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Advances and challenges in predicting agricultural management effects on soil hydraulic properties

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Abstract

Agricultural management practices can significantly affect soil hydraulic properties and processes in space and time. These responses are coupled with the processes of infiltration, runoff, erosion, chemical movement, and crop growth. It is essential to quantify and predict management effects on soil properties in order to model their consequent effects on production and the environment. We present work done thus far on this topic area along with the challenges that lie ahead. The effects of tillage and reconsolidation, wheel-track soil compaction, crop residue management, macropore development and management interactions with natural sources of variability, such as topography, are addressed. Whether explicitly or implicitly, the available field studies include interactions between treatments, such as tillage, crop rotation and residue management. Controlled equipment traffic has been shown to have significant effects on soil compaction and related hydraulic properties in some soils and climates, but in others, landscape and temporal variability overwhelm any effects of wheel tracks. New research results on wheel-track effects in Colorado are highlighted along with initial attempts to predict their effects on hydraulic properties. The greatest challenge for the future is improved process-based prediction using a systems approach to include tightly coupled process interactions in space and time.

Keywords: Soil management; Modeling; Hydrology; Agriculture; Agrophysics; Spatial data

1. Introduction

The purpose of this paper is to present the advances made thus far in quantifying and predicting the effects of agricultural management on soil hydraulic properties. The basic

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0016-7061/03/$ - see front matter
doi:10.1016/S0016-7061(03)00091-0

soil hydraulic properties of interest are soil porosity, soil-water content-matric potential relationship ($\theta(h)$, commonly called the soil-water retention characteristic), and hydraulic conductivity as a function of soil-water content or potential, $K(\theta)$ or $K(h)$. A particular goal is to characterize the management-induced temporal and spatial variability in observed or estimated soil hydraulic properties and processes. There is limited information available on this topic area, despite many field studies of soil variability and management effects. The sparcity of quantitative research on management effects has been noted at various times in the literature (Cassel, 1983; Mapa et al., 1986; Hill, 1990; Cresswell et al., 1993; van Es et al., 1999).

Nevertheless, we found many studies in the literature relating management practices to soil hydraulic properties and processes in a non-predictive sense. A comprehensive review of this literature is beyond the scope of this paper. Instead, we focus on the available quantitative, predictive studies and highlight the needs and challenges for further work.

2. Tillage and reconsolidation

Tillage is the most widely researched management practice affecting soil hydraulic properties and processes in the field. Results of tillage treatments, however, have not always been consistent across locations, soils and experimental designs (Klute, 1982; Hines, 1986; Ahuja and Nielsen, 1990). This situation has not changed.

No-tillage (NT) and minimum tillage (MT) have been compared with various conventional tillage (CT) practices over different time periods with mixed results. In general, the tendency in the long term is for NT to increase macropore connectivity while leaving total porosity and soil bulk density unchanged compared with CT practices. This corresponds to a general increase in ponded or near-zero tension infiltration rates and saturated hydraulic conductivity K_s. Deeper movement of surface-applied tracers has also been observed under NT. The results were inconsistent across soils, climates, and CT practices, however, and this may be due to spatial and temporal "noise" (natural and management-induced variability that cannot be isolated). Thus, given the current state of knowledge concerning NT versus CT, it is not possible to extrapolate the results from any given study without detailed information on all controlling factors. Such inconsistencies motivate the need for establishing causality and quantitative prediction of tillage effects on soil hydraulic properties, as well as the need to identify spatial and temporal variability prior to comparison between tillage treatments.

Spatial and temporal variability have often overshadowed the particular management treatments studied. Logsdon et al. (1993), for example, noted that temporal variability in real systems can overwhelm treatment effects. Even with intensive measurements on a relatively uniformly cultivated field, Logsdon and Jaynes (1996) were unable to capture the complexity of space-time variability in K. van Es (1993) showed that the tillage effects on infiltration varied temporally (within a season) and spatially (within fields and between rows) under plowed and ridge-tilled corn. Later, van Es et al. (1999) found that tillage and temporal effects were greatest for medium- and fine-textured soils, and spatial variability in water retention parameters was significant.

There have been some controlled studies on measurement of the short-term effects of tillage and subsequent reconsolidation on soil hydraulic properties that aid quantification and prediction of these effects. The fact that tillage initially decreases soil bulk density and increases porosity is well established. The increase in bulk density and decrease in porosity due to natural reconsolidation during cycles of wetting and drying after tillage has been studied by several investigators (Cassel, 1983; Onstad et al., 1984; Mapa et al., 1986; Rousseva et al., 1988).

Mapa et al. (1986) were the first to conduct controlled experiments in the field and laboratory to measure the initial effects of tillage and the effects of wetting and drying cycles following tillage on porosity, sorptivity, soil-water retention characteristics and unsaturated hydraulic conductivity relationships of two tropical (Hawaii) soils: Molokai silty clay loam (Typic Torrox) and Waialua clay loam (Vertic Haplustolls) on the island of O'ahu. Drip irrigation provided intermittent wetting following plowing. The effects of wetting and drying cycles on sorptivity are shown in Fig. 1 for both soils, where an asymptotic value is reached after only two cycles. Note that "Cycle 0" is post-tillage and pre-wetting. Water retention characteristics also displayed distinct changes over the low-suction/high-water-content range after only one wetting/drying cycle, and corresponding results were shown for unsaturated hydraulic conductivity. Finally, the authors demonstrated the effects of such temporal changes in hydraulic properties on predicted soil-water profiles.

Based on the above and related controlled studies, the current concepts for prediction of the effects of tillage and subsequent reconsolidation on soil hydraulic properties are described below.

2.1. Predicting soil porosity and bulk density

The total soil porosity, ϕ, is related to soil bulk density as:

$$\phi = 1 - \rho/\rho_p \tag{1}$$

where ρ is the soil bulk density and ρ_p is the soil particle density (g cm^{-3} or Mg m^{-3}). The ρ_p value varies somewhat with soil type, and should be determined in the laboratory by standard methods (Klute and Dirksen, 1986). However, a commonly accepted average value of ρ_p is 2.65 g cm^{-3}.

For field conditions, it can be important to separate the total porosity, ϕ, into soil matrix porosity, ϕ_s, and soil macroporosity, ϕ_m. In this context, the macropores are defined as large voids in a soil, such as decayed root channels, worm holes, and structural cleavages or cracks with radii ≥ 0.25 mm. Under surface ponded conditions, the continuous macropores allow a rapid downward movement of water that by-passes the soil matrix. This by-pass or preferential flow is not considered in classical soil physical models of water flow in the soil matrix. Macropore connectivity in the field is very difficult to determine. The best way might be to estimate it indirectly from infiltration measurements (Timlin et al., 1993).

Tillage decreases soil bulk density of the tilled zone (one or two thin horizons), which later gradually reverts back to the original state due to reconsolidation by natural forces. These changes depend upon soil type and implements used for tillage. No information

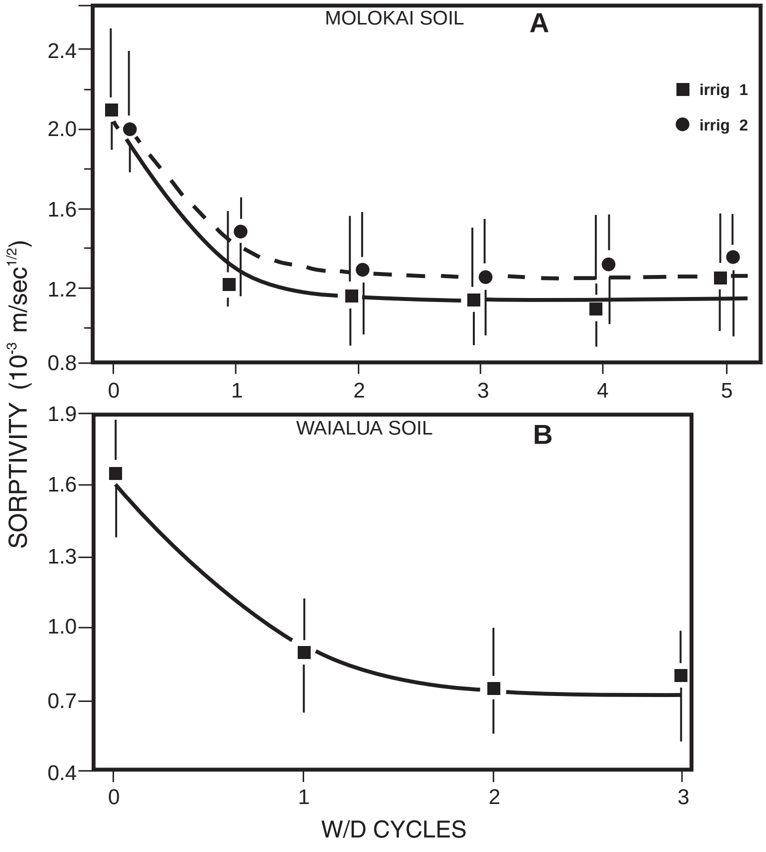

Fig. 1. Soil sorptivity versus number of wetting/drying cycles for (A) Molokai silt loam and (B) Waialua clay loam (from Mapa et al., 1986 with permission from SSSA). Symbols are geometric means and whiskers show 68% confidence intervals. Irrigation ("irrig") levels 1 and 2 represent different numbers of drip emitters per area yielding 3.6 and 2.0 cm per irrigation event, respectively.

exists in the literature on quantifying these changes. An approximate empirical equation used in the EPIC model (Williams et al., 1984) is:

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

where ρ(I) is the bulk density after tillage, ρ_o the bulk density before tillage (g cm^{-3}), and ρ_c the consolidation bulk density at 33-kPa pressure (g cm^{-3}). The tillage intensity, I, is a factor ranging from 0 to 1 that depends on the implement used and crop residue type on the soil surface. Williams et al. (1984) provided values for the tillage intensity for 29 different tillage implements for corn and soybean residues. The value of ρ_c may be set equal to the bulk density after complete reconsolidation.

The bulk density increases after tillage due to reconsolidation during cycles of wetting and drying (Cassel, 1983; Onstad et al., 1984; Mapa et al., 1986; Rousseva et al., 1988) in an asymptotic manner. Onstad et al. (1984) gave the following empirical equation to describe changes in bulk density of a tilled soil over time:

$$\rho(t) = \rho_i + a\frac{P(t)}{1 + P(t)} \tag{3}$$

where ρ_i is the bulk density just after tillage, $\rho(t)$ is the bulk density over time, $P(t)$ is the cumulative rainfall or applied water, and a is an empirical constant. Thus, time is expressed in terms of cumulative rainfall. Comparison of Eq. (3) with data shows that the bulk density reached a near-maximum value at about 10 cm of simulated rainfall application. Results of Rousseva et al. (1988) showed that bulk density did not reach a plateau even at much higher amounts of rainfall. Eq. (3) can be modified to allow this behavior by replacing the term $(1+P)$ by $(b+P)$ where b is another constant. Linden and van Doren (1987) gave another algorithm for changes in total porosity ϕ (directly related to bulk density) of a tilled soil as a double exponential function of cumulative rainfall energy and cumulative rainfall amount. A modified form of this equation has given reasonable results in applications of the Root Zone Water Quality Model (Ahuja et al., 2000). Further research is needed for testing the physical basis and improvement of the above equations.

2.2. Predicting changes in soil-water retention characteristics, θ(h)

Gupta and Larson (1979) and Rawls et al. (1982, 1983) presented regression equations to predict water content, θ, at fixed matric potential, h, values from soil texture, bulk density, and organic matter content. Knowing the change in soil bulk density due to tillage from Eq. (2) and due to subsequent reconsolidation from Eq. (3), one could use these regression equations to estimate the changes in $\theta(h)$ curves. Application and testing of these equations to predict changes in $\theta(h)$ brought about by tillage and reconsolidation is awaiting future research.

Ahuja et al. (1998) proposed a practical method for estimating the soil-water retention characteristics of a tilled soil from that of an untilled soil, given the change in porosity or bulk density. Previous field measurements have shown that most of the dynamic changes in pore-size distributions occur in the larger fraction of pores, and thus at the wet end of the soil-water retention curve (Hamblin and Tennant, 1981; Lindstrom and Onstad, 1984; Mapa et al., 1986). Other results also indicated that the air-entry or the bubbling pressure value is not significantly affected by tillage (Powers et al., 1992). These findings in the literature led Ahuja et al. to propose two semi-empirical methods for determining changes in parameters of the Brooks and Corey (1964) form of $\theta(h)$ curve caused by tillage and subsequent reconsolidation. The simpler of the two methods (Method 1) is summarized as follows:

1. The changes in soil bulk density and hence soil porosity, ϕ or θ_s, due to tillage are assumed known from Eqs. (1) and (3) presented above.
2. The residual water content, θ_r, and the bubbling pressure head parameter h_b of the soil after tillage stay the same as the values before tillage or at full natural reconsolidation.

3. The parameter λ, slope of the $\log\theta - \log h$ line below h_b, increases with tillage in the wet range only, between $h = h_b$ and $h = 10\ h_b$. In this range of h, the tilled soil value, λ_{till}, is computed from tilled soil saturated water content, $\theta_{s,till}$:

$$\lambda_{till} = \frac{\log(\theta_{s,till} - \theta_r) - \log[\theta(10h_b) - \theta_r]}{\log|h_b| - \log|10h_b|} \tag{4}$$

4. Below the above range, i.e., for h values $< 10\ h_b$, the λ value does not change.

Method 2 is based on similar assumptions, except that between h_b and 10 h_b the θ is assumed to change inversely with the h value. Fig. 2 shows the results of Method 2 to fit the experimental data from Mapa et al. (1986).

2.3. Predicting changes in hydraulic conductivity, K(h)

For saturated hydraulic conductivity, K_s, Ahuja et al. (1984, 1989a) showed that a modified Kozeny–Carman equation of the form

$$K_s = B_1\phi_e^n \tag{5}$$

is applicable to a wide range of soils from the southern region of the U.S., Hawaii and Arizona, where B_1 and n are empirical coefficients. Here, ϕ_e is the effective porosity, calculated as the saturated water content (θ_s) minus the water content at 33 kPa matric suction. Even though the coefficients of Eq. (5), fitted to the data, varied slightly with soil type, Eq. (5) fitted to K_s data for nine different soil series had an r^2 as good as for individual soil series. In other words, Eq. (5) exhibited a degree of universality. In fact, the coefficients, B_1 and n obtained from the above fit of Eq. (5) to data for nine soils, estimated

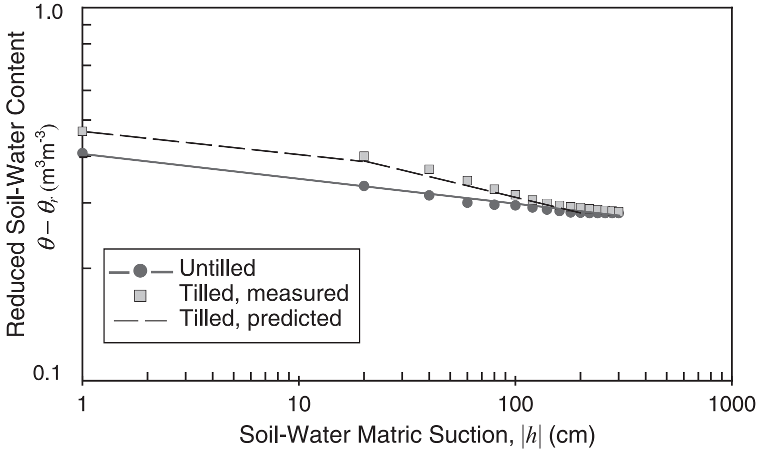

Fig. 2. Measured and predicted (Method 2) soil–water retention curves for Molokai silty clay loam under tilled and untilled conditions (from Ahuja et al., 1998).

K_s with acceptable accuracy for several soils from Korea (Ahuja et al., 1989b) and a variety of soils from Indiana (Franzmeir, 1991). Messing (1989) presented data for some Norwegian soils for which Eq. (5) fit the data for individual soils well, although the coefficients varied slightly with soil type. 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. (5) by incorporating the effect of slope λ of the $\theta(h)$ curve.

Once the $\theta(h)$ curve of the tilled soil is obtained from the previous equations, the new θ_s and $\theta_{33\ \mathrm{kPa}}$ are used to obtain the new ϕ_e in Eq. (5). Substituting the ϕ_e in Eq. (5) then provides the new K_s value. The other parameters of the $K(h)$ curve of the tilled soil are determined from the parameters of the new $\theta(h)$ curve of the tilled soil, based on the work of Campbell (1974) and others.

Comegna et al. (2000) adopted the approach of Ahuja et al. (1998) to scale the spatial distributions of effective porosity and K_s. They found no significant difference due to tillage treatments (conventional and minimum tillage) between the distributions of soil parameters for their vertic soils.

From a theoretical perspective, Or et al. (2000) developed a stochastic model that coupled probabilistic pore-size distributions with physically based deformation using the Fokker–Planck (advection–diffusion type) equation. The pore-space evolution model provided changes in the total porosity, mean pore radius, and variance of the pore-size distribution. Furthermore, changes in the soil structure caused by wetting and drying were shown to affect the soil-water retention and hydraulic conductivity curves. Recently, Leij et al. (2002a,b) derived analytical solutions to the governing equation using known temporal functions for the drift. Such mechanistic approaches are very much needed to further improve the prediction of $\theta(h)$ and $K(h)$ changes due to tillage and reconsolidation in real soils. Further research is needed to drive the temporal behavior of reconsolidation with basic data, such as rainfall timeseries.

2.4. Tillage effects on surface crusting, roughness and detention storage

Rainfall on a freshly tilled soil may result in the formation of a thin, but dense, surface seal or crust (Duley, 1939). The most important hydraulic parameter of the crust is its K_s value, denoted here as K_{sc}. van Doren and Allmaras (1978) related K_{sc} to the effective rainfall kinetic energy instrumental in crusting, E_{sc}, as follows:

$$K_{sc} = K_f + (K_o - K_f)e^{-CE_{sc}} \tag{6}$$

where K_f is the final steady value of K_{sc}, K_o is the K_s of the uncrusted soil, and C is an empirical constant. Linden (1979) expressed the E_{sc} of a partially covered and rough soil surface as:

$$E_{sc} = E_o B\cos(R/A) \tag{7}$$

where E_o is the rainfall energy, B is the fraction of uncovered surface, R is the average angle of inclination of the rough surface, and A is the surface area of the soil exposed to rainfall per unit horizontal area. Linden also related the term $\cos(R/A)$ to the random roughness.

Surface roughness affects the hydraulic resistance to overland flow, transient flow depths, and the amount of rainfall or irrigation kept in surface detention storage, which can affect the cumulative infiltration at a point in the landscape. Tillage initially increases surface roughness, which is a function of the implement used and the soil mechanical condition at the time of tillage. Based on experience and some limited data, Williams et al. (1984) assigned potential random roughness, RR, values to 23 different tillage implements. The value of RR immediately after tillage was then predicted from:

$$\mathrm{RR}_{\mathrm{till}} = \mathrm{RR}_i T_{\mathrm{i}} + \mathrm{RR}_{\mathrm{o}}(1 - T_{\mathrm{i}}) \qquad (8)$$

where RR_i is the potential RR for an implement i, T_{i} is its tillage intensity, and RR_{o} is the RR before tillage. Onstad et al. (1984) modeled the degradation of RR with rainfall after tillage using an equation similar to Eq. (3), but with a different constant.

The surface detention storage is a function of the surface roughness and may be derived assuming an appropriate representation of the geometry of the depressions. Huang and Bradford (1990) used Markov–Gaussian random fields to represent microtopography. The resulting detention storage decreased as the mean slope increased. Further work is needed to include connectivity in roughness patterns and its effect on surface detention storage.

3. Mechanical compaction

Mechanical loading of soils under vehicles used for management practices can compact the soil, causing increased bulk density, decreased porosity, and altered pore shapes and size distributions (Warkentin, 1971). Changes in these basic soil properties change the soil-water retention and hydraulic conductivity characteristics, and changes in these hydraulic properties affect the amount of infiltration and available soil water.

The amount of soil compaction depends on the applied load, soil type and water status, landscape position, and year (Liebig et al., 1993; Lindstrom and Voorhees, 1995; Alakukku, 1996). Several investigators have reported the effect of wheel tracks on soil hydraulic 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). The effects varied from study to study depending upon the prevailing conditions, and some interpretations have been primarily qualitative. Hill and Sumner (1967) measured soil-water retention for a variety of soils artificially compacted to various bulk densities. Compaction-induced changes in the measured water retention curves varied by soil textural class. Logsdon et al. (1992) studied responses of soil infiltration characteristics in a clay loam to wheel compaction under three axle loads (4.5, 9 and 18 Mg) and wet and dry soil conditions. The control (4.5 Mg) produced lower bulk density than the higher loads under dry conditions, and compaction under high loads decreased ponded infiltration and K_{s}. Measuring 2-cm depth increments in the top 30 cm, Logsdon et al. (1999) found no significant difference in soil bulk density between tillage treatments without controlled traffic.

3.1. New studies on Colorado soils

Benjamin et al. (1990) presented detailed water retention curves and K_s data for wheel-track and no-track areas under field conditions for three different soil types. There is a need for more data of the type collected by Benjamin et al. (1990) to quantify the effects of wheel-track compaction in the Central Great Plains of the USA using robust, practical approaches. Recently, we measured the effects of wheel tracks at different landscape positions on soil-water retention and K_s in selected plots of two long-term field studies of alternative crop rotations in eastern Colorado. At a farm near Sterling, CO (Peterson et al., 2000), crop rotation treatments run down a soil catena through summit, side-slope and toe-slope topographic positions. The soil texture varies from sandy loam at the summit to sandy clay loam at the toe slope. Four cores from each landscape position and wheel-track or no-track area were collected in the wheat-fallow rotations (two replications). Similar core samples were also collected from the second study site in Akron, CO, on a silt loam. Soil cores were analyzed in the laboratory for K_s using a constant head method, and for water retention using pressure plate and chamber methods.

The modified Kozeny–Carman equation relating K_s to effective porosity (Eq. (5)) has been shown to apply to a wide range of soils (Ahuja et al., 1984, 1989a), and was applied here to both wheel-track and no-track data for K_s from the Colorado studies (Fig. 3). There is large variability in K_s, but no significant difference in mean values between wheel-track and no-track areas. It is interesting to note that in both sites the K_s (K_{sat} in Fig. 3) data are described quite well by the regression equation derived earlier (Ahuja et al., 1989a,b) for nine other, totally unrelated soils.

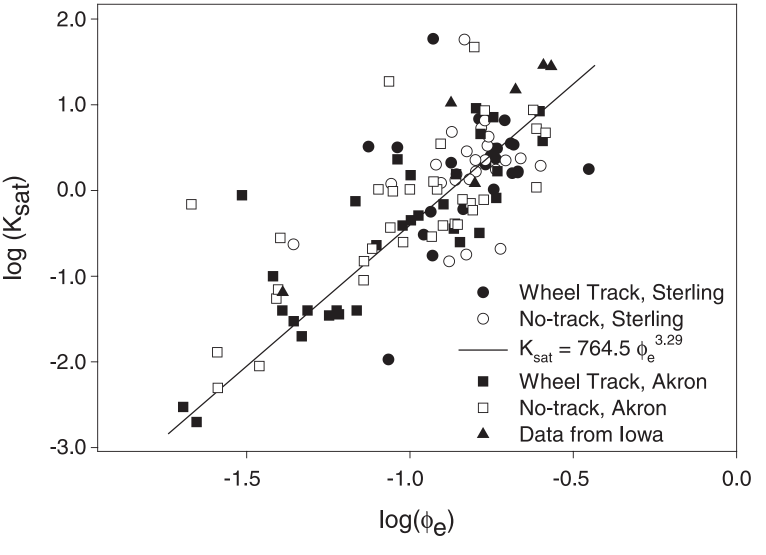

Fig. 3. Power-law (log–log linear) relationship between saturated hydraulic conductivity K_{sat} and effective porosity ϕ_e data from wheel-track and no-track cores. The regression line was derived by Ahuja et al. (1989b) for nine other soils.

The average water retention curves for each landscape position and treatment of the Sterling site are shown in Fig. 4. The figure shows results from two replications. There is no consistent difference between wheel-track and no-track areas for either replication, and the landscape spatial variability masks any difference between treatments. The average soil bulk densities for wheel-track and no-track cores from Sterling were 1.36 ± 0.07 and 1.33 ± 0.09 g cm^{-3}, respectively ($p = 0.086$). The water retention data from the Akron site averaged separately over wheel-track and no-track areas demonstrated little or no compaction effects on water retention (plot not shown). The average soil bulk densities

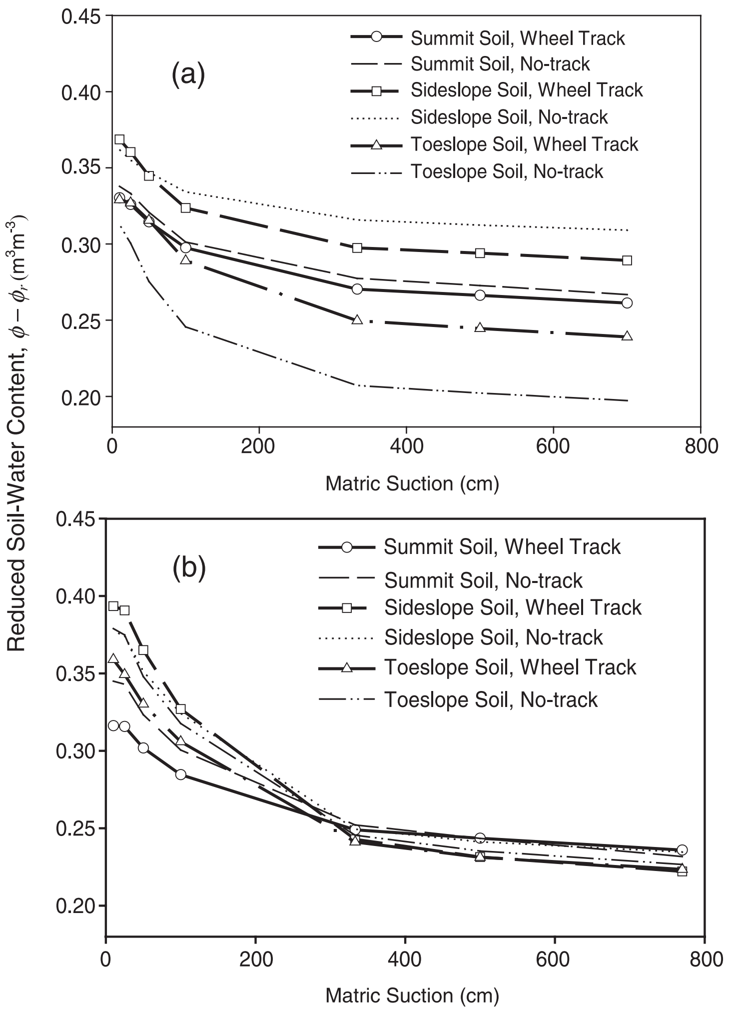

Fig. 4. Soil–water retention for wheel-track and no-track areas in no-till, wheat-fallow at three landscape positions near Sterling, CO, for: (a) replication 1 and (b) replication 2.

for wheel-track and no-track cores from Akron were 1.45 ± 0.07 and 1.39 ± 0.07 g cm^{-3}, respectively ($p = 0.34$).

The results indicate that under semi-arid conditions and sandy loam to silt loam soils of the Central Great Plains of the U.S., wheel tracks did not cause a significant effect on the average soil hydraulic property curves. However, there were large differences among the individual soil cores. In a separate study, Benjamin (1999, personal communication) found that these large differences in the water retention curves for Akron cores could be described extremely well by a one-parameter model (Gregson et al., 1987; Ahuja and Williams, 1991; Williams and Ahuja, 1992). The one-parameter model requires knowledge of only soil bulk density and 33-kPa water content value to estimate the $\theta(h)$ curve, as well as the K_s (Eq. (5)) and the $K(h)$ curve.

3.2. Quantifying wheel-track effects on Iowa soils

Since the data from our current studies showed no consistent effect of wheel tracks on soil hydraulic properties, we decided to analyze the field data for three soils from Iowa, reported by Benjamin et al. (1990), where significant effects were found. To estimate the wheel-track curve from that of no track, we used two observations from the data: (1) one value of water retention at 100 kPa for the tracked area curve is assumed known; and (2) assuming that at 1500-kPa suction the soil water is present primarily as thin films around the particles and not in pores or necks, the volumetric water content at this suction for the tracked soil is equal to water content in no-track sample times the ratio of their bulk densities. The measured water retention curves for wheel-track and no-track interrows, along with the results of our analysis, are shown in Fig. 5. Estimates of the tracked area Brooks–Corey-type curve for the three soils are reasonably good.

For the data of Benjamin et al. (1990), we also explored changes in the slope of the log–log curves between 100 and 1500 kPa suctions as a function of the soil bulk density. For all three soils and for both wheel-track and no-track interrow curves, as well as additional no-track row curves (not shown in Fig. 5), the slope versus bulk density is shown in Fig. 6, where $r^2 = 0.58$. We then obtained the slope from this fitted function for each wheel-track curve using the known bulk density, and used this slope value instead of the one known value from the water retention curve, with the calculated 1500 kPa water content, to estimate the wheel-track curve. The estimates were slightly worse but comparable to those shown in Fig. 5. This approach should be investigated further, since it omits having to measure one value of water retention (e.g., 100 kPa). The slope-bulk density relationship may have to be expressed on a relative basis for a given soil. That is, the change in slope of wheel-track soil relative to that of no-track soil will be a function of bulk density.

3.3. Prediction based on theoretical/statistical approaches

More theoretical work and stochastic-physical models of soil compaction are limited. Or and Ghezzehei (2002) reviewed the state of the science in this area, and they discussed recent progress in their approach to modeling soil structural dynamics at the pore scale under viscous deformation and elastic stress–strain relationships. It is possible to simulate

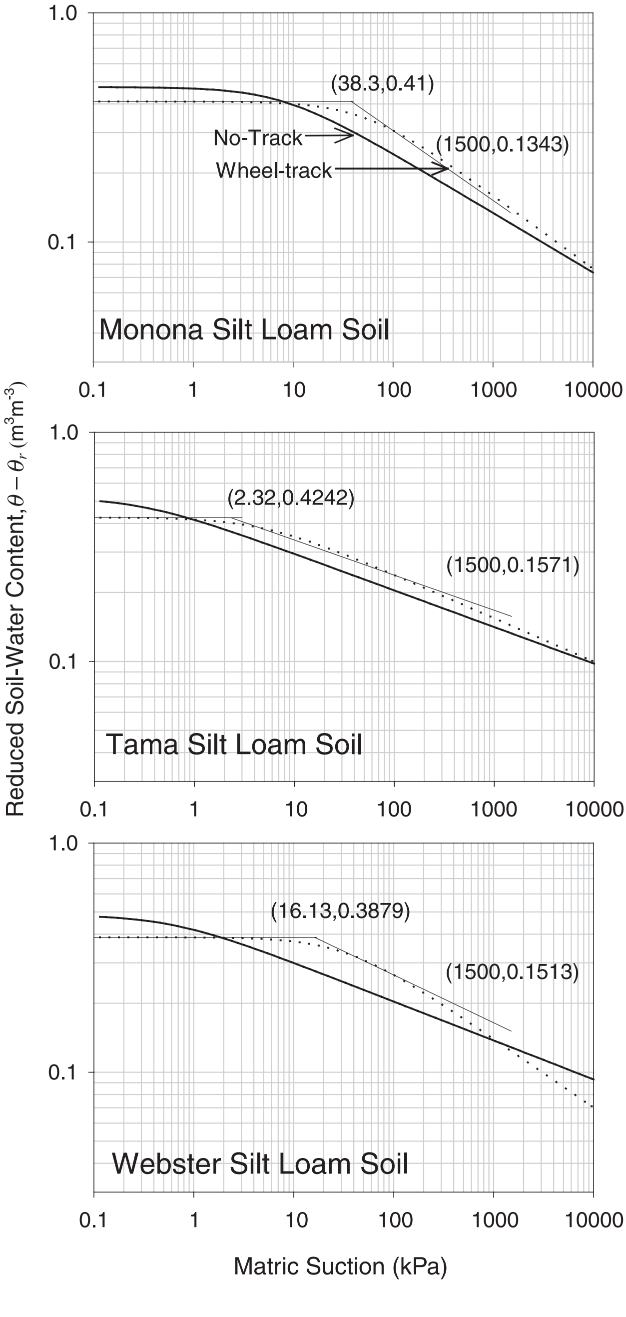

Fig. 5. Soil retention curves for the three Iowa soils with estimated slopes and air entry values based on estimated soil-water contents at 1500 kPa suction and known water contents at 100 kPa. Solid curves are for no-track interrows; dotted curves for wheel-track interrows, and solid lines are estimates of the track curve based on a known value for 100-kPa water content and a theoretical estimate at 1500 kPa.

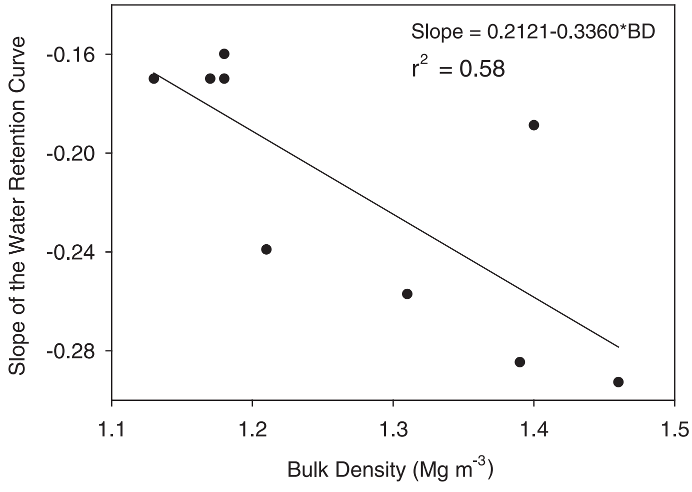

Fig. 6. Fitted slopes versus soil bulk density from the water retention curves in Fig. 5. Slopes were estimated from the log–log soil-water retention curves between 100 and 1500 kPa of matric suction.

aggregate rejoining by capillary forces and strain due to both steady and transient (e.g., cyclical) stresses. The authors also gave an illustrative application of the theory; they pointed to the promise of upscaling the microscale results to an aggregate bed.

For the analyses and predictions presented above, we assumed that the soil bulk density and porosity of the compacted soil were known. Theoretical approaches are available to estimate bulk density under wheel tracks, based on the knowledge of soil-water content, soil mechanical properties, and characteristics of the vehicle creating wheel tracks. Defossez et al. (this issue) give details of this approach.

4. Crop residue management

Studies of the direct effects of crop residue management on soil hydraulic properties and processes have focused on the use of surface residue to control soil crusting or sealing. Duley (1939) studied the effects of surface factors on infiltration using residue cover and man-made material to protect the soil surface. Fig. 7 provides an illustration of infiltration (soil intake) rates with two surface covers (straw and burlap), which subsequently were removed to allow the soil to seal, thus decreasing the infiltration rates.

Ruan et al. (2001) conducted numerical experiments of the effects of residue cover and associated surface sealing on two-dimensional infiltration. Crop residue was assumed to occur in distinct, regular patches beneath which the hydraulic conductivity of the surface soil was maintained at its original value, and bare soil areas were assumed to seal to various fractions of the saturated hydraulic conductivity. The results were sensitive to the degree of sealing and percentage of area covered by residue, but not to the patch geometry, which is consistent with the findings of Baumhardt and Lascano (1996) for cotton. Ruan et al. also showed that one-dimensional simulations with weighted average K_s of the surface

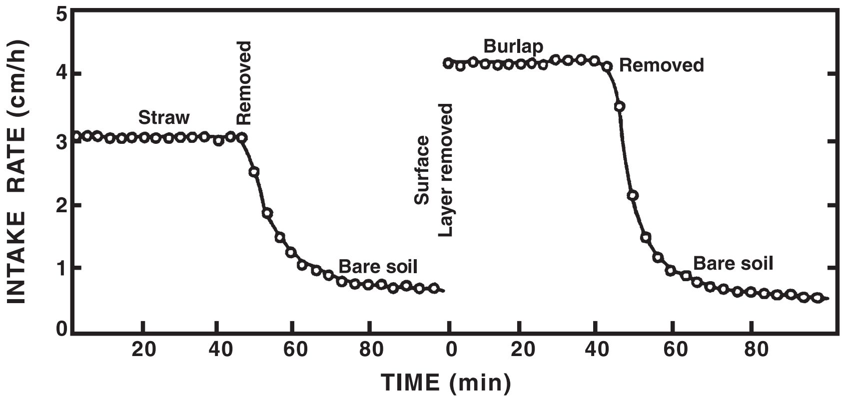

Fig. 7. Illustration of the effect of soil crusting (sealing) on infiltration in relation to surface residue cover (from Duley, 1939 with permission from SSSA).

seal over the whole area were similar to the two-dimensional results for all but complete sealing of the non-residue areas. Model results were compared with available results from field studies for corn and cotton residues (Lang and Mallett, 1984; Baumhardt and Lascano, 1996) as shown in Fig. 8. It is interesting to note that the corn and cotton results coalesce when expressed as a function of percent residue cover, and the one-dimensional model predicts both field data sets.

Additional field experiments have been conducted on wheat-fallow systems in the Great Plains of the USA (Greb et al., 1967; Smika and Wicks, 1968; Tanaka and Aase, 1987; Peterson et al., 1996). Fig. 9 (Nielsen, 2002) shows the combined effects of residue

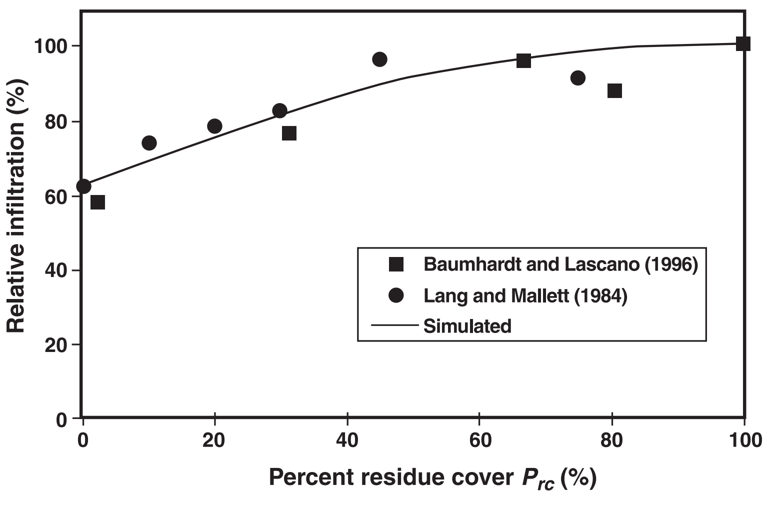

Fig. 8. Comparison of experimental studies and one-dimensional simulation results (from Ruan et al., 2001) showing relative infiltration versus percent residue cover. The square symbols represent data for cotton residue, whereas the round dots are for corn residue.

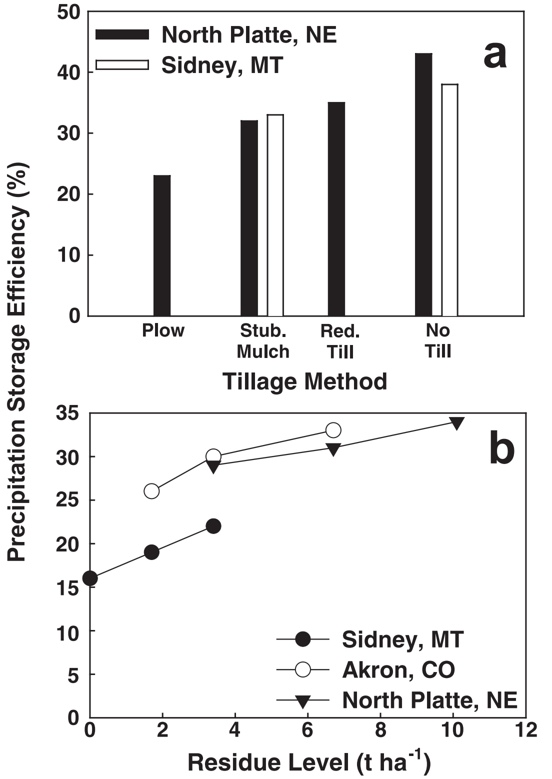

Fig. 9. Precipitation storage efficiency versus (a) tillage method based on wheat-fallow systems in Colorado and Nebraska (data from Smika and Wicks, 1968) and in Montana (data from Tanaka and Aase, 1987) and (b) residue level (data from Greb et al., 1967). Figure taken from Nielsen (2002).

management and tillage method on precipitation stored in the soil. The results for residue effects are qualitatively similar to the numerical experiments of Ruan et al. (2001) in that the response to residue cover is greatest initially (steepest change for low residue levels) then approaches some asymptotic value (Figs. 8 and 9).

In the long-term, the crop residues increase organic matter content of the surface soil, and, in conjunction with biological activity (e.g., Trojan and Linden, 1994), modify its bulk density, aggregation, and hydraulic properties. 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. Further work is needed to predict and simulate the effects of residues.

5. Additional work and challenges for prediction

Several challenges and needs for further research have been highlighted in the sections above. The following section reviews studies that may be viewed as the first steps toward quantitative prediction in some of the most challenging areas. In particular, we highlight the need for innovative research on cropping systems and management practices affecting soil macropores, followed by the effects of interactions between some of the management practices reviewed above. In addition to management interactions, there are interactions with natural landscape variability and other factors.

5.1. No tillage and crop rooting effects on macropores

Most natural soils contain some macropores. Water flow and transport in soils containing a network of macropores open at the soil surface can differ substantially from predictions for soils without connected macropores (Thomas and Phillips, 1979; Beven and Germann, 1982; White, 1985; Heathman et al., 1995). Macropores formed by earthworms and decayed plant roots can be preserved in a no-till soil and affect infiltration (Edwards et al., 1979; Scotter and Kanchanasut, 1981; Dick et al., 1989). Conventional tillage, on the other hand, tends to destroy the continuity of macropores in the topsoil. Thus, water movement from the soil surface to macropore channels in the subsoil is reduced (Bouma et al., 1982).

Macropore volume is generally a small fraction of the soil volume (0.001 to 0.05), but its contribution to ponded infiltration can be very high (White, 1985; Watson and Luxmore, 1986). Watson and Luxmore (1986) have used the difference between ponded (zero tension) and 3-cm tension infiltration rates to estimate macropore volume and hydraulic conductivity. In that case, the lower limit of macropore equivalent diameter was 1.0 mm, but there is no unique basis for selecting a particular size, despite attempts to establish size classes for micro-, meso-, and macropores (Luxmore, 1981). Beven and Germann (1982) reported values ranging from 30 μm to 3.0 mm.

Root growth may decrease ponded infiltration rates initially, but decomposition of roots leaves channels or macropores that can increase infiltration (Barley, 1954). Disparte (1987) measured higher infiltration rates in plots planted with alfalfa compared with unplanted controls. Meek et al. (1989, 1990) found increases from 140% to 240% in infiltration rates with time in soils planted with alfalfa. Shirmohammadi and Skaggs (1984) reported a 70% increase in hydraulic conductivity in the top 20 cm of soil planted with fescue grass and a 40% increase with soybeans compared with soil columns without any crop. Chan and Heenan (1993) found a strong correlation ($R^2 = 0.82$) between transmitting macropores and earthworm population, but tillage rather than residue removal (stubble burning) appeared to reduce the earthworm population. Yet, tillage did not change the total number of macropores.

Further research is required to provide quantitative predictions of no-tillage and cropping effects on the number and flow capacity of continuous macropores in different soils and climates, and under different management practices.

Plant roots also can change the pattern of water movement and chemical transport under plant rows in addition to their effect on soil macropores. 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. Vanwesenbeeck 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 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 zone than in the interrows 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 rows (Timlin et al., 2001).

5.2. Management interactions

Interacting factors have complicated analysis of many field studies. Logsdon et al. (1993) stated, "Tillage and residue management practices influence soil surface compaction and sealing, but the effects vary with time and weather history." Various tillage studies include the effects of wheel traffic on infiltration (Ankeny et al., 1990, 1995; Freese et al., 1993; Kaspar et al., 2001). In one study, Betz et al. (1998) used the Least Limiting Water Range (LLWR) to evaluate the combined effects of tillage and wheel tracks on a poorly drained clay loam with a plow pan. Linear regression of water retention versus bulk density was sensitive to wheel tracks and tillage, but reductions in LLWR varied between tillage treatments in a less consistent manner.

Interactions between tillage and wheel traffic effects on soil biochemistry have also been studied (Lee et al., 1996) where some effects on soil hydraulic properties can be inferred. Contrary to common expectation, Lee et al. found that the combination of wheel traffic and conventional tillage may promote soil microbial activity on a coarse-textured soil.

The interaction between tillage and residue has important effects on soil properties, and the two topics are often studied together. Stubble-mulch tillage, for example, has been shown to affect soil bulk density (Dao, 1996; Unger and Jones, 1998). Previously, Tanaka (1985) related stubble mulch to seasonal water contents. Potter et al. (1995) identified the effect of tillage on residue as the most important factor for infiltration in their field site. Various other papers have addressed the combined effects of tillage and residue management (Benoit and Lindstrom, 1987; Zachmann et al., 1987; McFarland et al., 1990; Thorburn, 1992; Dao, 1993; Logsdon et al., 1993; Karlen et al., 1994; Lal et al., 1994; Rawitz et al., 1994; Singh et al., 1994; Trojan and Linden, 1994; Sembiring et al., 1995; Peterson et al., 1996; Sharratt, 1996; Unger et al., 1997; Trojan and Linden, 1998; Baumhardt and Jones, 2002). Further research is needed to predict the process interactions involved.

Another related issue is the effect of tillage on mixing of surface residues and surface-applied chemicals. Allmaras et al. (1996), for example, characterized the depth distributions of oat residues and ceramic spheres incorporated by tillage into the top 30 cm. Chisel plowing incorporated >90% of the residue in the depth interval between 1 and 11 cm, but moldboard plowing incorporated 67% between 10 and 20 cm. Secondary tillage (i.e., cultivation) did not affect these depth distributions significantly, but 35% of the 2-cm samples indicated effective mixing of residue and agrichemicals into the soil.

Trojan and Linden (1994) studied the combined effects of residue management, tillage, rainfall and earthworm activity on the movement of a strongly sorbed organic tracer, and found significant effects of residue and related earthworm activity on dye concentrations below 20 cm. Trojan and Linden (1998) also found that a dye solution infiltrated faster for no-till and tillage treatments with residue than for other treatments, but there were no significant differences between treatments for the steady infiltration rates. Others have also investigated residue-related earthworm effects on water flow and chemical transport (Zachmann et al., 1987; Zachmann and Linden, 1989; Edwards et al., 1990; Logsdon and Linden, 1992; Monnier, 1992; Carter et al., 1994), and Karlen et al. (1994) measured long-term effects of residue cover on earthworm population and CO_2 evolution in combination with effects on soil aggregation and bulk density. These types of studies could be further evaluated and used to develop predictive models of such biological process effects on macropore transport.

To investigate the effects of macropores and soil aggregates on (conservative) chemical transport, Heathman et al. (1995) conducted laboratory experiments on soil columns using surface application of a Bromide tracer. Ahuja et al. (1995) quantified these experiments using a one-dimensional transport model included in RZWQM (Ahuja et al., 2000). Fig. 10a,b shows the effects of surface aggregates in the absence of macropores on the distribution of tracer concentration with depth. The aggregates retarded vertical transport rates, reducing the peak concentration and depth, while causing a tail of measurable concentrations near the surface. Fig. 10c,d includes the effects of macropores. In both cases (with and without aggregates), macropores enhanced vertical transport and reduced the peak concentrations. Rapid, deep transport below the main wetting front was observed and simulated only in the presence of surface aggregates due to mixing of bromide held in the aggregates with ponded water that subsequently flowed through macropores. Simulated results matched the measured concentrations well, and Ahuja et al. (1995) identified the critical calibration parameters including correction factors to K_s (due to viscous resistance and entrapped air) and absorption (due to compaction along macropore walls), a mixing parameter, and the microporosity of the surface (1 cm) layer.

The above results strongly indicate that future research must take into account multiple management interactions in devising process-based predictions of management effects. Interactions with landscape factors must also be considered explicitly.

In all of these studies, the results may be affected by the methods used to estimate hydraulic properties. Mechanical compaction and methods of wetting (full saturation from the top or partial saturation from the bottom of cores in the laboratory) were shown to affect the estimated water retention using a direct evaporation method in the laboratory compared with inverse modeling of field measurements (Richard et al., 2001). Likewise, values of K_s measured in the laboratory on core samples may be unreliable. Klute and Dirksen (1986, p. 691) stated, “To characterize a field or plot of soil, in situ measurement of hydraulic properties is preferred.” Thus, measurement uncertainty contributes to the difficulty in detecting real differences between treatments.

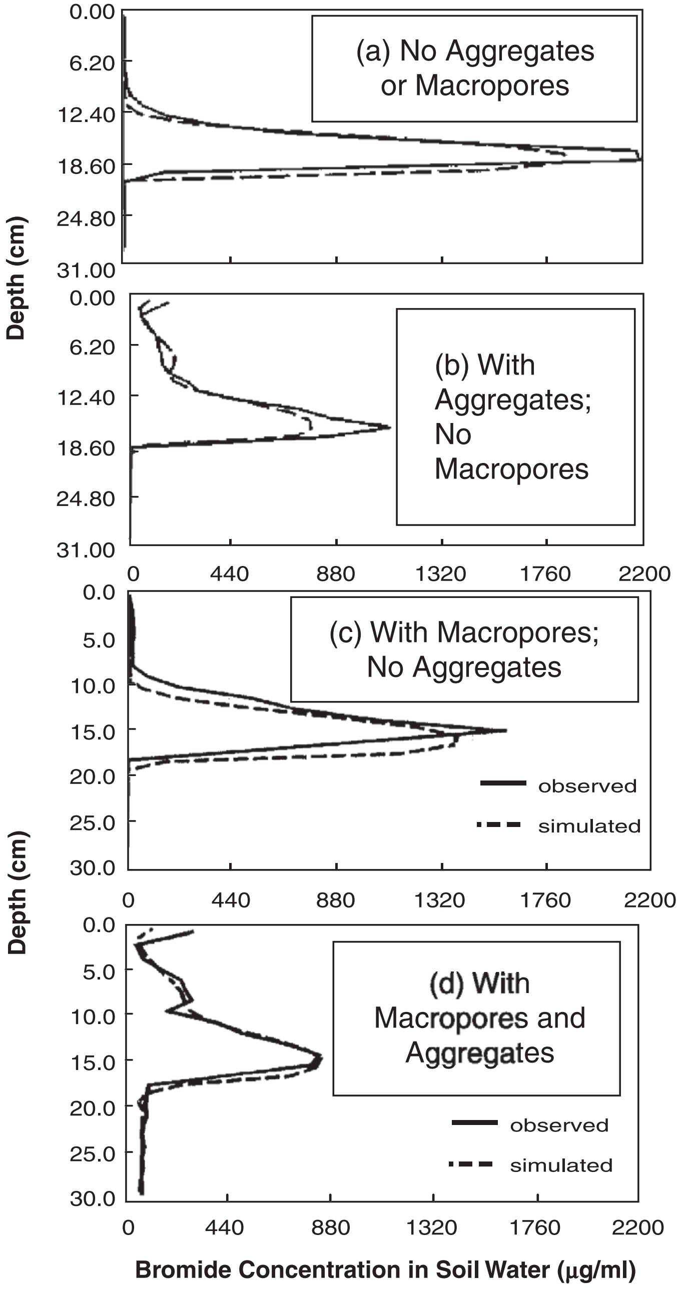

Fig. 10. Bromide tracer concentration profiles: observed (solid lines) and simulated with RZWQM (dashed lines) into initially dry soil comparing with and without soil aggregates for (a,b) without macropores and (c,d) with macropores (from Ahuja et al., 1995).

6. Discussion and summary

We have provided an overview of the advances and challenges in quantifying agricultural management effects on soil hydraulic properties particularly relevant to temporal, but also spatial, variability. Despite a shortage of investigations directly addressing our topic, we have identified a number of studies quantifying management effects on at least a few basic soil properties, and their relevance to more detailed characterization of soil hydraulic properties and processes.

Experimental results from field and laboratory studies do not support consistent effects of management on soil hydraulic properties. Controlled equipment traffic has been shown to have significant effects on soil compaction and related hydraulic properties on some soils, but on others, landscape and temporal variability overwhelm any effects of wheel tracks. These contradictions need to be resolved based on basic principles.

The literature demonstrates an awareness of interactions between management practices, as well as some appreciation of the complexity of spatial and temporal variability. However, quantitative algorithms for computer simulation are scarce and typically limited to the short-term effects of tillage on soil hydraulic properties.

Spatial and temporal variability have often overshadowed any measured differences between management treatments. Most tillage practices have pronounced short-term effects on soil hydraulic properties immediately following tillage application, as expected, but these effects can diminish rapidly (even after the first wetting/drying cycle). Long-term effects on the order of a decade or more are less pronounced and often impossible to distinguish from natural and unaccounted management-induced variability. Furthermore, soil type and climate affect the patterns of management-induced temporal changes, and landscape position affects the magnitude and pattern of temporal variability.

Future work should aim to quantify process interactions, and experimental designs must consider the dominant factors affecting soil hydraulic properties. Such research will help us develop improved predictive equations and more robust computer simulations, carefully tested against field data. The application of such predictive tools could provide valuable aid to producers and conservationists.

Acknowledgements

The authors are grateful to Dr. Gale Dunn and Mike Murphy for collection of sample cores in Colorado. Dr. Liwang Ma was instrumental in data analyses for wheel-track effects. We also thank Prof. Gary Peterson for collaboration at the Lindstrom Farm, Colorado, and Mr. and Mrs. Gilbert Lindstrom for the use of their land for long-term field experiments.

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