesis, Michigan State University, MI

Debele B, Srinivasan R, Yves Parlange J (2007) Accuracy evaluation of weather data generation and disaggregation methods at finer timescales. Adv Water Resour 30:1286–1300

Défossez P, Richard G, Boizard H, O'Sullivan MF (2003) Modeling change in soil compaction due to agricultural traffic as function of soil water content. Geoderma 116:89–105

Hobbs PR, Sayre K, Gupta R (2008) The role of conservation agriculture in sustainable agriculture. Philos Trans R Soc B Biol Sci 363:543–555

Hoogenboom G, Jones JW, Wilkens PW, Porter CH, Batchelor WD, Hunt LA, Boote KJ, Singh U, Uryasev O, Bowen WT, Gijsman AT, White JW, Tsuji GY (2009) Decision support system for agrotechnology transfer, DSSAT4.5. University of Hawaii, CD-ROM, Honolulu

Hunt LA, White JW, Hoogenboom G (2001) Agronomic data: advances in documentation and protocols for exchange and use. Agric Syst 70:477–492

Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ, Ritchie JT (2003) DSSAT cropping system model. Eur J Agron 18:235–265

Kandel DD, Western AW, Grayson RB, Turral HN (2004) Process parameterization and temporal scaling in surface runoff and erosion modelling. Hydrol Processes 18:1423–1446

Kladivko EJ (2001) Tillage systems and soil ecology. Soil Till Res 61:61–76

Knowler D, Bradshaw B (2007) Farmers' adoption of conservation agriculture: a review and synthesis of recent research. Food Policy 32:25–48

Licht MA, Al-Kaisi M (2005) Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Till Res 80:233–249

Lipiec J, Hatano R (2003) Quantification of compaction effects on soil physical properties and crop growth. Geoderma 116:107–136

Lobb DAR, Huffman E, Reicosky DC (2007) Importance of information on tillage practices in the modelling of environmental processes and in the use of environmental indicators. J Environ Manage 82:377–387

McMaster GS, Palic DB, Dunn GH (2002) Soil management alters seedling emergence and subsequent autumn growth and yield in dryland winter wheat-fallow systems in the Central Great Plains on a clay loam soil. Soil Till Res 65:193–206

Nihoul JCJ (1994) Do not use a simple model when a complex one will do. J Mar Syst 5:401–406

Passioura JB (1996) Simulation models: science, snake oil, education, or engineering? Agron J 88:690–694

Reynolds JF, Acock B (1985) Predicting the response of plants to increasing carbon dioxide: a critique of plant growth models. Ecol Modell 29:107–129

Ritchie JT (1998) Soil water balance and plant water stress. In: Tsuji GY, Hoogenboom G, Thornton PK (eds) Understanding options for agricultural production. Kluwer, Dordrecht, pp 41–54

Sommer R, Wall PC, Govaerts B (2007) Model-based assessment of maize cropping under conventional and conservation agriculture in highland Mexico. Soil Till Res 94:83–100

van Dijk AIJM, Bruijnzeel LA, Rosewell CJ (2002) Rainfall intensity-kinetic energy relationships: a critical literature appraisal. J Hydrol 261:1–23

Porter CH, Jones JW, Gijsman AJ, Adiku S, Dzotsi K, Gargiulo O, Naab JB (2009) Modeling organic carbon in DSSAT v4.5. ORIJ. doi:10.1007/s12351-009-0059-1