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Soil water retention and hydraulic conductivity dynamics following tillage

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Abstract

Soil bulk density (ρb) may be purposely reduced in agricultural fields using tillage to improve hydraulic properties. However, tillage alters the soil structure, resulting in unstable soils. As the soil stabilizes, ρb increases over time. While this is known, studies on soil hydraulic properties in tilled soils, including comparisons between tilled and non-tilled soils, commonly assume a rigid soil structure. This study presents changes in soil water retention and saturated hydraulic conductivity (*K*sat) as ρb increased dynamically with time following tillage at a loam-textured field site. Over the summer of 2015, soil cores were collected at several depths below the surface following precipitation events. Soil water retention curves and *K*sat were determined using pressure cells and the constant head method, respectively. Tillage reduced ρb to 0.94 g cm−3. Changes in ρb increased with depth, reaching a ρb of 1.11 g cm−3 in the 0–5 cm layer, and a ρb of 1.42 g cm−3 at the deepest tilled layer. Soil water retention curves were markedly steeper for samples with higher ρb, indicating an overall increase in water retained at a soil matric potential (*Ψ*) of −33 kPa. Evaluation of two modeling approaches for water retention as a function ρbindicated that changes in water retention with increases in ρb could be reasonably estimated if a matching point was used. No clear relationship between *K*sat and ρbwas obvious for ρb < 1.06 cm3 cm−3, but for ρb > 1.06 cm3 cm−3, *K*sat decreased markedly (order of magnitude) as ρb increased. Hydraulic properties varied strongly depending on time since tillage and soil depth, and results have implications for models of tilled soils, as well as for studies comparing tilled and non-tilled soils.

Keywords

Bulk density, Hydraulic properties, Water desorption curve, Moisture characteristic curve, Van genuchten model, Saturated hydraulic conductivity, Tillage

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Soil water retention and hydraulic conductivity dynamics following tillage

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ABSTRACT

Soil bulk density (ρ_b) may be purposely reduced in agricultural fields using tillage to improve hydraulic properties. However, tillage alters the soil structure, resulting in unstable soils. As the soil stabilizes, ρ_b increases over time. While this is known, studies on soil hydraulic properties in tilled soils, including comparisons between tilled and non-tilled soils, commonly assume a rigid soil structure. This study presents changes in soil water retention and saturated hydraulic conductivity (K_{sat}) as ρ_b increased dynamically with time following tillage at a loam-textured field site. Over the summer of 2015, soil cores were collected at several depths below the surface following precipitation events. Soil water retention curves and K_{sat} were determined using pressure cells and the constant head method, respectively. Tillage reduced ρ_b to 0.94 g cm^{-3}. Changes in ρ_b increased with depth, reaching a ρ_b of 1.11 g cm^{-3} in the 0–5 cm layer, and a ρ_b of 1.42 g cm^{-3} at the deepest tilled layer. Soil water retention curves were markedly steeper for samples with higher ρ_b, indicating an overall increase in water retained at a soil matric potential (Ψ) of −33 kPa. Evaluation of two modeling approaches for water retention as a function ρ_b indicated that changes in water retention with increases in ρ_b could be reasonably estimated if a matching point was used. No clear relationship between K_{sat} and ρ_b was obvious for $\rho_b < 1.06$ cm^3 cm^{-3}, but for $\rho_b > 1.06$ cm^3 cm^{-3}, K_{sat} decreased markedly (order of magnitude) as ρ_b increased. Hydraulic properties varied strongly depending on time since tillage and soil depth, and results have implications for models of tilled soils, as well as for studies comparing tilled and non-tilled soils.

1. Introduction

Low soil bulk density (ρ_b) is generally associated with better conditions for plant growth (Klute, 1982), as larger porosity may increase hydraulic conductivity, water infiltration, and soil water retention (Kribaa et al., 2001), and may reduce erosion and run-off (Mohammadshirazi et al., 2016). Soil structure and ρ_b also affect energy and gas exchanges at the soil surface interface (Schwartz et al., 2010), as well as CO_2 production in the soil (Han et al., 2014). Soil tillage is a common practice aimed at lowering ρ_b and improving soil conditions, as well as weed control (Strudley et al., 2008). However, while tillage increases soil porosity, it also alters soil structure, resulting in a very unstable soil (Kribaa et al., 2001; Or and Ghezzehei, 2002). Soil properties in freshly tilled soils change dynamically with time until a new, more stable state is reached (Meek et al., 1992). The speed and degree of change may vary with depth and depends on soil physical properties such as texture and aggregation (van Es et al., 1999), as well as the frequency, intensity, and cumulative amount of precipitation or irrigation (Augeard et al., 2008; Mubarak et al., 2009). The resulting reduction in porosity disproportionally affects macropores (Kribaa et al., 2001; Sandin et al., 2017). Considering the dynamic conditions of tilled soils, it is no surprise that studies comparing different till and no-till systems often report conflicting results on whether or not tillage improves porosity and hydraulic properties (Kribaa et al., 2001; Strudley et al., 2008). A literature review on studies that report ρ_b increases following tillage is summarized in Table 1. Several studies reported that the highest increases in ρ_b occur within 2–4 weeks following tillage (Al-Jabri et al., 2006; Alletto and Coquet, 2009; Mubarak et al., 2009; Tian et al., 2018b). The increases in ρ_b varied, and may have depended on how early after tillage the initial measurement was taken. However, minimum ρ_b was commonly between 1 and 1.3 g cm^{-3} near the surface and increased with depth (Table 1). Maximum ρ_b tended to be lower for finer textured soils.

While there is ample evidence for increases in ρ_b following tillage, some studies indicated no changes over a season, or even a decline in ρ_b towards the season end (Afzalinia and Zabihi, 2014; Schwen et al.,

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Table 1
Literature review on temporal changes in bulk density following tillage.

Study details					Bulk density (g cm^{-3}) range over time for soil layers:				
Reference	Soil type	Time[a]	Tillage (depth)[a]	Cover	0 − 5 cm	5 − 10 cm	10 − 15 cm	15 − 20 cm	20 − 30 cm
Logsdon and Cambardella (2000)	*Clay loam*	*3 y*	*D (18 cm)*	*Maize/soy rotation*	*~1 1.2-1.3*	*1.3-1.4*[c]			
Tian et al. (2018b)	*Loamy sand*	*6 w*	*C (10 cm)*	*Bare*	*1.0-1.3 1.1-1.3*	*~1.4*	*~1.5*		
	Sand	*6 w*			*1.1-1.5 1.1-1.5*	*1.15-1.55*	*1.55-1.70*		
Osunbitan et al. (2005)	*Loamy sand*	*8 w*	*Hoe (15 cm)*	*Bare*	*1.15-1.20*				
			D + D (15 cm)		*1.09-1.15*				
			D + H (15 cm)		*1.07-1.12*				
Alletto and Coquet (2009)	*Loam*	*5 m*	*MB (30 cm) + C + H (8 cm)*	*Interrow*	*1.1-1.4*		*1.0-1.5*		
Zhang et al (2017)	*Sandy loam*	*1 m*	*Manual (20 cm)*		*0.97-1.14*	*1.09-1.25*	*1.09-1.33*		
Salem et al. (2015)	*Loam*	*4 m*	*MB (30 cm) + C (10 cm)*	*Maize*	*1.19-1.30*	*1.20-1.34*	*1.28-1.42*	*1.27-1.36*	*1.34-1.37*[c]
			Ch (20 cm) + C (10 cm)		*1.23-1.38*	*1.27-1.39*	*1.27-1.43*	*1.29-1.47*	*1.37-1.51*[c]
Franzluebbers et al. (1995)	*Silty clay loam*	*2 y*	*D (15 cm) + Ch (25 cm)*	*Sorghum/ wheat/ soy*	*1.0-1.3*	*1.3-1.6*	*~1.6*		
Moret and Arrúe, (2007)	*Loam*	*1 m*	*MB (40 cm) + C (15 cm)*	*Bare*	*1.18-1.22*				
			Ch (30 cm) + C (15 cm)		*1.15-1.16*				
Cassel and Nelson (1985)	*Loamy sand*	*2 m*	*MB (25 cm)*	*Soy*	*1.3-1.6*	*1.7-1.75*		*~1.8*	
Gantzer and Blake, (1978)	*Clay loam*	*4 m*	*MB + D*	*Maize*		*1.05-1.12*			
Kargas et al. (2016)	*Loam*	*8 m*	*C (15 cm)*	*Bare*	*1.05-1.20*				
Liu et al. (2014)	*Silt loam*	*6 w*	*Manual (25 cm)*	*Bare*	*1.0-1.33*		*1.0-1.33*		
	Sandy loam	*8 w*			*1.11-1.36*		*1.11-1.41*		
Logsdon (2012)	*Various*[b]	*5 y*	*Various*	*Various*	*1.1-1.4*		*1.3-1.5*		*1.25-1.45*

[a] Abbreviations: years (y), months (m), weeks (w), Cultivator (C), Chisel (Ch), Disk (D), Harrow (H), Moldboard (MB).
[b] Averages for 10 clay loam, 1 sandy loam, 2 sandy clay loam, 1 silty clay, and 2 loam sites.
[c] Values were reported for smaller increments, averages are shown in this table for the sake of clarity.

2011; Suwardji and Eberbach, 1998). This may be because in some cases tillage-induced decreases in ρ_b were so short-term that the seasonal effect of tillage was limited (Somaratne and Smettem, 1993). In systems with plants, root growth may have impacted ρ_b and hydraulic properties: Mubarak et al. (2009) reported that near-surface ρ_b increased early in the season, but started to decline mid-season when plant roots increased. Research on how different tillage practices compare may therefore benefit from a better understanding of the dynamics in soil physical and hydraulic properties with time.

As a general rule, lower ρ_b is associated with higher saturated hydraulic conductivity (K_{sat}) and higher water contents for matric potentials (Ψ) above −100 kPa (Reicosky et al., 1981). However, finer textured soils are more likely to aggregate, with inter-aggregate pores draining quickly at relatively high water potentials while intra-aggregate pores may retain water for longer periods of time (Bristow et al., 1994; Horton et al., 1989; Klute, 1982). Hydraulic properties in the field will therefore change not only as ρ_b increases but also as soil structure develops and pores change in shape, size, continuity and tortuosity (Dec et al., 2008; Horton et al., 1994). Since modeling approaches rely heavily on specific soil parameters to determine hydraulic properties, in-situ measurements of how these properties vary in the field are paramount to improve our understanding of water movement in unstable soils (Assouline and Or, 2013). The objective of this study is therefore to determine dynamic ρ_b with time and depth for a bare loamy soil and the associated changes in soil water retention and K_{sat}. A second objective is to evaluate some recently developed models for their ability to estimate soil hydraulic properties based on changes in ρ_b in this medium-textured soil.

2. Materials and methods

2.1. Field site

The study was conducted at a bare soil site, classified as a Nicollet Loam (USDA-NRCS Web Soil Survey; 31% sand, 43% silt, 26% clay) at the Agronomy and Agricultural Engineering Farm in Boone, IA. Soil particle density (ρ_s) was determined to be 2.67 g cm^{-3} using a pycnometer. Longterm precipitation averaged 974 mm y^{-1} and air temperatures varied between average highs of 28.8 °C in July and average lows of −12.9 °C in January (US climate data). On 9 June 2015, the soil was roto-tilled to a depth of approximately 25–30 cm. The soil was kept bare throughout the season using herbicides.

2.2. Hydraulic property measurements

Soil core samples were collected for 5 cm depth increments between 0 and 15 cm using stainless steel cylinders (250 cm^3) and for the 15–22.5 cm layer using aluminum cylinders (340 cm^3) on 10, 18, and 30 June, 9 July, and 5 September 2015. Sample collection followed rainfall events monitored at a nearby weather station (Iowa Environmental Mesonet, BOOI4). Four replicates were collected for each depth, wrapped in aluminum foil, and stored in plastic bags at 4 °C. Each core was saturated in a vacuum chamber (> 12 h), allowing a 0.01 *M* $CaCl_2$ solution to move upward into the core to minimize air entrapment. Saturated cores were then transferred to a home-built pressure cell apparatus following Ankeny et al. (1992). The first volumetric water content (θ_v) measurement was for a gravity-drained core at atmospheric pressure, where average Ψ inside the core was equal to half the height of the core (5 cm core, Ψ = -2.5 cm H_2O = −0.25 kPa). Subsequent measurements were at Ψ of −1, −2.5, −5, −10, −20, -33, and −50 kPa. For two samples with a ρ_b of 1.09 *g* cm^{-3} and two samples with a ρ_b of 1.17 *g* cm^{-3} additional points of the water retention curve were determined using pressure plates at -100 and −1500 kPa (Dane et al., 2002). Following water desorption at −50 kPa, the cores were re-saturated to determine K_{sat} using the constant head method (Klute, 1965).

2.3. Model evaluation

Tian et al. (2018a) recently introduced two approaches to incorporate changes in ρ_b into the van Genuchten model. The van Genuchten (1980) model of θ_v as a function of Ψ is,

$$\frac{\theta_v - \theta_{res}}{\theta_{sat} - \theta_{res}} = \left[\frac{1}{1 + (\alpha\ |\Psi|)^n}\right]^{(1-\frac{1}{n})} \tag{1}$$

where θ_{res} and θ_{sat} are residual and saturated θ_v, respectively, and α and n are empirical shape parameters. Both of the Tian et al. (2018a) approaches require an initial value for θ_{res}, θ_{sat}, α, and n, at a specific (preferably lowest) ρ_b. In this study, these parameters were determined using water retention measurements immediately following tillage. θ_{res} was set as the measured θ_v at -1500 kPa, and θ_{sat} was determined from soil porosity, while α and n were determined by curve-fitting.

In both approaches, θ_{res}, θ_{sat}, and α, for a different (new) ρ_b were determined using the following equations:

$$\theta_{res1} = \theta_{res0}\frac{\rho_{b1}}{\rho_{b0}} \tag{2}$$

$$\theta_{sat1} = \theta_{sat0}\frac{\rho_s - \rho_{b1}}{\rho_s - \rho_{b0}} \tag{3}$$

$$\alpha_1 = \alpha_0\left(\frac{\rho_{b1}}{\rho_{b0}}\right)^{-\omega} \tag{4}$$

where subscripts 1 and 0 refer to new and initial values, respectively, and ω is an empirical parameter set to 3.97 (Tian et al., 2018a).

In Approach 1, n at a new ρ_b value is determined based on soil texture, using:

$$n_1 = 1 + (n_0 - 1)\left(\frac{\rho_{b1}}{\rho_{b0}}\right)^{\left(-0.97+1.28\frac{\%silt}{\%clay}\right)} \tag{5}$$

Approach 2 requires a matching point to determine n_1, preferably at the highest ρ_b (ρ_{bMatch}). After determining θ_{res}, θ_{sat}, and α, for ρ_{bMatch} using Eq. (2–4), the van Genuchten equation is optimized for a single θ_v measurement at a Ψ of -33 kPa to determine n at ρ_{bMatch} (n_{Match}). Subsequently n_1 can be determined using linear interpolation:

$$n_1 = n_0 + (\rho_{b1} - \rho_{b0})\left(\frac{n_0 - n_{Match}}{\rho_{b0} - \rho_{bMatch}}\right) \tag{6}$$

The changes in K_{sat} with increases in ρ_b can be estimated using the Assouline (2006a) model:

$$K_{sat1} = K_{sat0}\frac{\eta_1}{\eta_0}\left(\frac{\rho_{b1}}{\rho_{b0}}\right)^{(\delta-7)} \tag{7}$$

where η is porosity (cm^3 cm^{-3}) and δ is an empirical factor related to texture, varying between 2 and 4 for loamy soils and 4 and 6 for sandy soils.

3. Results

3.1. Bulk density dynamics following tillage

The initial ρ_b value on 10 June 2015, one day after tillage, averaged 0.94 g cm^{-3} for the 0–22.5 cm soil layer. Following 69 mm of rainfall over the course of a week, ρ_b increased to 0.97–1.11 g cm^{-3} for the 0–15 cm soil layer and to 1.33 g cm^{-3} for the 15–22.5 cm layer (Fig. 1), after which the 15–22.5 cm layer remained relatively stable. At the 0–15 cm layer, regular rainfall events resulted in pronounced increases in ρ_b until 9 July. Despite continued rainfall events, ρ_b appeared to stabilize after this date. Total changes in ρ_b increased with depth, with ρ_b of the dynamic 10–15 cm layer increasing by as much as 0.37 g cm^{-3}. This change in density resulted in a decline of the tilled layer thickness and reduction in pore volume. The 0–15 cm layer at the end of the season was equivalent to a 0–17.3 cm layer immediately after tillage, indicating a soil settling of 15%.

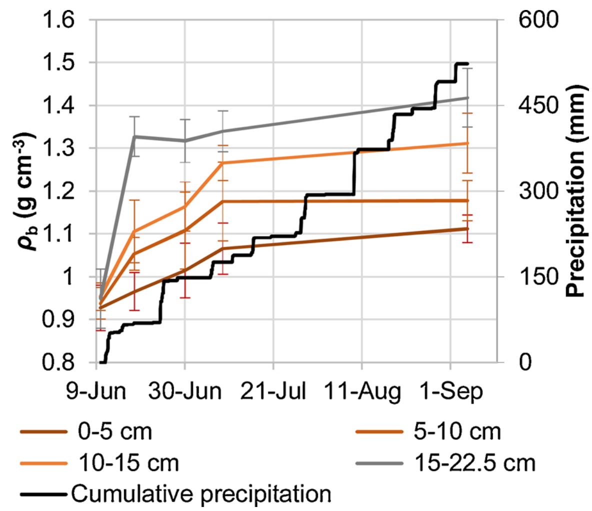

Fig. 1. Bulk density (ρ_b) and cumulative precipitation following tillage on 9 June 2015. Soil cores were collected for layers 0–5, 5–10, 10–15 and 15–22.5 cm on 10, 18, and 30 June, 9 July and 5 September 2015 (n = 4).

3.2. Soil water retention

Soil water retention curves at all four sampled soil layers showed pronounced changes with time (Fig. 2). As expected, the layers that showed largest changes in ρ_b also showed the most marked differences in water retention. In the 0–5 cm layer where changes in ρ_b were smallest, the water retention curves were the most similar over the season. In the most dynamic 10–15 cm layer, θ_v at a Ψ of -33 kPa, changed from 0.20 cm^3 cm^{-3} early in the season to 0.36 cm^3 cm^{-3} towards the end of the season. During the first weeks increases in θ_v at a Ψ of -33 kPa were almost linear with rainfall amounts, averaging 0.0007 cm^3 cm^{-3} per mm rainfall. In the final two months the increase was only 0.0001 cm^3 cm^{-3} per mm rainfall. The high pore volume early in the season, along with lower water retention at $\Psi < -2.5$ kPa, allowed only one third of the pore volume to retain water at a Ψ of -33 kPa immediately after tillage. Towards the end of the season, as the pore volume declined and water retention increased, two thirds of the pore volume retained water at a Ψ of -33 kPa. Assuming a 30 cm thickness of the tilled layer immediately after tillage, the total amount of water retained in this layer at -33 kPa is 0.2×30 cm = 6 cm. On 5 September, approximating the thickness of the tilled layer to be 22.5 cm, the total amount of water retained increased to 7.3 cm. Thus, despite the decrease in the thickness of the tilled layer, the changes in water retention allowed for greater amounts of water to be retained in the tilled layer at -33 kPa towards the end of the season.

Extended water retention curves, including θ_v values obtained at Ψ of -100 kPa and -1500 kPa, are shown for samples with a ρ_b of 1.09 and 1.17 g cm^{-3} (Fig. 3). Between -1 and -15 kPa, θ_v declined by about 0.08, with indications of a somewhat bimodal shape of the water retention curve. These curves were then used to evaluate whether Approaches 1 and 2 could estimate the water retention curve at ρ_b of 1.17 g cm^{-3} from the data at a ρ_b of 1.09 g cm^{-3}. The first step was to fit the van Genuchten function to the data for ρ_b = 1.09 g cm^{-3} which gave a RMSE of 0.02 cm^3 cm^{-3} with minimum errors around a Ψ of -10 kPa (Fig. 2). The fitted curve was used to assess how well Approaches 1 and 2 could approximate water retention curves for the samples with a ρ_b of 1.17 g cm^{-3}, as well as for the average maximum ρ_b observed for the 10–15 cm layer (1.31 g cm^{-3}). The θ_v at -33 kPa measured for the average maximum ρ_b at the 15–22.5 cm layer (1.42 g

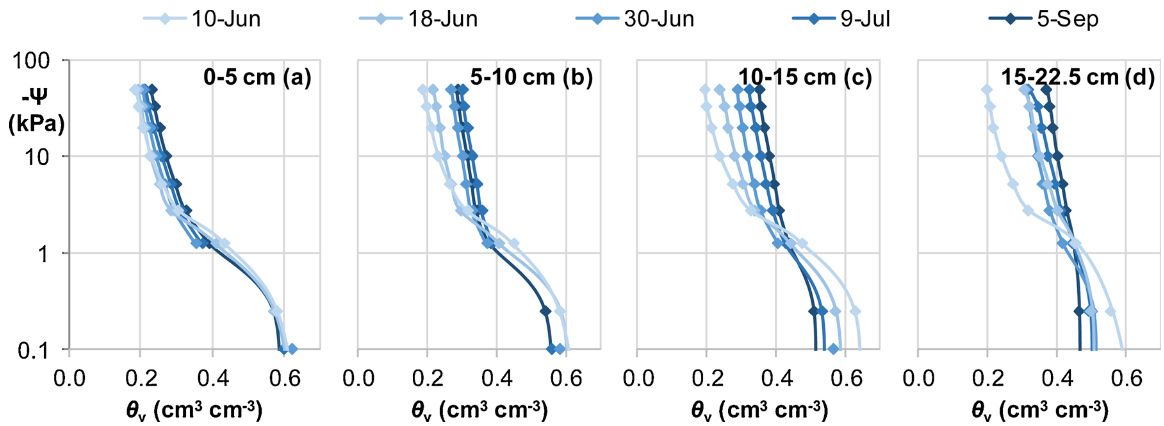

Fig. 2. Soil matric potential (Ψ) versus volumetric water content (θ_v) for cores collected from soil layers 0–5, 5–10, 10–15, and 15–22.5 cm on 10, 18, and 30 June, 9 July, and 5 September 2015. Each point represents the average of four measurements.

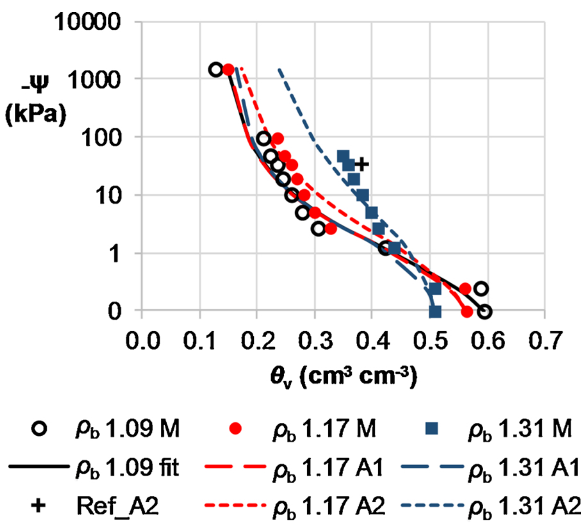

Fig. 3. Measured (M) and modeled Approach 1 and Approach 2 (A1, A2) volumetric water contents (θ_v) versus soil matric potentials (Ψ) for bulk densities (ρ_b) of 1.09, 1.17, and 1.31 g cm^{-3}. Modeled curves are based on a fitted van Genuchten curve (ρ_b 1.09 fit). For model A2 the reference point was for a ρ_b of 1.42 g cm^{-3} (Ref_A2).

cm^{-3}) was used as the reference point for Approach 2. For $\rho_b = 1.17$ g cm^{-3}, Approach 1 gave reasonable values for θ_v for $\Psi \geq -10$ kPa, with an RMSE of 0.02 cm^3 cm^{-3}. For $\Psi < -10$ kPa, the RMSE was 0.04 cm^3 cm^{-3}. Conversely, Approach 2 performed better for $\Psi < -10$ kPa, with an RMSE of 0.01 cm^3 cm^{-3}, while for $\Psi \geq -10$ kPa, the RMSE was 0.03 cm^3 cm^{-3}. For $\rho_b = 1.31$ g cm^{-3}, Approach 1 only gave reasonable values for θ_v for $\Psi \geq$ -1.25 kPa, with an RMSE of 0.02 cm^3 cm^{-3}, while for -1.25 > Ψ ≥ −50 kPa, the RMSE was 0.12 cm^3 cm^{-3}. Approach 2 outperformed Approach 1 with an overall RMSE of 0.02 cm^3 cm^{-3} for $\rho_b = 1.31$ g cm^{-3}. As Approach 1 is based on texture, one would expect improved estimates at lower Ψ. However, the measured difference between $\rho_b = 1.09$ g cm^{-3} and $\rho_b = 1.17$ g cm^{-3} at −1500 kPa was 0.021 cm^3 cm^{-3}, as opposed to a modeled difference of 0.005 cm^3 cm^{-3}. This difference was better reproduced by Approach 2, which gave a modeled difference of 0.024 cm^3 cm^{-3}. Unfortunately no data at −1500 kPa were available for higher bulk densities. Using fitted θ_r rather than θ_v at −1500 kPa, an alternative suggested by Tian et al. (2018a), did not improve Approach 1 as it resulted in $\theta_r > \theta_v$ at −1500 kPa. This unreasonable result is likely due to the bimodal nature of the water retention curves (data not shown).

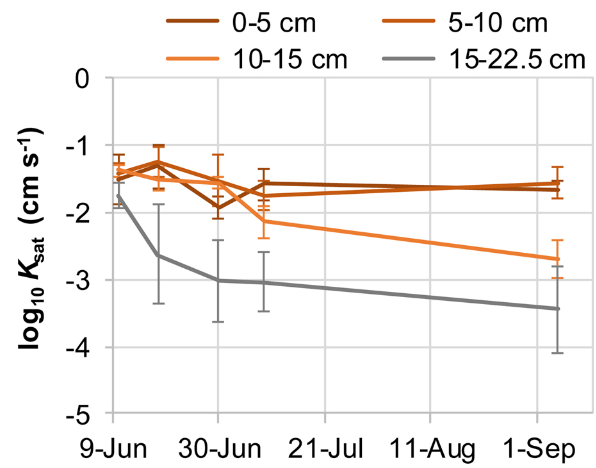

Fig. 4. Saturated hydraulic conductivity (K_{sat}) for cores collected from soil layers 0–5, 5–10, 10–15, and 15–22.5 cm on 10, 18, and 30 June, 9 July, and 5 September 2015 (n = 4).

3.3. Saturated hydraulic conductivity

Distinction between the 0–5 and 5–10 cm soil layers was less pronounced for K_{sat} (Fig. 4) than was observed for ρ_b or the water retention curves (Figs. 1 and 2). Initial K_{sat} for the 0–10 cm layers varied between 0.04 and 0.06 cm s^{-1} in the first week following tillage, decreasing to 0.02-0.03 cm s^{-1} on July 5 and September 5. Over the course of the season, K_{sat} at lower depths decreased by one to two orders of magnitude. The 10–15 cm soil layer K_{sat} declined sharply from 0.03-0.04 cm s^{-1} in June to 0.01 cm s^{-1} on 9 July and 1.90 × 10^{-3} cm s^{-1} on 5 September, while the 15–22.5 cm soil layer average K_{sat} reached values as low as 6.42 × 10^{-4} cm s^{-1}.

Considering a relationship between K_{sat} and ρ_b to be exponential rather than linear (Eq. 7), comparing the average K_{sat} for an average ρ_b might give skewed results. Individual sample K_{sat} and ρ_b rather than the average of four replicates is therefore shown in Fig. 5. A pattern emerged where samples with $\rho_b > 1.06$ g cm^{-3} showed a steep reduction in K_{sat} as ρ_b increased, while for $\rho_b < 1.06$ g cm^{-3} samples the reduction was much more gradual. The exponential regressions shown in Fig. 5 had coefficients of determination of 0.02 (n = 27, p = 0.5) for $\rho_b < 1.06$ g cm^{-3} and 0.59 (n = 51, p < 0.001) for $\rho_b > 1.06$ g cm^{-3}. The Assouline model (2006a) was applied to both sections of the data, using the average values for four samples with $\rho_b = 1.07$ to determine K_{sat0} (0.03 cm s^{-1}) and η_0 (0.60). The empirical factor δ is dependent on soil texture, and changes the slope of the curve. Since the slopes of exponential regressions y_1 and y_2 are quite different, δ may also depend

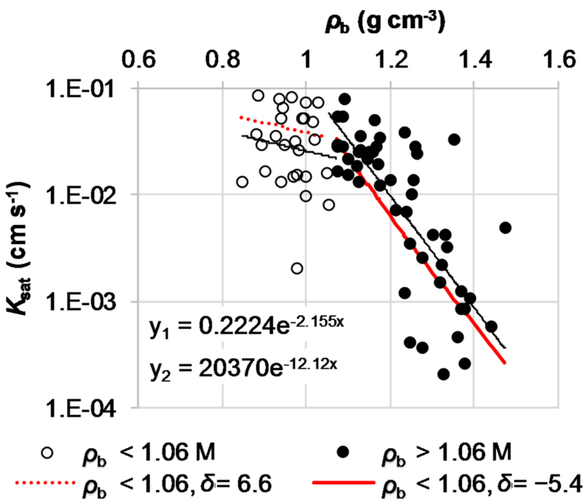

Fig. 5. Measured (M) and modeled ($\delta = 6.5$, $\delta = -5$) saturated hydraulic conductivity (K_{sat}) versus bulk density (ρ_b). Data for $\rho_b < 1.06\ \mathrm{g\ cm^{-3}}$ ($n = 27$, exponential regression y_1) and $\rho_b > 1.06\ \mathrm{g\ cm^{-3}}$ ($n = 51$, exponential regression y_2) are shown separately.

on soil structure. Optimizing the Assouline model to the slopes of the regression functions gave a δ of 6.6 for $\rho_b < 1.06\ \mathrm{g\ cm^{-3}}$, similar to the expected δ for very coarse textures (Assouline, 2006a). For $\rho_b > 1.06\ \mathrm{g\ cm^{-3}}$, δ was -5.4, which was much lower than the 2–4 range expected for loamy soils.

4. Discussion

Changes in ρ_b from ˜1 to 1.3 $\mathrm{g\ cm^{-3}}$ were within the range of values reported elsewhere (Table 1). The initial more or less linear increase, was similar to the 30-day rapid increase period reported by Liu et al. (2014). The magnitude of increase showed considerable contrast between depths, with the 0–5 cm layer showing relatively minimal changes compared to values shown in Table 1.

Unsurprisingly, soil water retention was strongly affected by changes in ρ_b. In addition, the total amount of water retained in the tilled layer was affected by changes in the layer thickness. The reduction in bulk density decreased the till layer thickness by 25% over the season, an issue that may pose additional challenges when rigid models are applied to tilled soils. When modeling plant available water for example, temporal changes in both the hydraulic properties and the soil volume must be considered. Soil surface decline also affects sampling of soil water content and carbon measurements, where the soil layer that is represented by the sample might change over time (Chang et al., 2007; Fraser et al., 2010; Wuest, 2009).

As expected for freshly tilled soil, water retention was relatively large at near-saturated conditions, with indications of a bimodal shape (Klute, 1982; Or, 1996; Or et al., 2000). The increase in steepness of the water retention curve as ρ_b increased is similar to what has been shown for packed soils with varying ρ_b (Reicosky et al., 1981). However, packed soils cannot capture the bimodal or even trimodal (Pires et al., 2017) nature of the water retention curve of undisturbed samples from (semi) structured soils. This complicates modeling of the water retention curve as a function of ρ_b. While the two evaluated approaches do not capture the bimodal changes, it appears that compared to Approach 1, Approach 2, which uses a matching point, produces reasonable water retention curves. Similar results can be expected for approaches developed using the Brooks and Corey water retention function (Assouline, 2006b). During measurements, some soil shrinkage was observed inside low-density cores during measurements, which potentially reduced the difference between high and low density cores for drier conditions (Gregory et al. (2010); Lu et al., 2004; Salager et al., 2010). However, results indicated large differences in θ_v for different ρ_b at -50 kPa. Even at -1500 kPa differences were still evident, contradicting the results of Ahuja et al. (1998); as well as modeling assumptions that at low Ψ, the water retention for different ρ_b is similar (Tian et al., 2018a). In-situ water retention measurements for a sandy soil (Zhang et al., 2017, Table 1) showed markedly similar changes in water retention, with water contents at -33 kPa ranging from 0.15-0.20 $\mathrm{cm^3\ cm^{-3}}$ for a ρ_b of ˜1 $\mathrm{g\ cm^{-3}}$ and 0.28 $\mathrm{cm^3\ cm^{-3}}$ for a ρ_b of 1.33 $\mathrm{g\ cm^{-3}}$.

The range in K_{sat} values was similar to the 1×10^{-3} to 1×10^{-4} cm $\mathrm{s^{-1}}$ range reported by Kargas et al. (2016) and Alletto and Coquet (2009) and to the 1×10^{-2} to 1×10^{-3} cm $\mathrm{s^{-1}}$ range reported by Moret and Arrúe (2007) for loamy soils with ρ_b from ˜1 to 1.2 $\mathrm{g\ cm^{-3}}$, 1.1–1.4 $\mathrm{g\ cm^{-3}}$, and ˜1.2 $\mathrm{g\ cm^{-3}}$, respectively. While K_{sat} values between 0.1 and 0.01 cm $\mathrm{s^{-1}}$ are unusually large, values exceeding 0.014 cm $\mathrm{s^{-1}}$ have been reported for granular soils with high biological activity (McKeague et al., 1982). It was expected that K_{sat} would decrease with time following tillage (Kribaa et al., 2001), but K_{sat} remained large in the 0–10 cm layer throughout the season. For the deeper soil layers with greater changes in ρ_b the changes in K_{sat} were more evident. Reicosky et al. (1981) noted that both saturated and unsaturated hydraulic conductivity increased with lower ρ_b, as long as θ_v was below 0.45, while for θ_v above 0.45 the relationship was less clear. However, few studies report such a strong alteration in the relationship between K_{sat} and ρ_b as shown in Fig. 5.

In the presence of vegetation, soil structure may be further altered by biological activity such as root growth and senescence. In non-tilled soils changes in hydraulic properties have been reported that cannot be explained by changes in ρ_b but are likely due to biological activities in the soil (Hu et al., 2009; Kodešová et al., 2006; Sandin et al., 2017). Thus, while the results of this study clearly support the importance of considering changes in ρ_b following tillage for the determination of hydraulic properties, much remains to be illuminated to better quantify soil structure.

5. Conclusion

Low ρ_b is associated with favorable hydraulic properties for agricultural purposes. Tillage can reduce ρ_b, but this new low ρ_b is not stable. This study showed that the largest change in ρ_b happened within the first few weeks after tillage and that changes were more pronounced with depth. Changes in ρ_b reduced the thickness of the tilled layer by 25%. The increase in ρ_b strongly affected water retention: for the initial ρ_b of 0.94 $\mathrm{g\ cm^{-3}}$ a θ_v of 0.19 $\mathrm{cm^3\ cm^{-3}}$ at a Ψ of -33 kPa, indicated that water was retained in only about one third of the pore volume, while at a ρ_b of 1.31 $\mathrm{g\ cm^{-3}}$, the decrease in pore volume along with increased water retention resulted in water being retained in two thirds of the pore volume at a Ψ of -33 kPa. Of the two modeling approaches evaluated for changes in water retention as a function of ρ_b, only the approach that used a matching point gave reasonable results for the entire range, despite not accounting for the bimodal shape of the curve. The model for K_{sat} required separate estimates for $\rho_b < 1.06\ \mathrm{g\ cm^{-3}}$, and $\rho_b > 1.06\ \mathrm{g\ cm^{-3}}$. The effect on K_{sat} was not obvious for $\rho_b < 1.06\ \mathrm{g\ cm^{-3}}$, but for $\rho_b > 1.06\ \mathrm{g\ cm^{-3}}$, K_{sat} decreased by an order of magnitude as ρ_b increased. The results have implications for models of tilled soils, as well as for studies comparing tilled and non-tilled soils. Hydraulic properties of tilled soils will vary strongly depending on the time since tillage and the soil depth.

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