Available online at www.sciencedirect.com
ScienceDirect
Soil & Tillage Research 99 (2008) 4–48
Soil & Tillage Research
www.elsevier.com/locate/still

Review

Tillage effects on soil hydraulic properties in space and time: State of the science

Mark W. Strudley, Timothy R. Green *, James C. Ascough II

USDA-ARS, Agricultural Systems Research Unit, 2150-D Centre Avenue, Suite #200, Fort Collins, CO 80526, USA

Received 17 January 2007; received in revised form 24 December 2007; accepted 16 January 2008

Abstract

Soil tillage practices can affect soil hydraulic properties and processes dynamically in space and time with consequent and coupled effects on chemical movement and plant growth. This literature review addresses the quantitative effects of soil tillage and associated management (*e.g.*, crop residues) on the temporal and spatial variability of soil hydraulic properties. Our review includes incidental management effects, such as soil compaction, and natural sources of variability, such as topography. Despite limited research on space–time predictions, many studies have addressed management effects on soil hydraulic properties and processes relevant to improved understanding of the sources of variability and their interactions in space and time. Whether examined explicitly or implicitly, the literature includes studies of interactions between treatments, such as tillage and residue management. No-tillage (NT) treatments have been compared with various tillage practices under a range of conditions with mixed results. The trend, if any, is for NT to increase macropore connectivity while generating inconsistent responses in total porosity and soil bulk density compared with conventional tillage practices. This corresponds to a general increase in ponded or near-zero tension infiltration rates and saturated hydraulic conductivities. Similarly, controlled equipment traffic may have significant effects on soil compaction and related hydraulic properties on some soils, but on others, landscape and temporal variability overwhelm wheel-track effects. Spatial and temporal variability often overshadows specific management effects, and several authors have recognized this in their analyses and interpretations. Differences in temporal variability depend on spatial locations between rows, within fields at different landscape positions, and between sites with different climates and dominant soil types. Most tillage practices have pronounced effects on soil hydraulic properties immediately following tillage application, but these effects can diminish rapidly. Long-term effects on the order of a decade or more can appear less pronounced and are sometimes impossible to distinguish from natural and unaccounted management-induced variability. New standards for experimental classification are essential for isolating and subsequently generalizing space–time responses. Accordingly, enhanced methods of field measurement and data collection combined with explicit spatio-temporal modeling and parameter estimation should provide quantitative predictions of soil hydraulic behavior due to tillage and related agricultural management.
Published by Elsevier B.V.

Keywords: Soil management; Tillage; Soils; Agrophysics; Hydrology; Spatial data

* Corresponding author. Tel.: +1 970 492 7335; fax: +1 970 492 7310.
E-mail address: tim.green@ars.usda.gov (T.R. Green).

0167-1987/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.still.2008.01.007

Contents

1. Introduction

In recent decades, investigations documenting spatially averaged comparisons between tillage practices, usually contrasting ‘‘snap shots’’ of tillage versus no-tillage (NT), have become relatively common and have provided scientists and producers with broad insight about resultant, fundamental differences in soil physical properties and crop production. Currently our technological ability to apply precision agricultural practices for efficient resource management and crop yield enhancement outpaces our understanding of, and ability to predict, temporal and spatial variability of soil hydraulic behavior in response to management practices. Soil tillage represents, arguably, the most influential manipulation or alteration of soil physical properties because of repetitive application, its depth range extending up to tens of centimeter, and because it influences the type of residue management applied. Likewise, informed tillage application in response to temporal variability in soil hydraulic properties can invoke attractive benefits in areas that have suffered from low yield and inefficient resource allocation in the past (Raper et al., 2000). The research community is just beginning to explore the dynamic temporal and spatial variability in soil physical properties and processes in light of various tillage management practices, and the time is ripe to summarize the state of knowledge for this aspect of agricultural management.

The purpose of this paper is to review the literature and state of the science concerning: (1) causes of continuous temporal and spatial variability in observed soil hydraulic properties and processes as a result of tillage practices and (2) our ability to quantify and predict the effects of tillage practices on dynamically evolving soil hydraulic properties. We do not attempt to provide a review of studies that quantify spatial and temporal variability of soil properties and processes alone; rather, we address spatial and temporal variability resulting from soil tillage and its incidental effects, such as compaction from wheel traffic and crop residue management. Our paper begins with a background discussion of relevant soil hydraulic properties and processes, and follows with a brief overview of spatial and temporal inter-relationships between management practices and anthropogenic and natural variability, with specific emphasis on soil tillage practices. We then review numerous experimental studies dealing with spatio-temporal variability in soil physical properties and processes as a result of tillage management, including responses from coupled tillage and irrigation activities/experiments. Subsequently, we present a brief discussion of residue management and mechanical compaction, since these activities are often directly impacted by tillage practices and affect soil physical characteristics in space and time. We also review modeling endeavors designed to address tillage effects on dynamically evolving soil physical and hydraulic properties. We conclude with a discussion and summary of the need for a more mechanistic understanding of spatio-temporal dynamics of soil physical processes and properties from soil tillage, and the need to develop modeling tools that accurately characterize and predict this variability for prediction purposes.

2. Background

This review focuses on how soil hydraulic properties and processes vary dynamically in space and time as affected by tillage practices. We begin by identifying a brief taxonomy of the topic areas, first in terms of the soil hydraulic properties and processes being affected, and then by management practices and other causative factors. As in the literature review that follows, we present soil hydraulic properties in the order: soil bulk density, porosity, pore geometry, and soil structure; water retention characteristics; hydraulic conductivity (variably saturated); infiltration capacity; soil crusting and cracking. This sequence roughly mirrors the effects of tillage; soil physical properties are immediately modified, resulting in a change in state (water retention) followed by dynamically evolving process-responses in water and solute transport. Soil crusting and cracking may subsequently occur as a result of these process interactions, but our literature review does not dedicate an independent subsection for this response and instead presents crusting and cracking effects within the other response group subsections.

2.1. Soil hydraulic properties and processes

Many studies focus on soil properties and processes as intermediary conditions that support an outcome (*e.g.*, crop yield or erosion rate) with which producers and other practitioners are most concerned. In this review, we do not focus on these types of studies, except where the process-based understanding of soil property effects on a management outcome is made explicit. Despite producers' emphasis on the importance of outcome, we place an importance on soil hydraulic properties and processes due to a desire for improved process understanding, which in turn, leads to better predictions of both agricultural production and environmental impact.

Management practices typically are applied as events, but their effects may be active over various time scales. The resulting variability in hydraulic properties is dynamic in space and time as an overlay on what might be viewed as natural variability. Both natural and human-induced variability have been characterized and quantified to various levels of detail in the hydrologic, agronomic, soils, and earth sciences literature.

2.1.1. Soil bulk density, porosity, pore geometry, and soil structure

Two of the most commonly measured soil properties affecting hydraulic properties and processes are the soil bulk density and (effective) porosity. Conventional sampling methods (*e.g.*, intact soil core data) remain useful for quantifying these properties in the near surface. However, collection of undisturbed and uncompacted samples is difficult, particularly at depth, and leads to uncertainty between reported values from field- and laboratory-based measurements. This uncertainty is important because these measured values are used in highly nonlinear transfer functions to estimate the soil hydraulic properties in both diagnostic and prognostic spatio-temporal modeling endeavors.

Soil bulk density and porosity are also fundamental to soil compaction and related agricultural management issues. Thus, the importance of these quantities is readily apparent to practitioners. Although scaling of these properties is simple given known patterns of spatial variability, characterization of their cross-correlated variability in space and time is complex.

Understanding of soil pore geometry and structure is fundamental to identification of tillage effects on soil physical and hydraulic properties. Kay and Angers (2002) provided standard definitions (*e.g.*, weak to strong soil structure), classifications (*e.g.*, macropores $> 75\ \mu m$), and a useful discussion of factors affecting soil structure, including texture and mineralogy, organic matter, inorganic materials, pore fluid, microorganisms, soil fauna, plants, climate, and management.

Others have focused on measuring and quantifying soil pore geometry. Bruand et al. (1993) used mercury porosimetry to identify three types of pore volumes resulting from (1) packing of clay particles; (2) packing of silt and sand particles with clay; and (3) tillage and biological activity. Pagliai et al. (1995) also used mercury intrusion porosimetry and image analysis on thin sections of a silty loam and clay soils. They were able to distinguish differences in microporosity and elongation of pores affecting core-scale hydraulic conductivity. This work followed their previous research on micromorphology of clay loam soils affected by tillage (Pagliai et al., 1983, 1984).

Differences in soil density and macroporosity can be measured in detail on soil cores using ultra-high-resolution (0.1 mm thick) X-ray tomography (Gantzer and Anderson, 2002). Alternatively, soil samples impregnated with resin containing fluorescent dye were cut into thin sections, and images of ultraviolet light were analyzed to classify the pore space and quantify the structure (Ringrose-Voase, 1996). The effects of tillage (CT versus NT) on soil structure and porosity have also been studied using ultraviolet-dye-impregnated thin sections of a clay loam (Miller et al., 1998).

Development of soil structure and aggregation are dynamic properties that depend upon soil parent material in addition to climate and management factors. Shrink/swell clays may play an important role in both the natural variability of soil structure and potential responses of soil hydraulic properties to management practices (Horn et al., 1994; McGarry et al., 2000). Changes in soil pore structure in swelling clays have been evidenced in studies of gas and water flow (Angulo-Jaramillo et al., 2000; Horn and Smucker, 2005) and solute transport (Bouma and Woesten, 1979). Swelling clays may also account for some reversal of soil disturbances, such as self-healing of cracks (Eigenbrod, 2003; McDonald et al., 2006) and re-formation of surface cracks upon drying (Radford et al., 2000). Smiles (1995, 2000) provided reviews of the physics of swelling soils, noted here for general reference. To our knowledge, Smiles (2000) has never been cited before, which points to the lack of active advances in this area, with the exception of the few studies cited here on interactions of tillage with the shrink/swell behavior of soils.

2.1.2. Water retention characteristics

Soil water retention is simply a set of state-dependent storage values. It can be upscaled along with the hydraulic conductivity, and simple (linear) volume averaging should suffice (Constantz, 1995; Green et al., 1996; Smith and Diekkruger, 1996). Scaling or functional normalization of different textural materials can also be addressed by invoking the similar media concept (Miller and Miller, 1956; Warrick et al., 1977). We address these topics within this review to help identify useful methods for predicting space–time variability in water retention characteristics.

2.1.3. Hydraulic conductivity (variably saturated)

Soil hydraulic conductivity (saturated and unsaturated) typically varies by orders of magnitude in space, and unsaturated values can change dramatically in time with the moisture state. Such space–time variability confounds our ability to scale hydraulic conductivity in a generic manner (under all transient gradient and moisture conditions), but various authors (Yeh et al., 1985; Mantoglou and Gelhar, 1987; Russo, 1992; Green and Freyberg, 1995) have addressed some important conditions for upscaling hydraulic conductivity and its directional properties (anisotropy). For the purposes of this review, we will assume that hydraulic conductivity is defined at the measurement scale (*i.e.*, core, disc, or ring), and that it varies at all spatial scales above this and at any measurable temporal scale. Furthermore, because of its high natural spatial and temporal variability, hydraulic conductivity is often a poor indicator of soil hydraulic response to management practices because natural variability often obfuscates treatment variability.

Saturated hydraulic conductivity and early-time intake rates into dry soils are affected by the presence of connected macropores, which can result from biological activity. Trojan and Linden (1998) contended that, "Understanding the relationship between macropore structure and hydraulic properties under different tillage-residue conditions is critical to our understanding of (the) flow of water and solutes in earthworm-affected soils and our efforts to model these flow characteristics," emphasizing the importance of interactions between soil management, biological activity, and soil hydraulic properties.

It has been difficult to quantify saturated hydraulic conductivity, K_s, and sorptivity, S, derived from field infiltration tests. Robust estimates of these soil hydraulic parameters are needed to differentiate management effects and space–time variability with statistical significance. Falleiros et al. (1998) used the Darcy-Buckingham flux-gradient approach to model water flow in soil, but failed on account of field-scale variability in soil properties. However, Ali and Swartzendruber (1994) derived an improved three-parameter infiltration equation to avoid the common problem of computing negative K_s values and to help detect differences among cropping systems. As a result, Ali and Swartzendruber (1994) found significant differences between crop rotations, where sorghum

Table 1
Space–time applications and effects of management practices on soil hydraulic properties

Practice	Space		Time	
	Application	Effect	Application	Effect
Planting	Uniform	Shallow	Seasonal/annual	Seasonal/variable
Irrigation/drainage	Uniform	Distributed or localized	Periodic events	Attenuated[a]/cumulative[b]
Harvesting/residue	Uniform/localized	Distributed or localized	Annual (usually)	Attenuated[a] (w/o till)
Fertilization/manuring	Uniform/localized	Lateral/vertical transport	Seasonal/annual	Cumulative[b] (*e.g.*, roots)
Pesticide application	Uniform/localized	Lateral/vertical transport	Seasonal	Attenuated/cumulative[b]
Tillage	Uniform	Uniform/depth varies	Seasonal/annual	Attenuated[a]

[a] ''Attenuated'' refers to a reduction of the magnitude of an effect on a soil hydraulic property with time after application. Values of different properties may increase or decrease with time.
[b] ''Cumulative'' refers to an effect that accumulates in time from the listed practice due to response times of other factors affecting soil hydraulics.

exhibited the largest S values, and the smallest K_s values were associated with soybean.

2.1.4. *Infiltration capacity*

Although the infiltration capacity can be predicted from measured soil hydraulic properties and an initial moisture state, this quantity often is measured directly without knowing the more fundamental soil hydraulic properties. Thus, studies of the direct effects of management on space–time infiltration rates and related runoff, erosion, and chemical transport are relatively common. The infiltration capacity is a particularly important quantity (or curve) for irrigation scheduling and storm event modeling.

Infiltration rates are measured under either ponded (positive soil water pressure) or matric tension conditions. Comparison between the two can be used to infer macropore hydraulic conductivity and porosity. Conservative tracers and dyes are also useful for determining flow paths and fluid velocities.

2.1.5. *Soil crusting and cracking*

Near-surface soil properties, such as crusting or sealing and subsequent cracking, are readily observed but difficult to quantify. Characterization of these properties in space and time is important to prediction of water intake rates and associated runoff and erosion rates. Some investigators have also addressed the effects of crusting on seedling emergence and plant growth; however, we do not cover this specific aspect of crusting further.

2.2. *Agricultural management, natural variability, and soil tillage*

Space–time variability may not be addressed directly in some of the literature cited herein, but we include studies of management effects that can be interpreted in the context of space–time variability. Table 1 shows a matrix of management practices versus spatial and temporal applications and effects. In this review, we focus on tillage effects (listed last in Table 1) and related management activities such as planting and harvest/residue management (listed first and third, respectively, in Table 1). This table highlights the differences between intended application coverage in space and time, and the resulting effects. For example, even uniform applications in space have effects that vary in space, and discrete application events have attenuated and cumulative effects in time. Thus, knowledge of the management history can be very important due to cumulative effects on soils.

Table 2 highlights other important natural and human factors that interact with the management practices in Table 1 and affect the spatial and temporal patterns of changes in soil hydraulic properties and processes. Table 2 is similar to Table 1, but it lists only the possible effects of each factor. The first factor, wheel tracks, is not a direct management practice, but results as an indirect consequence of most management practices, including tillage. Geology, soil type, and topography are all coupled or cross-correlated at the landscape scale and are important factors for identifying zones of differential management and/or response. Topography has both short- and long-term effects on soil water status and transport by water and wind, and is well known as one of the five factors of soil formation (Jenny, 1946) affecting within-field spatial variability. Climate and weather events interact with the temporal application of every management practice, affecting both management decisions and the resulting effects on soils. On-site and off-site surface and subsurface contributions to flow at a given location are related to the landscape topography and can have significant effects on soil properties. Finally, plants (agricultural crops) can have drastic effects on soil physical properties, for example, through

Table 2
Spatio-temporal scales defining other management and landscape factors

Factor	Space	Time
Wheel tracks	Linear/periodic	Seasonal
Geology	Large structures	Stable
Soil type (matrix and macropores)	Soil units/topographically controlled	Stable/seasonal
Topography	Micro (cm) to macro (km) scale	Stable (macro)/unstable (micro)
Weather/climate	Variable/uniform and micro (m) to macro (>10^2 km)	Event/seasonal/>decadal (climate)
Surface/subsurface hydrology (on/off-site contributions)	Non-uniform; distributary (*e.g.*, transmission through soil) or localized (*e.g.*, channels)	Event to seasonal or greater
Plants	Linear/periodic; micro (mm) to macro (m) root effects	Annual (seasonal) and perennial (quasi-stable)

the influence of roots on soil strength and structure (roots from wheat breaking apart plow pans, etc.).

Tillage is intrinsically a complex management practice in terms of spatial and temporal application. Tillage implements or tools vary in terms of both width and depth of plowing and in terms of the intensity in soil overturn administered by the implement design (disc versus moldboard plow, etc.). Furthermore, interactions between natural factors (*e.g.*, soil type, geology, topography, climate and weather patterns—see Table 2) and crop selection, in part, determine the intensity, depth, frequency, and timing of tillage, which highlights the need for a mechanistic understanding of tillage effects on soil hydraulic properties and processes in space and time. Even incidental effects of tillage, such as wheel traffic, can lead to complicated and seemingly stochastic soil hydraulic response where changes in seasonal crop rotation row spacing result in a random template of wheel compaction upon a field. Prediction of soil hydraulic response to tillage is further complicated by heuristic human application; time of planting and associated management are often based on ''expert knowledge'' handed down through generations on family owned farms. Many studies discussed in the subsequent literature review address site-specific effects, dealing with localized conditions, management practices, and crop selection, which provide limited, but important, insight into spatio-temporal response to tillage practices. The collection of studies outlined here is intended to provide a more generalized, versatile understanding of spatio-temporal responses.

3. Literature review

The following literature review first presents information on both short- and long-term effects, as well as spatially variable effects, of soil tillage on soil hydraulic and physical properties and processes (Section 3.1). Although the work covered may not be exhaustive, it is representative and fairly comprehensive concerning recent advances and the state of the science. We include a sampling of literature that outlines long-term, spatially averaged, process response to changes in tillage practices (Section 3.1.1) to set the stage for the focus of this paper: a synopsis of more detailed temporal and spatial variability (Sections 3.1.2, 3.2 and 3.3) in soil hydraulic traits as a result of tillage and related management (including residue management and mechanical compaction). Section 4 discusses the capabilities of work aimed at predicting soil responses to tillage practices and provides guidance for how scientists may begin to approach modeling endeavors of soil physical and hydraulic properties and behavior. In addition to specific research investigations, we highlight broader perspectives and previous literature reviews on related topics. We also finish with a discussion regarding the summarized literature and how agricultural land management agencies and other institutions and individuals may address soil tilth with a more dynamic approach and understanding.

3.1. Tillage

From the first record of history, humans understood the value of tillage, ''Cain worked the soil'' (Genesis 4:2), but only the effects on production were documented: ''In the course of time Cain brought some of the fruits of the soil . . .'' (Genesis 4:3). Of course, the hydraulic properties of soils were not defined as we know them until recent generations (Richards, 1931; Horton, 1940), and there was little in the literature on management effects on soil hydraulic properties until the 1980s, with one very early exception (Duley, 1939) limited to soil cover effects on infiltration rates.

The publication history in the area of spatial and temporal variability in soil properties due to tillage

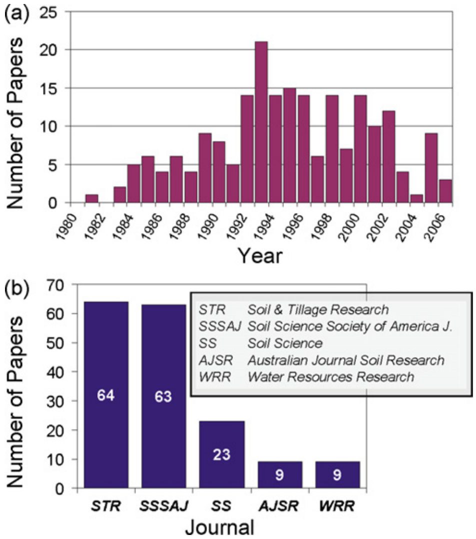

Fig. 1. Papers published on the effects of soil tillage and related management on soil hydraulic properties and properties relevant to space-time variability. (a) Time series of papers found per year; and (b) major source journals for papers found in (a) (plot includes the top 5 journals, totaling 168 papers out of the 220 references cited here). Data include papers through 2006. Pre-1980 papers include 12 papers going back to the 1930's.

Fig. 2. Various tillage implements: (a) three-bottom rollover plow and (b) strip tiller at the Agricultural Research, Development, and Education Center, CO. Photos courtesy of Ardell Halvorson, USDA, Fort Collins, CO.

(Fig. 1a) shows a rapid increase in the 1980s followed by a peak rate of publication in the 1990s slowing into the 21st century. Fig. 1b shows the primary sources of journal papers found for the literature review concerning spatial and temporal variability. More than half of the papers were found in two journals, but the publishers and authors reflect international interest and input.

Tillage is the most widely researched management practice affecting soil hydraulic properties and processes. Results of tillage treatments, however, have not always been consistent across locations, soils, and experimental designs. The literature below highlights both trends across all studies and apparent contradictions. Such inconsistencies further 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.

The terminology for tillage practices varies geographically and culturally. We follow the authors' descriptions in places, but attempt to use universal terms whenever possible. Common terms are abbreviated as follows: conventional tillage (CT; Fig. 2), including chisel plowing (CP) and moldboard plowing (MP), conservation or minimum tillage (MT), and no-till systems (NT; Fig. 3). The ambiguity of CT, in particular, is noted due to different "conventional" or "traditional" tillage practices in different parts of the world. The interested reader is referred to the original papers for more details, where available, but it should be understood that CT represents the most intensive of all tillage treatments within each study reviewed.

In a previous literature review, Unger and Cassel (1991) highlighted variations in tillage effects on soil mechanical and hydraulic properties due to both tillage implements and soil factors, noting that "soil properties for a given operation are difficult to visualize, let alone predict." Unger and Cassel (1991) emphasized the need for better control and reporting of factors such as the depth and speed of tillage, historical soil management, and availability of crop residues. In the same year, Gupta et al. (1991) reviewed models for predicting tillage effects on bulk density, hydraulic and thermal conductivity, and water retention characteristics, among other variables. Much of the need for laboratory and field-testing of the methods outlined by Gupta et al. (1991) remains crucial to the state of the science over a decade later. More recently, Guerif et al. (2001) reviewed tillage effects on seedbed tilth, including a discussion of some approaches for predicting hydraulic properties from soil structure. Or and Ghezzehei (2002)

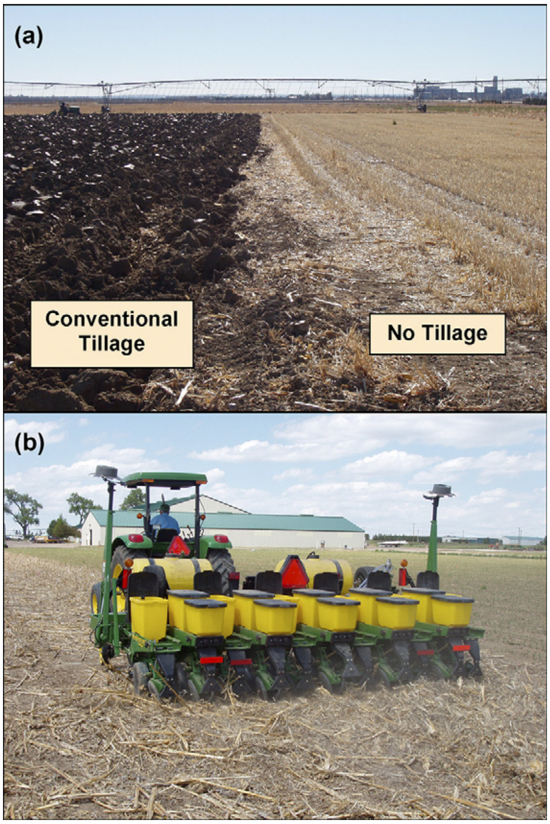

Fig. 3. No-tillage practices: (a) NT vs. CT (moldboard plow) and (b) corn planter in NT at the Agricultural Research, Development, and Education Center, CO. Photos courtesy of Ardell Halvorson, USDA, Fort Collins, CO.

discussed advances in physically based simulation, and suggested a means by which aggregate-scale modeling of dynamic soil aggregate stability and rheology can be upscaled to model the behavior of an aggregate bed. Most recently, Ahuja et al. (2006) reviewed interdisciplinary topics in soil physics and agricultural systems research, including quantifying effects of tillage on soil properties and soil–plant–atmosphere processes. Although these reviews contribute important background information and suggestions on how to move forward in understanding the effects of tillage, here we present a more detailed look at the dynamic variability in space and time of soil hydraulic properties caused by tillage.

3.1.1. Long-term, spatially averaged, process responses to changes in tillage practices

This subsection summarizes some basic, field-averaged responses observed between different tillage practices, usually involving long-term split-plot studies or a perceived result of changing from one type of tillage practice to another during a subsequent season on the same experimental site. These observations of long-term, spatially averaged, process responses to changes in tillage practices are summarized in Table 3.

Most field studies of tillage practices in modern times have included comparisons with NT systems. Changing from CT to NT practices has previously been thought to negatively impact the soil properties. NT systems, also known as ‘‘direct drilling’’ systems, have been applied and tested in Australia (Burch et al., 1986; Chan and Mead, 1988; Carter and Steed, 1992; Cresswell et al., 1992; Packer et al., 1992; Chan and Heenan, 1993; Murphy et al., 1993; Somaratne and Smettem, 1993; Carter et al., 1994; Suwardji and Eberbach, 1998), New Zealand (Ross and Hughes, 1985; Francis et al., 1987; Horne et al., 1992; Francis and Knight, 1993), Europe (Harris et al., 1993; Hansen and Djurhuus, 1997; Soane and Ball, 1998), and in the Americas (including Canada and South America; see below).

3.1.1.1. Soil bulk density, porosity, pore geometry, and soil structure. We explore reported sensitivities in soil structure and pore geometry to tillage. NT on duplex soils (sandy clay loam over a clay B horizon) in southeastern Australia resulted in lower bulk density near the surface, while field sampling of bulk density in 2-cm intervals throughout the top 30 cm of Iowa fine-loamy soils showed no significant changes during transition to NT for any depth increment (Logsdon and Cambardella, 2000). Likewise, after 8 years of tillage, Chang and Lindwall (1989, 1990, 1992) measured the effects of tillage treatments on a loam soil in Canada and found the soil bulk density did not differ among crop rotations. However, after 10 years of NT with continuous winter wheat, the bulk density was higher than under CT. Horne et al. (1992) also measured increases in aggregate size and bulk density under NT compared with MT and CT (using MP) after 10 years in a New Zealand silt loam, while total porosity declined under NT after tillage. Long-term (28-year) studies on two Ohio silt loam soils (Mahboubi et al., 1993) showed significantly greater soil aggregation under NT, while the volume of micropores (radii < 14 mm) were significantly less under CT than NT for both silt loam and sandy loam gray luvisols of the northwestern Canadian prairies (Azooz and Arshad, 1996). Comia et al. (1994), in their 8-year study on clay and clay loams using MP to 25 cm and cultivation to 13 cm, found bulk density to be greater under cultivation in the layer 13–25 cm deep, but there was no significant difference between treatments in the 0–13 cm layer.

Table 3
Effects of NT on soil hydraulic and physical properties: long-term, spatially averaged process response

Direction of response	Location	Soil texture[a]	Comments	Reference(s)
Hydraulic conductivity				
Increase	SE Australia	Duplex (SCL over C)	–	Carter et al. (1994)
Decrease (K_s)	Canada	L	30–60 mm depth only; not detectable in first 8 years	Chang and Lindwall (1989, 1990, 1992)
No change (K_s)	New Zealand	SiL	Top 10 cm; before seedbed preparation	Horne et al. (1992)
Increase (K_s)	Ohio	SiL	–	Mahboubi et al. (1993)
Increase (K_s; various tensions)	BC, Canada	SiL and SL	–	Azooz and Arshad (1996, 2001)
Increase (K_s)[b]	Ohio/Iowa	Si and CL	–	Benjamin (1993)
Decrease	Alberta, Canada	L and CL	–	Miller et al. (1998)
Increase	Waseca, MN; Lancaster, WI	Si and CL	–	Wu et al. (1995)
Increase (K_s)	Uppsala, Sweden	C and CL	25–30 cm depth; macropore continuity greater at all depths	Comia et al. (1994)
Increase (K_s)[c]	New Zealand	SiL	Minimum tillage	Cresswell et al. (1993)
Soil water retention[d]				
Low WHC	Canada	L	30–60 mm depth only	Chang and Lindwall (1989, 1990, 1992)
Higher SWC	Scott, Saskatchewan, Canada	L	9 out of 36 cases; remaining cases—no response	Brandt (1992)
Higher SWC	Slavonia, Croatia	SiL	–	Kosutic et al. (2001)
Higher SWC	Ohio	SiL	–	Mahboubi et al. (1993)
Higher SWC	BC, Canada	SiL and SL	Decreased soil drying rate; increased soil wetting rate	Azooz and Arshad (2001)
No change in SWC	New Zealand	SiL	Minimum tillage	Cresswell et al. (1993)
Soil bulk density, porosity, pore geometry, and soil structure[e]				
Lower BD	SE Australia	Duplex (SCL over C)	–	Carter et al. (1994)
No change	Iowa	Fine L	Top 30 cm	Logsdon and Cambardella (2000)
Higher BD	Canada	L	30–60 mm depth only; not detectable in first 8 years	Chang and Lindwall (1989, 1990, 1992)
Higher BD; larger aggregate size; lower porosity	New Zealand	SiL	Top 10 cm; before seedbed preparation	Horne et al. (1992)
Greater soil aggregation	Ohio	SiL	–	Mahboubi et al. (1993)
Increased vol. micropores	NW Canada	SiL and SL	–	Azooz and Arshad (1996)
Higher BD	Uppsala, Sweden	C and CL	13–25 cm depth; no change in 0–13 cm layer	Comia et al. (1994)
Increased pore connectivity; larger mean pore size; more earthworm channels	Lexington, KY	SiL	–	Drees et al. (1994)
No change in total porosity	Canada	C	Interclod porosity affected	Derdour et al. (1993)
Higher BD; reduced macroporosity	Latin America	Various	–	Alegre et al. (1991)
Higher BD; decreased macro- and total porosity	East Lansing, MI	L	Short-term	Pierce et al. (1994)

Table 3 (*Continued*)

Direction of response	Location	Soil texture[a]	Comments	Reference(s)
Infiltration capacity				
Higher sorptivity	SE Australia	Duplex (SCL over C)	–	Carter and Steed (1992)
Lower infiltration (steady state) rates	New Zealand	SiL	Top 10 cm; before seedbed preparation	Horne et al. (1992), Ross and Hughes (1985)
Lower infiltration (steady state and early-time) rates	BC, Canada	SiL and SL	Ponded rates	Azooz and Arshad (1996)
Lower infiltration (steady state and early-time) rates	Latin America	Various	–	Alegre et al. (1991)
Enhanced leaching with subsoiling vs. disk tillage	North Carolina	LS	–	Agus and Cassel (1992)

[a] S = sand, Si = silt, C = clay, L = loam, SL = sandy loam, SiL = silty loam, CL = clay loam, LS = loamy sand, SCL = sandy clay loam.
[b] 30–180% greater than CT.
[c] 11(CT)–15(MT) cm h^{-1}.
[d] WHC = water-holding capacity; SWC = soil water content.
[e] BD = bulk density.

Seeking to explain reported differences in unsaturated K between CT and NT soils, Drees et al. (1994) measured pore geometries from thin sections of a silt loam in plots under CT and NT. NT had interconnected fine pores (50–100 mm) at four depth intervals to 25 cm, along with platy structure near the surface. The average pore size in NT was greater than in CT, and earthworm channels were numerous in NT, but absent in CT. Likewise, Derdour et al. (1993) compared MP, CP, and NT systems on a clay soil with continuous barley in Canada, where they identified tillage effects on the structural (*e.g.*, interclod) porosity, but showed that tillage did not affect the total porosity. Alegre et al. (1991) summarized the results of previous tillage research in Latin America, concluding that NT and MT caused higher bulk density in the surface soil, along with reduced macroporosity compared with conventional disk tillage. Other tillage studies show short-term decreases in bulk density and/or increases in (total and macro-) porosity due to plowing versus NT treatment (*e.g.*, Pierce et al., 1994).

3.1.1.2. Soil water retention characteristics. Water storage can change in tandem with flux parameters, and the response to tillage may be equally uncertain. Chang and Lindwall (1989, 1990, 1992), in their 10-year studies of NT on a loam soil in Canada with continuous winter wheat, observed lower water-holding capacity in the 30–60 mm depth interval despite no discernable tillage effects above and below this zone. Brandt (1992) investigated 12 years of CT versus NT, and found that NT resulted in greater soil water content (SWC) in 9 of 36 cases and no significant difference in the rest. Weed control on NT was considered to be an important factor. Kosutic et al. (2001) estimated soil water availability in the A_p horizon (0–35 cm) from measured gravimetric SWC of a silty loam in Slavonia, Croatia under five tillage systems. Three of the five were variants of conservation or MT, and the extremes were NT and CT for a winter wheat–soybean rotation. Available soil water decreased in the order: NT > MT > CT. Likewise, Mahboubi et al. (1993) detected greater water-holding capacity in two Ohio silt loams during a 28-year study of the effects on NT practices. Azooz and Arshad (2001) measured water retention at six matric suctions from 5 to 160 kPa. The rate of soil drying in the top 30 cm was significantly greater in CT than NT, while the rate of wetting (based on a recharge coefficient) was significantly greater in NT. Finally, laboratory results showed higher water retention in NT than CT. All results led to the suggestion of a modified NT practice to maximize beneficial soil hydraulic properties. These results contrast with those of Cresswell et al. (1993), who demonstrated insensitivity of tillage to SWC in a silt loam in New Zealand. Thus, the empirical evidence for changes in SWC with tillage has not been generalized.

3.1.1.3. Hydraulic conductivity. NT systems exhibit variations in conductivity response. On duplex soils (sandy clay loam over a clay B horizon) in southeastern Australia, NT resulted in an increase in vertical transport of a bromide tracer compared with CT (Carter et al., 1994). Chang and Lindwall (1989, 1990, 1992) observed lower K_s in the 30–60 mm depth interval after 10 years of NT (compared to CT) on a loam soil in Canada with continuous winter wheat, despite no detectable differences during the first 8 years of observation nor in soil layers above and below this zone. Horne et al. (1992) extended a tillage study (Ross and Hughes, 1985) for 10 years under NT, MT, and CT (using MP) on a silt loam soil in New Zealand and discovered that K_s values in soil cores taken from the top 10 cm immediately before seedbed preparation did not differ significantly. This result was obtained despite declines in total porosity and infiltration rates and increased bulk density and aggregate size under NT compared with MT and CT after tillage. Long-term (28-year) studies on two Ohio silt loam soils (Mahboubi et al., 1993) showed significantly greater mean hydraulic conductivity in NT than in chisel and moldboard plowing. Azooz and Arshad (1996, 2001) studied long-term CT and NT practices on two soils (silt loam and sandy loam gray luvisols) of the northwestern Canadian prairies and concluded that "Long-term NT practices kept soil pore structure and continuity undisturbed, which contributed to significantly greater hydraulic conductivity. . .in NT than in CT for both soils." Benjamin (1993) reported the effects of eight long-term tillage and rotation studies on soil hydraulic properties, in which continuous corn exhibited much more pronounced tillage effects than either corn–soybean or corn–oats–alfalfa rotations. The K_s values were 30–180% greater in NT than for both moldboard and chisel plowing. The volume of large pores (radii > 150 μm) in MP was 23–91% greater than in NT on two soils, but these results were not consistent across all soils. Thus, quantitative predictions of the tillage outcomes were complicated by cropping and soil interactions. Miller et al. (1998) conducted tension infiltration measurements on loam and clay loam soils in Alberta, Canada under CT, MT, and NT after 26 years of tillage treatments. Values of K at different tensions determined from infiltrometer readings showed a significant ($p < 0.05$) difference in geometric means between NT and CT, where K was lower under NT. In contrast, Wu et al. (1995) evaluated the effects of tillage on solute transport in silt loams and a clay loam. The NT treatment showed more solute bypass and greater macropore conductivity than in MP. Wu et al. (1995) also concluded that the mean pore-water velocity of the mobile domain and the fraction of mobile water could be estimated from the macropore conductivity, which is more readily measured. Comia et al. (1994) conducted field experiments over 8 years on clay and clay loam soils using MP to 25 cm and cultivation to 13 cm. Values of K_s and the volume of macropores (radii > 100 μm) at 25–30 cm were greater under shallow cultivation than MP, and macropore continuity was greater at all depths without MP. Similarly in New Zealand (Cresswell et al., 1993), maximum tillage on a silt loam reduced the macropore (radii > 300 μm) volume and reduced the mean K_s somewhat (11 cm h^{-1} versus 15 cm h^{-1} compared with minimum tillage).

3.1.1.4. Infiltration rates and capacity. NTs effect on infiltration capacity and sorptivity has been documented by a number of researchers in various parts of the world. In southeastern Australia, NT resulted in higher sorptivity in duplex soils (Carter and Steed, 1992), while in New Zealand, NT resulted in the lowest infiltration rates compared with MT and CT on a silt loam during a 10-year study (Horne et al. (1992). Azooz and Arshad (1996, 2001) measured significantly lower ponded infiltration rates under CT than for NT on silt and sandy loam gray luvisols of the northwestern Canadian prairies, which contrasts with Alegre et al. (1991) who summarized results of multiple studies in Latin America documenting reduced infiltration rates for NT compared with conventional disk tillage. Cassel and colleagues have a strong history of research in the area of tillage effects on soil hydraulic properties and processes (Cassel, 1983; Anderson and Cassel, 1984; Cassel et al., 1985, 1995; Cassel and Nelson, 1985; Porro and Cassel, 1986; Simmons et al., 1989; Agus and Cassel, 1992; Bathke et al., 1992; Freese et al., 1993; Wagger and Cassel, 1993; Thapa et al., 2000, 2001), including the effects of NT systems on infiltration behavior. For example, Agus and Cassel (1992) conducted bromide tracer experiments in the field on a Norfolk soil in North Carolina (cf. Cassel, 1983) to test the effects of subsoiling on leaching depths. Subsoiling for both 1 and 2 years increased the depth of Br^- leaching compared with disk tillage, but the tracer moved below the root zone for all three treatments. There was no significant relationship between leaching depth and penetration resistance using a cone index (CI).

In summary, studies of NT management have produced mixed results, but the tendency is for NT to increase macropore connectivity while generating inconsistent responses in total porosity and soil bulk density, compared with CT practices. This corresponds to a general increase in ponded or near-zero tension infiltration rates and K_s for NT. Deeper movement of surface-applied tracers has also been observed under NT. The results appear inconsistent across soils, climates, and CT practices; however, this may be due to spatial and temporal "noise" (*i.e.*, natural and management-induced variability that cannot be isolated). Measurement uncertainty may be another important factor in determining treatment differences, but this has not been addressed to our knowledge. Thus, given the current state of knowledge concerning NT versus CT, it is not possible to generalize the results from any given study without detailed information on all controlling factors. Even if the differences between extreme practices (NT and intensive CT) were significant, effects of conservation or MT were intermediate and usually indistinguishable from NT over long periods.

3.1.2. Temporal and spatial variability in soil hydraulics from field studies of tillage practices

3.1.2.1. Soil bulk density, porosity, pore geometry, and soil structure. A variety of experiments have been performed to assess the effects of tillage on soil structural properties. Somaratne and Smettem (1993) measured greater total porosity under CT than for NT prior to seeding on a sandy loam in South Australia in the seventh year of tillage treatments, but it decreased in CT from 0.56 at pre-seeding to 0.48 after harvest, which equaled the porosity under NT. These growing-season effects also affected bulk density measurements in a silt loam in Clarksville, MD (Starr (1990), in which bulk density under MT increased during the early growing season, but did not experience decreased infiltration rates. In Oklahoma silt loams, Dao (1993, 1996) observed that NT had the highest SWC in the top 1.2 m every growing season, which was consistent with decreased bulk density. Specifically, NT had the lowest bulk density (1.24 ± 0.05 g cm^{-3}) at the end of the measurement period, and the tillage treatments had nearly equal mean values [1.31 ± 0.06 g cm^{-3} for MP and 1.30 ± 0.05 g cm^{-3} for stubble-mulch tillage (ST)]. Although Dao (1996) noted apparent temporal changes in bulk density under all three systems, the results were not statistically significant. Gomez et al. (1999) recorded spatial variability in bulk density in an olive orchard vertisol in southern Spain, where bulk density was greater in rows between the trees.

Hammad and Dawelbeit (2001) conducted experiments in sugarcane fields in Sudan under different intensive tillage practices to depths of 10, 20, and 30 cm. There were no significant differences in bulk density, clod size, penetration resistance, or residue cover between treatments. Yet, some effects of tillage on yield were observed, but remained unexplained by soil hydraulic properties. In a similar study, Mubarak et al. (2005) found that cultivation, again, had no effect on bulk density in the 0–10 cm depth interval of a tilled, clayey soil in semi-arid Sudan cultivated with sugarcane. However, observations from long-term (>40 years) plots showed a lower bulk density (1.5 mg m^{-3}) than short-term (<10 years; 1.8 mg m^{-3}) and native vegetation plots (1.7 mg m^{-3}). Osunbitan et al. (2005) observed an increase in soil bulk density with time after tillage on a loamy sand in SW Nigeria due to rainfall and particle resettlement, with NT bulk density increasing by 48%, manual hoe (MH) by 61%, disc-disc (DD) tillage by 55%, and plow-harrow (PH) tillage by 57%. In general, Osunbitan et al.'s (2005) results yielded a soil density hierarchy of NT > MH > DD > PH. Hammel (1989) examined tillage and rotation effects on bulk density and soil impedance in northern Idaho after 10 years of continuous (MP), minimum (chisel), and NT tillage treatments, and found that tillage had a significant effect on bulk density, but not on impedance. Hammel (1989) asserted that higher impedance values under reduced tillage practices may limit root function and decrease crop growth when combined with cool and wet conditions during spring.

Carter (1988) discussed temporal variability in soil macroporosity measured over a 3-year period where both MP and direct drilling treatments were applied for spring cereals in Atlantic Canada. Soil at this site, having a low plasticity index, high silt content, and a high ratio of fine to coarse sand, undergoes repeated freeze/thaw events and exhibits a propensity for structural instability and compaction, resulting in cracking and fissures despite the humid climate. Differences in measured porosity between tillage systems were most evident in the top 8 cm of soil, and direct drilling yielded <10 vol.% macropores for extended periods whereas tillage operations maintained 11–18 vol.% macropore content. Fissures were reduced under NT but generally regenerated themselves during winter, while tillage effects on porosity usually persisted over the winter months and produced more fissures than direct drilling.

In Josa and Hereter's (2005) study of temporally variable SWC in a clayey calcic soil near Barcelona, Spain, crop yield was not enhanced under NT because natural compaction processes at this site eliminated macropores containing plant-available water. This finding contradicts most other studies supporting the notion of increased macropore development for NT treatments and highlights the importance of understanding site-specific hydraulic response to local climate as a function of soil characteristics.

Yang and Wander (1998) examined temporal change in dry aggregate stability for a long-term tillage experiment [NT, disk cultivation (DT), and MP/CP] on a silt loam in Illinois. In the experiment, dry mean weight diameter (DMWD) of soil aggregates increased from October (7.3 mm) to December (9.4 mm) and decreased by April to 6.3 mm due to freeze–thaw over the winter, regardless of tillage practice. DMWD increased with SWC in October, but the relationship did not persist into December or into April. Wet aggregate stability was significantly higher in December than in either October or April, but decreased with tillage intensity. For NT and MP, the wet aggregate stability decreased for both corn and soybean rotations during the spring. These results contradict others suggesting a link between SWC at sampling time and the size and stability of aggregates; moisture effects were either masked or interacted with other variables to create the observed effects (Yang and Wander, 1998). For example, in December, aggregate size and wet aggregate stability were at their highest because crop roots, exudates, microbial by-products, and wet/dry cycles during winter maximized stability.

Chen et al. (2005) monitored short-term tillage (CT to 5.0–7.5 cm, NT, and subsoiling) effects on soil cone index in a 2-year study in poorly drained, heavy clay soil in Manitoba, Canada. Here, wheel traffic created a hardpan at 175 mm depth each fall, which was naturally removed each winter. CI values in the spring of the second year of sampling were 34% lower than those the previous fall, although the hardpan at 175 mm depth was absent during each spring of the measurement campaign. CI values also increased continuously with depth to the hardpan. Overall, tillage was less important than weather on CI values: CI values between CT and NT in the fall of the first year were not statistically different, and in spring of the second year CI was the same regardless of tillage practice. These results contrast with those of Osunbitan et al. (2005), above, who show CI increasing with time for all tillage treatments and converging after 8 weeks duration for the 0–5 cm depth interval, while NT exhibited consistently higher CI values at 5–15 cm depth for the entire 8-week study.

Castrignano et al. (2003) illustrated high temporal cross-correlation (between different sampling times) of the spatial variance of soil strength measured at different depths for a fine, silty clay vertisol in Italy managed under two tillage depths (MP at 40–45 cm and disc at 20–25 cm). However, random variations of soil impedance on the surface, controlled by SWC, yielded a small range for horizontal (in space) variance and poor to non-existent temporal correlation in spatial variation of soil strength. SWC in this experiment, controlled by random rainfall patterns, rendered tillage management ineffective at producing statistically noticeable differences in soil strength between management strips during different measurement dates.

In Franzluebbers et al.'s (1995) study of soil CO_2 evolution from cropping and tillage, tillage-induced soil bulk density exhibited large seasonal dynamics (similar to SWC; see below), but exhibited a more dampened signal. Soil bulk density increased monotonically for both NT and CT in all crop sequences through time, although differences in bulk density were seasonally dependent between tillage practices for all crops, and was especially sensitive in the 50–125 mm depth interval immediately after tillage. Franzluebbers et al. (1995) observed large seasonal CO_2 differences between different tillage practices because tilled soil underwent more physical changes than NT that may have influenced biological activity by increasing aeration, uniformly distributing and concentrating substrates, and disturbing microbial communities.

Spatial structure of soil properties can be characterized using standard geostatistical methods. Cambardella et al. (1994) sought to describe field-scale variability of 28 different soil parameters (including physical and chemical characteristics) at two sites undergoing different tillage practices in central Iowa. Directional semivariograms did not exhibit any anisotropy for any of the soil parameters, suggesting the appropriateness of isotropic spatial models at these sites. Soil bulk density on the CT site was moderately spatially dependent (37% nugget effect, range = 129 m), while bulk density at the NT site was moderately spatially dependent for both the 0–7.5 and 7.5–15 cm sampled depths (30% nugget effect, range = 223 m; and 25% nugget, range = 115 m, respectively). Wendroth et al. (2006) found that the semivariance for a variety of soil hydraulic properties (*e.g.*, clay and sand content, resistivity) in a glacial till landscape under cereal production in NE Germany increased up to a range of about 20 m. However, they suggested that although pedotransfer functions provided reasonable estimates of soil hydraulic properties in space that can be improved by site-specific calibration, they were not flexible enough to model the spatial variability at their field site.

Utset and Cid (2001) measured penetrometer resistance (PR) in a deep, well-drained red clay soil immediately after tillage and before sugar cane seeding in Cuba, and found the spatial variability in PR to be normally distributed for dry soil and after irrigation. PR semivariance was higher for dry soils and shows almost a pure nugget effect with an 80-m range, while irrigation yields a spatial structure with a range of about 8–10 m. PR appeared to be correlated with topography 24 h after irrigation at lag distances between 5 and 12 m, and was spatially correlated with bulk density after irrigation. The latter may be explained by clay migration from runoff erosion (Utset and Cid, 2001), and illustrates nicely the coupling between landscape properties and spatial variability in soil properties after tillage.

Brubaker et al. (1993) examined the effect of landscape position on soil properties and particle redistribution (erosion and deposition) as well, although no comparison was made between the studied sites, which exhibit ridge-till cropping, and NT management. At field sites in eastern Nebraska, clay concentration increased downslope and with increasing sampling depth, while sand concentration increased downslope but remained relatively uniform with depth. Likewise, organic matter, which can potentially impact soil hydraulic properties and crop growth, decreased downslope and changed according to landscape position in the upper 30–45 cm of the soil profile, but remained constant from 45 to 120 cm depth, regardless of landscape position.

Studies of between-site and regional variability in soil physical properties can also provide additional information that may teach us about the effects of large-scale differences driven by climate, geologic substrate, or other geographically varying attributes. Comparison of CT and NT at two sites in northern British Colombia, Canada resulted in greater steady ponded infiltration and water retention (see below) under NT, despite negligible differences in bulk density (Arshad et al., 1999). This appears to be due to a change in the pore-size distribution that decreased larger pores and increased smaller pores. Water-stable aggregation was also greater under NT than under CT. Francis and Knight (1993) conducted field trials of CT and NT for 9 years at two sites in New Zealand that had been under long-term pasture (Lismore site) or cropping (Wakanui site) prior to tillage treatments. Their work focused on organic matter and N mineralization, but also addressed some soil physical properties, as the two are interrelated. Tillage effects on bulk density were not significant at the Lismore site, but bulk density in the top 15 cm was greater under NT for most of the experiment at Wakanui. Macroporosity was generally less, despite greater earthworm populations, under NT at both sites. Khakural et al. (1992) also examined between-site variability in the glaciated western corn belt of South Dakota, where four different tillage practices (MP, chisel, ridge-till, and NT) and two cropping systems (continuous corn and corn/soybean) were administered to well-drained (Beadle; fine loam) and poorly drained (Worthing; fine) soils. They found that ridge-till and NT on the Beadle soil led to higher bulk density and aggregate stability than did plowing. Although the increase in bulk density observed for ridge-till and NT for both soils was not high enough to limit root growth, soil drainage class had an over-arching effect on soil hydraulic properties that often masked any beneficial or adverse effects of tillage practices.

The effects of irrigation and drainage may also partly explain temporal and spatial differences in soil physical properties between tillage practices. Using a chloride tracer and tension infiltrometers, Angulo-Jaramillo et al. (1997) reported that only the more homogeneous sandy soil (without stones) in their study, under furrow irrigation, had a significant decrease in hydraulic conductivity and sorptivity, which was related to increased bulk density and surface sealing, which may be aided by irrigation. Similarly, raindrop impact under simulated rainfall on a sandy loam in South Australia reduced porosity at two stages in the seventh year of tillage treatments (Somaratne and Smettem (1993). Bielders et al. (1996) also examined the effects of tillage and rainfall on the spatial distribution of soil crusts in a fine-loamy soil induced by textural redistribution from erosion on microrelief features. Over a 6-week period, 217 mm of natural rainfall fell on the experimental plots, and the microtopography was measured three times. They found that the spatial distribution of soil crusts was better correlated with the initial rather than final microtopography (crusts are history dependent), and that tillage interferes with crust development.

3.1.2.2. Soil water retention characteristics. Many of the workers listed above also examined state-change in soil water retention characteristics along with structural properties, while other studies examined soil water retention and content in isolation due to tillage effects. For example, Dao (1993, 1996) measured tillage and crop residue effects on silt loams in Oklahoma, USA (see previous section), where three tillage practices [MP, ST, and NT] began in 1983. NT had the highest mean SWC in the top 1.2 m every growing season, which was consistent with increased water-holding capacity. Hammad and Dawelbeit (2001), in their experiments in sugarcane fields in Sudan under different intensive tillage practices to depths of 10, 20, and 30 cm, found no significant differences in SWC between treatments, mirroring their results examining bulk density, clod size, and penetration resistance above. In a 3-year study of temporal variability in soil macroporosity in Atlantic Canada, Carter (1988) found that SWC and water-filled pore space followed similar temporal trends for both MP and direct drilling, with direct drilling having generally higher levels of both over time. The results of this study led Carter (1988) to conclude that direct drilling may not provide adequate aeration and water-filled pore space that annual tillage might provide in humid environments. Josa and Hereter (2005) provided a temporal depiction of SWC and near-surface soil water storage (n-SWS) evolution in clayey calcic soil near Barcelona, Spain as a function of CT, MT, and NT tillage. Their results showed generally higher SWC and n-SWS for NT plots. Chen et al. (2005) monitored short-term tillage (CT to 5.0–7.5 cm, NT, and subsoiling) effects in a 2-year study in poorly drained, heavy clay soil in Manitoba, Canada. Here, SWC responded to seasonal variations in rainfall and tillage, with NT generating an 8% increase and subsoiling an 11% decrease in SWC compared to that of CT.

Zhai et al. (1990) also provided a useful description of the interrelated effects of spatial and temporal variability of soil hydraulic properties in differently tilled landscapes. Measurements every 1–2 days in the top 20 cm at all sampling positions yielded higher spatial variance in SWC for CT (moldboard) than for LNT (>15-year NT) treatments, and temporal variance in SWC was consistently higher in row positions than in interrow positions for CT, SNT (1-year NT), and LNT. Large differences in SWC between CT and both types of NT plots early in the season were attributed to increased evaporation caused by spring secondary tillage in CT plots and can persist for several weeks depending on rainfall amount and distribution. Additionally, seasonal trends in row and interrow SWC were apparent for both CT and NT treatments, with the differences between positions being more pronounced for CT than NT. No systematic temporal pattern of spatial variance was observed for any tillage treatment, although the rate of change in spatial variance for CT and SNT were generally lower than for LNT because of larger spatial differences in recharge and drying (see below) between positions in LNT. Zhai et al. (1990) confirmed the time-dependent effects of tillage observed by others: porosity and infiltration increase immediately after tillage, but may not remain in this state due to compaction, aggregate instability, and surface sealing.

Zhai et al. (1990) also spent a great deal of effort quantifying drying rates and patterns in space and time. Generally, drying rates in the LNT interrow position were much lower than in the CT and SNT interrow positions, and all tillage treatments showed a significant seasonal trend in drying rate coefficients calculated for every major drying period and sampling location. Drying of row positions was almost always more efficient than interrow positions. The spatial differences between drying rates throughout the season were greater for the LNT treatment than for either the SNT or the CT treatments. Here, the importance of LNT became apparent, where preserved crop residues lowered early-season drying rate coefficients greatly. During later crop growth stages, the difference is not as apparent; after canopy closure, water loss occurs mainly through transpiration from root uptake, and thus tillage treatment is not as important.

To determine soil CO_2 evolution from intensive cropping and tillage, Franzluebbers et al. (1995) examined seasonal dynamics and soil depth distributions of SWC and water-filled pore space in a silty clay loam soil, and found that CT consistently experienced more rapid drying than NT. In fact, the yearly mean water-filled pore space was consistently greater for NT at all soil depths because of residue cover, with the largest differences between tillage regimes occurring during fallow for the sorghum–wheat/soybean rotation. Tillage-induced SWC exhibited large seasonal dynamics, with greater temporal variations in SWC for CT for all crop sequences during most parts of the year. In general, SWC from September to December was greater for NT than CT, whereas the relationship reversed between January and June.

In a study meant to examine nitrous oxide emissions from a tilled, New Zealand, silt loam soil, Choudhary et al. (2002) provided insight into spatial and temporal variability in SWC due to CT (MP to 25 cm), NT, and permanent pasture. Choudhary et al. (2002) found a strong correlation between log-transformed SWC and N_2O emission in all treatments, and different seasonal variations in N_2O emissions between tillage treatments. For CT, emissions followed the hierarchy: winter > autumn = summer; for pasture: winter = autumn > summer; and for NT: winter > autumn = summer. NT provided higher SWC during dryer months and during periods of infrequent rainfall, which explains the seasonal variations. Short-term variations on CT plots yielded reduced N_2O emissions (up to 65%) within the first hour after harrowing, with rates returning to pre-harrow levels by the next sampling period 1 month later due to increased SWC. Spatial variability in all treatments showing large inherent variations in N_2O fluxes, however, reflect natural soil heterogeneity and, perhaps, measurement error rather than tillage treatment effects.

In terms of spatial variability, Wendroth et al. (2006) found that the semivariance of SWC in a glacial till landscape under cereal production in NE Germany increased up to a range of about 20 m, but as stated previously, pedotransfer functions were not flexible enough to model the spatial variability at their field site. Brubaker et al. (1993), however, found robust spatial distributions in soil texture caused by landscape position and particle redistribution, resulting in observations of increased base saturation downslope and with increasing sampling depth.

Investigations of spatial variability also address small-scale and often systematic variability commensurate with tillage treatment. For example, Van Wesenbeeck and Kachanoski (1988) took TDR measurements of SWC from a tilled silty clay loam during the growing season every 1–2 days, and obtained measurements that contradicted the hypothesis that interrow drying rates would be greater because of shading patterns and energy available for evaporation. Interrow SWC was almost always greater than the row due to significantly lower soil bulk density in the row positions, while significantly higher drying rates in the row caused greater differences in SWC later in growing season. Likewise, soil water recharge was greater in the row than interrow due to interception and stemflow, matching some results obtained by Zhai et al. (1990). The net effect of the latter is a decrease in the spatial variance of SWC as the mean SWC increases during recharge, followed by an increase in spatial variance during drying. In a separate but related study, Van Wesenbeeck et al. (1988) observed soil drying and recharge occurring at specific scales, equal to the crop row spacing, elucidated by a transfer function (time varying spectrum) showing the scale at which the change in the spatial pattern was occurring. Starr and Timlin (2004) implemented a more detailed spatial analysis by measuring SWC at row, non-traffic interrow, and traffic interrow positions over a 2.5-year period, and examining spatial patterns during different water balance seasons (high recharge [wet] versus high ET [dry]) and rainfall event magnitudes (cumulative amount and intensity) (Fig. 4). In general, water uptake rates during dry down periods were higher for CT than NT treatments, and row water uptake exceeded interrow uptake during an initial uptake stage for both tillage treatments while the spatial relationship reversed during a second, subsequent uptake stage. Their data also suggest that during drying, as soil water content decreased, water uptake fell off more rapidly in the row than in the interrow positions, especially for CT.

Arshad et al. (1999) documented greater water retention under NT at two sites in northern British Colombia, while Khakural et al.'s (1992) study in South Dakota (see previous section) yielded higher SWC under ridge-till and NT as well on the Beadle soil,

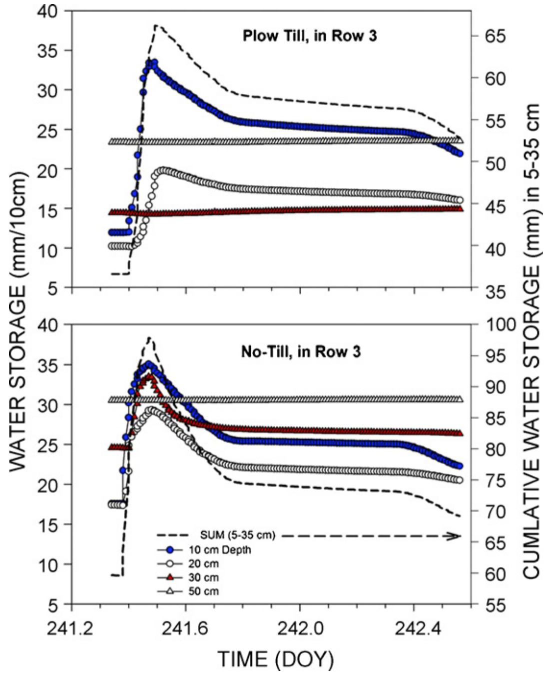

Fig. 4. Soil water storage and cumulative water storage (infiltration) over time at various depth intervals around a 41-mm sprinkler irrigation event under full corn canopy. Soil water dynamics measured within a row position under tillage (top panel) and no-till (bottom panel) treatments. Taken from Starr and Timlin (2004) with permission.

compared to chisel plowing. Likewise, the Beadle soil experienced differences in SWC in year 2 between tillage treatments (NT and ridge-till > CT), while the Worthing soil did not. This changed in year 3 due to stable clod formation in the Worthing soil; MP resulted in consistently lower SWC than other tillage treatments.

Irrigation practices can yield noticeable effects on soil water content, as well. Mapa et al. (1986) conducted field experiments and laboratory analyses to quantify the effects of wetting and drying cycles in two Hawaiian soils following tillage: Molokai silty clay loam (typic torrox) and Waialua clay loam (vertic haplustolls), both on the island of O'ahu. Drip irrigation provided intermittent wetting following plowing. The effects of wetting and drying cycles on sorptivity resulted in an asymptotic value after only two cycles. Water retention characteristics changed significantly over the low-suction/high water content range after only one wetting/drying cycle. Finally, the authors demonstrated the effects of such temporal changes in hydraulic properties on predicted soil water profiles.

3.1.2.3. Hydraulic conductivity. Hydraulic conductivity, being a highly variable process in space and time, tends to exhibit a complex response to tillage that may depend on other secondary effects of tillage related to plant growth, and climatic and pedologic attributes may ultimately drive response to tillage. Murphy et al. (1993) measured soil hydraulic conductivity at two suctions (10 and 40 mm) through the growing season at three locations in the wheat belt of New South Wales, Australia. The hydraulic properties varied temporally due to tillage, wetting/drying, and plant growth. Differences between tillage systems were greatest late in the growing season (flowering to postharvest). NT resulted in greater values of the hydraulic properties at 10 mm tension than CT, but there were no consistent differences between tillage treatments at 40 mm tension. This supports the results of other studies herein, where the primary effect of tillage appears to be on larger pores and their connectivity. In contrast, Somaratne and Smettem (1993) measured tension infiltration at 20 and 40 mm suction on a sandy loam in South Australia at two stages in the seventh year of tillage treatments and found that the hydraulic conductivity at 20 mm was also greater in NT than CT (36 mm h^{-1} versus 15 mm h^{-1}) at pre-seeding, but not later in the year. Somaratne and Smettem (1993) concluded that there was no sustained difference in hydraulic properties between tillage practices. In southern Italy, tillage caused a short-term increase in K_s of one or two orders of magnitude, but the tillage effects on K_s decreased with time based on monthly measurements for 2 years (Ciollaro and Lamaddalena, 1998). Azevedo et al. (1998) measured tension infiltration from 0 to 90 mm for 3 months of the growing season in Iowa, and compared infiltration under NT (without cultivation) and MT (with cultivation) at the soil surface and 15 cm deep. Under NT, macropore flow increased over time at the soil surface such that the mean macropore flow and surface K_s values were similar for MT and NT at the end of the September growing season. Thus, within-season effects of cultivation diminished

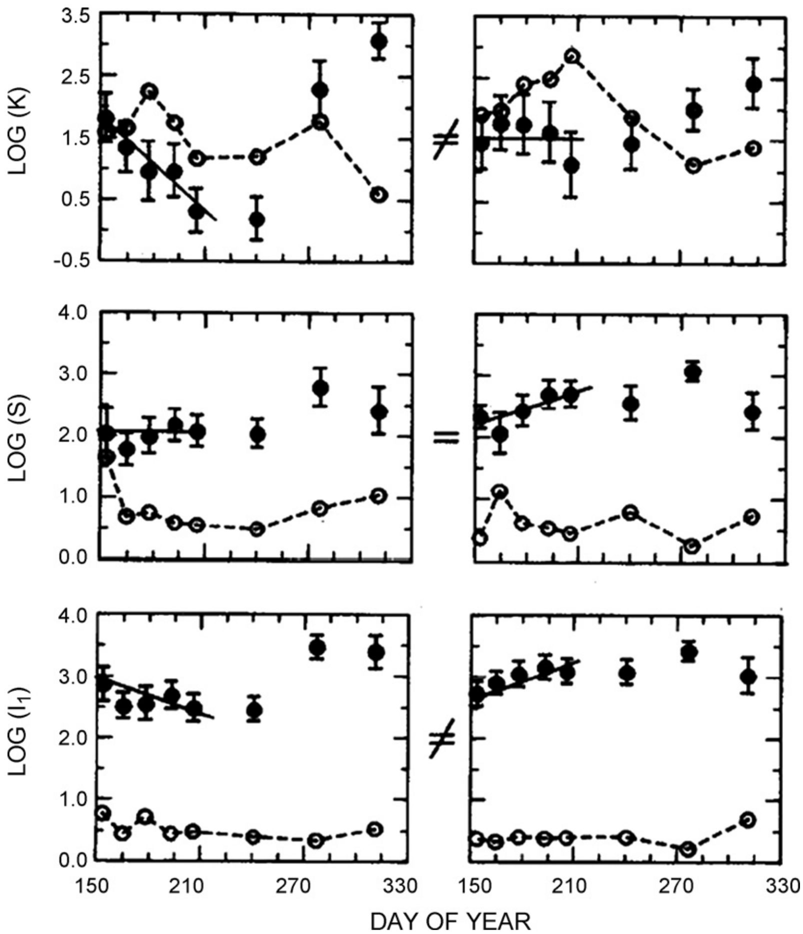

Fig. 5. Log means (solid circles; $n = 32$), variances (open circles), and 90% confidence limits (vertical bars) of saturated hydraulic conductivity (K), sorptivity (S), and cumulative 1-h infiltration ($I1$) vs. time for plow (CT; left panels) and conservation (MT; right panels) tillage. Significantly different slopes of regression lines are indicated by ≠ between adjacent panels. Taken from Starr (1990) with permission.

with time. Starr (1990) documented significant differences in early and midseason calculated K_s values between tillage treatments (Fig. 5), but found that postseason values converged for a silt loam in Clarksville, MD under plowing (CT) and conservation tillage (MT) on 8 days between June 3 and November 7. Seasonal variations were much larger for CT than for MT plots, with calculated K_s values decreasing during the first few weeks under CT while K_s remained nearly constant over the same time period for MT. This early season decrease in K_s under CT suggests that the mean soil pore diameter was continuously decreasing from increasing density and reconsolidation following spring plowing and subsequent early season rainstorms.

Seasonal variations in hydraulic conductivity, related to the timing of management practices (including tilling and harrowing), were also outlined in a study conducted by Messing and Jarvis (1993), in which significant variations in K existed at the surface between tillage treatments from disc harrowing in August, but not at depths between 15 and 25 cm. Specifically, K values decreased during the growing season (June–August) due to structural breakdown by rain impact and surface capping and sealing. The largest K values were obtained during October, following autumn cultivation and the creation of greater macroporosity. However, K values changed over time through a loss of mesopores followed by macropore degeneration, and the mesopore system was not totally restored by autumn tillage. Soil type (clay soil, in this case), climate, and tillage played a role in midseason mesopore restoration; frost action in winter and harrowing the following spring likely contributed to increases in K during a given year.

Subsequently, Logsdon and Jaynes (1996) measured ponded and tension infiltration along a transect in a cultivated field on four dates (Fig. 6a and b). Values of K at 150-mm tension were spatially correlated and periodic over different distances at different dates (July 1991–May 1992). A period of 46 m corresponded to traffic patterns from the previous year, but spatial periodicity on other dates could not be explained without further measurements (though we note that the periods were approximately two and three times the 46-m distance). Correlation lengths for K decreased with applied water tension (Fig. 7a and b), and ponded K values were spatially uncorrelated except between paired measurements (<1 m apart). 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.

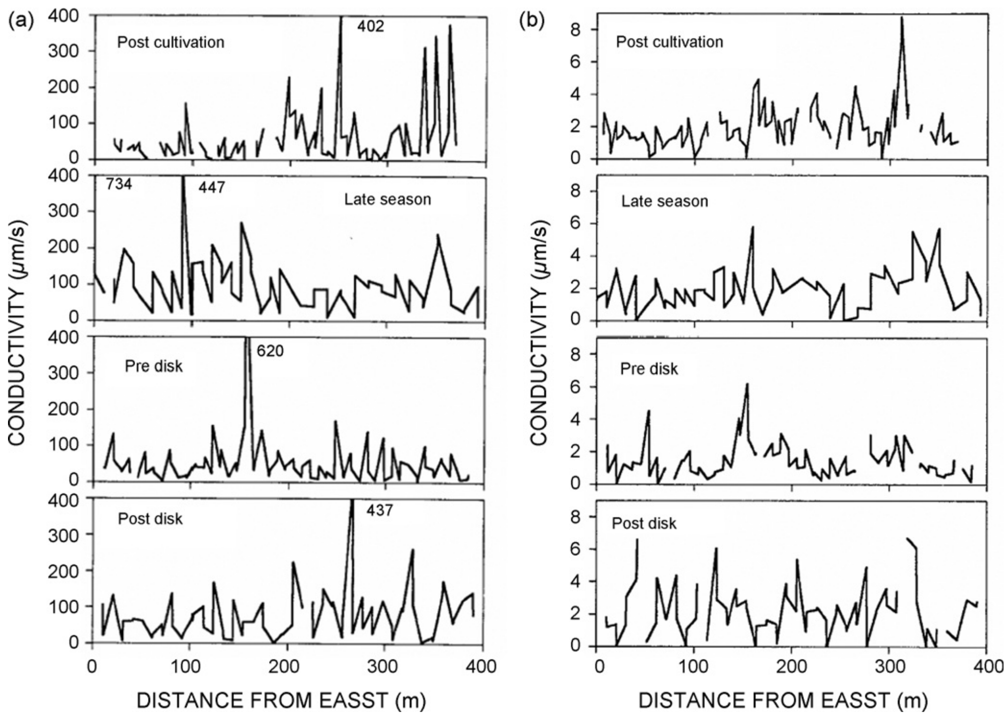

Fig. 6. Temporal (postcultivation, late season, pre disk, postdisk) and spatial (distance from east) variability in hydraulic conductivity (K) at a head of (a) 10 mm and (b) −150 mm. Disconnected sections indicate missing data. Numbers in (a) indicate off-scale K. Taken from Logsdon and Jaynes (1996) with permission.

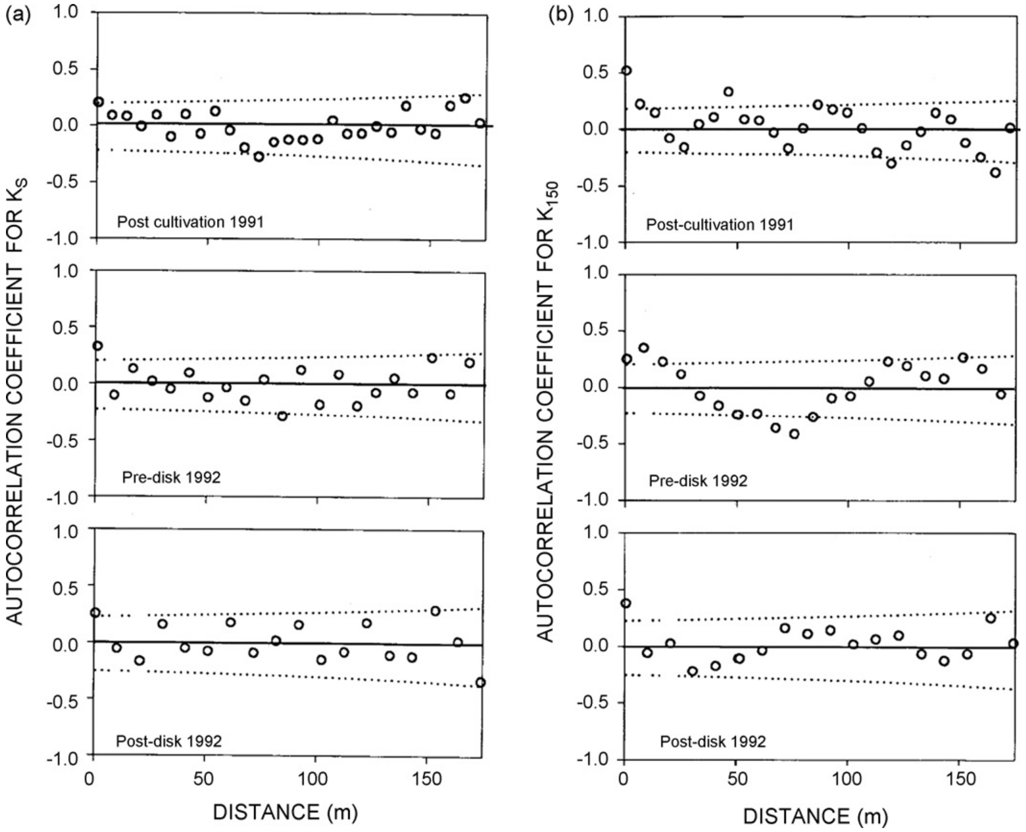

Fig. 7. Correlogram for (a) saturated hydraulic conductivity (K_s) and (b) hydraulic conductivity (K) at a head of −150 mm for three dates. Dashed lines indicate 95% confidence limits. Taken from Logsdon and Jaynes (1996) with permission.

We have found little work on small-scale spatial variability in hydraulic conductivity resulting from tillage practices, but some workers have documented regional variability in soil hydraulics from field studies. For example, in Khakural et al.'s (1992) examination of between-site variability in the glaciated western corn belt of South Dakota, ridge-till and NT increased K_s over time on the Beadle soil. During the second year of their study, however, K_s was higher under CT practices. Root channel preservation in year 3 reversed the relationship. In contrast, the Worthing soil did not exhibit statistically different K_s values between tillage treatments until year 3, when values for MP exceeded those for NT. This study highlights the temporal complexity exhibited by related, but different, soils despite similarity in climate, geologic history, and cropping practices.

Other work has addressed the effects of wetting and drying, irrigation, and drainage on soil hydraulics following tillage. Specifically, Mapa et al. (1986) found that hydraulic conductivity changed significantly over the low-suction/high water content range after only one wetting/drying cycle in Molokai silty clay loam (typic torrox) and Waialua clay loam (vertic haplustolls) in O'ahu, Hawaii (Fig. 8). Angulo-Jaramillo et al. (1997) used tension infiltrometers and a chloride tracer to determine the seasonal effects on soil hydraulic properties between post-tillage and the end of the growing season. Two sandy soils, one heterogeneous with stones and the other without, were tilled and cropped with corn under furrow and sprinkler (gun) irrigation. Only the more homogeneous sandy soil (without stones) under furrow irrigation had a significant decrease in hydraulic conductivity, and tracer results indicated a decrease in micropore connectivity in both soils. Dick et al. (1989) developed a 6-year lysimeter study in which the statistically significant amount of combined leachate and surface runoff that left the lysimeters differed according to season. Specifically, lysimeters managed under CT and NT showed little difference in the amount of flux leaving the systems during summer and autumn seasons, while significantly greater amounts left the NT lysimeters than CT lysimeters during the winter and spring. It is important to note, however, that two times more surface water left the CT lysimeters than the NT

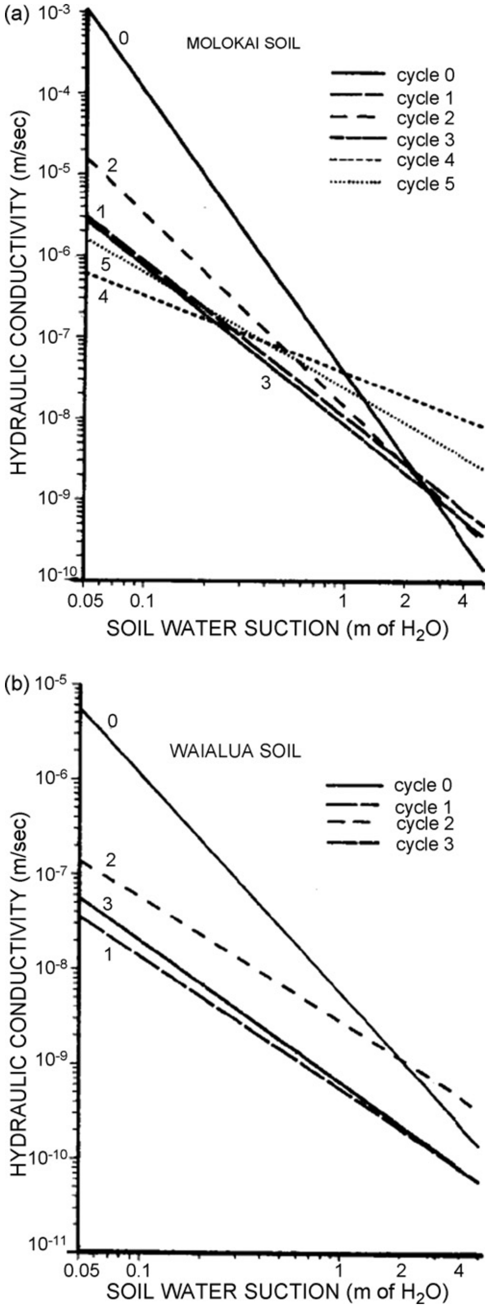

Fig. 8. Hydraulic conductivity as a function of soil water suction with successive wetting and drying cycles for (a) Molokai and (b) Waialua soils (0–5 cm depth). Taken from Mapa et al. (1986) with permission. Each "cycle" included wetting (18 h of irrigation) followed by drying (7–10 days), and "cycle 0" was measured immediately after tillage.

lysimeters, indicating the efflux from the NT lysimeters was mostly composed of leachate. Cross-correlation and power-spectra analyses indicated a similar temporal pattern of precipitation and leachate production for both NT and CT lysimeters, and that the CT lysimeters exhibited a stronger temporal relationship than NT lysimeters between precipitation and runoff. The tillage study of Somaratne and Smettem (1993) discussed above included a temporal effect of rainfall within a year of their cropping cycle. They discovered that K at 20 mm tension was reduced by raindrop impact under simulated rainfall, whereas K at 40 mm tension was not affected. Thus the temporal variability due to raindrop impact affected surface pores with radii > 0.75 mm, and this negated the effects of tillage on measured hydraulic properties by the end of the cropping cycle. Temporal decreases in K at saturation and 40 mm tension after planting were also measured by Suwardji and Eberbach (1998) after 16 years of tillage treatments in New South Wales, Australia. As a result, differences in hydraulic properties between tillage treatments were not significant by the end of the growing season. Nonetheless, seedbed conditions were affected by tillage early in the year.

3.1.2.4. Infiltration rates and capacity. Infiltration rates and capacity, like hydraulic conductivity, exhibit complex response to tillage supplemented or dominated by the same temporally and spatially variable complexities of plant growth, climate, and soil type. Along with the hydraulic conductivity (above), Murphy et al. (1993) measured sorptivity at two suctions (10 and 40 mm) through the growing season at three locations in the wheat belt of New South Wales, Australia. The response of sorptivity was identical to that of conductivity: temporally varying due to tillage, wetting/drying, and plant growth; differences most pronounced late in the growing season; and, NT sorptivity exceeded that for CT at 10 mm tension but differences were not consistent at 40 mm tension. This work contrasts with the field study in South Australia of Somaratne and Smettem (1993) who measured tension infiltration at 20 and 40 mm suction and concluded that there was no sustained difference in hydraulic properties between tillage practices.

Freese et al. (1993) measured infiltration after 4 years of three tillage treatments (NT, CP, and MP with disking) on a sandy clay loam. The sprinkler infiltrometer application rate was 2.6 cm in 30 min over 1 m^2, and percentages of water that infiltrated were reported (see Table 4). Infiltration was greater in NT before spring tillage; the rates increased for MP and CP immediately after tillage, making the three treatments more similar for that sampling date. Two weeks after tillage, the rates had reduced for all three treatments (even NT), and MP with disking experienced a threefold reduction in infiltration. Freese et al. (1993) concluded

Table 4
Temporal effects of various tillage practices on sprinkler infiltration rates and grain yield[a]

Tillage treatment	Infiltration (%) pre-till	Infiltration (%) post-till	Infiltration (%) 2 weeks post-till	Grain yield (Mg ha^{-1})
No-till (NT)	84	77	62	6.46
Chisel (CP)	77	83	54	4.77
Moldboard (MP) and disking	68	83	26	2.45

[a] Adapted from Freese et al. (1993).

that surface sealing was responsible for the dramatic decrease in infiltration for MP with disking, and grain yields reflected the same trend (Table 4) due to the growth stage (silking and tasseling) in that period.

Azevedo et al. (1998) measured tension infiltration from 0 to 90 mm for 3 months of the growing season in Iowa, and compared infiltration under NT (without cultivation) and MT (with cultivation) at the soil surface and 15 cm deep. Under MT, macropores transmitted 70–80% of the water applied at zero tension at the surface, and at 15 cm, macropore flow decreased from 69% in July to 44% in September.

Starr (1990) measured ponded infiltration in a silt loam in Clarksville, MD under plowing (CT) and conservation tillage (MT) on 8 days between June 3 and November 7, and found that early season mean values often systematically increased or decreased over time, while midseason values remained constant, and post-season values after corn harvest increased. Additionally, cumulative 1-h infiltration (I_1) decreased during the first few weeks under CT and I_1 increased over the same time period for MT (Fig. 9).

In a much longer study, Gomez et al. (1999) measured infiltration in an olive orchard in southern Spain on a vertisol under CT and NT systems. After 15 years of management, the infiltration rate under NT was less than CT. However, spatial variability (*e.g.*, increased macroporosity under trees) and temporal variability (*e.g.*, due to self-mulching soil) resulted in moderate average infiltration capacity in both NT and CT, and yield was not affected significantly by tillage most years.

Dunn and Phillips (1991) compared infiltration rates on a Maury silt loam (cf. Drees et al., 1994) under CT

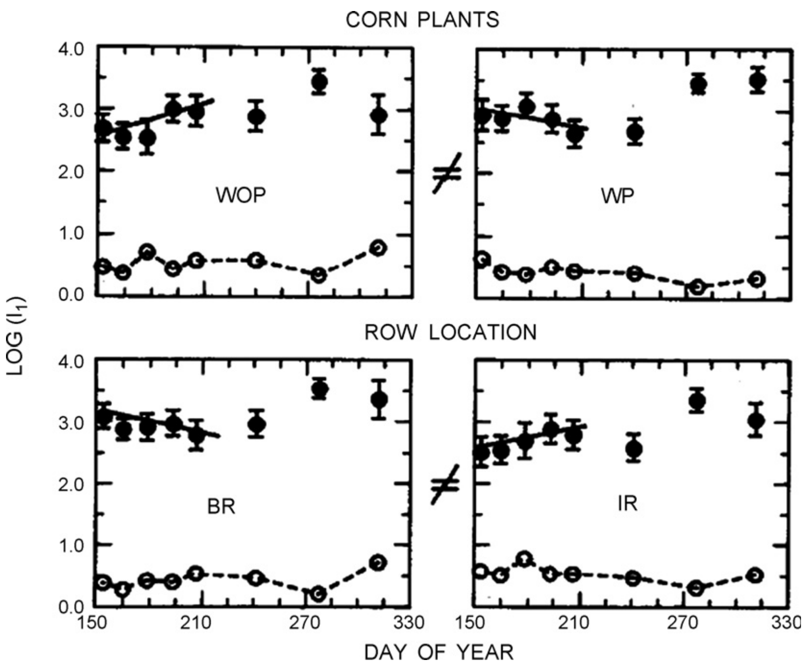

Fig. 9. Log means (solid circles; $n = 32$), variances (open circles), and 90% confidence limits (vertical bars) of cumulative 1-h infiltration (I1) vs. time for plow (CT; left panels) and conservation (MT; right panels) tillage, illustrating temporal and spatial (plant [top] and row [bottom] locations) variability. Significantly different slopes of regression lines are indicated by ≠ between adjacent panels. Taken from Starr (1990) with permission.

and NT. Both tillage systems had been applied in continuous corn since 1970, and the authors took field measurements in June of two consecutive years (1987–1988). Dunn and Phillips (1991) measured ponded and tension infiltration at suctions corresponding to equivalent pore diameters of 0.21, 0.33, 0.75, and 5 mm. Infiltration rates were lower under NT than CT for low suctions (0.75 and 5 mm pore sizes) in the first year (1987), but greater under NT than CT for all suctions the following year (1988). Thus, temporal variability from year to year dominated the tillage effects on infiltration even after almost two decades of consistent tillage and cropping systems. Dao (1993, 1996), who measured tillage and crop residue effects on silt loams in Oklahoma, USA (see above), observed higher seasonal variability of infiltration in plowed soils, but infiltration into NT was significantly higher than the tilled soils at similar initial SWC.

Tillage effects on infiltration have been shown to vary temporally (within a season) and spatially (within fields and between rows) under plowed and ridge-tilled corn (van Es, 1993). Although infiltration varied significantly within a growing season, year-to-year variability (between 2 years) was low. Spatial variability was greatest between rows and interrows due to ridge tillage, but not under CT. More extensive measurements over 3 years and four sites (two in New York and two in Maryland) were analyzed by van Es et al. (1999), including water retention on 875 cores and 2054 permeameter measurements of infiltration. Tillage and temporal effects were greatest for medium- and fine-textured soils, and spatial variability in water retention parameters was significant.

Temporal and spatial variability in real systems can overwhelm treatment effects. For example, Logsdon et al. (1993) measured ponded and tension infiltration on a loam soil in Iowa under four tillage systems and two crop rotations. Although tillage effects were statistically different (highest infiltration rates under MT) for the first date alone, the results were not consistent across all four measurement dates. Logsdon et al. (1993) noted: "Temporal changes in infiltration were greater than tillage or rotation differences. To quantify management effects on surface soil properties we conclude that several well-documented measurements are required. If possible, the measurements should be taken soon after rainfall events."

Results of Prieksat et al. (1994) reiterate the importance of spatio-temporal coupling of ponded infiltration rates in a silty clay loam corn field west of Ames, Iowa. Measurements were taken at the center of untrafficked interrows (UNT), between corn plants in a row (BPIR), in the center of a trafficked interrow (TRK), and directly over the base of a plant in a row (OPIR). Chisel plow and NT treatments were applied. In plowed plots, infiltration for TRK and UNT remained constant during the 2-year study, with temporary increases after tillage and cultivation. However, BPIR and OPIR sites experienced increases in infiltration rate steadily over the growing season (OPIR increased from 43 to 211 μm s^{-1} in 1990; 63 to 257 μm s^{-1} in 1991), most likely a result of root growth- and water uptake-derived shrink/swell cracks. OPIR had the highest infiltration rates and TRK the lowest at the end of both growing seasons. Conversely, in NT, infiltration rates at all positions remained relatively constant throughout the first growing season, with BPIR and OPIR rates being similar, both greater than 200 μm s^{-1}, and both higher than TRK and UNT.

Cressie and Horton (1987) discovered a strong spatial dependence (12 m lag distance) in infiltration rates for a silty clay loam near Ames, Iowa undergoing moldboard plowing, while paraplow had only weak spatial dependence and chisel plow and NT had no spatial dependence over the same lag distance. Sepaskhah et al. (2005) documented spatial structure in sorptivity on tilled and NT loamy soils in Iran using 0.5 m $\times$ 0.5 m grid spacing; however, spatial structure was absent at larger grid spacing of 5 m $\times$ 5 m (although the 5 m $\times$ 5 m semivariograms do not agree with this conclusion; see their Figs. 3 and 4). These results differ markedly with referenced results in Sepaskhah et al. (2005) [see Gupta et al., 1991, therein] which suggest a spatial structure in sorptivity up to 35–55 m, highlighting the importance of local soil type.

Spatial patterns and variability in chemical transport also serve to illustrate tillage-modified soil hydraulic properties. Ogden et al. (1999) applied atrazine and bromide tracers prior to a sequence of five simulated rainfall events on a clay soil under NT and CT. Space–time patterns of water outflow and chemical breakthrough curves were measured on a grid of large columns installed with wick lysimeters. Spatial patterns of outflow were more spatially variable under NT and varied temporally between rainfall events (separated by 4, 8, 9, and 50 days). Miller et al. (2000) measured chloride breakthrough in the laboratory on soil columns taken from a clay loam soil under CT (heavy cultivation) and NT in Alberta, Canada. Chloride breakthrough indicated preferential flow patterns that tended to be greater under CT than NT, contrary to other studies.

Hangen et al. (2002) used infiltrated dye tracer (methylene blue) on small plots in sandy and silty loams under CT and MT (or conservation tillage). On the silty loam, dye stains were much deeper under MT than under CT, indicating greater vertical connectivity of the macropore network. Yet, dye patterns were not related to the locations of root crowns and worm casts in any of the plots.

Another dye-tracer test was administered by Petersen et al. (1997) to investigate preferential flow paths in sandy loams over a 2-year period in variously tilled soils. Water flowed downwards after application around structural units left unbroken by the plow, while some flow was diverted horizontally by up to 10–15 cm upon reaching a horizontal interface created by the last plow at 20–25 cm depth. Furthermore, most power spectra showed a periodicity in flow pathways corresponding to the furrow width (35 cm), while others exhibited a concentration of variance at smaller frequency bands corresponding to a spatial scale of 70 cm. Larger spatial structure in the dye coverage, which decreased in strength over distance, may have been due to field operations and traffic operating in wider-spaced paths. Overall, Petersen et al. (1997) found that cultivation was effective in reducing the number of active preferential flow paths, and the relationship between flow pathways and past management was more likely to show up in soils with a higher clay content.

Tillage and cropping effects on infiltration were related to landscape position in adjacent fields in Saskatchewan, Canada (Elliott and Efetha, 1999). A crop–fallow rotation with CT was compared with NT continuously cropped for 11 years. The average infiltration rate was greater under NT than CT, and tillage effects were greatest at shoulder positions. By comparing measured infiltration rates in the landscape with expected rainfall intensities, Elliott and Efetha (1999) deduced that runoff would be much less under NT than under CT.

A few studies have dealt with between-site and regional variability in infiltration rates due to differing tillage practices. The effects of tillage (CP versus NT) on ponded and tension infiltration were measured along with compaction effects (see Section 3.3) at five locations in the Midwestern USA (Ankeny et al., 1995). Ponded infiltration rates were affected significantly by tillage at only two sites. Infiltration under NT in untrafficked interrows was 33% less in the Minnesota site and 64% less in Nebraska than under CP. There was no significant difference between tillage systems in wheel-track interrows at any of the five locations. Alternatively, comparison of CT and NT at two sites in northern British Colombia, Canada resulted in greater steady ponded infiltration under NT, despite negligible differences in bulk density (Arshad et al., 1999).

Likewise, irrigation and drainage may play roles in determining infiltration response to tillage practices. For example, Angulo-Jaramillo et al. (1997), using tension infiltrometers to determine seasonal effects between post-tillage and the end of the growing season (see discussion above), discovered that only the more homogeneous sandy soil under furrow irrigation had a significant decrease in sorptivity, which was related to increased bulk density and surface sealing.

Shipitalo and Edwards (1993), likewise, experimented with tilled and NT column lysimeters to investigate seasonal patterns of water and chemical movement within a soil profile. Four tilled and four NT soil columns were fitted with lysimeters 30 cm in diameter and 75 cm long, and tillage was applied to the topmost 15 cm in the tilled columns. The NT columns transmitted 36% more water than the tilled columns during their 2-year experiment, while Br^- and NO_3^- tracers yielded equivalent yearly totals of leachate for both treatments with NT columns losing more leachate during the growing season. Conversely, Sr^{2+} and NH_4^+ losses from the NT treatment were 2.6 and 6.6 times greater, respectively, than the tilled columns, a result attributed to preferential flow through macropores in the NT columns. Because runoff from the lysimeters was precluded by design, the differences in percolate between NT and CT columns would have probably been greater had runoff been possible. Plants were also absent from the lysimeters, potentially obfuscating realistic percolate losses due to plant uptake over time. Shipitalo and Edwards (1993) recorded the largest differences in percolate volume and chemical transport between tillage treatments in the first few rainfalls after chemical application and during summer months when potential evaporation was high; however, the tilled columns produced percolate for a longer time period after application than did the NT columns.

Packer et al. (1992) measured runoff annually for 7 years on two soils in the wheat belt of New South Wales, Australia (sandy loam and loam) using a rainfall simulator, along with measuring soil hydraulic properties. Runoff was significantly less in NT than CT or reduced tillage, but temporal variability in the hydraulic properties was greater than any differences between tillage treatments. Packer et al. (1992) concluded, ‘‘Although improvements in soil physical properties were measured, a period of at least five years. . .was required before they became significant and consistent.’’ This research highlights the somewhat fortuitous case of being able to detect and identify a long-term

Table 5
Effects of tillage on soil hydraulic and physical properties: temporal and spatial variability

Reference	Direction of response[a]	Temporal response[a]	Spatial response[a]	Location	Soil texture[b]	Factors affecting property[a]	Comments[a]
Hydraulic conductivity							
Murphy et al. (1993)	Increase at −10 mm tension, no change at −40 mm tension under NT	Greatest late in growing season	–	NSW, Australia	Palexeralfs, haploxeralfs	Tillage, wetting/drying, plant growth	–
Somaratne and Smettem (1993)	Increase at −20 mm tension under NT; decrease from rainfall following tillage	Pre-seeding; cropping cycle	–	S Australia	SL	Rainfall	Change not apparent later in the year; no sustained difference
Ciollaro and Lamaddalena (1998)	Short-term increase (K_s) under NT	–	–	Southern Italy	SC	–	Change decreases with time over 2-year period
Azevedo et al. (1998)	Increase at surface K_s under NT	3 months growing season ending in September	–	Iowa	L	Cultivation	Cultivation effects diminish with time
Starr (1990)	MT K_s constant and seasonally dampened; CT K_s decreases	First few weeks of growing season	–	Clarksville, MD	SiL	Spring plowing, rainstorms, seasonality	Postseason convergence
Messing and Jarvis (1993)	Increase (0 to −11 cm) from tillage and winter frost; decrease during growing season	Throughout year	Surface; not at depth	Ultuna, Sweden	C	Rain impact, surface sealing, autumn cultivation, frost action	–
Logsdon and Jaynes (1996)	Decrease (ponded, 5, −30, −60, −150 mm tension) pre-disk and from traffic	Throughout year	46 m traffic periodicity	Iowa	Fine L	Traffic patterns and timing, SWC, tillage	Tillage obliterates soil differences
Khakural et al. (1992)	Increase (K_s) from NT and ridge-till first and third years; higher (K_s) under CT in second year (Beadle); no change (K_s) until third year (MP > NT) (Worthing)	Throughout year	–	South Dakota	Fine L	Root channels, soil type	–
Mapa et al. (1986)	Decreases (low suction) after tillage	–	–	O'ahu, Hawaii	SiCL, CL	Wetting/drying	–

Table 5 (*Continued*)

Reference	Direction of response[a]	Temporal response[a]	Spatial response[a]	Location	Soil texture[b]	Factors affecting property[a]	Comments[a]
Angulo-Jaramillo et al. (1997)	Decrease (0 to −100 mm tension)	Seasonal; between post-tillage and end of growing season	–	Coria del Rio, Spain; La Cote Saint Andre, France	S	Irrigation, stone content	–
Dick et al. (1989)	Increase (leachate flux) in NT compared to CT	Winter and spring	–	Coshocton & Wayne County, Ohio	SiL	Precipitation	–
Suwardji and Eberbach (1998)	Initial decrease (K_s and −40 mm tension); no change by end of growing season	After planting; growing season	–	NSW, Australia	n/a	–	–
Soil water retention							
Dao (1993, 1996)	Increased SWC for NT	Growing season	–	Oklahoma	SiL	WHC	–
Hammad and Dawelbeit (2001)	SWC insensitive to tillage intensity	–	–	Sudan	C	–	–
Carter (1988)	SWC and WFPS higher for direct drilling	SWC and WFPS follow similar temporal trends	–	Atlantic Canada	Fine SL	–	–
Josa and Hereter (2005)	Higher SWC and *n*-SWS for NT	–	–	Barcelona, Spain	Calcic C	–	
Chen et al. (2005)	8% SWC increase for NT; 11% SWC decrease for subsoiling (compared to CT)	Growing season	–	Manitoba, Canada	Heavy C	Seasonality (rainfall), tillage	–
Zhai et al. (1990)	No systematic temporal trend, except for drying rate; higher SWC spatial variance for CT than LNT; temporal SWC variance higher in row than interrow	Early season, multi-week persistance; seasonal trends stronger in CT than NT	Row and interrow	Guelph, Ontario, Canada	L	Evaporation, secondary tillage, rainfall (amount & dist.), compaction, aggregation stability, sealing, crop residues (drying rate)	Porosity and infiltration increase immediately after tillage, but does not persist
Franzluebbers et al. (1995)	WFPS greater for NT than CT; greater seasonal SWC variability for CT than NT; SWC for NT in fall > SWC for CT; SWC for NT in spring, summer < SWC for CT	Seasonal	–	Southcentral Texas	SiCL	Drying rates, residue cover	–

Choudhary et al. (2002)	CT SWC: winter > autumn = summer; NT SWC: winter > autumn = summer; pasture SWC: winter = autumn > summer	Seasonal	–	New Zealand	SiL	–	–
Wendroth et al. (2006)	SWC semivariance increases to 20 m range	–	–	NE Germany	SL	–	–
Brubaker et al. (1993)	Increased base saturation from ridge-till	–	Downslope and at depth	Nebraska	fine Si	Landscape position, particle redistribution	–
Van Wesenbeeck and Kachanoski (1988)	Interrow SWC > row SWC	Growing season; differences greater later in season	Interrow and row; spatial variance increases during drying	Guelph, Ontario, Canada	SiCL	Bulk density, drying rates, interception and stemflow	–
Van Wesenbeeck et al. (1988)	Drying and recharge occur at scale of crop row spacing	–	Crop row spacing	Guelph, Ontario, Canada	SiCL	–	–
Starr and Timlin (2004)	NT water uptake < CT water uptake during drydown; row water uptake > interrow but reverses for subsequent uptake	Seasonal; event-based	Row, non-traffic interrow, traffic interrow	Beltsville, MD	SiL	–	–
Arshad et al. (1999)	Higher water retention for NT vs. CT	–	–	BC, Canada	SL, SiL	–	–
Khakural et al. (1992)	Higher SWC under ridge-till and NT than CT, MP lowest SWC	Seasonal; yearly	Beadle soil responds in year 2 while Worthing does not	South Dakota	Fine L	Root channels, soil type, clod formation	–
Mapa et al. (1986)	SWC responds after only 1 cycle	Wetting/drying cycles	–	O'ahu, Hawaii	SiCL, CL	Wetting/drying	–
Soil bulk density, porosity, pore geometry, and soil structure							
Somaratne and Smettem (1993)	Porosity greater under CT than NT; decreased for CT after harvest to NT levels	Growing season	–	S Australia	SL	Rainfall	–
Starr (1990)	MT bulk density increased in early growing season	Growing season	–	Clarksville, MD	SiL	–	No effect on infiltration
Dao (1993, 1996)	Decreased bulk density for NT	Growing season; temporal changes not significant	Top 1.2 m soil	Oklahoma	SiL	–	–
Gomez et al. (1999)	Increased bulk density in rows between trees	–	Orchard rows	Southern Spain	CL	–	Olive orchard
Hammad and Dawelbeit (2001)	No significant differences in bulk density, clod size, penetration resistance	–	–	Sudan	C	–	Effects on yield not due to tillage-hydraulic response

Table 5 (*Continued*)

Reference	Direction of response[a]	Temporal response[a]	Spatial response[a]	Location	Soil texture[b]	Factors affecting property[a]	Comments[a]
Mubarak et al. (2005)	Long-term (40 years) bulk density lower than short term (<10 year) and native vegetation	Multi-year	–	Sudan	C	–	–
Osunbitan et al. (2005)	Increased bulk density with tillage (NT > MH > DD > PH); CI increases with time for all tillage 0–5 cm; CI higher for NT at 5–15 cm	8 weeks (convergence for 0–5 cm interval)	0–5 cm and 5–15 cm depth intervals	SW Nigeria	LS	Rainfall, particle resettlement	–
Hammel (1989)	Tillage affects bulk density but not impedance (higher impedance under reduced tillage)	Multi-year	–	Idaho	SiL	–	–
Carter (1988)	NT < 10% macropore vol.; CT 11–18% macropore vol.; porosity from tillage persists through winter	Seasonal	Top 8 cm soil	Atlantic Canada	Fine SL	–	–
Josa and Hereter (2005)	Decreased macroporosity under NT	Seasonal	–	Barcelona, Spain	Calcic C	–	–
Yang and Wander (1998)	DMWD increased Oct.–Dec., decreased by April; WAS higher for NT than CT	Seasonal	–	Illinois	SiL	Crop roots, exudates, microbial by-products, wet/dry cycles	WAS not linked to SWC
Chen et al. (2005)	CI lower in spring than fall	Seasonal	CI increase with depth	Manitoba, Canada	Heavy C	–	CI not responsive to tillage
Castrignano et al. (2003)	High temporal cross-correlation of spatial variance of soil strength at depth	Event-based	–	Italy	Fine SiC	SWC, rainfall	soil strength not responsive to tillage
Franzluebbers et al. (1995)	Soil bulk density exhibits large seasonal variations from tillage, increases through time	Seasonal	–	Southcentral Texas	SiCL	Drying rates, residue cover	–
Cambardella et al. (1994)	Bulk density on CT and NT spatially dependent	–	Isotropic	Iowa	SiCL, L, SiL	–	–
Wendroth et al. (2006)	Semivariance in clay and sand content increases up to 20 m range	–	–	NE Germany	SL	–	–
Utset and Cid (2001)	PR normally distributed; irrigation yields spatial structure; PR correlated with topography from tillage erosion	Event-based, seasonal	Topographically controlled; various ranges for semivariance	Cuba	C	Tillage-induced erosion, topography, irrigation	–
Brubaker et al. (1993)	Clay and sand increased downslope; sand content uniform with depth; clay content increases with depth	–	Topographically controlled	Nebraska	Fine Si	Landscape position, particle redistribution	–

Arshad et al. (1999)	Negligible differences in bulk density between NT and CT; greater water-stable aggregation under NT	–	–	BC, Canada	SL, SiL	Dynamic pore-size distribution	–
Francis and Knight (1993)	Bulk density not affected by tillage at Lismore, but greater under NT at Wakanui; macroporosity decreased under NT	–	Lismore and Wakanui sites	New Zealand	Stony SiL, SiL	–	–
Khakural et al. (1992)	Ridge-till and NT increase bulk density and aggregate stability	–	–	South Dakota	L	Root channels, soil type, clod formation	Soil drainage class overwhelms tillage effects
Angulo-Jaramillo et al. (1997)	Increased bulk density and surface sealing aided by tillage and irrigation	–	–	Coria del Rio, Spain; La Cote Saint Andre, France	S	Irrigation, stone content	–
Bielders et al. (1996)	Spatial distribution of soil crusts related to initial microtopography; tillage reduces crust	Event-based	Microtopography controlled	Togo	Fine L	Textural redistribution from erosion	–
Infiltration rates and capacity							
Murphy et al. (1993)	NT sorptivity > CT at −10 mm tension, no difference at −40 mm tension; temporally varying sorptivity from tillage	Seasonal, event-based	–	NSW, Australia	Palexeralfs, haploxeralfs	Tillage, wetting/drying, plant growth	–
Somaratne and Smettem (1993)	No sustained difference in sorptivity after 7 years	–	–	S Australia	SL	Rainfall	Change not apparent later in the year; no sustained difference
Freese et al. (1993)	Infiltration (30 min. cum.) greater for NT before spring tillage; MP, NT, CT not significantly different immediately after tillage; rates reduce after 2 weeks	Event-based; weekly	–	Reidsville, NC	SCL	Irrigation, surface sealing	–
Azevedo et al. (1998)	MT infiltration due to macropores at zero tension; at 15 cm depth macropore flow decreases from July to Sept.	Monthly	–	Iowa	L	Cultivation	Cultivation effects diminish with time
Starr (1990)	Early season infiltration (near sat.) increased/decreased, midseason constant, postseason increase; I_1 decreased in CT and increased in MT over first few weeks of season	Seasonal	–	Clarksville, MD	SiL	Spring plowing, rainstorms, seasonality	Postseason convergence
Gomez et al. (1999)	NT infiltration (early-time, cum.) < CT; macroporosity under trees increases MT and CT infiltration	Self-mulching time scale	Orchard rows	Southern Spain	CL	–	Olive orchard

Table 5 (*Continued*)

Reference	Direction of response[a]	Temporal response[a]	Spatial response[a]	Location	Soil texture[b]	Factors affecting property[a]	Comments[a]
Dunn and Phillips (1991)	June NT infiltration < CT for low suction in first year; NT infiltration > CT all suctions second year	Year-to-year	–	Kentucky	SiL	Yearly variability	–
Dao (1993)	NT infiltration (variably saturated) < CT; higher seasonality in CT infiltration	Seasonal	–	Oklahoma	SiL	–	–
van Es (1993)	Ridge-till row infiltration (field-saturated) variability > CT; infiltration varies during growing season	Growing season, year-to-year	Field-scale, rows	Aurora, NY	SiL	–	–
van Es et al. (1999)	Tillage and temporal effects on infiltration (field saturated) greatest for medium-, fine-textured soils	Various	Field-scale, site variability	New York, Maryland	SL (MD), SiL (MD, NY), CL (NY)	–	–
Logsdon et al. (1993)	MT infiltration (ponded, various tensions) highest initially, but no significant differences subsequently	Daily	–	Iowa	L	Temporal variability	Temporal changes overwhelm tillage or rotation effects on infiltration
Prieksat et al. (1994)	Temporary infiltration (steady state) increase in plowed interrow after tillage/cultivation; row infiltration increases over growing season; NT infiltration relatively constant	Growing season	Row and interrow	Ames, Iowa	SiCL	Root growth, shrink/swell cracks	–
Cressie and Horton (1987)	Strong spatial dependence for MP, moderate for paraplow, weak for NT and chisel (cum. 30 min.)	–	Field-scale	Ames, Iowa	SiCL	–	–
Sepaskhah et al. (2005)	Small-scale spatial structure in sorptivity	–	m-Scale	Iran	L	–	–
Ogden et al. (1999)	Higher spatio-temporal variability in outflow for NT than CT	Daily	–	Willsboro Exp. Farm, NY	C	Simulated rainfall	–
Miller et al. (2000)	CT has greater preferential flow paths than NT	Immediate-daily	–	Alberta, Canada	CL	–	–
Hangen et al. (2002)	MT infiltration (macropore) deeper than CT for silt loam;	Immediate-daily	–	Lower Saxony and Brandenburg, Germany	SL, SiL	–	Infiltration not related to root crowns or worm casts
Petersen et al. (1997)	Furrow-width periodicity in flow pathways	Event-based	Furrow, traffic patterns	Copenhagen, Denmark	SL	Clay content	Unplowed structural units determine flow paths

Elliott and Efetha (1999)	NT infiltration (steady state) > CT; tillage effects greatest at shoulder positions	–	Landscape position	Saskatchewan, Canada	SiL, SiC	–	Less inferred runoff under NT
Ankeny et al. (1995)	NT infiltration (ponded, various tensions) in untrafficked interrows in MN & NE > CP; no difference in trafficked interrows	–	Row and interrow	Midwestern USA (IA, NE, MO, WI, MN)	SiCL (IA, MN, NE), L (IA); SiL (MO, WI)	–	–
Arshad et al. (1999)	NT infiltration (steady state) > CT	–	Site variability	BC, Canada	SL, SiL	–	Negligible bulk density differences
Angulo-Jaramillo et al. (1997)	Sandy soil w/furrow irrigation had sorptivity decrease	Seasonal	Site variability	Coria del Rio, Spain; La Cote Saint Andre, France	S	Irrigation, stone content, bulk density, surface sealing	–
Shipitalo and Edwards (1993)	NT infiltration (lysimeter percolate) > tilled; greater macropore flow in NT; longer duration of percolate release in tilled lysimeters	Event-based, seasonal	–	Coshocton, OH	SiL	Rainfall	–
Packer et al. (1992)	Infiltration (based on runoff measurements) reduced under CT and MT compared with NT	Event-based, multi-year	–	Wheat belt, NSW, Australia	SL, L	–	Temporal variability overwhelms treatment effects; >5 years required for significant, consistent response

[a] CT = conventional tillage; DD = disc-disc; NT = no-tillage; LNT = long-term no-tillage; MH = manual hoe; MT = minimum (conservation) tillage; MP = moldboard plow; PP = paraplow; PH = plow-harrow; SWC = soil water content; *n*-SWS = near-surface water storage; WHC = water-holding capacity; WFPS = water-filled pore space; CI = cone index; DMWD = dry mean weight diameter; WAS = wet aggregate stability; PR = penetration resistance; I_1 = cumulative 1-h infiltration; MN = Minnesota; NE = Nebraska.

[b] S = sand, Si = silt, C = clay, L = loam, SL = sandy loam, SiL = silty loam, SiC = silty clay, CL = clay loam, LS = loamy sand, SCL = sandy clay loam, SiCL = silty clay loam.

response time scale (here, ≥5 years) in which management practices eventually out-compete natural hydraulic variability. This case, and others presented earlier, also conveys the importance of documenting short-term response from event-based and seasonal-to-annual scale processes as well as long time scale hydraulic response that may be more diagnostic of site-specific soil and climatic properties.

The last section on tillage effects is summarized in abbreviated tabular form in Table 5. Overall, spatial and temporal variability have often overshadowed the particular management effects studied. Most tillage practices have pronounced 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 can be less pronounced and are sometimes impossible to distinguish from natural and unaccounted management-induced variability. In other cases, researchers were able to identify a "lag time" over which these long-term effects became more apparent and consistent, compared with short-term effects that clouded a picture of long-run dynamics or attracting states in soil hydraulic behavior. Temporal variability was particularly noted as an obfuscating factor, but the magnitude and pattern of temporal variability was affected by spatial location, particularly the landscape position. This affirms our hypothesis that agricultural management effects (Table 1) and other space–time factors (Table 2) have coupled effects on soil hydraulic properties and processes.

Irrigation (or natural rainfall) and drainage effects on soils subsequent to tillage have not been studied very extensively. Even though irrigation scheduling is regularly based on measured SWC or tension, very little work has been done to measure the effects of irrigation on soil hydraulic properties. Theoretical advances are similarly limited (Or, 1995; Or et al., 2000; Leij et al., 2002a,b; Or and Ghezzehei, 2002).

The effects of tillage treatments on irrigation and drainage are not yet well constrained due to strong controls by soil type and seasonality at specific field sites. Again, temporal variability often overshadowed management-induced variability, and rapid decay in measurable differences in soil hydraulic behavior rendered conclusions from short-term studies less reliable. However, it is clear that the role of macropore creation and longevity played a significant role in drainage processes between CT and NT soils in most studies, where NT treatment usually left macropores undisturbed, thus changing the temporal patterns and magnitude of drainage from that of CT.

3.2. Residue management affected by tillage practices

Producers and researchers alike are very aware of the importance of organic matter to the soil–plant system. Most of the interest, however, has been in the area of soil fertility and factors such as the carbon/nitrogen ratio. To a lesser extent, there has been interest in the relationships between organic matter, biological activity, soil properties, and plant production (Trojan and Linden, 1994, 1998). Furthermore, crop residue management comes into play in NT and MT practices, where crop residue is often left undisturbed or stubble is left to enhance beneficial hydraulic properties of the soil (right side of Fig. 3a). Various 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, 1998; Sembiring et al., 1995; Peterson et al., 1996; Sharratt, 1996; Unger et al., 1997; Baumhardt and Jones, 2002), and we highlight some important studies below.

3.2.1. Soil bulk density, porosity, pore geometry, and soil structure

The interaction between tillage and residue has important effects on soil properties, and the two topics are often studied together. Stubble-mulch tillage has been shown to affect soil bulk density (Dao, 1996; Unger and Jones, 1998), and (Starr and Timlin, 2004) have observed higher bulk density in NT treatments that exacerbated the effects of residue retention on increased SWC and infiltration rates. Karlen et al. (1994) has also measured the long-term effects of residue cover on increased earthworm population in combination with effects on soil aggregation and bulk density.

3.2.2. Soil water retention characteristics

Dadoun (1993) studied residue effects on soil temperature, SWC, and plant growth on a loam soil in Michigan, USA. On fully covered plots, soil temperature (2.5 cm deep) was lower by 2 °C, and SWC above 50 cm was higher than in bare soil. Simulated leaf development using the CERES model was improved by changing the soil temperature predictions to account for residue cover. More recently, Tejedor et al. (2002) showed the effects of mulching on the soil water balance, causing increased SWC, and thus presenting a problem of non-uniqueness in soil taxonomy based on aridity. 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). Nielsen (2006) showed the combined effects of residue 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. Tanaka (1985) related stubble-mulch to seasonal SWC. Starr and Timlin (2004) attributed consistently and significantly higher initial soil water contents to greater depth intervals (prior to irrigation or rainfall) in NT treatments than in CT (plow-till) to residue retention (Fig. 4).

3.2.3. Hydraulic conductivity

We are not able to describe alterations to hydraulic conductivity due to residue management activities, largely because of the difficulty in measuring K_s and/or $K(\theta)$ when residue is present, which is reflected in the literature. The presence of residue complicates the installation of measurement instruments or the removal of undisturbed samples and cores, and may produce order of magnitude variation in conductivity values at small scales (cm) due to macropores and other structural attributes left in tact by infrequent or absent tillage and residue removal/mixing. The effects of residue on hydraulic conductivity are largely due to the production and preservation of macropores by undisturbed root channels, decaying stalks and stems in the near surface and subsurface, and earthworm and other faunal passageways. The above subsection on soil structural variation in the presence of residue, along with infiltration rate and capacity response (below) highlight the effects that may influence hydraulic conductivity, but specific measurements are lacking in the literature.

3.2.4. Infiltration rates and capacity

Studies of the direct effects of plant 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. Infiltration (soil intake) rates were measured with two surface covers (straw and burlap), which subsequently were removed to allow the soil to seal, thus decreasing the infiltration rates. Residue retention in NT systems also increased infiltration rates prior to irrigation or rainfall (Starr and Timlin, 2004), while Potter et al. (1995) identified the effect of tillage on residue as the most important factor for infiltration in their field site. Chan and Heenan (1993) compared NT with CT systems with both stubble retention and burning after 10 years of treatment. A controlling factor for infiltration appeared to be water repellency of the stubble (residue). Application of a wetting agent, instead of pure water, increased the tension infiltration rate (at 40 mm suction) by more than four times where stubble was retained, but did not affect the infiltration significantly where stubble was removed by burning. Chan and Heenan (1993) also 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. Infiltration with dye revealed a much larger number of transmitting macropores in NT with stubble retention (65% of all macropores) versus CT with stubble burning (1%). Tillage did not change the total number of macropores.

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 (Rhodamine WT). They found significant effects of residue and related earthworm activity on dye concentrations below 20 cm. Trojan and Linden (1998) conducted additional experiments in the same vane using a methylene blue solution for instantaneous ponding (transient infiltration) and a disc permeameter for steady state infiltration. The dye solution infiltrated faster for NT and tillage treatments with residue than for other treatments, but there were no significant differences between treatments for the steady infiltration rates. Others (Zachmann et al., 1987; Zachmann and Linden, 1989; Edwards et al., 1990; Logsdon and Linden, 1992; Monnier, 1992; Carter et al., 1994) have also investigated residue-related earthworm effects on water flow and chemical transport.

The following two studies describe the effect of various types of tillage practices on the incorporation of tracers and residue into the soil profile, and lend insight to the understanding of tillage effects on infiltration and percolation via residue-induced macroporosity. Allmaras et al. (1996) characterized the depth distributions of oat residues and ceramic spheres incorporated by tillage into the top 30 cm. Green spheres served as a residue tracer under primary tillage, followed by secondary tillage of red spheres as a tracer or surrogate for herbicides. Oat residue and green spheres (residue surrogate) placed on the soil surface were incorporated by chisel and moldboard plowing with penetration depths of 15 and 25 cm, respectively. Red spheres (herbicide surrogate) were then cultivated with a secondary tillage depth of 17 cm. The residue mass and sphere numbers were measured in 2-cm intervals of 30-cm deep cores of 1.84 cm diameter. 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 contained both red and green spheres, indicating effective mixing of residue and agrichemicals into the soil.

In a similar study, Staricka et al. (1991) investigated the depth and concentration variations in oat crop residue, ceramic spheres, and polyethylene chip tracers in a fine-loamy mixed soil under disk, chisel, and moldboard plow. Their findings suggested that tillage buried but did not disperse crop residue, the frequency distribution of residue concentration was monotonic with depth, and residue and tracers were generally in a 10-cm band, regardless of tillage treatment. Overall, MP was more effective in terms of depth of incorporation and concentration of residue and tracers than either chisel or disk treatments.

In general, residue retention on the surface, associated with NT treatment, enhances water retention, but the effects of incorporating residue into the subsurface by tillage is indeterminate regarding soil hydraulic behavior. Some tillage buries residue in a relatively distinct layer, while other methods efficiently mix the material over the tillage depth. Furthermore, the presence of macropores from earthworms and decaying roots and stems permits efficient hydraulic transmission at the surface and within the soil column, but soil crusts, which tend to inhibit infiltration, are left undisturbed. Surface sealing operates over relatively short time scales, while the development of macropores is a seasonal to multi-annual process. Thus, ascertaining the relative importance (or dominance) of short-term surface sealing versus long-term macropore development may determine the overall infiltrability, which may help explain the variability across environments and soil types.

3.3. Mechanical compaction

Mechanical loading of soils under equipment used for management practices can compact the soil, causing increased bulk density, decreased porosity, and altered pore shapes and size distributions (Warkentin, 1971). The amount of soil compaction depends on the applied load, soil type and moisture status, landscape position, and year (Lindstrom and Voorhees, 1995). Changes in these basic soil properties change the soil water retention and hydraulic conductivity characteristics; changes in these hydraulic properties affect the amount of infiltration and available soil water. Several investigators have reported the effect of wheel tracks on soil hydraulic properties. The effects varied from study to study depending upon the prevailing conditions, and some interpretations have been primarily qualitative.

3.3.1. Soil bulk density, porosity, pore geometry, and soil structure

It is clear, at least in the short term, that mechanical compaction will increase bulk density and decrease porosity in most soils. However, the temporal response to mechanical compaction, along with spatial variability (in both horizontal and vertical dimensions) affected by wheel spacing, landscape position, and other variables remains to be sufficiently quantified. In Liebig et al.'s (1993) study of compaction in permanent wheel tracks of a ridge tillage system on a silty clay loam in southeastern Nebraska, USA, the axle load was 4 Mg and the compaction effects dissipated by the 15–30-cm soil depth. Significant variability in soil properties (bulk density, aggregate size, and soil strength) was observed between landscape positions in the top 7.5 cm, and variability of all soil properties tended to be greatest in the wheel tracks. The mean of the K_s values in wheel tracks was approximately 25% of the mean value of non-trafficked areas. Liebig et al. (1993) concluded, "Because of the dissimilarity in soil properties among positions, ridge-tilled fields should be conceptualized and managed as three distinct soil zones, not as a single unit."

Alakukku (1996a,b) conducted plot experiments where heavy axle loads were applied with up to four passes on two soils (16 Mg on clay and 19 Mg on an organic mixture) and measured total porosity and pore-size distribution for 3 years after the loading (Alakukku, 1996a). The total porosity to 0.5 m depth decreased by approximately the macroporosity of the clay, but did not change significantly on the organic soil. The microporosity increased and offset a decrease in the macroporosity.

Other vehicle compaction studies have focused primarily on effects on bulk density and/or penetration resistance. Logsdon et al. (1992) studied responses of soil pore 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. The amount of biopores in the dry control was an order of magnitude greater than under wet conditions. 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. They concluded, ''Chisel management did not result in less dense soil than NT unless traffic was carefully controlled.'' This conclusion also highlights the importance of interaction between management practices. Mahboubi et al. (1993) found greater bulk density and penetration resistance in the top 15 cm of the traffic zone versus row zone under NT, while Pierce et al. (1994) found that wheel traffic increased bulk density substantially in plowed soils (0.14–0.18 Mg m^{-3}), but minimally under NT. The reader is referred to the literature for additional information (Bullock et al., 1985; Blackwell et al., 1986; Johnson et al., 1989; Lal et al., 1989a,b; Hill and Mezamontalvo, 1990; Bathke et al., 1992; Bruand and Cousin, 1995; Fritz et al., 1995; Dao, 1996; Assouline et al., 1997; Lal and Ahmadi, 2000; Logsdon and Cambardella, 2000).

3.3.2. Soil water retention characteristics

Mechanical compaction's effect on soil physical and structural properties tend to have mixed influences on soil water retention characteristics. 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. Benjamin et al. (1990) also presented more complete water retention curves (along with K_s data; see below) for wheel-track and no-track areas under field conditions for three different soil types. Green et al. (2003), who measured the effects of wheel tracks at different landscape positions on K_s (see below), also examined the effects on soil water retention, and found no consistent difference in the average water retention curves between wheel-track and no-track areas, and the landscape spatial variability masked any difference between treatments. Green et al. (2003) also analyzed field data for three Iowa soils (Benjamin et al., 1990) where significant compaction effects were found. Wheel tracks appeared to consistently reduce the saturated SWC while increasing the air-entry suction. Thus, different soils under different climates may exhibit different responses to mechanical loading. Mahboubi et al. (1993) studied long-term interactions between tillage practices and wheel-track effects (cf. Section 3.1.1) and found that differences in water-holding capacity between tillage treatments were greater in the row zone than in the traffic zone.

Soil compaction effects on rooting can be related to a least limiting water range (LLWR) concept as a function of the bulk density. Betz et al. (1998) used the LLWR to evaluate the effects of tillage and wheel tracks on a poorly drained clay loam with a plow pan. Undisturbed soil cores were used to measure K_s, water retention, and other physical properties. 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.

Interacting factors have complicated analysis of many field studies. For example, ''Tillage and residue management practices influence soil surface compaction and sealing, but the effects vary with time and weather history'' (Logsdon et al., 1993). Starr and Timlin (2004) found that during the site-specific ''recharge season'' (wet season) under high rainfall events, CT exhibited greater cumulative and net soil water storage and drainage at all row/interrow positions than for NT treatment. However, the traffic interrow position yielded the only significantly different soil water parameter values for the ''high ET season'' (dry season) under high rainfall events, with CT values exceeding those for NT.

In all of these field studies, there are interactions between management practices and 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).

3.3.3. Hydraulic conductivity

Hydraulic conductivity response to mechanical compaction exhibits myriad behaviors in space and time. Benjamin et al. (1990) presented K_s data for wheel-track and no-track areas under field conditions for three different soil types. Subsequently, Ahuja et al. (2000) identified the 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. Results of this study have been reported in detail by Green et al. (2003), who measured the effects of wheel tracks at different landscape positions on K_s in selected plots of two long-term field studies of alternative crop rotations in eastern Colorado. A modified Kozeny-

Carman equation relating K_s to effective porosity (Carman, 1956; Ahuja et al., 1984, 1989) was applied to both wheel-track and no-track data for K_s from the Colorado studies. There was large variability in K_s, but no significant difference in mean values between wheel-track and no-track areas. Liebig et al. (1993) studied compaction in permanent wheel tracks of a ridge tillage system on a silty clay loam in southeastern Nebraska, USA. The mean of the K_s values in wheel tracks was approximately 25% of the mean value of non-trafficked areas. Logsdon et al. (1992) also studied responses of soil pore characteristics in a clay loam to wheel compaction under three axle loads (4.5, 9, and 18 Mg) in wet and dry soil conditions, and found that compaction under high loads decreased K_s. In short-term field experiments on clay soils of southern Italy, Marsili et al. (1998) found significantly reduced macroporosity following compaction with a rubber-track versus metal-track tractor and commensurate reductions in K_s.

Heddadj and Gascuel-Odoux (1999) measured steady infiltration at four tensions, two landscape positions, wheel-track and no-track areas, and three dates (June and October 1995 and April 1996). Hydraulic conductivity at all tensions decreased in time by factors of 2–3 for no tracks and 1–6 under wheel tracks. The temporal change was greater in the downslope position, and the effect of topography was significant but less than temporal effects. Furthermore, the degree of landscape-related spatial variability in K changed with time. Heddadj and Gascuel-Odoux (1999) concluded that topographic variations in K "help explain the spatial and temporal distributions of sheet flow and erosional processes that themselves may contribute to a redistribution of soil particles and induce feedback effects on sheet flow and infiltration."

In another study analyzing row-scale variability, Mohanty et al. (1994) made measurements of hydraulic conductivity at various tensions (0, 30, 60, and 150 mm) in corn rows, no-track interrows, and wheel-track interrows on a glacial till soil in central Iowa (silt loam). K and K_s were maximum in the corn rows and minimum in the wheel-track interrows, with no-track interrows exhibiting intermediate values. Spatial structure between K and K_s was mostly absent, although a small, five-row periodic variation matched traffic configurations. In general, external factors dominated the spatial structure of K variability for corn rows and wheel-track interrows, while a soil-type signal was discernible for no-track interrows. Old corn roots in corn rows may have caused K values at 150 mm tension to be similar to those for 30–60 mm tension, while bigger pores in wheel-track interrows were smeared from traffic and smaller pores survived the compaction.

Coutadeur et al. (2002) performed a similar study in which the infiltration rates in vertical and horizontal soil compartments (plowed, seed bed, untilled soil; wheel tracks, no tracks) in a silty loam Calcic soil in the Parisian Basin were measured to derive hydraulic conductivity estimates within a maize crop undergoing MP tillage to 30 cm depth. With the exception of saturation, a hierarchy of K reflects: seed bed > untilled layer > plowed layer, although seed bed and untilled layer K values were not significantly different between no-track and track areas. Soil in the wheel-track areas exhibited K values only 40% as great as those in no-track zones in the plowed layer. Overall, plowing tended to reduce K values and disrupt macropores, and the magnitude of K tended to persist in Δ (delta) clods between wheel tracks from compaction during the preceding year's cultivation.

Alakukku (1996a,b) conducted plot experiments where heavy axle loads were applied with up to four passes on two soils (16 Mg on clay and 19 Mg on an organic mixture). Cereal crops were grown for 9 years following the heavy traffic, then Alakukku (1996b) measured K_s, macroporosity, and the number and size of biopores. The effects of compaction on the subsoil were measurable after 9 years, with K_s and macroporosity decreasing by 60–98% and 37–70%, respectively.

3.3.4. Infiltration rates and capacity

Various tillage studies include the effects of wheel traffic on infiltration. The work of Freese et al. (1993) discussed above (Section 3.1.1) showed the greatest effect of wheel tracks on sprinkle infiltration in chisel-plowed areas, where the percentage of applied water infiltrating was reduced from 94% on no-track to 59% on wheel-track positions. Ankeny et al. (1990, 1995) studied the effects of wheel tracks on infiltration in CP and NT systems at five locations in the Midwest USA. Both ponded and tension infiltration measurements at three head values were collected (1995). Ponded infiltration was reduced on wheel tracks for all locations and tillage systems, and the ponded infiltration rates in trafficked interrows were very similar for both tillage systems.

Sprinkler infiltration and runoff experiments were conducted in Iowa under oats and rye cover crops (Kaspar et al., 2001). No-track interrows had less interrill runoff and erosion than tracked interrows, but wheel tracks had no apparent effect on rill erosion. Potter et al. (1995) conducted sprinkler, ponded, and tension infiltration measurements on a self-mulching vertisol and found that wheel tracks greatly reduced infiltration rates.

The inability of freeze–thaw and wetting–drying processes to ameliorate compaction was addressed by Wu et al. (1997), who measured soil structural properties and long-term compaction under two treatments (9 and 18 Mg axle loads) in a clay loam, including shrinkage and water retention characteristics. Although shrinkage and dry bulk density differed between the A_p layer and subsoil, no significant differences were found between compaction treatments.

Studies designed specifically to quantify differences in the spatial variability of soil hydraulic properties under different management practices are limited. Mohanty et al. (1996) measured infiltration at four tension-heads (0, 30, 60, and 150 mm) at 296 locations in the rows, wheel-track, and no-track interrows of a corn field in Iowa on a glacial till soil. Mean infiltration rates at any given tension were consistently greatest in the corn rows, followed by the no-track interrows, and least in the trafficked interrows. Spatial patterns of infiltration at zero tension (saturation) had a different scale of variability than infiltration at higher tensions, and the total coefficient of variation (CV) was greatest at saturation (CV values in the rows, wheel-track, and no-track interrows were 85%, 95%, and 124%, respectively). Although geostatistical measures demonstrated some spatial structure, there was a large nugget effect (random noise). Vervoort et al. (2001) also identified wheel tracks as sources of spatial variability in infiltration. Ponded infiltration rates on a silt loam averaged 86.5 mm h^{-1} for plant rows, 18.6 mm h^{-1} for no-track interrows, and 2.4 mm h^{-1} for wheel-track interrows.

4. Toward predicting tillage-affected soil hydraulic properties

Synthesis of the above studies points to the need for improved quantification of tillage-induced changes in soil hydraulic properties in space and time. For example, 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). This and other findings in the literature led Ahuja et al. (1998) to apply a Brooks-Corey water retention curve with similar media scaling. The modified scaling theory fit the experimental data fairly well. A second method offered slightly improved model fits by allowing the SWC between air entry and 10 times this matric suction to change as the inverse of the suction value. 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 (CT and MT) between the distributions of soil parameters for their vertic soils.

Santini et al. (1995) applied a Crank-Nicolson type finite-difference solution of Richards' equation coupled with a nonlinear optimization model to: (1) examine the extent to which different tillage practices affect the magnitude and variability of the hydraulic properties of a clay loam and (2) evaluate the effectiveness of a laboratory inverse method employed for characterizing the soil from the hydraulic point of view. Overall, the results of water retention and hydraulic conductivity characterization for soil samples at an experimental farm in the Agri River basin region (Italy) revealed no significant differences among tillage treatments.

Chen et al. (1998a,b) reviewed over two decades of literature to compile data sets for regression models to predict K_s and bulk density from soil texture, organic matter content, and tillage practices. Although none of the previously published relationships agreed with field measurements on a sandy soil in Quebec, Canada (Chen et al., 1998a) calibrated Campbell's (1974) soil hydraulic function using field data. Subsequently, Chen et al. (1998b) correlated bulk density primarily with clay content and organic matter for NT systems, then superimposed changes in bulk density due to tillage.

Or et al. (2000) developed a stochastic model that coupled probabilistic pore size distributions with physically based deformation using the Fokker–Planck 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. In a separate study aimed at quantifying temporal and spatial variability in soil aggregate stability and porosity due to tillage practices, Pirmoradian et al. (2005) demonstrated that a non-linearly derived fractal dimension was the most appropriate measure to use for this purpose, and that the fractal dimension increased over experiment years, particularly for the more intense tillage practices tested. Perfect and Kay (1995) also championed the use of fractals for quantifying soil physical properties, and described how they can be extracted from the slope of *log–log* plotted semivariograms of a spatial (or temporal) phenomenon or from the slope of a power spectrum. Spatial distributions of soil microtopography, pH, penetrability, and K_s have been examined using these techniques (see Perfect and Kay, 1995 and references therein).

Roger-Estrade et al. (2000b) developed a different model aimed at simulating changes over several years in soil structure from cropping systems and moldboard plowing. In the model, the proportion of severely compacted clods in the plowed layer was monitored in elementary compartments corresponding to wheel tracks and the action of tillage tools, and changed through time due to transfer between compartments during plowing, compaction, and fragmentation. The proportion changed exponentially until it reached a plateau after about 8 years, and was sensitive to the rate of clod loss. However, the model's simplicity and assumptions limit its predictive capability and versatility. For example, wheels and compaction are confined to the same tracks over time; SWC effects are not made explicit; Δ (delta) clods (clods resulting from severe, repetitive, high-load compaction under high moisture content) are not all lost from within the seed bed—they are protected from fragmentation in this compartment; vertical positions of clods are not taken into account; furrow turnover is modeled crudely; there is coincidence between limits of compartments and the passage of the plow; and the model invokes a uniform distribution of Δ clods in compartments. The model represents a valiant initial step, but a more detailed and versatile mechanistic treatment will be needed to enable more reliable predictions. Furthermore, Roger-Estrade et al. (2000a) tested a field-scale model (SISOL) that simulates tillage and compaction of a soil profile, including spatial variability of compaction due to wheel tracks, and suggested potential areas for improvement in the simulations.

Van Oost et al. (2000) described the results of field experiments carried out with a moldboard plow showing that an important net downslope translocation and dispersion of soil was associated with tillage. They modeled the redistribution of soil constituents by convoluting the displacement probability distribution with the spatial distribution of the soil constituent. A comparison of soil property data with model simulations indicated that soil tillage was a major factor when assessing the effects of erosion processes on the variability of soil properties. Subsequently, Van Oost et al. (2003) expanded the convolution modeling structure to allow for simulation of the redistribution of soil properties on complex topographies for various tillage implements. The effects of topography and tillage direction on the displacement probability distributions were characterized and implemented in the model, and a first application showed that the direction of tillage significantly affected the long-term redistribution of soil properties.

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. (2001) also showed that one-dimensional simulations with effective hydraulic parameters 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 (Lang and Mallett, 1984; Baumhardt and Lascano, 1996) as shown in Fig. 10.

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 discussed 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 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.

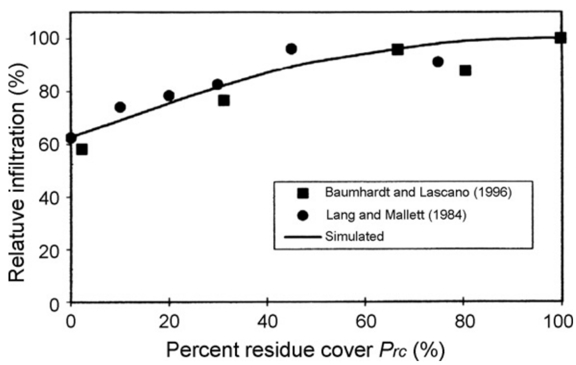

Fig. 10. Comparison of experimental studies and simulation results showing relative infiltration vs. percent residue cover. Taken from Ruan et al. (2001) with permission.

Subsequently, Leij et al. (2002a,b) solved the governing equation analytically for known temporal driving functions (*i.e.*, drift and degradation terms).

Finally, Xu and Mermoud (2003) sought to model the soil water balance under CT, NT, and subsoiling tillage (ST) based on time-dependent hydraulic conductivity during summer maize growth in wet, normal, and dry years. The model incorporates tillage by temporally modifying the soil hydraulic properties, based on measured SWC, K_s, and infiltration data. Differences in modeled K were small between CT and NT, but ST had a larger effect. ST promoted lower evaporation and higher infiltration and deep percolation. In normal and dry years, NT and CT provided more water storage during the initial stage of the growing season, but differences diminished between tillage treatments during the rest of the season. Although the model provides intriguing promise towards predictive capability of soil physical properties due to tillage, the description of mechanistic detail in the model is limited and based largely on site-specific empiricism.

5. Conclusions and recommendations

We have provided a detailed synopsis of the state-of-the-science for quantifying agricultural management effects, specifically tillage and related management activities, on soil hydraulic properties particularly relevant to space–time variability. We identified relationships between a large number of studies of management effects on basic soil properties and consequent detailed characterization of soil hydraulic properties in space and time. The literature demonstrates an awareness of interactions between management practices, as well as some appreciation of the complexity of spatial and temporal variability. More than half of the papers reviewed focused primarily on tillage effects, yet many tillage studies also considered residue management, compaction, and irrigation effects.

Experimental results from field and laboratory studies do not support consistent effects of management on soil hydraulic properties. For example, comparisons of no-till (NT) with conventional tillage (CT) practices produced mixed results across all studies. The trend, if any, is for NT to increase macropore connectivity while generating inconsistent responses in total porosity and soil bulk density compared with CT practices. This corresponds to a general increase in ponded or near-zero tension infiltration rates and hydraulic conductivities. Similarly, 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.

Agricultural management effects (Table 1) and other space–time factors (Table 2) have coupled effects on soil hydraulic properties and processes. Spatial and temporal variability have often overshadowed any measured differences between management treatments. Most tillage practices have pronounced 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 can be less pronounced and sometimes impossible to distinguish from natural and unaccounted management-induced variability. Furthermore, soil type and climate affect the resulting soil hydraulic properties, such that treatment effects may not transfer simply from one study location to another. Temporal variability was particularly noted as an obfuscating factor, but the magnitude and pattern of temporal variability was affected by spatial location, particularly the landscape position.

The intent of this review is to motivate and facilitate many more fruitful investigations into agricultural management practices, natural variability, and their interacting influences on soil hydraulic properties. The importance of casting results of spatio-temporal soil hydraulic behavior in terms of local pedologic and hydrologic conditions should be apparent from the widely varying interpretations summarized above, despite the fact that the underlying physics are the same for all environments. Specific documentation of different treatments (*e.g.*, depth and speed of tillage) is also critical to interpretation of results across study locations and to improved prediction of agricultural management effects across time and space.

One possible way to approach the analysis of the myriad effects imposed by environmental conditions and drivers on soil hydraulic response to tillage is to conduct more extensive sensitivity analyses of these effects under controlled conditions. For example, it may be worthwhile to measure soil hydraulic properties at locations representing end-member environmental conditions and drivers (*e.g.*, a statistically valid number of samples to replicate different landscape positions, soils of different type or age, or from differing parent material or climate). Short-term temporal effects and small-scale spatial responses may be more readily identified as a function of controlling environmental factors under this ‘‘end-member’’ sampling strategy. To examine larger scale dependencies and seasonal or inter-annual effects on soil hydraulic response, weighing lysimeter studies at representative end-member environmental conditions may provide useful data within the context of a classification system that incorporates cyclic and/or episodic weather events alongside soil type, lithologic provenance, landscape position, and tillage and planting practices.

Enhanced data collection and measurement campaigns, combined with improved methods of parameter estimation and mechanistic incorporation of management practices and effects within an explicit spatio-temporal modeling framework should aid in the understanding of soil hydraulic behavior due to tillage and related agricultural management. Predictive capability through modeling soil hydraulic response should become more robust and accurate with improved measurements of critical parameters at the spatial and temporal scales of interest. Remotely operated, wireless sensor networks provide a potentially inexpensive and efficient means of achieving this goal. An alternative or supplement to extensive measurement is ‘‘scaling up’’ small-scale observations to provide more reliable ways to describe, model, and predict hydraulic behavior at larger scales. Work has already begun in this arena (*e.g.*, Green et al., 1996; Kozak and Ahuja, 2005; Kozak et al., 2005), but numerous gaps remain. Future work should also aim to quantify process interactions, such as tillage and compaction, explicitly in time and space by integrating experimental observations with soil–plant system simulations. Modeling work should also be accompanied by rigorous parameter estimation and sensitivity and uncertainty analysis.

Based on the main findings above, we recommend the following actions to help generalize and predict space–time soil hydraulic properties in different environments:

1. Classify field experiments based on terrain attributes (or more qualitative landscape position), soil type, and climatic regime. Although uniform definitions of classes and strict controls on these factors may be difficult to maintain, improved standards are needed to test soil hydraulic responses to different management practices.
2. Document different treatments (*e.g.*, depth, style, and speed of tillage).
3. Identify all possible factors (not only ‘‘treatment’’ effects) to further constrain the classification of experiments for cross-comparison and process understanding, which should improve generalizations of results within and across classes.
4. Conduct experiments on end-member (classes) point samples or lysimeter studies to isolate the effects of environmental and management conditions.
5. Enhance data collection to elucidate spatial and temporal trends (potentially with wireless sensor networks), and to more adequately constrain parameter values in process-based numerical models of soil hydraulic response to tillage.
6. Design both event-based and seasonal/annual measurement campaigns to clarify short-term responses. Long-term studies are needed as well to elucidate the time scale over which short-term variability fades in deference to long-term persistence of management related effects.
7. Scale up core-scale values to address landscape scale variability and terrain effects on soil hydraulic response to tillage.
8. Develop and improve mechanistic descriptions of tillage effects on soil properties for incorporation in simulation models.

Advances in the research areas identified here will aid development of more robust computer simulation models, carefully tested against field data. Such multidisciplinary approaches are the most promising and robust ways of contributing to our knowledge of space–time interactions leading to improved methods of predicting soil hydraulic responses. The unattractive alternative is to continue the promulgation of individual studies that are difficult to classify and generalize for predictive use. On a more optimistic note, broad application of quantitative predictive tools ensuing from the recommendations herein could provide valuable aid to agricultural scientists, and by extension, to producers worldwide.

References

Agus, F., Cassel, D.K., 1992. Field-scale bromide transport as affected by tillage. Soil Sci. Soc. Am. J. 56 (1), 254–260.

Ahuja, L.R., Naney, J.W., Nielsen, D.R., 1984. Scaling soil-water properties and infiltration modeling. Soil Sci. Soc. Am. J. 48 (5), 970–973.

Ahuja, L.R., Cassel, D.K., Bruce, R.R., Barnes, B.B., 1989. Evaluation of spatial distribution of hydraulic conductivity using effective porosity data. Soil Sci. 148 (6), 404–411.

Ahuja, L.R., Fiedler, F., Dunn, G.H., Benjamin, J.G., Garrison, A., 1998. Changes in soil water retention curves due to tillage and natural reconsolidation. Soil Sci. Soc. Am. J. 62 (5), 1228–1233.

Ahuja, L.R., Benjamin, J.G., Dunn, G.H., Ma, L., Green, T.R., Peterson, G.A., 2000. Quantifying wheel track effects on soil hydraulic properties for agricultural systems modeling. In: Proceedings of the 4th International Conference on Soil Dynamics, Adelaide, Australia, pp. 407–414.

Ahuja, L.R., Ma, L., Timlin, D.J., 2006. Trans-disciplinary soil physics research critical to synthesis and modeling of agricultural systems. Soil Sci. Soc. Am. J. 70 (2), 311–326.

Alakukku, L., 1996a. Persistence of soil compaction due to high axle load traffic. 1. Short-term effects on the properties of clay and organic soils. Soil Till. Res. 37 (4), 211–222.

Alakukku, L., 1996b. Persistence of soil compaction due to high axle load traffic. 2. Long-term effects on the properties of fine-textured and organic soils. Soil Till. Res. 37 (4), 223–238.

Alegre, J.C., Cassel, D.K., Amezquita, E., 1991. Tillage systems and soil properties in Latin America. Soil Till. Res. 20 (2–4), 147–163.

Ali, A.-S.I., Swartzendruber, D., 1994. An infiltration equation to assess cropping effects on soil water infiltration. Soil Sci. Soc. Am. J. 58 (4), 1218–1223.

Allmaras, R.R., Copeland, S.M., Copeland, P.J., Oussible, M., 1996. Spatial relations between oat residue and ceramic spheres when incorporated sequentially by tillage. Soil Sci. Soc. Am. J. 60 (4), 1209–1216.

Anderson, S.H., Cassel, D.K., 1984. Effect of soil variability on response to tillage of an Atlantic coastal plain ultisol. Soil Sci. Soc. Am. J. 48 (6), 1411–1416.

Angulo-Jaramillo, R., Moreno, F., Clothier, B.E., Thony, J.L., Vachaud, G., Fernandez-Boy, E., Cayuela, J.A., 1997. Seasonal variation of hydraulic properties of soils measured using a tension disk infiltrometer. Soil Sci. Soc. Am. J. 61 (1), 27–32.

Angulo-Jaramillo, R., Vandervaere, J.P., Roulier, S., Thony, J.L., Gaudet, J.P., Vauclin, M., 2000. Field measurement of soil surface hydraulic properties by disc and ring infiltrometers—a review and recent developments. Soil Till. Res. 55 (1–2), 1–29.

Ankeny, M.D., Kaspar, T.C., Horton, R., 1990. Characterization of tillage and traffic effects on unconfined infiltration measurements. Soil Sci. Soc. Am. J. 54 (3), 837–840.

Ankeny, M.D., Kaspar, T.C., Prieksat, M.A., 1995. Traffic effects on water infiltration in chisel plow and no-till systems. Soil Sci. Soc. Am. J. 59 (1), 200–204.

Arshad, M.A., Franzluebbers, A.J., Azooz, R.H., 1999. Components of surface soil structure under conventional and no-tillage in northwestern Canada. Soil Till. Res. 53 (1), 41–47.

Assouline, S., Tavares-Filho, J., Tessier, D., 1997. Effect of compaction on soil physical and hydraulic properties: experimental results and modeling. Soil Sci. Soc. Am. J. 61, 390–398.

Azevedo, A.S., Kanwar, R.S., Horton, R., 1998. Effect of cultivation on hydraulic properties of an Iowa soil using tension infiltrometers. Soil Sci. 163 (1), 22–29.

Azooz, R.H., Arshad, M.A., 1996. Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. Can. J. Soil Sci. 76 (2), 143–152.

Azooz, R.H., Arshad, M.A., 2001. Soil water drying and recharge rates as affected by tillage under continuous barley and barley–canola cropping systems in northwestern Canada. Can. J. Soil Sci. 81 (1), 45–52.

Bathke, G.R., Cassel, D.K., Hargrove, W.L., Porter, P.M., 1992. Modification of soil physical-properties and root-growth response. Soil Sci. 154 (4), 316–329.

Baumhardt, R.L., Lascano, R.J., 1996. Rain infiltration as affected by wheat residue amount and distribution in ridged tillage. Soil Sci. Soc. Am. J. 60 (6), 1908–1913.

Baumhardt, R.L., Jones, O.R., 2002. Residue management and paratillage effects on some soil properties and rain infiltration. Soil Till. Res. 65, 19–27.

Benjamin, J.G., Blaylock, A.D., Brown, H.J., Cruse, R.M., 1990. Ridge tillage effects on simulated water and heat transport. Soil Till. Res. 18, 167–180.

Benjamin, J.G., 1993. Tillage effects on near-surface soil hydraulic properties. Soil Till. Res. 26 (4), 277–288.

Benoit, G.R., Lindstrom, M.J., 1987. Interpreting tillage residue management effects. J. Soil Water Conserv. 42 (2), 87–90.

Betz, C.L., Allmaras, R.R., Copeland, S.M., Randall, G.W., 1998. Least limiting water range: traffic and long-term tillage influences in a Webster soil. Soil Sci. Soc. Am. J. 62 (5), 1384–1393.

Bielders, C.L., Baveye, P., Wilding, L.P., Drees, L.R., Valentin, C., 1996. Tillage-induced spatial distribution of surface crusts on a sandy paleustult from Togo. Soil Sci. Soc. Am. J. 60 (3), 843–855.

Blackwell, P.S., Graham, J.P., Armstrong, J.V., Ward, M.A., Howse, K.R., Dawson, C.J., Butler, A.R., 1986. Compaction of a silt loam soil by wheeled agricultural vehicles. 1. Effects upon soil conditions. Soil Till. Res. 7 (1–2), 97–116.

Bouma, J., Woesten, J.H.M., 1979. Flow patterns during extended saturated flow in two undisturbed swelling clay soils with different macropores. Soil Sci. Soc. Am. J. 43, 16–22.

Brandt, S.A., 1992. Zero vs conventional tillage and their effects on crop yield and soil moisture. Can. J. Plant Sci. 72 (3), 679–688.

Bruand, A., Dacqui, L.P., Nyamugafata, P., Darthout, R., Ristori, G.G., 1993. Analysis of porosity in a tilled crusting soil in Zimbabwe. Geoderma 59 (1–4), 235–248.

Bruand, A., Cousin, I., 1995. Variation of textural porosity of a clay loam soil during compaction. Eur. J. Soil Sci. 46 (3), 377–385.

Brubaker, S.C., Jones, A.J., Lewis, D.T., Frank, K., 1993. Soil properties associated with landscape position. Soil Sci. Soc. Am. J. 57 (1), 235–239.

Bullock, P., Newman, A.C.D., Thomasson, A.J., 1985. Porosity aspects of the regeneration of soil structure after compaction. Soil Till. Res. 5 (4), 325–341.

Burch, G.J., Mason, I.B., Fischer, R.A., Moore, I.D., 1986. Tillage effects on soils—physical and hydraulic responses to direct drilling at Lockhart, NSW. Aust. J. Soil Res. 24 (3), 377–391.

Cambardella, C.A., Moorman, T.B., Novak, J.M., Parkin, T.B., Karlen, D.L., Turco, R.F., Konopka, A.E., 1994. Field-scale variability of soil properties in central Iowa soils. Soil Sci. Soc. Am. J. 58 (5), 1501–1511.

Campbell, G.S., 1974. A simple method for determining unsaturated conductivity from moisture retention data. Soil Sci. 114, 311–314.

Carman, P.C., 1956. Flow of Gases through Porous Media. Academic Press, New York, NY.

Carter, M.R., 1988. Temporal variability of soil macroporosity in a fine sandy loam under mouldboard ploughing and direct drilling. Soil Till. Res. 12 (1), 37–51.

Carter, M.R., Steed, G.R., 1992. The effects of direct drilling and stubble retention on hydraulic properties at the surface of duplex soils in northeastern Victoria. Aust. J. Soil Res. 30 (4), 505–516.

Carter, M.R., Mele, P.M., Steed, G.R., 1994. The effects of direct drilling and stubble retention on water and bromide movement and earthworm species in a duplex soil. Soil Sci. 157 (4), 224–231.

Cassel, D.K., 1983. Spatial and temporal variability of soil physical properties following tillage of Norfolk loamy sand. Soil Sci. Soc. Am. J. 47 (2), 196–201.

Cassel, D.K., Martin, C.K., Lambert, J.R., 1985. Corn irrigation scheduling in humid regions on sandy soils with tillage pans. Agron. J. 77 (6), 851–855.

Cassel, D.K., Nelson, L.A., 1985. Spatial and temporal variability of soil physical properties of Norfolk loamy sand as affected by tillage. Soil Till. Res. 5 (1), 5–17.

Cassel, D.K., Raczkowski, C.W., Denton, H.P., 1995. Tillage effects on corn production and soil physical conditions. Soil Sci. Soc. Am. J. 59 (5), 1436–1443.

Castrignano, A., Maiorana, M., Fornaro, F., 2003. Using regionalised variables to assess field-scale spatiotemporal variability of soil impedance for different tillage management. Biosyst. Eng. 85 (3), 381–392.

Chan, K.Y., Mead, J.A., 1988. Surface physical properties of a sandy loam soil under different tillage practices. Aust. J. Soil Res. 26 (3), 549–559.

Chan, K.Y., Heenan, D.P., 1993. Surface hydraulic properties of a red earth under continuous cropping with different management practices. Aust. J. Soil Res. 31 (1), 13–24.

Chang, C., Lindwall, C.W., 1989. Effect of long-term minimum tillage practices on some physical properties of a chernozemic clay loam. Can. J. Soil Sci. 69 (3), 443–449.

Chang, C., Lindwall, C.W., 1990. Comparison of the effect of long-term tillage and crop rotation on physical properties of a soil. Can. Agric. Eng. 32 (1), 53–55.

Chang, C., Lindwall, C.W., 1992. Effects of tillage and crop rotation on physical properties of a loam soil. Soil Till. Res. 22 (3–4), 383–389.

Chen, Y., Tessier, S., Gallichand, J., 1998a. Estimates of tillage effects on saturated hydraulic conductivity. Can. Agric. Eng. 40 (3), 169–177.

Chen, Y., Tessier, S., Rouffignat, J., 1998b. Soil bulk density estimation for tillage systems and soil textures. Trans. ASAE 41 (6), 1601–1610.

Chen, Y., Cavers, C., Tessier, S., Monero, F., Lobb, D., 2005. Short-term tillage effects on soil cone index and plant development in a poorly drained, heavy clay soil. Soil Till. Res. 82 (2), 161–171.

Choudhary, M.A., Akramkhanov, A., Saggar, S., 2002. Nitrous oxide emissions from a New Zealand cropped soil: tillage effects, spatial and seasonal variability. Agric. Ecosyst. Environ. 93 (1–3), 33–43.

Ciollaro, G., Lamaddalena, N., 1998. Effect of tillage on the hydraulic properties of a vertic soil. J. Agric. Eng. Res. 71 (2), 147–155.

Comegna, V., Damiani, P., Sommella, A., 2000. Scaling the saturated hydraulic conductivity of a vertic ustorthens soil under conventional and minimum tillage. Soil Till. Res. 54 (1–2), 1–9.

Comia, R.A., Stenberg, M., Nelson, P., Rydberg, T., Hakansson, I., 1994. Soil and crop responses to different tillage systems. Soil Till. Res. 29 (4), 335–355.

Constantz, J., 1995. Determination of water retention in stratified porous materials. Transp. Porous Media 18 (3), 217–229.

Coutadeur, C., Coquet, Y., Roger-Estrade, J., 2002. Variation of hydraulic conductivity in a tilled soil. Eur. J. Soil Sci. 53 (4), 619–628.

Cressie, N.A.C., Horton, R., 1987. A robust-resistant spatial analysis of soil water infiltration. Water Resour. Res. 23 (5), 911–917.

Cresswell, H.P., Smiles, D.E., Williams, J., 1992. Soil structure, soil hydraulic properties and the soil water balance. Aust. J. Soil Res. 30 (3), 265–283.

Cresswell, H.P., Painter, D.J., Cameron, K.C., 1993. Tillage and water content effects on surface soil hydraulic properties and shortwave albedo. Soil Sci. Soc. Am. J. 57 (3), 816–824.

Dadoun, F.A., 1993. Modelling Tillage Effects on Soil Physical Properties and Maize (*Zea mays* L.) Development and Growth (Michigan) Michigan State University, East Lansing, MI, p. 209.

Dao, T.H., 1993. Tillage and winter wheat residue management effects on water infiltration and storage. Soil Sci. Soc. Am. J. 57 (6), 1586–1595.

Dao, T.H., 1996. Tillage system and crop residue effects on surface compaction of a paleustoll. Agron. J. 88 (2), 141–148.

Derdour, H., Angers, D.A., Laverdiere, M.R., 1993. Characterization of the pore space of a clay soil—influence of soil constituents and tillage practices. Can. J. Soil Sci. 73 (3), 299–307.

Dick, W.A., Roseberg, R.J., McCoy, E.L., Edwards, W.M., Haghiri, F., 1989. Surface hydrologic response of soils to no-tillage. Soil Sci. Soc. Am. J. 53 (5), 1520–1526.

Drees, L.R., Karathanasis, A.D., Wilding, L.P., Blevins, R.L., 1994. Micromorphological characteristics of long-term and no-till and conventionally tilled soils. Soil Sci. Soc. Am. J. 58 (2), 508–517.

Duley, F.L., 1939. Surface factors affecting the rate of intake of water by soils. Soil Sci. Soc. Am. Proc. 4, 60–64.

Dunn, G.H., Phillips, R.E., 1991. Macroporosity of a well-drained soil under no-till and conventional tillage. Soil Sci. Soc. Am. J. 55 (3), 817–823.

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

Eigenbrod, K.D., 2003. Self-healing in fractured fine-grained soils. Can. Geotech. J. 40 (2), 435–449.

Elliott, J.A., Efetha, A.A., 1999. Influence of tillage and cropping system on soil organic matter, structure and infiltration in a rolling landscape. Can. J. Soil Sci. 79 (3), 457–463.

Falleiros, M.C., Portezan, O., Oliveira, J.C.M., Bacchi, O.O.S., Reichardt, K., 1998. Spatial and temporal variability of soil hydraulic conductivity in relation to soil water distribution, using an exponential model. Soil Till. Res. 45 (3–4), 279–285.

Francis, G.S., Cameron, K.C., Swift, R.S., 1987. Soil physical conditions after 6 years of direct drilling or conventional cultivation on a silt loam soil in New Zealand. Aust. J. Soil Res. 25 (4), 517–529.

Francis, G.S., Knight, T.L., 1993. Long-term effects of conventional and no-tillage on selected soil properties and crop yields in Canterbury, New Zealand. Soil Till. Res. 26 (3), 193–210.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995. Tillage-induced seasonal changes in soil physical properties affecting soil CO_2 evolution under intensive cropping. Soil Till. Res. 34 (1), 41–60.

Freese, R.C., Cassel, D.K., Denton, H.P., 1993. Infiltration in a piedmont soil under three tillage systems. J. Soil Water Conserv. 48 (3), 214–218.

Fritz, V.A., Allmaras, R.R., Pfleger, F.L., Davis, D.W., 1995. Oat residue and soil compaction influences on common root rot (*Aphanomyces euteiches*) of peas in a fine textured soil. Plant Soil 171 (2), 235–244.

Gantzer, C.J., Anderson, S.H., 2002. Computed tomographic measurement of macroporosity in chisel-disk and no-tillage seedbeds. Soil Till. Res. 64 (1–2), 101–111.

Gomez, J.A., Giraldez, J.V., Pastor, M., Fereres, E., 1999. Effects of tillage method on soil physical properties, infiltration and yield in an olive orchard. Soil Till. Res. 52 (3–4), 167–175.

Greb, B.W., Smika, D.E., Black, A.L., 1967. Effect of straw mulch rates on soil water storage during summer fallow in the Great Plains. Soil Sci. Soc. Am. Proc. 31 (4), 556–559.

Green, T.R., Freyberg, D.L., 1995. State-dependent anisotropy—comparisons of quasi-analytical solutions with stochastic results for steady gravity drainage. Water Resour. Res. 31 (9), 2201–2211.

Green, T.R., Constantz, J., Freyberg, D.L., 1996. Upscaled soil-water retention using van Genuchten's function. J. Hydrol. Eng. 1 (3), 123–130.

Green, T.R., Ahuja, L.R., Benjamin, J.G., 2003. Advances and challenges in predicting agricultural management effects on soil hydraulic properties. Geoderma 116 (1–2), 3–27.

Guerif, J., Richard, G., Durr, C., Machet, J.M., Recous, S., Roger-Estrade, J., 2001. A review of tillage effects on crop residue management, seedbed conditions and seedling establishment. Soil Till. Res. 61 (1–2), 13–32.

Gupta, S.C., Lowery, B., Moncrief, J.F., Larson, W.E., 1991. Modeling tillage effects on soil physical properties. Soil Till. Res. 20 (2–4), 293–318.

Hamblin, A.P., Tennant, D., 1981. The influence of tillage on soil water behavior. Soil Sci. 132, 233–239.

Hammad, E.A., Dawelbeit, M.I., 2001. Effect of tillage and field condition on soil physical properties, cane and sugar yields in vertisols of Kenana sugar estate, Sudan. Soil Till. Res. 62 (3–4), 101–109.

Hammel, J.E., 1989. Long-term tillage and crop rotation effects on bulk density and soil impedance in northern Idaho. Soil Sci. Soc. Am. J. 53 (5), 1515–1519.

Hangen, E., Buczko, U., Bens, O., Brunotte, J., Huttl, R.F., 2002. Infiltration patterns into two soils under conventional and conservation tillage: influence of the spatial distribution of plant root structures and soil animal activity. Soil Till. Res. 63 (3–4), 181–186.

Hansen, E.M., Djurhuus, J., 1997. Nitrate leaching as influenced by soil tillage and catch crop. Soil Till. Res. 41 (3–4), 203–219.

Harris, G.L., Howse, K.R., Pepper, T.J., 1993. Effects of moling and cultivation on soil water and runoff from a drained clay soil. Agric. Water Manage. 23 (2), 161–180.

Heddadj, D., Gascuel-Odoux, C., 1999. Topographic and seasonal variations of unsaturated hydraulic conductivity as measured by tension disc infiltrometers at the field scale. Eur. J. Soil Sci. 50 (2), 275–283.

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

Hill, R.L., Mezamontalvo, M., 1990. Long-term wheel traffic effects on soil physical properties under different tillage systems. Soil Sci. Soc. Am. J. 54 (3), 865–870.

Horn, R., Taubner, H., Wuttke, M., Baumgartl, T., 1994. Soil physical-properties related to soil-structure. Soil Till. Res. 30 (2–4), 187–216.

Horn, R., Smucker, A., 2005. Structure formation and its consequences for gas and water transport in unsaturated arable and forest soils. Soil Till. Res. 82 (1), 5–14.

Horne, D.J., Ross, C.W., Hughes, K.A., 1992. 10 years of a maize oats rotation under three tillage systems on a silt loam in New Zealand. 1. A comparison of some soil properties. Soil Till. Res. 22 (1–2), 131–143.

Horton, R.E., 1940. An approach toward a physical interpretation of infiltration capacity. Soil Sci. Soc. Am. J. 5, 131–143.

Jenny, H., 1946. Arrangement of soil series and types according to functions of soil-forming factors. Soil Sci. 61 (5), 375–391.

Johnson, B.S., Erickson, A.E., Voorhees, W.B., 1989. Physical conditions of a lake plain soil as affected by deep tillage and wheel traffic. Soil Sci. Soc. Am. J. 53 (5), 1545–1551.

Josa, R., Hereter, A., 2005. Effects of tillage systems in dryland farming on near-surface water content during the late winter period. Soil Till. Res. 82 (2), 173–183.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S., Jordahl, J.L., 1994. Crop residue effects on soil quality following 10 years of no-till corn. Soil Till. Res. 31 (2–3), 149–167.

Kaspar, T.C., Radke, J.K., Laflen, J.M., 2001. Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. J. Soil Water Conserv. 56 (2), 160–164.

Kay, B.D., Angers, D.A., 2002. Soil structure. In: Warrick , A.W. (Ed.), Soil Physics Companion. CRC Press, Boca Raton, FL, pp. 249–295.

Khakural, B.R., Lemme, G.D., Schumacher, T.E., Lindstrom, M.J., 1992. Effects of tillage systems and landscape on soil. Soil Till. Res. 25 (1), 43–52.

Kosutic, S., Husnjak, S., Filipovic, D., Bogunovic, M., 2001. Influence of different tillage systems on soil water availability in the Ap-horizon of an albic luvisol and yield in northwest Slavonia, Croatia. Bodenkultur 52 (3), 215–223.

Kozak, J.A., Ahuja, L.R., 2005. Scaling of infiltration and redistribution of water across soil textural classes. Soil Sci. Soc. Am. J. 69 (3), 816–827.

Kozak, J.A., Ahuja, L.R., Ma, L., Green, T.R., 2005. Scaling and estimation of evaporation and transpiration of water across soil textures. Vadose Zone J. 4 (2), 418–427.

Lal, R., Logan, T.J., Fausey, N.R., 1989a. Long-term tillage and wheel traffic effects on a poorly drained mollic ochraqualf in northwest Ohio. 1. Soil physical properties, root distribution and grain yield of corn and soybean. Soil Till. Res. 14 (4), 341–358.

Lal, R., Logan, T.J., Fausey, N.R., 1989b. Long-term tillage and wheel traffic effects on a poorly drained mollic ochraqualf in northwest Ohio. 2. Infiltrability, surface runoff, subsurface flow and sediment transport. Soil Till. Res. 14 (4), 359–373.

Lal, R., Mahboubi, A.A., Fausey, N.R., 1994. Long-term tillage and rotation effects on properties of a central Ohio soil. Soil Sci. Soc. Am. J. 58 (2), 517–522.

Lal, R., Ahmadi, M., 2000. Axle load and tillage effects on crop yield for two soils in central Ohio. Soil Till. Res. 54 (1–2), 111–119.

Lang, P.M., Mallett, J.B., 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.

Leij, F.J., Ghezzehei, T.A., Or, D., 2002a. Modeling the dynamics of the soil pore size distribution. Soil Till. Res. 64 (1–2), 61–78.

Leij, F.J., Ghezzehei, T.A., Or, D., 2002b. Analytical models for soil pore-size distribution after tillage. Soil Sci. Soc. Am. J. 66 (4), 1104–1114.

Liebig, M.A., Jones, A.J., Mielke, L.N., Doran, J.W., 1993. Controlled wheel traffic effects on soil properties in ridge tillage. Soil Sci. Soc. Am. J. 57 (4), 1061–1066.

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

Lindstrom, M.J., Voorhees, W.B., 1995. Soil Properties across a Landscape Continuum as Affected by Planting Wheel Traffic, Site-specific Management for Agricultural Systems. ASA-SSSA, Madison, WI, pp. 351–363.

Logsdon, S.D., Allmaras, R.R., Nelson, W.W., Voorhees, W.B., 1992. Persistence of subsoil compaction from heavy axle loads. Soil Till. Res. 23 (1–2), 95–110.

Logsdon, S.D., Linden, D.R., 1992. Interactions of earthworms with soil physical conditions influencing plant growth. Soil Sci. 154 (4), 330–337.

Logsdon, S.D., Jordahl, J., Karlen, D.L., 1993. Tillage and crop effects on ponded and tension infiltration rates. Soil Till. Res. 28 (2), 179–189.

Logsdon, S.D., Jaynes, D.B., 1996. Spatial variability of hydraulic conductivity in a cultivated field at different times. Soil Sci. Soc. Am. J. 60 (3), 703–709.

Logsdon, S.D., Kaspar, T.C., Cambardella, C.A., 1999. Depth-incremental soil properties under no-till or chisel management. Soil Sci. Soc. Am. J. 63 (1), 197–200.

Logsdon, S.D., Cambardella, C.A., 2000. Temporal changes in small depth-incremental soil bulk density. Soil Sci. Soc. Am. J. 64 (2), 710–714.

Mahboubi, A.A., Lal, R., Faussey, N.R., 1993. 28 years of tillage effects on two soils in Ohio. Soil Sci. Soc. Am. J. 57 (2), 506–512.

Mantoglou, A., Gelhar, L.W., 1987. Effective hydraulic conductivities of transient unsaturated flow in stratified soils. Water Resour. Res. 23 (1), 57–67.

Mapa, R.B., Green, R.E., Santo, L., 1986. Temporal variability of soil hydraulic-properties with wetting and drying subsequent to tillage. Soil Sci. Soc. Am. J. 50 (5), 1133–1138.

Marsili, A., Servadio, P., Pagliai, M., Vignozzi, N., 1998. Changes of some physical properties of a clay soil following passage of rubber- and metal-tracked tractors. Soil Till. Res. 49 (3), 185–199.

McDonald, A.J., Riha, S.J., Duxbury, J.M., Steenhuis, T.S., Lauren, J.G., 2006. Soil physical responses to novel rice cultural practices in the rice–wheat system: comparative evidence from a swelling soil in Nepal. Soil Till. Res. 86 (2), 163–175.

McFarland, M.L., Hons, F.M., Lemon, R.G., 1990. Effects of tillage and cropping sequence on soil physical properties. Soil Till. Res. 17 (1–2), 77–86.

McGarry, D., Bridge, B.J., Radford, B.J., 2000. Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. Soil Till. Res. 53 (2), 105–115.

Messing, I., Jarvis, N.J., 1993. Temporal variation in the hydraulic conductivity of a tilled clay soil as measured by tension infiltrometers. J. Soil Sci. 44 (1), 11–24.

Miller, E.E., Miller, R.D., 1956. Physical theory for capillary flow phenomena. J. Appl. Phys. 27 (4), 324–332.

Miller, J.J., Kokko, E.G., Kozub, G.C., 1998. Comparison of porosity in a chernozemic clay loam soil under long-term conventional tillage and no-till. Can. J. Soil Sci. 78 (4), 619–629.

Miller, J.J., Lamond, B.J., Sweetland, N.J., Larney, F.J., 2000. Preferential leaching of water and chloride in a clay loam soil as affected by tillage and rainfall intensity. Water Q. Res. J. Canada 35 (4), 711–734.

Mohanty, B.P., Ankeny, M.D., Horton, R., Kanwar, R.S., 1994. Spatial analysis of hydraulic conductivity measured using disc infiltrometers. Water Resour. Res. 30 (9), 2489–2498.

Mohanty, B.P., Horton, R., Ankeny, M.D., 1996. Infiltration and macroporosity under a row crop agricultural field in a glacial till soil. Soil Sci. 161 (4), 205–213.

Monnier, G., 1992. Action of earthworms in terms of soil physics. Soil Biol. Biochem. 24 (12), 1197–1200.

Mubarak, A.R., Elshami, O.M.E., Azhari, A.A., 2005. Long- and short-term effects of cultivation on properties of a vertisol under sugarcane plantation. Soil Till. Res. 84 (1), 1–6.

Murphy, B.W., Koen, T.B., Jones, B.A., Huxedurp, L.M., 1993. Temporal variation of hydraulic properties for some soils with fragile structure. Aust. J. Soil Res. 31 (2), 179–197.

Nielsen, D.C., 2006. Water use efficiency, enhancing. In: Lal , R. (Ed.), Encyclopedia of Soil Science. second ed. Marcel Dekker, pp. 1870–1873.

Ogden, C.B., van Es, H.M., Wagenet, R.J., Steenhuis, T.S., 1999. Spatial-temporal variability of preferential flow in a clay soil under no-till and plow-till. J. Environ. Q. 28 (4), 1264–1273.

Or, D., 1995. Stochastic analysis of soil water monitoring for drip irrigation management in heterogeneous soils. Soil Sci. Soc. Am. J. 59 (5), 1222–1233.

Or, D., Leij, F.J., Snyder, V., Ghezzehei, T.A., 2000. Stochastic model for posttillage soil pore space evolution. Water Resour. Res. 36 (7), 1641–1652.

Or, D., Ghezzehei, T.A., 2002. Modeling post-tillage soil structural dynamics: a review. Soil Till. Res. 64 (1–2), 41–59.

Osunbitan, J.A., Oyedele, D.J., Adekalu, K.O., 2005. Tillage effects on bulk density, hydraulic conductivity and strength of a loamy sand soil in southwestern Nigeria. Soil Till. Res. 82 (1), 57–64.

Packer, I.J., Hamilton, G.J., Koen, T.B., 1992. Runoff, soil loss and soil physical property changes of light textured surface soils from long-term tillage treatments. Aust. J. Soil Res. 30 (5), 789–806.

Pagliai, M., Lamarca, M., Lucamante, G., 1983. Micromorphometric and micromorphological investigations of a clay loam soil in viticulture under zero and conventional tillage. J. Soil Sci. 34 (2), 391–403.

Pagliai, M., Lamarca, M., Lucamante, G., Genovese, L., 1984. Effects of zero and conventional tillage on the length and irregularity of elongated pores in a clay loam soil under viticulture. Soil Till. Res. 4 (5), 433–444.

Pagliai, M., Raglione, M., Panini, T., Maletta, M., Lamarca, M., 1995. The structure of two alluvial soils in Italy after ten years of conventional and minimum tillage. Soil Till. Res. 34 (4), 209–223.

Perfect, E., Kay, B.D., 1995. Applications of fractals in soil and tillage research: a review. Soil Till. Res. 36 (1–2), 1–20.

Petersen, C.T., Hansen, S., Jensen, H.E., 1997. Tillage-induced horizontal periodicity of preferential flow in the root zone. Soil Sci. Soc. Am. J. 61 (2), 586–594.

Peterson, G.A., Schlegel, A.J., Tanaka, D.L., Jones, O.R., 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Agric. 9 (2), 180–186.

Pierce, F.J., Fortin, M.C., Staton, M.J., 1994. Periodic plowing effects on soil properties in a no-till farming system. Soil Sci. Soc. Am. J. 58 (6), 1782–1787.

Pirmoradian, N., Sepaskhah, A.R., Hajabbasi, M.A., 2005. Application of fractal theory to quantify soil aggregate stability as influenced by tillage treatments. Biosyst. Eng. 90 (2), 227–234.

Porro, I., Cassel, D.K., 1986. Response of corn to tillage and delayed irrigation. Agron. J. 78 (4), 688–693.

Potter, K.N., Torbert, H.A., Morrison, J.E., 1995. Tillage and residue effects on infiltration and sediment losses on vertisols. Trans. ASAE 38 (5), 1413–1419.

Prieksat, M.A., Kaspar, T.C., Ankeny, M.D., 1994. Positional and temporal changes in ponded infiltration in a corn field. Soil Sci. Soc. Am. J. 58 (1), 181–184.

Radford, B.J., Bridge, B.J., Davis, R.J., McGarry, D., Pillai, U.P., Rickman, J.F., Walsh, P.A., Yule, D.F., 2000. Changes in the properties of a vertisol and responses of wheat after compaction with harvester traffic. Soil Till. Res. 54 (3–4), 155–170.

Raper, R.L., Reeves, D.W., Burmester, C.H., Schwab, E.B., 2000. Tillage depth, tillage timing, and cover crop effects on cotton yield, soil strength, and tillage energy requirements. Appl. Eng. Agric. 16 (4), 379–385.

Rawitz, E., Hadas, A., Etkin, H., Margolin, M., 1994. The effect of various residue mulch tillage combinations on soil physical conditions and performance of irrigated cotton. Soil Till. Res. 32 (4), 347–366.

Richard, G., Sillon, J.F., Marloie, O., 2001. Comparison of inverse and direct evaporation methods for estimating soil hydraulic properties under different tillage practices. Soil Sci. Soc. Am. J. 65 (1), 215–224.

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. Physics 1 (5), 318–333.

Ringrose-Voase, A.J., 1996. Measurement of soil macropore geometry by image analysis of sections through impregnated soil. Plant Soil 183 (1), 27–47.

Roger-Estrade, J., Richard, G., Boizard, H., Boiffin, J., Caneill, J., Manichon, H., 2000a. Modelling structural changes in tilled topsoil over time as a function of cropping systems. Eur. J. Soil Sci. 51 (3), 455–474.

Roger-Estrade, J., Richard, G., Manichon, H., 2000b. A compartmental model to simulate temporal changes in soil structure under two cropping systems with annual mouldboard ploughing in a silt loam. Soil Till. Res. 54 (1–2), 41–53.

Ross, C.W., Hughes, K.A., 1985. Maize oats forage rotation under three cultivation systems, 1978–83. 2. Soil properties. NZ J. Agric. Res. 28 (2), 209–219.

Ruan, H.X., Ahuja, L.R., Green, T.R., Benjamin, J.G., 2001. Residue cover and surface sealing effects on infiltration: numerical simulations for field applications. Soil Sci. Soc. Am. J. 65 (3), 853–861.

Russo, D., 1992. Upscaling of hydraulic conductivity in partially saturated heterogeneous porous formation. Water Resour. Res. 28 (2), 397–409.

Santini, A., Romano, N., Ciollaro, G., Comegna, V., 1995. Evaluation of a laboratory inverse method for determining unsaturated hydraulic properties of a soil under different tillage practices. Soil Sci. 160 (5), 340–351.

Sembiring, H., Raun, W.R., Johnson, G.V., Boman, R.K., 1995. Effect of wheat straw inversion on soil water conservation. Soil Sci. 159 (2), 81–89.

Sepaskhah, A.R., Ahmadi, S.H., Shahbazi, A.R.N., 2005. Geostatistical analysis of sorptivity for a soil under tilled and no-tilled conditions. Soil Till. Res. 83 (2), 237–245.

Sharratt, B.S., 1996. Tillage and straw management for modifying physical properties of a subarctic soil. Soil Till. Res. 38 (3–4), 239–250.

Shipitalo, M.J., Edwards, W.M., 1993. Seasonal patterns of water and chemical movement in tilled and no-till column lysimeters. Soil Sci. Soc. Am. J. 57, 218–223.

Simmons, F.W., Cassel, D.K., Daniels, R.B., 1989. Landscape and soil property effects on corn grain yield response to tillage. Soil Sci. Soc. Am. J. 53 (2), 534–539.

Singh, B., Chanasyk, D.S., McGill, W.B., Nyborg, M.P.K., 1994. Residue and tillage management effects on soil properties of a typic cryoboroll under continuous barley. Soil Till. Res. 32 (2–3), 117–133.

Smika, D.E., Wicks, G.A., 1968. Summer water storage during fallow in the central Great Plains as influenced by tillage and herbicide treatments. Soil Sci. Soc. Am. Proc. 32, 591–595.

Smiles, D.E., 1995. Liquid flow in swelling soils. Soil Sci. Soc. Am. J. 59 (2), 313–318.

Smiles, D.E., 2000. Hydrology of swelling soils: a review. Aust. J. Soil Res. 38, 501–521.

Smith, R.E., Diekkruger, B., 1996. Effective soil water characteristics and ensemble soil water profiles in heterogeneous soils. Water Resour. Res. 32 (7), 1993–2002.

Soane, B.D., Ball, B.C., 1998. Review of management and conduct of long-term tillage studies with special reference to a 25-yr experiment on barley in Scotland. Soil Till. Res. 45 (1–2), 17–37.

Somaratne, N.M., Smettem, K.R.J., 1993. Effect of cultivation and raindrop impact on the surface hydraulic properties of an alfisol under wheat. Soil Till. Res. 26 (2), 115–125.

Staricka, J.A., Allmaras, R.R., Nelson, W.W., 1991. Spatial variation of crop residue incorporated by tillage. Soil Sci. Soc. Am. J. 55 (6), 1668–1674.

Starr, J.L., 1990. Spatial and temporal variation of ponded infiltration. Soil Sci. Soc. Am. J. 54 (3), 629–636.

Starr, J.L., Timlin, D.J., 2004. Using high-resolution soil moisture data to assess soil water dynamics in the vadose zone. Vadose Zone J. 3 (3), 926–935.

Suwardji, P., Eberbach, P.L., 1998. Seasonal changes of physical properties of an oxic paleustalf (red kandosol) after 16 years of direct drilling or conventional cultivation. Soil Till. Res. 49 (1–2), 65–77.

Tanaka, D.L., 1985. Chemical and stubble mulch fallow influences on seasonal soil water contents. Soil Sci. Soc. Am. J. 49 (3), 728–733.

Tanaka, D.L., Aase, J.K., 1987. Fallow method influences on soil water and precipitation storage efficiency. Soil Till. Res. 9 (4), 307–316.

Tejedor, M., Jimenez, C.C., Diaz, F., 2002. Soil moisture regime changes in tephra-mulched soils: implications for soil taxonomy. Soil Sci. Soc. Am. J. 66 (1), 202–206.

Thapa, B.B., Garrity, D.P., Cassel, D.K., Mercado, A.R., 2000. Contour grass strips and tillage affect corn production on Philippine steepland oxisols. Agron. J. 92 (1), 98–105.

Thapa, B.B., Cassel, D.K., Garrity, D.P., 2001. Animal powered tillage translocated soil affects nutrient dynamics and soil properties at Claveria, Philippines. J. Soil Water Conserv. 56 (1), 14–21.

Thorburn, P.J., 1992. Structural and hydrological changes in a vertisol under different fallow management techniques. Soil Till. Res. 23 (4), 341–359.

Trojan, M.D., Linden, D.R., 1994. Tillage, residue, and rainfall effects on movement of an organic tracer in earthworm-affected soils. Soil Sci. Soc. Am. J. 58 (5), 1489–1494.

Trojan, M.D., Linden, D.R., 1998. Macroporosity and hydraulic properties of earthworm-affected soils as influenced by tillage and residue management. Soil Sci. Soc. Am. J. 62 (6), 1687–1692.

Unger, P.W., Cassel, D.K., 1991. Tillage implement disturbance effects on soil properties related to soil and water conservation—a literature review. Soil Till. Res. 19 (4), 363–382.

Unger, P.W., Schomberg, H.H., Dao, T.H., Jones, O.R., 1997. Tillage and crop residue management practices for sustainable dryland farming systems. Ann. Arid Zone 36 (3), 209–232.

Unger, P.W., Jones, O.R., 1998. Long-term tillage and cropping systems affect bulk density and penetration resistance of soil cropped to dryland wheat and grain sorghum. Soil Till. Res. 45 (1–2), 39–57.

Utset, A., Cid, G., 2001. Soil penetrometer resistance spatial variability in a ferralsol at several soil moisture conditions. Soil Till. Res. 61 (3–4), 193–202.

van Es, H.M., 1993. Evaluation of temporal, spatial, and tillage-induced variability for parameterization of soil infiltration. Geoderma 60 (1–4), 187–199.

van Es, H.M., Ogden, C.B., Hill, R.L., Schindelbeck, R.R., Tsegaye, T., 1999. Integrated assessment of space, time, and management-related variability of soil hydraulic properties. Soil Sci. Soc. Am. J. 63 (6), 1599–1608.

Van Oost, K., Govers, G., Van Muysen, W., Quine, T.A., 2000. Modeling translocation and dispersion of soil constituents by tillage on sloping land. Soil Sci. Soc. Am. J. 64 (5), 1733–1739.

Van Oost, K., Van Muysen, W., Govers, G., Heckrath, G., Quine, T.A., Poesen, J., 2003. Simulation of the redistribution of soil by tillage on complex topographies. Eur. J. Soil Sci. 54 (1), 63–76.

Van Wesenbeeck, I.J., Kachanoski, R.G., 1988. Spatial and temporal distribution of soil water in the tilled layer under a corn crop. Soil Sci. Soc. Am. J. 52 (2), 363–368.

Van Wesenbeeck, I.J., Kachanoski, R.G., Rolston, D.E., 1988. Temporal persistence of spatial patterns of soil water content in the tilled layer under a corn crop. Soil Sci. Soc. Am. J. 52 (4), 934–941.

Vervoort, R.W., Dabney, S.M., Romkens, M.J.M., 2001. Tillage and row position effects on water and solute infiltration characteristics. Soil Sci. Soc. Am. J. 65 (4), 1227–1234.

Wagger, M.G., Cassel, D.K., 1993. Corn yield and water use efficiency as affected by tillage and irrigation. Soil Sci. Soc. Am. J. 57 (1), 229–234.

Warkentin, B.P., 1971. Effects of compaction on content and transmission of water in soils. In: Barnes, K. (Ed.), Compaction of Agricultural Soils. ASAE, pp. 125–140.

Warrick, A.W., Mullen, G.J., Nielsen, D.R., 1977. Scaling field-measured soil hydraulic properties using a similar media concept. Water Resour. Res. 13 (2), 355–362.

Wendroth, O., Koszinski, S., Pena-Yewtukhiv, E., 2006. Spatial association among soil hydraulic properties, soil texture, and geoelectrical resistivity. Vadose Zone J. 5 (1), 341–355.

Wu, L., Swan, J.B., Allmaras, R.R., Logsdon, S.D., 1995. Tillage and traffic influences on water and solute transport in corn–soybean systems. Soil Sci. Soc. Am. J. 59 (1), 185–191.

Wu, L., Allmaras, R.R., Gimenez, D., Huggins, D.M., 1997. Shrinkage and water retention characteristic in a fine textured mollisol compacted under different axle loads. Soil Till. Res. 44 (3–4), 179–194.

Xu, D., Mermoud, A., 2003. Modeling the soil water balance based on time-dependent hydraulic conductivity under different tillage practices. Agric. Water Manage. 63 (2), 139–151.

Yang, X.-M., Wander, M.M., 1998. Temporal changes in dry aggregate size and stability: tillage and crop effects on a silty loam mollisol in Illinois. Soil Till. Res. 49 (3), 173–183.

Yeh, T.C.J., Gelhar, L.W., Gutjahr, A.L., 1985. Stochastic analysis of unsaturated flow in heterogeneous soils. 2. Statistically anisotropic media with variable alpha. Water Resour. Res. 21 (4), 179–194.

Zachmann, J.E., Linden, D.R., Clapp, C.E., 1987. Macroporous infiltration and redistribution as affected by earthworms, tillage, and residue. Soil Sci. Soc. Am. J. 51 (6), 1580–1586.

Zachmann, J.E., Linden, D.R., 1989. Earthworm effects on corn residue breakdown and infiltration. Soil Sci. Soc. Am. J. 53 (6), 1846–1849.

Zhai, R., Kachanoski, R.G., Voroney, R.P., 1990. Tillage effects on the spatial and temporal variations of soil water. Soil Sci. Soc. Am. J. 54 (1), 186–192.