Trans-Disciplinary Soil Physics Research Critical to Synthesis and Modeling of Agricultural Systems

Lajpat R. Ahuja,* Liwang Ma, and Dennis J. Timlin

ABSTRACT

Synthesis and quantification of disciplinary knowledge at the whole system level, via the process models of agricultural systems, are critical to achieving improved and dynamic management and production systems that address the environmental concerns and global issues of the 21st century. Soil physicists have made significant contributions in this area in the past, and are uniquely capable of making the much-needed and exciting new contributions. Most of the exciting new research opportunities are trans-disciplinary, that is, lie on the interfacial boundaries of soil physics and other disciplines, especially in quantifying interactions among soil physical processes, plant and atmospheric processes, and agricultural management practices. Some important knowledge-gap and cutting-edge areas of such research are: (1) quantification and modeling the effects of various management practices (e.g., tillage, no-tillage, crop residues, and rooting patterns) on soil properties and soil–plant–atmosphere processes; (2) the dynamics of soil structure, especially soil cracks and biochannels, and their effects on surface runoff of water and mass, and preferential water and chemical transport to subsurface waters; (3) biophysics of changes in properties and processes at the soil–plant and plant–atmosphere interfaces; (4) modeling contributions of agricultural soils to climate change and effects of climate change on soil environment and agriculture; and (5) physical (cause-effect) quantification of spatial variability of soil properties and their outcomes, new methods of parameterizing a variable field for field-scale modeling, and new innovative methods of aggregating output results from plots to fields to larger scales. The current status of the various aspects of these research areas is reviewed briefly. The future challenges are identified that will require both experimental research and development of new concepts, theories, and models.

Understanding real-world situations and solving significant agronomic, engineering, and environmental problems require process-based synthesis and quantification of knowledge at the whole system level. In the 20th Century, we made tremendous advances in discovering fundamental principles in different scientific disciplines using reduction methods, which created major breakthroughs in management and technology for agricultural systems. However, as we enter the 21st Century, agricultural research has more difficult and complex problems to solve. The environmental consciousness of the general public is challenging producers to modify farm management to protect water, air, and soil quality, while staying economically profitable. At the same time, market-based global competition in agricultural production and the global climate change are threatening economic viability of the traditional agricultural systems, and require the development of new and dynamic production systems. Site-specific, optimal management of spatially variable soil, appropriately selected crops, and available water resources on the landscape can help achieve both environmental and production objectives. Fortunately, the new electronic technologies can provide a vast amount of real-time information about soil and crop conditions via remote sensing with satellites or ground-based instruments, which, combined with near-term weather, can be utilized to develop a whole new level of site-specific management. However, we need the means to assimilate this vast amount of data. A synthesis and quantification of disciplinary knowledge at the whole-system level, via process-based modeling of agricultural systems, is essential to develop such means and the management systems that can be adapted to continual change. Interactions among disciplinary components of the agricultural systems are generally very important. Models are the only way to find and understand these interactions in a system, integrate various experimental results and observations for different conditions, and extrapolate limited experimental results to other soil and climate conditions.

An agricultural system is complex (Fig. 1; also see Fig. 3) and needs interdisciplinary field research and quantification. Integration of system models with field research has the potential to raise agricultural research to the next higher level. It is also an essential first step to improve model integrity, reliability, and usability. The integration will benefit both field research and models in the following ways:

- Promote a systems approach to field research, which looks at all component interactions
- Facilitate better understanding and quantification of research results
- Promote efficient and effective transfer of field research results to different soil and weather conditions, and to different cropping and management systems outside the experimental plots
- Help field researchers to focus on the identified fundamental knowledge gaps and make field research more efficient
- Provide the needed field test and improvement of the models before delivery to other potential users—agricultural consultants, farmers, ranchers, extension agencies, and action agencies (NRCS, EPA, and others).

Field-tested models can be used as decision aids or guides for best management practices, including site-specific management or precision agriculture (Ahuja

---

L.R. Ahuja and L. Ma, USDA-ARS, Great Plains Systems Research Unit, Fort Collins, CO 80526, USA; D.J. Timlin, USDA-ARS, Crop Systems and Global Change Lab., Beltsville, MD 20705. Received 29 June 2005. *Corresponding author (Laj.Ahuja@ars.usda.gov).

Published in Soil Sci. Soc. Am. J. 70:311–326 (2006).
Reviews and Analyses and Soil Physics
doi:10.2136/sssaj2005.0207

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: DSS, decision support system.

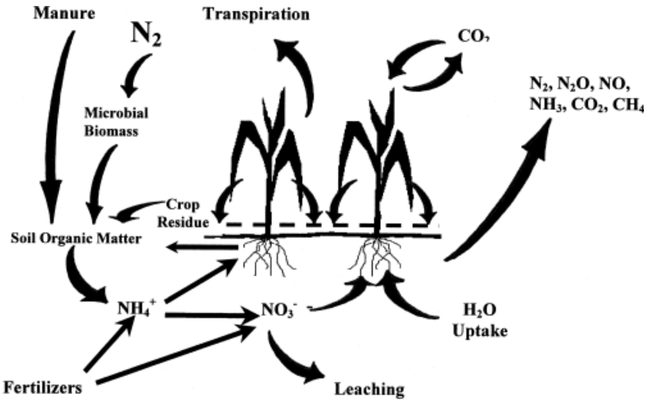

Fig. 1. Complex nature of an agriculture system, illustrated by the C-N cycle. Also see Fig. 3.

and Ma, 2002), as tools for in-depth analyses of problems in management, environmental quality, global climate change effects, and other emerging issues, and as guides for planning and policymaking (Ahuja et al., 2002). Models can be used to explore new ideas and strategies under different weather and climatic conditions before testing them in expensive field experiments. The most desirable vision for agricultural research and technology transfer is to have a continual two-way interaction among the cutting-edge field research, process-based models of agricultural systems, and management decision support systems (Fig. 2). Field research can certainly benefit from process models as described above, but also a great deal from the feedbacks from the management decision support systems (DSSs). On the other hand, field research forms the basis for models and DSSs.

System modeling has been a vital step in many scientific disciplines. We would not have gone to the moon successfully without the combined use of good data and models. In automobile designing, computer models of the system are increasingly replacing the scaled physical models of the past. Models have also been used extensively in designing and managing water resource reservoirs and distribution systems, and in analyzing waste disposal sites. Although agricultural system models have made substantial progress (Ahuja et al., 2002), a lot more work is needed to bring them to the level of physics, engineering, and hydraulic system models. In particular, we need to improve on the methods and structure of building models so that: (1) the models are modular, with each model component (module) clearly defined, documented, and assigned a degree of uncertainty; (2) each model component can be independently tested and improved, and can be easily substituted; (3) the whole world community can contribute to developing, testing, and improving components; (4) the components may vary with the scale of application; (5) hierarchical parameter estimation from varying degree of input information is a component of the model; (6) the assembled models of the system are kept compact and easy to use by customizing them to agroecosystem regions; (7) a user-friendly interface is provided for easy input of data and output of results; and (8) a well-illustrated user manual is provided to illustrate a step-by-step procedure for running the model and some examples of model application that demonstrate the benefits of using the model as well as the uncertainty in results. An Object Modeling System, with a library of components (modules), being developed by the USDA-ARS (Ahuja et al., 2005), will hopefully incorporate all the above features.

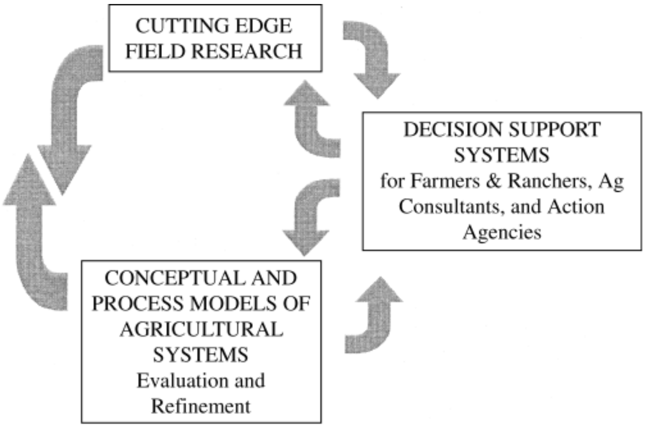

Fig. 2. The desirable continual two-way interactions among the field research, conceptual and process models of agricultural systems, and the simplified management decision support systems.

SOIL PHYSICISTS CAN MAKE A GREAT IMPACT

Variation of soil physical properties and their effects on soil water movement and retention, heat movement, soil temperature, chemical transport, root activity, and soil biota functioning, involving both measurements and theory, have been the core of soil physics research. However, the scope of soil physics has gradually expanded toward interdisciplinary boundaries (transdisciplinary) because of the central role of soil water in agricultural systems (Fig. 3). Examples of soil physics research in the interfacial areas include: modeling the linkage of transpiration and photosynthesis (Tanner, 1981; Tanner and Sinclaire, 1983), energy balance on crop canopies (van Bavel and Lascano, 1987), root water uptake (Nimah and Hanks, 1973; Feddes et al., 1976; Campbell, 1991), root growth modeling (Clausnitzer and Hopmans, 1994; Benjamin et al., 1996), and nutrient uptake by roots (Cushman, 1979). Due to the quantita-

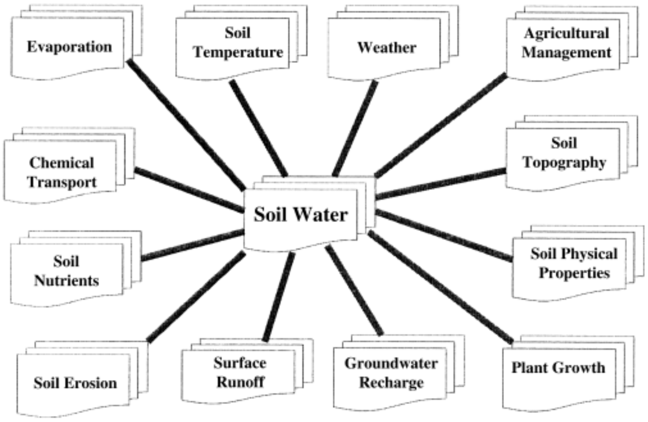

Fig. 3. The central role of soil water in agricultural systems.

tive nature of soil physics research, soil physicists have also contributed significantly to the development of agricultural system models in the past beyond the soil physics components (e.g., Nimah and Hanks, 1973; Seligman and van Keulen, 1981; Baker et al., 1983; Ritchie et al., 1986; Whisler et al., 1986; Ahuja et al., 2000a). They (soil physicists) have an important role to play in further understanding of interfacial areas and agricultural systems, especially in quantifying the interactions among the soil physical processes, plant and atmosphere processes, and agricultural management practices. Some important knowledge-gap and cutting-edge areas of such research in soil physics are given below.

1. The most important area is the quantification and modeling of agricultural management and cropping effects on soil properties and soil-plant-atmosphere processes. This quantification has to be a centerpiece of an agricultural system model, if it is to have useful applications in field research and decision support for improved management. Management practices such as tillage, no-tillage with crop residues and wheel tracks, cover crops, animal waste and by-product applications, and others affect soil physical and hydraulic properties, infiltration and runoff, erosion, root growth dynamics, preferential flow, evapotranspiration, crop productivity, and other agronomic aspects. Related to this research is a national need to quantify and assess the effect of conservation and best management practices for environmental (water, air, and soil) quality protection.
2. Dynamics of soil structural changes that greatly influence water flow and mass transport. Further work is needed to quantify the opening and closure of cracks as a function of soil water content changes, and preferential flow of surface water and chemicals through cracks to deeper soil layers and groundwater. How does root growth change soil physical properties—pore sizes, porosity, hydraulic conductivity, and hence water movement and transport in the rhizosphere?
3. Physics or biophysics of changes in properties and processes at the soil-root/shoot and shoot-atmosphere interfaces need much more work. These changes greatly affect the physical processes and many other processes in the system. This will require combined experimental and theoretical studies on: 1) root growth and uptake of water and nutrients under water limiting and non-limiting conditions and their effect on water movement and mass transport. Does the convective dispersion equation hold under extreme wetting-drying and plant uptake conditions? Is it possible to adequately handle water flow and chemical transport in row crops with 1-D models? and 2) biophysics of water and nutrient states and fluxes at the soil-root and canopy-atmosphere interfaces–passive versus active uptake, their effect on water, energy, and mass transport in the bulk soil and canopy.
4. Modeling the contribution of agricultural systems to greenhouse gas emissions, C sequestration, and global climate change; effect of climate change, especially the increased frequency of extreme events (droughts, heavy rainfalls), on soil environment and agriculture; and changes in management to mitigate or minimize adverse effects.
5. Spatial variability and model uncertainty; Cause-and-effect physical quantification of spatial variability of soil properties and soil water, such as by relating them to topographic attributes, land use, and management; new methods of parameterizing a spatially variable field for field scale modeling of water and chemical transport; new innovative methods for aggregating output results from plots to fields and larger scales, such as by relating to a key scaling parameter; large scale hydrologic processes.

The above goals will require new experimental research as well as development of new or improved concepts and theories. The areas of work are interrelated in some respects, and soil physicists are naturally positioned to provide synthesis bridges between them. These goals pose challenges to soil physicists, but ones that will be exciting and will provide joy and satisfaction of contributions toward real needs. In addition, there are several other trans-soil physics areas where further research needs to be continued, for example the mechanics of soil erosion by water and wind in relation to water and air quality.

CURRENT STATUS AND FUTURE CHALLENGES

Quantifying and Modeling Management Effects on Soil Properties and Processes

In the last 30 yr, soil physicists have taken on the challenge of addressing real-world problems, and moved on from laboratory scale studies to field and landscape scales. These studies have shown substantial evidence of significant temporal variability of soil physical properties and processes. Temporal variability in soil properties and processes may be greater than spatial variability (Van Es et al., 1999). Agricultural management practices, such as tillage and reconsolidation, other field operations with heavy machinery, no-tillage and surface residues, plants and crop rotations, irrigation, manure and fertilization practices, and grazing management, are major sources of temporal variability of soil properties and processes. The changes in soil properties and processes, in turn, impact soil water, mass transport, plant growth dynamics, and the environment. Weather-related factors, such as freezing-thawing and wetting-drying, may modify the management effects. Numerous field studies have shown evidence of the significant management effects on soil-water-nutrient-plant properties and processes. However, the results vary widely across locations, soils, and experiments, and are often inconsistent due, most likely, to variability of controlling factors. Very small effort has been made to synthesize the site-specific effects into hypotheses and theories, design well-controlled experiments to evaluate these, and quantify the effects for practical applications. Yet, it is only through such synthesis and quantification that we can develop suitable management practices to solve complex problems.

Below, we summarize the state-of-the-science of quantifications in important areas where knowledge gaps exist for future predictive research. The presentation is built on our earlier work (Ahuja et al., 2000a, 2000b; Rojas and Ahuja, 2000; Green et al., 2003).

Predicting Effects of Tillage and Natural Reconsolidation

Tillage and subsequent reconsolidation due to wetting and drying can change soil bulk density and porosity, soil hydraulic properties, surface roughness, and depression storage of rain.

Soil Bulk Density and Porosity

Tillage initially decreases soil bulk density and increases porosity of the tilled zone, which later gradually revert back to the original state due to reconsolidation during cycles of wetting and drying (Cassel, 1983; Onstad et al., 1984; Mapa et al., 1986; Rousseva et al., 1988). The depth of the tilled zone and decrease in bulk density due to tillage depend on tillage intensity, soil water content at the time of tillage, soil type, and cropping/management history. Allmaras et al. (1966, 1967) presented data on such changes in three different soil associations. Williams et al. (1984) used an approximate equation in their EPIC model to estimate soil bulk density after tillage:

$$\rho(I) = \rho_o - \left(\rho_o - \frac{2}{3}\rho_c\right)I \qquad [1]$$

where $\rho(I)$ is the bulk density after tillage, I is the mixing efficiency or the fraction of soil mixed, ρ_o the bulk density before tillage (g cm^{-3}), and ρ_c the bulk density of the soil when it is completely settled. The tillage intensity, I, is a factor ranging from 0 to 1 that depends on the implement used and surface soil conditions. Alberts et al. (1995) provided values for the tillage intensity for 78 different tillage implements or operations. For a tillage operation, such as a moldboard plow-disc-harrow, that completely mixes the soil ($I = 1$), the ρ after tillage will equal 2/3 ρ_c. Williams et al. (1984) did not give the basis or a test of this equation. A calculation by the authors of this paper on the data of Allmaras et al. (1966) indicated that it underpredicted the bulk density for a plow-disc-harrow operation. Nonetheless, this equation is being used in several agricultural system models (Ahuja et al., 2000a; Flanagan and Nearing, 1995).

After tillage, the soil bulk density increases with time due to reconsolidation by successive wetting and drying. Onstad et al. (1984) assumed that the amount of rainfall after tillage is a major factor governing this change, and described these changes by the following empirical equation:

$$\rho(t) = \rho_i + a\frac{P(t)}{1 + P(t)} \qquad [2]$$

where $\rho(t)$ is the bulk density at time, t, after tillage, ρ_i is the bulk density right after tillage, $P(t)$ is the cumulative rainfall, and a is a constant. The results from simulated rainfall experiments using Eq. [2] showed that the bulk density reached a near-maximum value at about 10 cm of rainfall. However, Rousseva et al. (1988) showed that the bulk density continued to change with rainfall beyond 10 cm. Equation [2] may be modified to allow this behavior by introducing another parameter. On the other hand, Linden and van Doren (1987) assumed that both rainfall amount and rainfall energy were the major factors governing reconsolidation, and gave the following empirical equation in terms of soil porosity (ϕ) changes with time:

$$\phi = \phi_1 - (\phi_1 - \phi_c)[1.0 - \exp(-1.5E - 0.015P)] \qquad [3]$$

where ϕ_1 is the initial porosity, ϕ_c is the final stable porosity, E is the cumulative rainfall energy (J cm^{-2}), and P is the cumulative rainfall (cm). This equation is used in the ARS Root Zone Water Quality Model (RZWQM) (Ahuja et al., 2000a). With slight modification of the coefficients for E and P terms, this equation has given good results in the application of this model. However, further research is needed for testing the physical basis and improvement of the above equations and the development of new equations.

Soil-Water Retention Characteristics, $\theta(h)$, and Hydraulic Conductivity, $K(h)$

Gupta and Larson (1979) and Rawls et al. (1982, 1983) were the leaders in developing regression equations to estimate $\theta(h)$ from soil texture, bulk density, and organic matter content. In this initial work, the equations predicted water content, θ at fixed matric potentials, h. Subsequent investigators extended this approach to estimate parameters of the commonly used functional forms of $\theta(h)$, for example, Brooks-Corey and van Genuchten equations (Saxton et al., 1986; Wösten and van Genuchten, 1988). Can these equations be used to estimate changes in $\theta(h)$ curves due to changes in soil bulk density with tillage and reconsolidation? Can these equations be adapted for dynamics of soil structure and biochannels? Evaluation of the above regression equations for the purpose requires further research.

Ahuja et al. (1998) reviewed the experimental evidence for tillage effects on the pore-size distribution and the soil water retention curve. In general, the field data indicated that the changes occurred mostly in larger pores, at the wet end of the soil water retention curve (Hamblin and Tennant, 1981; Lindstrom and Onstad, 1984; Mapa et al., 1986). Some data also indicated that the air-entry or the bubbling pressure value was not significantly affected by tillage (Powers et al., 1992). Ahuja et al. (1998) first showed that the application of extended similar-media approach (e.g., Ahuja et al., 1985) did not correctly represent the above field observations. Then, they proposed two semi-empirical methods for determining changes caused by tillage in the parameters of the Brooks and Corey (1964) form of $\theta(h)$ curve:

$$\theta(h) = \theta_s;\ h \le h_b$$

$$[\theta(h) - \theta_r] = (\theta_s - \theta_r)(h/h_b)^{-\lambda};\ h > h_b \qquad [4]$$

where θ_s is the saturated soil water content, θ_r is the so-called residual water content, h_b is the air entry or bubbling pressure head, and λ is the pore-size distribution index. In the first method, they assumed that: (1) the changes in soil bulk density and hence soil porosity, ϕ or θ_s, due to tillage were known (Eq. [1]); (2) the residual water content, θ_r, and the bubbling pressure head parameter h_b of the soil were not influenced by tillage; (3) the pore-size distribution index, λ, increased with tillage in the wet range, between $h = h_b$ and $h = 10h_b$, and in this range of h the tilled soil's λ value, $\lambda_{till,}$ was computed from tilled soil's saturated soil water content, $\theta_{s,till}$:

$$\lambda_{till} = \frac{\log(\theta_{s,till} - \theta_r) - \log[\theta(10h_b) - \theta_r]}{\log|h_b| - \log|10h_b|}; \qquad [5]$$

and (4) below the above range, that is, for h values < 10 h_b, the λ value remained unchanged.

The second method was based on similar assumptions, except that between h_b and 10 h_b the θ was assumed to change inversely with the h value, an intuitively appealing assumption. Test of these methods on four datasets gave good results. Method 2 was slightly better than Method 1. Ahuja et al. (1998) proposed that the above methods can also be used to estimate changes in $\theta(h)$ during reconsolidation. Hopefully, these methods will spur the development of more physically based methods.

To estimate effects of tillage and reconsolidation on the saturated hydraulic conductivity, K_s, we could consider the modified Kozeny-Carman equation (Ahuja et al., 1984; 1989):

$$K_s = B\phi_e^n \qquad [6]$$

where ϕ_e is the effective porosity, calculated as the saturated water content (θ_s) minus the water content at 33-kPa matric suction, and B and n are constants. Equation [6] exhibited a degree of universality in that it was applicable to a wide range of soils from the southern region of the USA, Hawaii, and Arizona to several soils from Korea (Ahuja et al., 1989) and a variety of soils from Indiana (Franzmeier, 1991). Messing's (1989) results for some Norwegian soils showed that Eq. [6] fitted data for individual soils well, although the coefficients varied slightly with soil type. However, some of these soils had high clay contents and likely exhibited shrink-swell behavior, which could possibly affect the values of the fitted coefficients. Rawls et al. (1998) found that $n = 3 - \lambda$ for the textural class mean K_s values. Timlin et al. (1999) presented a slightly improved version of Eq. [6] by incorporating the additional effect of λ on K_s. Ahuja et al. (2000b) found Eq. [6] to be applicable to K_s data from both wheel-tracked and non-wheel-tracked portions of the fields. Equation [6] will estimate changes in K_s due to tillage from changes in ϕ_e resulting from changes in θ_s and θ_{33kPa}. The complete unsaturated hydraulic conductivity curve, $K(h)$, of the tilled soil can be determined from K_s and the parameters of the new $\theta(h)$ curve of the tilled soil, based on the work of Campbell (1974) and other investigators (Schaap and Leij, 2000). The method should also apply during natural reconsolidation after tillage.

Recently, Or et al. (2000) presented a stochastic model that represented changes in pore-size distributions with the Fokker-Planck (advection-diffusion type) Equation (FPE). The model gave changes in total porosity, mean pore radius, and variance of the pore-size distribution. The wetting and drying were shown to affect the soil water retention and hydraulic conductivity. Leij et al. (2002a, 2002b) derived analytical solutions to the governing FPE equation using known temporal functions for the displacement of the mean pore size. Such mechanistic approaches should help to further improve the prediction of $\theta(h)$ and $K(h)$ changes due to tillage in field soils.

In the last two decades, considerable soil physics research has been conducted on the development of pedotransfer functions for estimating soil hydraulic properties from easily obtained data for soil physical properties (see recent book edited by Pachepsky and Rawls, 2004). Some research has also dealt with characterizing hydraulic properties of dual and triple porosity soils (e.g., Wilson et al., 1992; Mohanty et al., 1997). These developments also need to address the effects of tillage and related management on soil hydraulic properties, a focus of this review.

Surface Roughness and Detention Storage

Surface roughness retards overland flow and increases the transient depth and duration of this flow. These effects can increase cumulative infiltration in the field (Darboux and Huang, 2005). The surface roughness also affects soil erosion, soil thermal properties, and energy balance (Cogo, 1981; Allmaras et al., 1972, 1977; Cruse et al., 1980). Tillage increases surface roughness, the magnitude of which depends on the implements used and the soil condition at the time of tillage. Based on some limited data, Alberts et al. (1995) assigned potential random roughness, RR, values to 78 different tillage implements. The RR changes due to tillage were described by:

$$RR_{till} = RR_i T_i + RR_o(1 - T_i) \qquad [7]$$

where RR_i is the potential RR (cm) for an implement i, T_i is fraction of area tilled, and RR_o is the RR (cm) before tillage. Onstad et al. (1984) modeled the degradation of RR with rainfall after tillage using an equation similar to Eq. [2], but with a different constant. Zobeck and Onstad (1987) proposed an exponential decline with rainfall amount, similar to Eq. [3]. Earlier investigators tried exponential decline with cumulative rainfall energy (Zobeck and Onstad, 1987).

Surface detention storage is a function of surface roughness and slope. It may be derived mathematically by assuming an appropriate representation of the geometry of the depressions. Onstad (1984) improved on the conceptualizations of Mitchell and Jones (1976) and Moore and Larson (1979) for calculating depression storage from surface roughness (RR), and gave simple regression equations for calculating the maximum depression storage (DS):

$$\text{DS} = 0.0112\ \text{RR} + 0.031\ \text{RR}^2 - 0.012\ \text{RR (Slope)} \qquad [8]$$

They also gave a regression equation to calculate the precipitation excess required to satisfy this depression storage, based on the concept, supported by the experimental data, that all depression storage is not filled before runoff begins, due to connectivities. Hansen (2000) related depression storage to a mean upslope depression calculated from elevation data taken from a microrelief meter. Huang and Bradford (1990) used Markov-Gaussian random fields to represent microtopography. In all cases, the detention storage decreases as the soil slope increases; thus the slope significantly decreases infiltration. This is, therefore, an important area for further research to help enhance water infiltration.

Effects of Wheel-Track Compaction

Heavy vehicles used for tillage and other operations can compact the soil, resulting in an increase in bulk density, a decrease in porosity, and a change in the pore-size distribution (Warkentin, 1971; Ahuja et al., 2000b). The amount of soil compaction depends on the applied load, soil type, soil water status, and landscape position, but may also vary from year to year (Liebig et al., 1993; Lindstrom and Voorhees, 1995; Alakukku, 1996). The above changes in soil properties change the soil hydraulic properties and the amount of infiltration and available soil water. A great deal of knowledge exists on the stress-strain processes involved in soil deformation by compaction and shearing under load (Horn et al., 2000; Horn, 2003; Ghezzehei and Or, 2001; Or and Ghezzehei 2002), and on modeling these processes and the soil compaction (Young and Fattah, 1976; Smith, 1985; Van den Akker and van Wijk, 1987; O'Sullivan and Simota, 1995; O'Sullivan et al., 1999; Koolen et al., 1992; Gupta and Raper, 1994; Défossez and Richard, 2002; Défossez et al., 2003; Baumgartl and Kock, 2004; Braudeau et al., 2004a).

There are several reports of the effect of wheel track compaction on soil properties (Croney and Coleman, 1954; Hill and Sumner, 1967; Culley et al., 1987; Gupta et al., 1989; Hill and Meza-Montalvo, 1990; Lindstrom and Voorhees, 1995; Wu et al., 1992; Benjamin, 1993; Sillon et al., 2003). Lipiec and Hatano (2003) reviewed the compaction effects on various soil processes. The effects varied widely depending on the prevailing conditions. Hill and Sumner (1967) found that the changes in soil water retention for a variety of soils artificially compacted to various bulk densities varied by soil textural class. Logsdon et al. (1992) found a decrease in K_s and ponded-water infiltration in a clay loam soil due to wheel compaction under higher values of the axle loads tested (4.5, 9, and 18 Mg) for wet and dry soil conditions. Benjamin (1993) measured detailed water retention curves and K_s in wheel-track and no-track areas under field conditions for three different soil types. The wheel tracks caused significant changes in the curves. The λ value of the water retention curves roughly increased linearly with increase in bulk density (Ahuja et al., 2000b). Ahuja et al. (2000b) also showed that under semiarid conditions with sandy loam to silt loam soils of the Central Great Plains of the USA, wheel tracks did not cause a significant effect on the average soil hydraulic property curves. Sillon et al. (2003) found higher unsaturated hydraulic conductivity in a compacted calcareous soil, but no difference in a loess soil. The above results indicate a strong need to quantify the effects of compaction on soil hydraulic properties in terms of cause and effect relationships for reliable predictions and modeling.

Long-Term No-Tillage and Crop Residue Effects

Macropores

Comparisons of no-tillage (NT) and minimum tillage with various conventional tillage practices over different time periods have not been consistent across soils, climates, and experiments (e.g., Hines, 1986; Hill, 1990; Ahuja and Nielsen, 1990; Logsdon et al., 1999). In general, long term NT with crop residues has been observed to increase macropores and their connectivity with depth in the profile, with only small changes in bulk density and total porosity, even though NT may initially increase soil bulk density in some soils. No-till soils often show higher pesticide concentrations in percolate, shallow groundwater or drainage than tilled soils (Elliott et al., 2000; Masse et al., 1998; Kanwar et al., 1997; Isensee et al., 1990). With no-tillage, decayed root channels serve as continuous macropores, and residue cover associated with no-tillage helps increase the number of continuous earthworm channels (Meek et al., 1989; Edwards et al., 1990; Shipitalo et al., 2000). Tillage is expected to disrupt the continuity or increase the tortuosity of macropores, and also increase the saturated hydraulic conductivity of the tilled-zone soil matrix (soil between macropores), which tends to decrease macropore flow (e.g., Petersen et al., 2001; Vervoort et al., 2001). However, some studies have shown no difference in hydraulically active macropores between different management practices (Azevedo et al., 1998). Malone et al. (2003) re-analyzed the macropores estimated from the tension infiltrometer data for 20 different structured soils (Logsdon and Kaspar, 1995; Logsdon et al., 1993; Kaspar et al., 1995) to quantify number of surface (0–1 cm) and subsurface (15–35 cm) macropores as affected by tillage treatments (moldboard plow, disk, chisel, ridge, and no-tillage). They found no clear trend for the number of macropores between tillage treatments and soils. Of course, using the tension infiltrometer method to estimate active macropores has limitations—the infiltrometers wet only a small and ill-defined depth of soil (Logsdon, 1997), 5 to 7 cm, and thus do not represent continuous macroporosity for the soil profile, and they include the dead-end macropores that may be continuous only in the measurement depth. Further research and new methods are needed to: (1) characterize hydraulically active macropores that are continuous in the whole soil profile (Timlin et al., 1993), as well as noncontinuous dead-end macropores in different soil horizons; and (2) quantify the number and size of macropores as functions of tillage, crop root systems, crop residue mass, climate, and soil type.

Residue Cover Impacts on Infiltration

Crop residue cover has long been recognized to increase infiltration by preventing surface crusting or sealing. Duley (1939) was the leader in showing dramatic effects of surface covers on infiltration. Lang and Mallett (1984) and Baumhardt and Lascano (1996) presented experimental data for the effects of different levels of residue cover on infiltration. By a theoretical study, Ruan et al. (2001) elucidated the effects of the different levels of residue cover and incomplete surface sealing in a field using a two-dimensional infiltration model. Crop residue was assumed to be distributed in regular patches. Beneath the patches, the surface soil was assumed to retain its original K_s value, whereas the bare soil areas between the patches were assumed to form a seal with K_s value equal to a certain fraction of the original unsealed value. Interestingly, the results were sensitive to the degree of sealing and percentage of area covered by residue, but not to the patch geometry. Baumhardt and Lascano (1996) reported similar results. Ruan et al. (2001) also found that the use of a weighted average K_s of the surface seal for the whole area in a one-dimensional infiltration model reproduced the two-dimensional model results very well, except where the seal was assumed to have zero K_s. Model results also reproduced the results from field studies for corn and cotton residues (Lang and Mallett, 1984; Baumhardt and Lascano, 1996), where the corn and cotton data coalesced when expressed as a function of percentage of residue cover. Model results also compared well with the graph of precipitation storage efficiency vs. residue level during fallow periods of a wheat-fallow rotation from three different locations in the Great Plains of the USA (Greb et al., 1967; Nielsen, 2002). Further work is certainly needed to test these initial findings.

Crop Residues and Soil Properties

The frequent additions and decomposition of crop residues at the surface increase organic matter content of the surface soil and modify its structure and physical properties in the long term (Shaver et al., 2002, 2003; Sherrod et al., 2003). Heuscher et al. (2005) have shown that soil organic C was the strongest contributor to bulk density prediction in regression relations, among the soil properties including water content, silt content, and depth. Shaver et al. (2002, 2003) have shown that 12 yr of no-till and residues in several dryland cropping systems decreased bulk density, increased effective porosity, and increased organic C and macroaggregates in the top 2.5 cm of the surface soil. The magnitude of changes in these properties was linearly related to the amount of residue biomass produced and added to the surface in a given rotation. Ma et al. (1999) presented current models to simulate decomposition of surface residue as a function of C/N ratio, air temperature, and rainfall amount. The decomposing residues have shown to adsorb pesticides and may thus reduce their downward movement (Ma and Selim, 2005). Effects of different residues on soil properties is an exciting area for further experimental research, quantification, and modeling.

The amount of root mass added at different soil depths in different crop rotations should also have an effect on soil organic matter over the long term (Sherrod et al., 2003). Generally, the root mass added to soil is proportional to the above ground biomass produced. This is becoming an important issue with regard to C sequestration with respect to global climate change, but this will also change the soil properties at different depths. Application of manure also increases soil organic matter and modifies soil physical and hydraulic properties in the long term (Rawls et al., 2003, 2004). Some research is going on in these areas, but more quantitative long-term studies are needed.

Dynamics of Soil Structure and Water and Mass Transport

Effects of soil morphology, structure, and aggregation on soil hydraulic properties were recently addressed by Lilly and Lin (2004) and Guber et al. (2004). Dynamics of soil structure in response to soil mechanical disturbances have been expressed in terms of stress-strain relations by numerous investigators (Horn, 2003; Sillon et al., 2003; Lipiec and Hatano, 2003), and has been noted above for wheel-track compaction. Here, we emphasize the dynamics of soil cracks that cause a substantial preferential transport of water and chemicals from soil surface to deeper layers or groundwater, and effects of roots on soil structural changes.

Dynamics of Soil Cracks

The swelling and shrinking clayey soils develop cracks on drying that cause rapid movement of water and chemicals to deeper layers and groundwater. The cracks close on soil rewetting and crack surface area and depth vary with soil water content. This preferential flow through dynamic cracks can be important, but has not been studied much. Modeling of the flow requires quantification of opening and closing of cracks (dynamics). While many investigators have measured swelling and shrinking of small soil cores, several of them have also measured shrinkage and subsidence of soils in the field (Woodruff, 1936; Jamison and Thompson, 1967; Yule and Ritchie, 1980; Bronswijk, 1988, 1989, 1990, 1991a, 1991b). In an application of RZWQM, Hua (1995) assigned crack volume to be either a linear or a quadratic function of soil moisture, which showed success in simulating water table, nitrate, and pesticide concentrations. In his extensive work, Bronswijk developed and used the following equation to calculate subsidence and shrinkage in soils:

$$1-\frac{\Delta V}{V} = \left(1-\frac{\Delta z}{z}\right)^{r_g} \qquad [9]$$

where V is the initial volume of a soil cube, ΔV is the volume decrease on shrinking, z is the initial depth, Δz is the vertical subsidence, and r_g is the dimensionless shrinkage geometry factor. In case of subsidence without cracking, r_g is equal to 1, whereas in case of isotropic shrinkage r_g is equal to 3. In case of cracking without subsidence, r_g becomes infinity. With a known r_g, Bronswijk used this equation to estimate ΔV from measured subsidence. The subsidence volume (ΔVsub) and total crack volume (ΔVcr) are then given as:

$$\Delta \mathrm{Vsub} = z^2\,\Delta z \qquad [10a]$$

$$\Delta \mathrm{Vcr} = \Delta V - \Delta \mathrm{Vsub} \qquad [10b]$$

Bronswijk (1988, 1989) used these estimates in modeling the role of continuously changing cracks on water transport in soil matrix and cracks. In a recent paper, Chertkov et al. (2004) have improved on the Bronswijk's concepts and equations for estimating crack volume. Braudeau et al. (2004a, 2004b) have also addressed these issues. Peng and Horn (2005) presented a simple model of the soil shrinkage curve. Further work is needed to verify these estimates and their applications in modeling transport through dynamic cracks.

Influence of Roots on Soil Structure and Biochannels

Roots and root hairs enter soil pores as they grow into the soil. As such, they change the soil density, porosity, and hydraulic properties adjacent to the roots. Even though the volume of soil occupied by roots is generally <1% of the soil volume (Jungk, 1996), increased resistance to water flow at the root-soil interface may be important for water uptake and hence nutrient uptake. In addition, the roots also exude ions, organic acids, enzymes, and other substances in their vicinity (the rhizosphere), which increases nutrient availability from adsorbed phases and may also affect soil structure and water uptake. The decayed roots create biochannels or soil macropores that cause a substantial amount of preferential flow and transport as has already been discussed. Research is needed to characterize and quantify these soil structural changes caused by roots for different rooting systems, crop rotations, soils, climates, and management systems.

Physics or Biophysics of Changes in Properties and Processes at the Soil-Root/Shoot and Shoot-Atmosphere Interfaces

Modeling Root Growth Distributions and Their Effect on Water and Mass Transport

The magnitude and distribution of root growth in a soil profile vary widely between and within plant species (Cannon, 1949; Fitter, 1996; Moroke et al., 2005). The depth and temporal pattern of root growth also depends on soil properties, such as soil strength, temperature, water content regime, salinity, and nutrient deficiencies, which change with depth in a layered soil (Jones et al., 1991; Benjamin et al., 1996). The distribution of root growth with depth and time determines the distribution of water and nutrient uptake from the soil. This, in turn, influences water, chemical, and heat movement in the soil. Most current models of agricultural systems use very simplistic, one-dimensional, root growth and distribution with depth in the soil (Jones and Kiniry, 1986; Hoogenboom et al., 1992; Keating et al., 1999; Ahuja et al., 2000a), such as an exponential distribution. Are these root distributions correct for the various crops and soil profile conditions? Maximum root density is not always at the soil surface; the depth at which this occurs may vary with crop and soil conditions and layering. There is also the issue of the distribution of active roots rather than the total root mass. Further field research is needed to test and improve the current approaches to attain more realistic temporal root growth and distributions.

Most of the system models also use a one-dimensional water and mass transport, with root water uptake as a sink term assumed to be evenly distributed at each soil depth. These one-dimensional models may be adequate for closely seeded crops, like wheat, barley, and millets (provided their root distributions are correct). Are they adequate for row crops like corn, soybean, and sorghum? Plant roots also can change the pattern of water movement and chemical transport under plant rows versus inter-rows. Arya et al. (1975) measured spatial patterns of matric potential between two rows of a soybean crop, and reported appreciable lateral gradients at certain stages of growth. Van Wesenbeeck and Kachanoski (1988) reported similar gradients in soil-water content under corn, with water content beneath the crop row almost always lower than between rows. These hydraulic gradients are a result of the gradients in root-density distribution. One would expect from these results that there would be less deep percolation of water in the crop-row than in the interrow zone. Timlin et al. (1992) observed reduced chemical movement under crop rows compared with interrows. More recent measurements showed that evapotranspiration was significantly greater in the crop rows than in the interrows (Timlin et al., 2001). For these crops, we may need to have at least two-dimensional root growth and water/mass movement models (e.g., Timlin et al., 1996; Coelho and Or, 1996), even though this will increase the complexity of modeling for field applications. Other investigators have developed and employed three-dimensional root growth models, including fractal approaches (see excellent reviews by Lynch and Nielsen, 1996; Hopmans and Bristow, 2002; Clausnitzer and Hopmans, 1994; Berntson, 1996; Somma et al., 1997; Pages et al., 2004). We can use these models as research tools, along with good field data, to gain better understanding of the dynamics of root growth and water movement, and then use that understanding to develop improved one-dimensional or simple two-dimensional models.

Quantifying Water and Nutrient Uptake by Roots

Shani and Dudley (1996) and Hopmans and Bristow (2002) presented good reviews of the current models of water uptake by roots. The simple mechanistic models of Nimah and Hanks (1973) and Campbell (1991), and empirical models of Feddes et al. (1976) and its variants are still the latest macroscopic models of water uptake by plants. Some of the current agricultural system models use the simple mechanistic approach described above (e.g., RZWQM, Ahuja et al., 2000a), whereas others use an empirical approach that relates available soil water content to uptake (DSSAT Crop Models, Hoogenboom et al., 1992; APSIM, Keating et al., 1999). Considerably more research is needed for parameterizing, experimental testing and improving these simple approaches.

Silberbush (1996) and Hopmans and Bristow (2002) have reviewed the status of nutrient uptake models. The supply-limited mechanistic models, based on radial, steady-state, convective and diffusive transport of nutrients from soil to roots (Nye and Tinker, 1977; Barber, 1984), are still the latest developments. However, as Hopmans and Bristow (2002) point out, active uptake of nutrients can be important for some elements and for certain conditions, such as for high nitrate contents of the soil. The active uptake generally is assumed to be Michaelis–Menten type kinetics (Hanson 2000). Nonetheless, some current crop system models still use an empirical relation between uptake and nutrient concentration in the soil (e.g., DSSAT models), whereas others use just passive uptake or empirical combinations of passive and active uptakes (e.g., RZWQM) (Hanson 2000). Just as with water uptake, considerable research is needed for quantifying the role of passive versus active nutrient uptake, and then parameterizing, experimental testing and improving these simple approaches.

The Plant as a Hydraulic System

Water uptake and transport in plants is essentially a hydraulic flow process controlled by resistances in the flow system (porous soil and conducting vessels of the plant) and hydraulic gradients. Analytical and numerical techniques to model water flow in hydraulic systems are well known to soil physicists. As the water moves from soil to leaf, it passes through a series of resistances. Stomata control vapor phase resistance from the leaf to the atmosphere to balance transpiration demands and uptake. The leaf has to avoid dessication on one extreme and still allow atmospheric contact with moist surfaces to facilitate solution of CO_2 needed for photosynthesis. Soil physicists and hydrologists have analytical skills that are applicable to quantifying water transport in plants. The challenge to modeling water uptake and transport in plants is that water flow is controlled by a biological entity, the plant, operating within the physical limits of the system. The plant senses environmental conditions such as light, temperature, and humidity and constantly adjusts flow rates to maintain its own internal water status.

According to the cohesion-tension theory of water flow in plants, water tension in continuous water columns links water from the leaf to the roots (Meinzer et al., 2001; see Tyree, 1997 for a review). Water potential gradients between the soil and the atmosphere drive the flow. This results in a dynamic hydrologic flow system controlled by both physical and biological parameters. Knowledge of flow systems in plants and trees can lead to understanding of how plants partition biomass into leaves, stems and roots (Enquist, 2003) via allometric scaling relationships. Using such allometric relationships, flow in a plant vascular system can be modeled as a continuously branching hierarchical network running from the trunk to the petioles (West et al., 1999). Resistances can be calculated based on conduit sizes and knowledge of how these sizes change in the plant system with distance from the stem and ground surface. Plant hydrology and plant structure are closely tied together so an understanding of plant hydraulic relationships is essential if we are to model plant properties like leaf and stem sizes and arrangement. An exciting area of research would be to combine plant hydrology with an L-Systems description of plant architecture (Prusinkiewicz and Lindenmayer, 1990). Forestry researchers have made advances in modeling these systems, but more work is necessary, especially in the area of xylem hydraulics (see Sperry et al. 2003 for an overview).

Transpiration and Carbon Dioxide Fluxes at the Canopy-Atmosphere Interface Under Water Stress

All current crop system models need a great deal of improvement with respect to the effect of water stress on plant processes—particularly transpiration, C assimilation (photosynthesis), C allocation, canopy temperature, and the resulting water use efficiency for production. Most current crop models use a simple stress factor approach to simulate this effect. In some models, a daily crop water stress is calculated as 1 - AT/PT, where AT is the daily actual water uptake and PT is daily potential transpiration (Hanson, 2000; Sudar et al., 1981). A slight modification to the above definition is to use potential water uptake in place of actual water uptake, as in the DSSAT crop models (Ritchie, 1998). Dale and Daniels (1995), on the other hand, used ET/PET to quantify water stress, where ET and PET are actual and potential evapotranspiration. Morgan et al. (1980) used the ratio of available soil moisture to available soil moisture at field capacity in the soil profile as an indication of soil moisture stress. In the case of a shallow water table, crop wet stress (water stress under wet conditions) was quantified by summation of days when the water table is within the top 30 cm of the soil profile (Ahmad et al., 1992; Evans et al., 1991).

Some crop models rely on some form of stomatal resistance to simulate transpiration, for example, RZWQM (Farahani and Ahuja 1996) and SHAW (Flerchinger et al., 1996). Stomatal behavior is an important regulator of water flow from the soil and plant to the atmosphere and control mechanisms are still largely unknown. Are stomata responsive to leaf water potential or soil water potential or both, or other factors such as temperature and chemical signals? There is evidence that stomatal control works on a short time scale (minutes to hours) to optimize water loss, and over a long period (hours to days) to ultimately optimize C assimilation (Zavala, 2004). Tardieu and Davies (1993) developed a model integrating the water relations and chemical signals that control stomatal conductance in plants in dry soil. The authors concluded from simulation results that the signal from the roots would make the plant respond to the conditions for water uptake from the soil (water status in the soil and resistance to water flow) on a daily basis while, in the long term, the plant response to this signal would depend on the transpiration demand. This means that hydraulic resistances and chemical signaling are both important with respect to stomatal control. Xylem conductivity can also affect stomatal closure (Hubbard et al., 2001).

In reality, the photosynthetic process itself is relatively robust with respect to water stress. Stomatal closure decreases water loss more than it decreases C assimilation. As a result, water use efficiency increases under water stress. Leaf expansion is decreased long before significant effects of water stress are evident in photosynthesis. This means that linking water loss and photosynthesis as a linear relationship to simulate water stress will often result in underprediction of yields (Ferreyra et al., 2003). There is some controversy over whether or not drought reduces photosynthesis due to metabolic effects or through reduced stomatal conductance (see Medrano et al., 2002). An analyses of research reported in the literature led Medrano et al. (2002) to suggest that there is a strong downward regulation of photosynthesis with decreasing water availability and this downregulation is more closely associated with stomatal conductance than with other water status parameters such as leaf water potential or relative leaf water content. The question is, does downward-regulation of photosynthesis control stomatal conductance or vice versa? Some feedback mechanisms are probably involved. Hopmans and Bristow (2002) rightly pointed out that there must be a clear and intuitive understanding that plant transpiration and plant assimilation are physically connected by concurrent diffusion of water vapor and CO_2 through leaf stomata. Much better understanding of these related fluxes is needed under water stress conditions and for increased CO_2 concentrations.

Coupled models of photosynthesis and transpiration with an energy balance hold the greatest potential to model the effects of water stress in plants (Buckley et al., 2003; Tuzet et al., 2003). This provides a more physiologically based approach that takes into account processes that plants have developed to optimize C assimilation and minimize water loss under all conditions of water availability and especially water deficit situations. Coupled models are capable of calculating a leaf energy balance and coupled fluxes of water and CO_2 where stomatal conductance varies with leaf irradiance, leaf temperature, atmospheric water vapor pressure deficit, and CO_2 concentration. The application of these models in forestry have provided good representations of plant response to water stress (Misson et al., 2004). Many of the parameters in these models can be determined using photosynthetic gas flux equipment and sap flow measurements.

Soil physicists are well qualified to tackle the above biophysics and energy balance problem (Grossman-Clark et al., 2001). There is also a current need for quantifying the changes in C allocation among different plant parts, including roots, under water stress conditions. From an evolutionary standpoint, the plants tend to optimize survival and production under stress conditions. Will this concept help quantify the effects?

Modeling Climate Change, Soil Environment, and Agriculture

Major international issues with respect to global climate change are to improve understanding and quantification of the contributions of agricultural soils and current management practices to climate change; effects of climate change on soil environment, crop growth, and agricultural systems; and potential management changes to mitigate the adverse effects. The agricultural soils and management contribute to climate change primarily through emission of greenhouse gases, such as CO_2, CH_4, N_2O, NO, and NH_3. Enhanced decomposition of soil organic matter due to clearing and breaking of forest lands for agriculture and continued tillage and burning of crop residues are the chief sources of CO_2 emissions. Cultivation of submerged rice paddy and raising of large animal herds contribute to CH_4, and N fertilizers enhance releases of N_2O, NO, and NH_3. Land use changes are believed to account for about 8% and other agriculture sources about 15% of the anthropogenic greenhouse emissions (Rosenzweig and Hillel, 1995, 2000). Models are needed to quantify these emissions as functions of several dynamic variables and aggregate the results over large spatial areas and long time scales. Some models are available (Li, 2000; Matthews et al., 2000; Del Grosso et al., 2005; Zucong et al., 2003) that need more extensive evaluation and improvement. These models can also be utilized to devise and evaluate management practices that will minimize these emissions and increase C sequestration, such as no tillage and residue management, legumes in rotation, and manure applications.

Climate changes the soil environment, especially soil water and temperature, and a number of processes dependent on these, such as evapotranspiration, runoff, and erosion (Rosenzweig and Hillel, 2000; Doll, 2002). Some climate change models predict an increase in frequency of the extreme events, such as droughts and heavy rainfalls. How will these changes affect agricultural production in different regions? How will the extreme events change the soil resources, such as causing increased hydrophobicity of soils and preferential flow, and soil erosion by wind or water? Models are needed to evaluate the magnitude of these influences in different agricultural systems and different locations around the world and devise strategies for mitigating any adverse effects (e.g., Tubiello et al., 2000; Mearns et al., 1996). Models can also be used to guide special management practices during droughts. The mitigation strategies may include shift in production among regions and changes in crops, cultivars, and management practices, such as crop rotations and water conservation measures.

Physical Quantification of Spatial Variability and Scaling

Spatial Variability and Model Uncertainty

All models have an uncertainty in their simulation results. For field and larger scales, uncertainty is most often due to unaccounted for spatial variability of model parameters within a simulation unit, assumed homogeneous, and errors in estimating the so-called 'effective parameters'. For the highly nonlinear soil-hydrologic processes, strictly speaking there are no unique effective parameters (Zhu and Mohanty, 2003). For practical purposes, effective parameters may be calibrated for obtaining a selected output variable, for example, infiltration, for given initial and boundary conditions, but not for all output variables and conditions (Zhu and Mohanty, 2004). For a more reliable simulation, the spatial variability of the key governing parameters need to be characterized for various land use and management systems, and accounted for in some ways. Land use and management systems may add to the spatial variability and may also cause some temporal changes. At the same time, model uncertainty needs to be quantified with respect to this spatial variability and temporal changes (Neuman and Wierenga, 2003; Helton et al., 2004).

Quantifying Spatial Variability and Scaling

Over the last 30 yr, we have measured and statistically characterized the spatial variability of soil physical and hydraulic properties in numerous soils (Ahuja and Nielsen, 1990). However, for modeling and managing complex landscape and climate variability across multiple scales, we need to develop new physical, cause and effect, methods to quantify spatial variability of soils and new physical methods of scaling up results from plots to field, farm, and watershed scales. Management effects will need to be considered as well. As an example, for a given parent material, climate, biological factors, and time, topography is an important factor that may cause spatial variability of soil properties. Topographic data can now be easily and accurately measured at fine spatial intervals. Can a set of topographic attributes in a given management system be related to spatial variability of soil properties, soil water contents, and crop yield, and used for up-scaling? This is a hypothesis worth investigating (Pachepsky et al., 2001; Rawls and Pachepsky, 2002; Green and Erskine, 2004).

Another simple but physically based approach is the recent work of Kozak and Ahuja (2005) and Kozak et al. (2005). They found that soil hydraulic parameters of different soil textural classes were strongly related to their pore-size distribution index, λ. They then showed that λ could scale infiltration under several rainfall intensities and soil water content during redistribution across soil classes, as well as evaporation and transpiration. These encouraging results for simple cases could hopefully form the basis for research for more complex conditions in nature. Can the topography be combined with the knowledge of the spatial distribution of soil textural classes to give us a better basis for quantifying the spatial distributions of soil water?

Another issue is how to consider knowledge of spatial variability in modeling a watershed. Theoretically, one could divide a watershed into as many simulation units as necessary based on spatial variability of landscape and management. However, practically this will become unmanageable. The simulation units in most of the current watershed models are generally several square kilometers in size and each unit is considered homogeneous in properties and parameters. How then can one account for the spatial variability within a large simulation unit? As indicated above, it is generally not possible to derive weighted average parameters that give the same results as obtained by using a distribution of parameters. With a one-parameter model such as λ or K_s (Kozak and Ahuja, 2005), a weighted average parameter may be obtained for, say, infiltration under given rainfall and initial conditions from known distribution of λ or K_s within a simulation unit. Another approach might be to define empirical relations between the variability of the selected one parameter (λ or K_s) within a simulation unit to variability of the desired output variable, such as soil water content, deep percolation, and the leaching of chemicals for benchmark initial and boundary conditions. Then use parameters of a dominant part of the landscape in simulations and convert that result to a weighted average value for the unit using the empirical relationships.

Processes at Watershed Scale

From the edge of the field to watershed scale, several additional processes come into play, such as subsurface flow (including tile flow) of water and chemicals to a channel or a stream, flow of field surface runoff through a buffer strip or a riparian zone, gully erosion, and hydrologic processes and chemical dynamics and transport in channels and streams. In addition, there may be soil and water conservation practices, such as terraces, grass waterways, and water reservoirs. Soil physicists can contribute to quantification and modeling of some of these processes at this scale as well. Some examples of the past contributions in this area are the work on subsurface interflow (Lehman and Ahuja, 1985), tile flow (Johnsen et al., 1995), gully erosion (Zheng et al., 2000), and buffer strips (Seobi et al., 2005).

Watershed models have been developed that include the above processes between the edge of the field and watershed outlet, for example, the SWAT, AnnAGNPS, and REMM models (Arnold et al., 1998; Lowrance et al., 2000; Bingner and Theurer, 2001). These models are being used by USDA-ARS and USDA-NRCS to assess effects of conservation practices on water and water quality. These models are engineering models that simplify the simulation of physical processes for large simulation units. Soil physicists can help improve these simulations, as well as help assure that that the field-scale effects are appropriately aggregated up to the watershed scale.

CONCLUSIONS

The above review describes, in our judgment, the most important knowledge gap areas that have been encountered by developers of the agricultural system models. The development of new knowledge in these areas and its quantification will require both an innovative experimental research and the development of new concepts, theories, and models. Exciting and potentially high-impact areas of further research lie on the interfacial boundaries of soil physics and other disciplines. Soil physicists are uniquely qualified to tackle these challenges and make highly original and much-needed contributions. Integrated in agricultural systems, this soil physics research will create breakthroughs in knowledge that will help solve the major practical problems that agriculture is facing in the 21st century. The soil physics-agricultural systems models will also be excellent tools for teaching system modeling to graduate students. These accomplishments will be a source of great personal satisfaction for a new generation of soil physicists.

REFERENCES

Ahmad, N., R.S. Kanwar, T.C. Kaspar, and T.B. Bailey. 1992. Effect of soil surface submergence and a water table on vegetative growth and nutrient uptake of corn. Trans. ASAE 35:1173–1177.

Ahuja, L.R., J.W. Naney, R.E. Green, and D.R. Nielsen. 1984. Macroporosity to characterize spatial variability of hydraulic conductivity and effects of land management. Soil Sci. Soc. Am. J. 48:699–702.

Ahuja, L.R., J.W. Naney, and R.D. Williams. 1985. Estimating soil water characteristics from simpler properties or limited data. Soil Sci. Soc. Am. J. 49:1100–1105.

Ahuja, L.R., D.K. Cassel, R.R. Bruce, and B.B. Barnes. 1989. Evaluation of spatial-distribution of hydraulic conductivity using effective porosity data. Soil Sci. 148:404–411.

Ahuja, L.R., and D.R. Nielsen. 1990. Field water relations. Irrigation of agricultural crops. p. 143–190. ASA-CSSA-SSSA, Madison, WI.

Ahuja, L.R., F. Fiedler, G.H. Dunn, J.G. Benjamin, and A. Garrison. 1998. Changes in soil water retention curves due to tillage and natural reconsolidation. Soil Sci. Soc. Am. J. 62:1228–1233.

Ahuja, L.R., K.W. Rojas, J.D. Hanson, M.D. Shaffer, and L. Ma. (ed.). 2000a. Root Zone Water Quality Model: Modeling management effects on water quality and crop production. Water Resources Pub., LLC, Highland Ranch, CO.

Ahuja, L.R., J.G. Benjamin, G.H. Dunn, L. Ma, T.R. Green, and G.A. Peterson. 2000b. Quantifying wheel track effects on soil hydraulic properties for agricultural system modeling. p. 407–414. *In* Proc. 4th International Conf. Soil Dynamics. Adelaide, South Australia, 26–30 March 2000. Univ. of South Australia, Adelaide, Australia.

Ahuja, L.R., and L. Ma. 2002. Computer models to guide soil water management. p. 218–222. *In* Encyclopedia of soil science. Marcel Dekker Inc., Publishers, New York.

Ahuja, L.R., L. Ma, and T.A. Howell (ed.). 2002. Agricultural system models in field research and technology transfer. Lewis Publishers, Boca Raton, FL.

Ahuja, L.R., J.C. Ascough, II, and O. David. 2005. Developing natural resource models using the Object Modeling System: Feasibility and challenges. Adv. Geosciences 4:29–36.

Alakukku, L. 1996. Persistence of soil compaction due to high axle load traffic 2. Long-term effects on the properties of fine-textured and organic soils. Soil Tillage Res. 37:223–238.

Alberts, E.E., J.M. Laflen, W.J. Rawls, J.R. Simanton, and M.A. Nearing. 1995. Soil Component. p. 7.1–7.47. *In* D.C. Flanagan and M.A. Nearing (ed.) USDA-Water Erosion Prediction Project, Hill slope Profile and Watershed Model Documentation. NSERL Report 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, IN.

Allmaras, R.R., W.E. Burwell, W.E. Lartson, R.F. Holt, and W.W. Nelson. 1966. Total porosity and random roughness of the inter row zone as influenced by tillage. USDA-ARS, Conserv. Res. Rep. No. 7. USDA, Washington, DC.

Allmaras, R.R., W.E. Burwell, and R.F. Holt. 1967. Plow-layer porosity and surface roughness from tillage as affected by initial porosity and soil moisture at tillage time. Soil Sci. Soc. Am. Proc. 31:550–556.

Allmaras, R.R., W.W. Nelson, and E.A. Hallaur. 1972. Fall versus spring plowing and related soil heat balance in the Western Corn Belt. Minn. Agric. Exp. Sta. Tech. Bull. 283. Univ. of Minnesota, St. Paul, MN.

Allmaras, R.R., E.A. Hallaur, W.W. Nelson, and S.E. Evans. 1977. Surface energy balance and soil thermal property modification by tillage-induced soil structure. Minn. Agric. Exp. Sta. Bull. 306. Univ. of Minnesota, St. Paul, MN.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large area hydrologic modeling and assessment, Part 1: Model development. J. Am. Water Resour. Assoc. 34:73–89.

Arya, L.M., G.R. Blake, and D.A. Farrell. 1975. A field study of soil water depletion patterns in the presence of growing soybean roots. Ii. Effect of plant growth on soil water pressure and water loss patterns. Soil Sci. Soc. Am. J. 39:430–436.

Azevedo, A.S., R.S. Kanwar, and R. Horton. 1998. Effect of cultivation on hydraulic properties of an Iowa soil using tension infiltrometers. Soil Sci. 163:22–28.

Barber, D.A. 1984. Soil nutrient bioavailability. Wiley & Sons, New York.

Baker, D.N., J.R. Lambert, and J.M. McKinion. 1983. GOSSYM: A simulator of cotton crop growth and yield. South Carolina Exp. Stn. Tech. Bull. 1089. South Carolina Exp. Stn., Clemson, SC.

Baumgartl, T.H., and B. Kock. 2004. Modeling volume change and mechanical properties with hydraulic models. Soil Sci. Soc. Am. J. 68:57–65.

Baumhardt, R.L. and R.J. Lascano, 1996. Rain infiltration as affected by wheat residue amount and distribution in ridged tillage. Soil Sci. Soc. Am. J. 60:1908–1913.

Benjamin, J.G. 1993. Tillage effects on near-surface soil hydraulic properties. Soil Tillage Res. 26:277–288.

Benjamin, J.G., L.R. Ahuja, and R.R. Allmaras. 1996. Modeling corn root patterns and their effects on water uptake and nitrate leaching. Plant Soil 179:223–232.

Berntson, G.M. 1996. Fractal geometry, scaling, and the description of plant root architecture. p. 259–272. *In* Y. Waisel et al. (ed.) Plant roots: The hidden half. Mercel Dekker, Inc., New York.

Bingner, R.L., and F.D. Theurer. 2001. AnnAGNPS: Estimating sediment yield by particle size by sheet and rill erosion. p. I-1–I-7. *In* Proc. Sediment monitoring, modeling, and managing, 7th Federal Interagency Sedimentation Conf., Reno, NV. 25–29 March, 2001. U.S. Dep. of Interior, U.S. Geological Survey, Reston, VA.

Braudeau, E., J.P. Frangi, and R.H. Mohtar. 2004a. Characterizing non-rigid aggregated soil-water medium using its shrinkage curve. Soil Sci. Soc. Am. J. 68:359–370.

Braudeau, E., R.H. Mohtar, and N. Chahinian. 2004b. Estimating soil shrinkage parameters. p. 225–240. *In* Ya. A. Pachepsky and W.J. Rawls (ed.) Development of pedotransfer functions in soil hydrology. Elsevier Publishers, New York.

Bronswijk, J.J.B. 1988. Modeling of water balance, cracking and subsidence of clay soils. J. Hydrol. (Amsterdam) 97:199–212.

Bronswijk, J.J.B. 1989. Prediction of actual cracking and subsidence in clay soils. Soil Sci. 148:87–93.

Bronswijk, J.J.B. 1990. Shrinkage geometry of a heavy clay soil at various stresses. Soil Sci. Soc. Am. J. 54:1500–1502.

Bronswijk, J.J.B. 1991a. Relation between vertical soil movements and water-content changes in cracking clays. Soil Sci. Soc. Am. J. 55:1220–1226.

Bronswijk, J.J.B. 1991b. Drying, cracking, and subsidence of a clay soil in a lysimeter. Soil Sci. 152:92–99.

Brooks, R.H., and A.T. Corey. 1964. Hydraulic properties of porous media. Hydrology Paper 3, Colorado State University, Fort Collins.

Buckley, T.N., K.A. Mott, and G.D. Farquhar. 2003. A hydro mechanical and biochemical model of stomatal Conductance. Plant Cell Environ. 26:1767–1785.

Campbell, G.S. 1974. A simple method for determining unsaturated conductivity from moisture retention data. Soil Sci. 117:311–314.

Campbell, G.S. 1991. Simulation of water uptake by plant roots. p. 273–286. *In* R. J. Hanks and J.T Ritchie (ed.) Modeling plant and soil systems. Agron. Monogr. No. 31. ASA, CSSA, and SSSA, Madison, WI.

Cannon, W.A. 1949. A tentative classification of root systems. Ecology 30:452–458.

Cassel, D.K. 1983. Spatial and temporal variability of soil physical properties following tillage of Norfolk loamy sand. Soil Sci. Soc. Am. J. 47:196–201.

Chertkov, V.Y., I. Ravina, and V. Zadoenko. 2004. An approach for estimating the shrinkage geometry factor at moisture content. Soil Sci. Soc. Am. J. 68:1807–1817.

Clausnitzer, V., and J.W. Hopmans. 1994. Simultaneous modeling of transient three-dimensional root growth and water flow. Plant Soil 164:299–314.

Coelho, F.E., and D. Or. 1996. A parametric model for two-dimensional water uptake intensity by corn roots under drip irrigation. Soil Sci. Soc. Am. J. 60:1039–1049.

Cogo, N.P. 1981. Effect of residue cover, tillage-induced roughness, and slope length on erosion and related parameters. Ph.D. dissertation. Purdue Univ. West Lafayette, IN.

Croney, D., and J.D. Coleman. 1954. Soil structure in relationship to soil suction. J. Soil Sci. 5:75–84.

Cruse, R.M., D.R. Linden, J.K. Radke, W.E. Larson, and K. Larntz. 1980. A model to predict tillage effects on soil temperature. Soil Sci. Soc. Am. J. 44:378–383.

Culley, J.L.B., W.E. Larson, and G.W. Randall. 1987. Physical properties of a typical Haplaquoll under conventional and no-tillage. Soil Sci. Soc. Am. J. 51:1587–1593.

Cushman, J.H. 1979. An analytical solution to solute transport near root surfaces for low initial concentrations. 1. Equation development. Soil Sci. Soc. Am. J. 43:1087–1090.

Dale, R.F., and J.A. Daniels. 1995. A weather-soil variable for estimating soil moisture stress and corn yield probabilities. Agron. J. 87:1115–1121.

Darboux, F., and C. Huang. 2005. Does soil surface roughness increase or decrease water and particle transfer? Soil Sci. Soc. Am. J. 69:748–756.

Défossez, P., and G. Richard. 2002. Models of tilled compaction due to traffic and their field evaluation. Soil Tillage Res. 67:41–64.

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

Del Grosso, S.J., A.R. Mosier, W.J. Parton, and D.S. Ojima. 2005. DAYCENT model analysis od past and contemporary soil N2O and net greenhouse flux for major crops in the USA. Soil Tillage Res. 83:9–24.

Doll, P. 2002. Impact of climate change and variability on irrigation requirements: A global perspective. Clim. Change 54:269–293.

Duley, F.L. 1939. Surface factors affecting the rate of intake of water by soils. Soil Sci. Soc. Am. Proc. 9:60–64.

Edwards, W.M., M.J. Shipitalo, L.B. Owens, and L.D. Norton. 1990. Effect of Lumbricus terrestrial Burrows on hydrology of continuous no-till corn fields. Geoderma 46:73–84.

Elliott, J.A., A.J. Cessna, W. Nicholaichuk, and L.C. Tollefson. 2000. Leaching rates and preferential flow of selected herbicides through tilled and untilled soil. J. Environ. Qual. 29:1650–1656.

Enquist, B.J. 2003. Cope's Rule and the evolution of long-distance transport in vascular plants: Allometric scaling, biomass partitioning and optimization. Plant Cell Environ. 26:151–161.

Evans, R.O., R.S. Skaggs, and R.E. Sneed. 1991. Stress day index models to predict corn and soybean relative yield under high water table conditions. Trans. ASAE 34:1997–2005.

Farahani, H.J., and L.R. Ahuja. 1996. Evapotranspiration modeling of partial canopy/residue-covered fields. Trans. ASAE 39: 2051–2064.

Feddes, R.A., P.J. Kowalik, and H. Zaradny. 1976. Simulation of field water uptake by plants using a soil water dependent root extraction function. J. Hydrol. (Amsterdam) 31:13–26.

Ferreyra, R.A., J.L. Dardanelli, L.B. Pachepsky, D.J. Collino, P.C. Faustinelli, G. Giambastiani, V.R. Reddy, J.W. Jones. 2003. Nonlinear effects of water stress on peanut photosynthesis at crop and leaf scales. Ecol. Mod. 168:57–76.

Fitter, A. 1996. Characteristics and functions of root systems. Chap. 1. *In* Y. Waisel, A. Eshel, and U. Kafkafi (ed.) Plant roots—The hidden half. Marcel Dekker Publishers, New York.

Flanagan, D.C., and M.A. Nearing (ed.). 1995. USDA—Water Erosion Prediction Project, Hill Slope Profile and Watershed Model Documentation. NSERL Report No. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, IN.

Flerchinger, G.N., C.L. Hanson, and J.R. Wright. 1996. Modeling of evapotranspiration and surface energy budgets across a watershed. Water Resour. Res. 32:2539–2548.

Franzmeier, D.P. 1991. Estimation of hydraulic conductivity from effective porosity data for some Indiana soils. Soil Sci. Soc. Am. J. 55:1801–1803.

Ghezzehei, T.A., and D. Or. 2001. Rheological properties of wet soils and clays under steady and oscillatory stresses. Soil Sci. Soc. Am. J. 65:624–637.

Greb, B.W., D.E. Smika, and A.L. Black. 1967. Effect of straw mulch rates on soil water storage during summer fallow in the great plains. Soil Sci. Soc. Am. J. 31:556–559.

Green, T.R., L.R. Ahuja, and J.G. Benjamin. 2003. Advances and challenges in predicting agricultural management effects on soil hydraulic properties. Geoderma 116:3–28.

Green, T.R., and R.H. Erskine. 2004. Measurement. Scaling, and topographic analyses of spatial crop yield and soil water content. Hydrol. Processes 18:1447–1465.

Grossman-Clark, S., P.J. Pinter, T. Kartschall, B.A. Kimball, D.J. Hunsaker, G.W. Wall, R.L. Garcia, and R.L. LaMorte. 2001. Modeling a spring wheat crop under elevated carbon dioxide and drought. New Physiologist 150:315–336.

Guber, A., Ya.A. Pachepsky, E. Shein, and W.J. Rawls. 2004. Soil aggregates and water retention. p. 143–150. *In* Ya. A. Pachepsky and W.J. Rawls (ed.) Development of pedotransfer functions in soil hydrology. Elsevier Publishers, New York.

Gupta, S.C., and W.E. Larson. 1979. Estimating soil water retention characteristics from particle size distribution, organic matter percent, and bulk density. Water Resour. Res. 15:1633–1635.

Gupta, S.C., P.P. Sharma, and S.A. DeFranchi. 1989. Compaction effects on soil structure. Adv. Agron. 42:311–338.

Gupta, S.C., and R.L. Raper. 1994. Prediction of soil compaction under vehicle. p. 53–71. *In* B.D. Soane and C. van Ouwerkerk (ed.) Soil compaction and crop production, developments. Agric. Eng. 11, Elsevier Amsterdam.

Hamblin, A.P., and D. Tennant. 1981. The influence of tillage on soil and water behavior. Soil Sci. 132:233–234.

Hansen, B. 2000. Estimation of surface runoff and water-covered area during filling of surface micro-relief depressions. Hydrol. Processes 14:1235–1243.

Hanson, J.D. 2000. Generic crop production model for the root zone water quality model. p. 529–556. *In* L.R. Ahuja et al. (ed.). The Root Zone Water Quality Model. Water Resources Publications LLC. Highlands Ranch, CO.

Helton, J.C., J.D. Johmson, and W.L. Oberkampf. 2004. An exploration of alternative approaches to the representation of uncertainty in model predictions. Reliab. Eng. Syst. Safe. 85:39–71.

Heuscher, S.A., C.C. Brandt, and P.M. Jardine. 2005. Using soil physical properties to estimate bulk density. Soil Sci. Soc. Am. J. 69: 51–56.

Hill, J.N.S., and M.E. Sumner. 1967. Effect of bulk density on moisture characteristics of soils. Soil Sci. 103:234–238.

Hill, R.L. 1990. Long-term conventional and no-tillage effects on selected soil physical-properties. Soil Sci. Soc. Am. J. 54:161–166.

Hill, R.L., and M. Meza-Montalvo. 1990. Long-term wheel traffic effects on soil physical-properties under different tillage systems. Soil Sci. Soc. Am. J. 54:865–870.

Hines, J.W. 1986. Measurement and modeling of soil hydraulic conductivity under different tillage systems. M.S. Thesis, Univ. Minnesota, St. Paul.

Hoogenboom, G., J.W. Jones, and K.J. Boote. 1992. Modeling growth, development, and yield of legumes using SOYGRO, PEANUTGRO, and BEANGRO. A Review. Trans. ASAE. 35:2043–2056.

Hopmans, J.W., and K.L. Bristow. 2002. Current capabilities and future needs of root water nutrient uptake modeling. Adv. Agron. 77: 103–183.

Horn, R., J.H. van den Akker, and J. Arvidsson. 2000. Subsoil Compaction-Distribution, Processes, and Consequences. Adv.Geoecology 32. Catena Publication, Arcata, CA.

Horn, R. 2003. Stress-strain effects in structured unsaturated soils on coupled mechanical and hydraulic processes. Geoderma 116: 77–88.

Hua, Y. 1995. The role of variable cracking on agrichemical transport at the Missouri MSEA site using the Root Zone Water Quality Model. M. S. Thesis. Univ. Missouri-Columbia.

Huang, C., and J.M. Bradford. 1990. Depressional storage for Markov-Gaussian surfaces. Water Resour. Res. 26:2235–2242.

Hubbard, R.M., V. Stiller, M.G. Ryan, and J.S. Sperry. 2001. Stomatal conductance and photosynthesis vary linearly with plant hydraulic conductance in ponderosa pine. Plant Cell Environ. 24:113–121.

Isensee, A.R., R.G. Nash, and C.S. Helling. 1990. Effect of conventional vs. no-tillage on pesticide leaching to shallow groundwater. J. Environ. Qual. 19:434–440.

Jamison, V.C., and G.H. Thompson. 1967. Layer thickness changes in a clay-rich soil in relation to water content changes. Soil Sci. Soc. Am. Proc. 31:441–444.

Johnsen, K.E., H.H. Liu, J.H. Dane, L.R. Ahuja, and S.R. Workman. 1995. Simulating fluctuating water tables and tile drainage with the Root Zone Water Quality Model and a new model WAFLOWM. Trans. ASAE 38:75–83.

Jones, C.A., and J.R. Kiniry. 1986. CERES-Maize: A simulation model of maize growth and development. Texas A & M Univ. Press, College Station TX.

Jones, C.A., W.L. Bland, J.T. Ritchie, and J.R. Williams. 1991. Simulation of root growth. p. 92–124. *In* J. Hanks and J.T. Ritchie (ed.). Modeling plant and soil systems. Agron. Monogr. No. 31. ASA, CSSA, and SSSA, Madison, WI.

Jungk, A.O. 1996. Dynamics of nutrient movement at the soil-root interface.p. 247–258. *In* Y. Waisel et al. (ed.) Plant roots—The hidden half. Marcel Dekker Publishers, New York.

Kanwar, R.S., T.S. Colvin, and D.L. Karlen. 1997. Ridge, moldboard, chisel, and no-till effects on tile water quality beneath two cropping systems. J. Prod. Agric. 10:227–234.

Kaspar, T.C., S.D. Logsdon, and M.A. Prieksat. 1995. Traffic patterns and tillage system effects on corn root and shoot growth. Agron. J. 87:1046–1051.

Keating, B.A., M.J. Robertson, R.C. Muchow, and N. Huth. 1999. Modeling sugarcane production systems 1. Development and performance of the sugarcane module. Field Crop Res. 61:253–271.

Koolen, A.J., P. Lerink, D.A.G. Kurstjens, J.J.H. Van den Akker, and W.B.M. Arts. 1992. Prediction of aspects of soil-wheels systems. Soil Tillage Res. 24:381–396.

Kozak, J.A., and L.R. Ahuja. 2005. Scaling of infiltration and redistribution across soil textural classes. Soil Sci. Soc. Am. J. 69: 819–827.

Kozak, J.A., L.R, Ahuja, L. Ma, and T.R. Green. 2005. Scaling and estimation of evaporation and transpiration across soil textural classes. Vadose Zone J. 4:418–427.

Lang, P.M., and J.B. Mallett. 1984. Effect of the amount of surface maize residue on infiltration and soil loss from a clay loam soil. S. African J. Plant Soil 1:97–98.

Lehman, O.R., and L.R. Ahuja. 1985. Interflow of water and tracer chemical on sloping field plots with exposed seepage faces. J. Hydrol. (Amsterdam) 76:307–317.

Leij, F.J., T.A. Ghezzehei, and D. Or. 2002a. Analytical models for soil pore-size distribution after tillage. Soil Sci. Soc. Am. J. 66: 1104–1114.

Leij, F.J., T.A. Ghezzehei, and D. Or. 2002b. Modeling the dynamics of the soil pore-size distribution. Soil Tillage Res. 64:61–78.

Li, C.S. 2000. Modeling trace gas emissions from agricultural ecosystems. Nutri. Cycling Agroecosyst. 58:259–276.

Liebig, M.A., A.J. Jones, L.N. Mielke, and J.W. Doran. 1993. Controlled wheel traffic effects on soil properties in ridge- tillage. Soil Sci. Soc. Am. J. 57:1061–1066.

Lilly, A., and H. Lin. 2004. Using soil morphological attributes and soil structure in pedotransfer functions. p. 115–141. *In* Ya. A. Pachepsky and W.J. Rawls (ed.) Development of pedotransfer functions in soil hydrology. Elsevier Publishers, New York.

Linden, D.R., and D.M. van Doren, Jr. 1987. Simulation of interception, surface roughness, depression storage, and soil settling. p. 90–93. *In* M.J. Schaffer and W.E. Larson (ed.) NTRM, a soil crop simulation model for nitrogen, tillage, and crop-residue management. USDA-ARS, Conservation Research Rep. 31–1. USDA, Washington, DC.

Lindstrom, M.J., and C.A. Onstad. 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. J. Soil Water Conserv. 39:149–152.

Lindstrom, M.J., and W.B. Voorhees. 1995. Soil properties across a landscape continuum as affected by planting wheel traffic. p. 351–363. *In* P.C. Roberts et al. (ed.) Site-specific management for agricultural systems. ASA, CSSA, and SSSA, Madison, WI.

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

Logsdon, S.D., R.R. Allmaras, W.W. Nelson, and W.B. Voorhees. 1992. Persistence of subsoil compaction from heavy axle loads. Soil Tillage Res. 23:95–110.

Logsdon, S.D., J.L. Jordahl, and D.L. Karlen. 1993. Tillage and crop effects on pond and tension infiltration rates. Soil Tillage Res. 28: 179–189.

Logsdon, S.D., and T.C. Kaspar. 1995. Tillage influences as measured by pond and tension infiltration. J. Soil Water Conserv. 50:571–575.

Logsdon, S.D. 1997. Transient variation in the infiltration rate during measurement with tension infiltrometers. Soil Sci. 162:233–241.

Logsdon, S.D., T.C. Kaspar, and C.A. Cambardella. 1999. Depth-incremental soil properties under no-till or chisel management. Soil Sci. Soc. Am. J. 63:197–200.

Lowrance, R.R., L.S. Altier, R.G. Williams, S.P. Inamdar, D.D. Bosch, R.K. Hubbard, and D.L. Thomas. 2000. The riparian ecosystem management model. J. Soil Water Conserv. 55:27–36.

Lynch, J., and K.L. Nielsen. 1996. Simulation of root systems. p. 1399–1402. *In* Y. Waisel et al. (ed.) Plant roots—The hidden half. Marcel Dekker Publishers, New York.

Ma, L.W., G.A. Peterson, L.R. Ahuja, L. Sherrod, M.J. Shaffer, and K.W. Rojas. 1999. Decomposition of surface crop residues in long-term studies of dryland agro-ecosystems. Agron. J. 91:401–409.

Ma, L., and H.M. Selim. 2005. Predicting pesticide transport in mulch-amended soils: A two-compartment model. Soil Sci. Soc. Am. J. 69:318–327.

Malone, R.W., S. Logsdon, M.J. Shipitalo, J. Weatherington, L.R. Ahuja, and L. Ma. 2003. Tillage effects on macroporosity and herbicide transport in percolate. Geoderma 116:191–216.

Mapa, R.B., R.E. Green, and L. Santo. 1986. Temporal viability of soil hydraulic-properties with wetting and drying subsequent to tillage. Soil Sci. Soc. Am. J. 50:1133–1138.

Masse, L., N.K. Patni, P.Y. Jui, and B.S. Clegg. 1998. Groundwater quality under conventional and no tillage. II. Atrazine, deethylatrazine, and metolachlor. J. Environ. Qual. 27:877–883.

Matthews, R.B., R. Wasssmann, and J. Arah. 2000. Using a crop/soil simulation model and GIS techniques to assess mathane emissions from rice fields in Asia. 1. Model development. Nutr. Cycl. Agroecosyst. 58:141–159.

Mearns, L.O., C. Rosenzweig, and R. Goldberg. 1996. The effect of changes in daily and interannual climatic variability on CERES-Wheat: A sensitivity study. Clim. Change 32:257–292.

Medrano, H., J.M. Escalona, J. Bota, J. Gulias, and J. Flexas. 2002. Regulation of photosynthesis of C3 plants in response to progressive drought: Stomatal conductance as a reference parameter. Ann. Bot. 89:895–905.

Meek, B.D., E.R. Rechel, L.M. Carter, and W.R. DeTar. 1989. Changes in infiltration under alfalfa as influenced by time and wheel traffic. Soil Sci. Soc. Am. J. 53:238–241.

Meinzer, F.C., M.J. Clearwater, and G. Goldstein. 2001. Water transport in trees: Current perspectives, new insights and some controversies. Environ. Exp. Biol. 45:239–262.

Messing, I. 1989. Estimation of saturated hydraulic conductivity in clay soils from soil moisture retention data. Soil Sci. Soc. Am. J. 53: 665–668.

Misson, L., J.A. Panek, and A.H. Goldstein. 2004. A comparison of three approaches to modeling leaf gas exchange in annually drought-stressed ponderosa pine forests. Tree Physiol. 24:529–541.

Mitchell, J.K., and B.A. Jones. 1976. Micro-relief surface depression storage: Analysis of models to describe the depth of storage function. AWRA Water Resour. Bull. 12:1205–1222.

Mohanty, B.P., R.S. Bowman, J.M.H. Hendricks, and M.T. van Genuchten. 1997. New piecewise-continuous hydraulic functions for modeling preferential flow in an intermittent-flood-irrigated field. Water Resour. Res. 33:2049–2063.

Moore, I.D., and C.L. Larson. 1979. Estimating micro-relief surface storage from point data. Trans. ASAE 22:1073–1077.

Morgan, T.H., A.W. Biere, and E.T. Kanemasu. 1980. A dynamic model of corn yield response to water. Water Resour. Res. 16:59–64.

Moroke, T.S., R.C. Scwartz, K.W. Brown, and A.S.R. Juo. 2005. Soil water and root distribution of three dryland crops. Soil Sci. Soc. Am. J. 69:197–205.

Neuman, S.P., and P.J. Wierenga. 2003. A comprehensive strategy of hydrogeologic modeling and uncertainty analysis for nuclear facilities and sites. NUREG/CR-6805. U.S. Nuclear Regulatory Commission, Washington, D.C.

Nielsen, D.C. 2002. Enhancing water use efficiency. p. 635– 642. *In* R. Lal (ed.) Encyclopedia of soil science, Marcel Dekker, New York.

Nimah, M.N., and R.J. Hanks. 1973. Model for estimating soil water, plant, and atmospheric relations: 1. Description and sensitivity. Soil Sci. Soc. Am. J. 37:522–527.

Nye, P.H., and P.B. Tinker. 1977. Solute movement in the soil-root system. Studies in ecology Vol. 4. Blackwell, Oxford, UK.

Onstad, C.A. 1984. Depression storage on tilled soil surfaces. Trans. ASAE 27:729–732.

Onstad, C.A., J.L. Wolfe, C.L. Larson, and D.C. Slack. 1984. Tilled soil subsidence during repeated wetting. Trans. ASAE 27:733–736.

Or, D., F.J. Leij, V. Snyder, and T.A. Ghezzehei. 2000. Stochastic model for post tillage soil pore space evolution. Water Resour. Res. 36:1641–1652.

Or, D., and T.A. Ghezzehei. 2002. Modeling post-tillage soil structural dynamics: A review. Soil Tillage Res. 64:41–59.

O'Sullivan, M.F., and C. Simota. 1995. Modeling the environmental impacts of soil compaction: A review. Soil Tillage Res. 35:69–84.

O'Sullivan, M.F., J.K. Henshall, and J.W. Dickson. 1999. A simplified method for estimating soil compaction. Soil Tillage Res. 49: 325–335.

Pachepsky, Ya.A., D.J. Timlin, and W.J. Rawls. 2001. Soil water retention as related to topographic variables. Soil Sci. Soc. Am. J. 65: 1787–1795.

Pachepsky, Ya., and W.J. Rawls (ed.). 2004. Development of pedotransfer functions in soil hydrology. Elsevier publishers, New York.

Pages, L., G. Vercambre, J.L. Drouet, F. Lecompte, C. Collet, and J.L. Bot. 2004. Root Type: A generic model to depict and analyze the root system architecture. Plant Soil 258:103–119.

Peng, X., and R. Horn. 2005. Modeling soil shrinkage curve across a wide range of soil types. Soil Sci. Soc. Am. J. 69:584–592.

Petersen, C.T., H.E. Jensen, S. Hansen, and C. Bender Koch. 2001. Susceptibility of a sandy loam soil to preferential flow as affected by tillage. Soil Tillage Res. 58:81–89.

Powers, W.L., J.U. Baer, and J. Skopp. 1992. Alternative soil-water release parameters for distinguishing tillage effects. Soil Sci. Soc. Am. J. 56:873–878.

Prusinkiewicz, P., and A. Lindenmayer. 1990. The algorithmic beauty of plants. Springer-Verlag, New York.

Rawls, W.J., D.L. Brakensiek, and K.E. Saxton. 1982. Estimation of soil water properties. Trans. ASAE 25:1316–1320.

Rawls, W.J., D.L. Brakensiek, and B. Soni. 1983. Agricultural management effects on soil water processes. Part 1: Soil water retention and Green and Amp infiltration parameters. Trans. ASAE 26:1747–1752.

Rawls, W.J., D. Gimenez, and R. Grossman. 1998. Use of soil texture, bulk density, and slope of the water retention curve to predict saturated hydraulic conductivity. Trans. ASAE 41:983–988.

Rawls, W.J., and Ya.A. Pachepsky. 2002. Using field topographic descriptors to estimate soil water retention. Soil Sci. 167:423–435.

Rawls, W.J., Ya.A. Pachepsky, J.C. Ritchie, T.M. Sobecki, and H. Bloodworth. 2003. Effect of soil organic matter on soil water retention. Geoderma 116:61–76.

Rawls, W.J., A. Nemes, and Ya.A. Pachepsky. 2004. Effect of soil organic matter on soil hydraulic properties. p. 95–111. *In* Ya. A. Pachepsky and W.J. Rawls (ed.) Development of pedotransfer functions in soil hydrology. Elsevier Publishers, New York.

Ritchie, J.T., D.C. Godwin, and S. Otter-Nacke. 1986. CERES-Wheat: A simulation model of wheat growth and development, CERES Model description. Dep. of Crop and Soil Science, Michigan State University, East Lansing, MI.

Ritchie, J.T. 1998. Soil water balance and plant water stress. p. 41–54. *In* G.Y. Tsuji et al. (ed.) Understanding options for agricultural production. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Rojas, K.W., and L.R. Ahuja. 2000. Management practices. *In* L.R. Ahuja et al. (ed.) Root Zone Water Quality Model: Modeling management effects on water quality and crop production. Water Resources Publ., LLC, Highland Ranch, CO.

Rosenzweig, C., and D. Hillel. 1995. Updated 2004. Potential impacts of climate change on agriculture and food supply. Consequences 1(2). U.S. Climate Change Information Office, Washington, DC.

Rosenzweig, C., and D. Hillel. 2000. Soils and global climate change: Challenges and opportunities. Soil Sci. 165:47–56.

Rousseva, S.S., L.R. Ahuja, and G.C. Heathman. 1988. Use of a surface gamma-neutron gauge for in-situ measurement of changes in bulk density of the tilled zone. Soil Tillage Res. 12:235–251.

Ruan, H.X., L.R. Ahuja, T.R. Green, and J.G. Benjamin. 2001. Residue cover and surface-sealing effects on infiltration: Numerical simulations for field applications. Soil Sci. Soc. Am. J. 65:853–861.

Saxton, K.E., W.J. Rawls, J.S. Romberger, and R.I. Papendick. 1986. Estimating generalized soil water characteristics from texture. Soil Sci. Soc. Am. J. 50:1031–1036.

Schaap, M.G., and F. J. Leij. 2000. Improved prediction of unsaturated hydraulic conductivity with the Mualem-van Genuchten Model. Soil Sci. Soc. Am. J. 64:843–851.

Seligman, N.G., and H.H. van Keulen. 1981. PAPRAN: A simulation model of annual pasture production limited by rainfall and nitrogen. p. 192–221. *In* M. J. Frissel and J. A. van Veen (ed.) Simulation of nitrogen behavior of soil-plant systems, Proc. Workshop, Wageningen.

Seobi, T., S. H. Anderson, R. P. Udawatta, and C. J. Gantzer. 2005. Influence of grass and agroforestry buffer strips on soil hydraulic properties for an Albaqualf. Soil Sci. Soc. Am. J. 69:893–901.

Shani, U., and L.M. Dudley. 1996. Modeling water uptake by roots under water and salt stress: Soil-based and crop response root sink terms. p. 643–658. *In* Y. Waisel et al. (ed.) Plant roots-The hidden half. Marcel-Dekker Publishers, New York.

Shaver, T.M., G.A. Peterson, L.R. Ahuja, D.G. Westfall, L.A. Sherrod, and G. Dunn. 2002. Surface soil physical properties after 12 years of dryland no-till management. Soil Sci. Soc. Am. J. 66:1296–1303.

Shaver, T.M., G.A. Peterson, and L.A. Sherrod. 2003. Cropping intensification in dry land systems improves soil physical properties: Regression relations. Geoderma 116:149–164.

Sherrod, L.A., G.A. Peterson, D.G. Westfall, and L.R. Ahuja. 2003. Cropping intensity enhances soil organic carbon and nitrogen in a no-till agro-ecosystem. Soil Sci. Soc. Am. J. 67:1533–1543.

Shipitalo, M.J., W.A. Dick, and W.M. Edwards. 2000. Conservation tillage and macropore factors that affect water movement and the fate of chemicals. Soil Tillage Res. 53:167–183.

Silberbush, M. 1996. Simulation of ion uptake from the soil. p. 643–658. *In* Y. Waisel et al. (ed.) Plant roots–The hidden half. Dekker Publishers, New York.

Sillon, J.F., G. Richard, and I. Cousin. 2003. Tillage and traffic effects on soil hydraulic properties and evaporation. 2003. Geoderma 116: 29–46.

Smith, D.L.O. 1985. Compaction by wheels: A numerical model for agricultural soils. J. Soil Sci. 36:621–632.

Somma, F., V. Clausnitzer, and J.W. Hopmans. 1997. An algorithm for three-dimensional simultaneous modeling of root growth, transient water flow, and transport and uptake. Plant Soil 202:281–293.

Sperry, J.S., V. Stiller, and U.G. Hacke. 2003. Xylem hydraulics and the soil-plant-atmosphere continuum: Opportunities and unresolved issues. Agron. J. 95:1362–1370.

Sudar, R.A., K.E. Saxton, and R.G. Spomer. 1981. A predictive model of water stress in corn and soybeans. Trans. ASAE 24:97–102.

Tanner, C.B. 1981. Transpiration efficiency of potato. Agron. J. 73:59–64.

Tanner, C.B., and T.R. Sinclaire. 1983. Efficient water use in crop production: Research or re-search. p. 1–27. *In* H. M. Taylor et al. (ed.) Limitations to efficient water use in crop production. ASA, CSSA, and SSSA, Madison, WI.

Tardieu, F., and W.J. Davies. 1993. Integration of hydraulic and chemical signaling in the control of stomatal conductance and water status of drought plants. Plant Cell Environ. 16:341–349.

Timlin, D.J., G.C. Heathman, and L.R. Ahuja. 1992. Solute leaching in crop row vs. inter-row zones. Soil Sci. Soc. Am. J. 56:384–392.

Timlin, D.J., L.R. Ahuja, and M.D. Ankeny. 1993. Comparison of three methods to measure maximum macropore flow. Soil Sci. Soc. Am. J. 57:278–284.

Timlin, D.J., Ya.A. Pachepsky, and B. Acock. 1996. A design for a modular generic soil simulator to interface with plant models. Agron. J. 88:162–169.

Timlin, D.J., L.R. Ahuja, Y. Pachepsky, R.D. Williams, D. Gimenez, and W.J. Rawls. 1999. Use of Brooks-Corey parameters to improve estimates of saturated conductivity from effective porosity. Soil Sci. Soc. Am. J. 63:1086–1092.

Timlin, D., Y. Pachepsky, and V.R. Reddy. 2001. Soil water dynamics in row and inter-row positions in soybean (*Gycine max* l.). Plant Soil 237:25–35.

Tubiello, F.N., M. Donatelli, C. Rosenzweig, and C.O. Stockle. 2000. Effects of climate change and elevated CO_2 on cropping systems: Model predictions at two Italian locations. Eur. J. Agron. 12:179–189.

Tuzet, A., A. Perrier, and R. Leuning. 2003. A coupled model of stomatal conductance, photosynthesis and transpiration. Plant Cell Environ. 26:1097–1116.

Tyree, M.T. 1997. The Cohesion-Tension theory of sap ascent: Current controversies. J. Exp. Bot. 48:1753–1765.

Van Bavel, C.H.M., and R.J. Lascano. 1987. ENWATBAL: A numerical model to compute the water loss from a crop by transpiration and evaporation. Experiment Station, Texas A&M Univ., College Station, TX.

Van den Akker, J.J.H., and A.L.M. van Wijk. 1987. A model to predict subsoil compaction due to field traffic. p. 69–84. *In* G. Monnier and M.J. Gross (ed.) Soil Compaction and Regeneration, A.A. Balkema, Rotterdam.

van Es, H.M., C.B. Ogden, R.L. Hill, R.R. Schindelbeck, and T. Tsegaye. 1999. Integrated assessment of space, time, and management-related variability of soil hydraulic properties. Soil Sci. Soc. Am. J. 63:1599–1608.

Van Wesenbeeck, I.J., and R.G. Kachanoski. 1988. Spatial and temporal distribution of soil-water in the tilled layer under a corn crop. Soil Sci. Soc. Am. J. 52:363–368.

Vervoort, R.W., S.M. Dabney, and M.J.M. Romkens. 2001. Tillage and row position effects on water and solute infiltration characteristics. Soil Sci. Soc. Am. J. 65:1227–1234.

Warkentin, B.P. 1971. Effects of compaction on content and transmission of water in soils. p. 125–140. *In* K. Barnes (ed.) Compaction of agricultural soils. ASAE Monograph, ASAE, St. Joseph, MI.

West, G.B., J.H. Brown, and B.J. Enquist. 1999. A general model for the structure and algometry of plant vascular systems. Nature (London) 400:664–667.

Whisler, F.D., B. Acock, D.N. Baker, R.E. Fye, H.F. Hodges, J.R. Lambert, H.E. Lemmon, J.M. Mckinion, and V.R. Reddy. 1986. Crop simulation models in agronomic systems. Adv. Agron. 40: 142–208.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27:129–142.

Wilson, G.V., P.M. Jardine, and J.P. Gwo. 1992. Modeling the hydraulic properties of a multi-region soil. Soil Sci. Soc. Am. J. 56:1731–1737.

Woodruff, C.M. 1936. Linear changes in the Selby loam profile as a function of soil moisture. Soil Sci. Soc. Am. Proc. 1:65–69.

Wösten, J.H.M., and M.Th. van Genuchten. 1988. Using texture and other properties to predict unsaturated soil hydraulic functions. Soil Sci. Soc. Am. J. 52:1762–1770.

Wu, L., J.B. Swan, W.H. Paulson, and G.W. Randall. 1992. Tillage effects on measured soil hydraulic properties. Soil Tillage Res. 25: 17–33.

Young, R.N., and E.A. Fattah. 1976. Prediction of wheel-soil interaction and performance using the finite element method. J. Terramech. 13:227–240.

Yule, D.F., and J.T. Ritchie. 1980. Soil shrinkage relationships of Texas vertisols. II. Large Cones. Soil Sci. Soc. Am. J. 44:1291–1295.

Zavala, M.A. 2004. Integration of drought tolerance mechanisms in Mediterranean sclerophylls: A functional interpretation of leaf gas exchange simulators. Ecol. Mod. 176:211–226.

Zheng, F.-L., Chi-hua Huang, and L. Darrell Norton. 2000. Vertical hydraulic gradient and run-On water and sediment effects on erosion processes and sediment regimes. Soil Sci. Soc. Am. J. 64: 4–11.

Zhu, J., and B.P. Mohanty. 2003. Upscaling of hydraulic properties of heterogeneous soils. p. 97–117. *In* Y. Pachepsky et al. (ed.) Methods of scaling in soil physics. CRC Press, Boca Raton, FL.

Zhu, J., and B. P. Mohanty. 2004. Soil hydraulic parameter upscaling for steady-state flow with Root Water Uptake. Vadose Zone J. 3:1464–1470.

Zobeck, T.M., and C.A. Onstad. 1987. Tillage and rainfall effects on random roughness: A review. Soil Tillage Res. 9:1–20.

Zucong, C., T. Sawamoto, C. Li, G kang, J. Boonjawat, A. Mosier, R. Wassmann, and H. Tsuruta. 2003. Field validation of DNDC model for greenhouse gas emissions I East Asian cropping systems. Global Biogeochem. Cycles 17:1107, 18:1–10.