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A modeling framework to quantify the effects of compaction on soil water retention and infiltration

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Abstract

The water retention curve (WRC) of arable soils from the southeastern United States at different levels of compaction (no compaction, and 10 and 20% increases in soil bulk density) was estimated using the van Genuchten–Mualem (VG) model. The VG water retention parameters of the noncompacted soils were obtained first by fitting measured soil hydraulic data. To construct the WRC of the compacted soils, gravimetric values of the permanent wilting point (θ_{gw}, 1,500 kPa) and the residual (θ_{gr}) water content were assumed to remain unchanged with compaction. The VG parameter α and exponent η after compaction were estimated using two approaches. In Approach 1, α and η were estimated from saturation, the permanent wilting point, and the residual water content. In Approach 2, the value of η was assumed to remain unchanged with compaction, which allowed α to be estimated immediately from the VG equation. Approach 2 was found to give slightly better agreement with measured data than Approach 1. The effect of compaction on the saturated hydraulic conductivity (K_s) was predicted using semitheoretical approaches and the VG-WRC function. HYDRUS-1D was further used to simulate vertical infiltration into a single-layered soil profile to determine the impact of compaction on the infiltration characteristics of the soils used in our analyses. Results showed that a 10–20% increase in soil bulk density, due to compaction, reduced cumulative infiltration (I_c) at time $T = T_{final}$ (steady-state) by 55–82%, and the available water storage capacity by 3–49%, depending upon soil type.

Abbreviations: AWSC, available water storage capacity; SOC, soil organic carbon; SOM, soil organic matter; VG, van Genuchten–Mualem model; WRC, water retention curve.

1 | INTRODUCTION

Compaction has detrimental effects on the physical and hydraulic properties of soils, thereby affecting important plant–soil–water processes and soil functions that affect crop productivity and the wider soil environment (O'Sullivan & Simota, 1995; Soane & van Ouwerkerk, 1995). Compaction has long been known to affect water retention and transmission processes in soils (internal drainage), thereby changing the distribution of water within a soil profile (Horton et al., 1994). Changes in soil hydraulic properties induced by compaction also affect biogeochemical processes that relate to gaseous exchange between the soil and atmosphere (Antille et al., 2015; Vomocil & Flocker, 1961), while additionally influencing nutrient availability, uptake by plants, and losses (Hussein et al., 2021a, 2021b; Tullberg et al., 2018).

Compressive and shear processes that occur when (moist) soil is trafficked (Kirby, 1989; Vero et al., 2014) may induce changes in the porosity and pore size distribution, as well as the soil pore connectivity, particularly between the larger and vertically oriented drainage pores (Alaoui et al., 2011). Related effects on soil structure may significantly affect water infiltration rates and the saturated hydraulic conductivity (Gupta et al., 1989; Whalley et al., 2012). The combination of both compressive and shear loadings applied to soil during traffic also induces changes in the soil water retention characteristics (Ngo-Cong et al., 2021; Tian et al., 2018). The extent to which these changes occur largely depends on the compactive effort, soil texture, soil organic matter (SOM), and the soil moisture conditions at the time of traffic (which influences soil strength and therefore the susceptibility of soil to undergo deformation; Antille et al., 2013; Howard et al., 1981). Hill and Sumner (1967) showed that the effect of compaction on the water retention curve (WRC) is mainly due to changes (reductions) in the proportion of large pores, the distribution of smaller pores, and the overall reduction in total pore space and pore connectivity. Smith et al. (2001) showed that compaction tends to flatten the typical S-shaped WRC (when plotted on a semi-log scale), which agrees with observations made in earlier studies (Connolly et al., 1997) for soils under long-term (50-yr) conventional tillage.

Several studies (Arya & Paris, 1981; Reeve et al., 1973) described the effects of compaction on the WRC based on measurements of the soil bulk density, either alone or in combination with other readily available soil information such as the particle size composition and SOM. These properties are known to correlate well with the soil hydraulic properties as reflected by many pedotransfer functions that have been developed over the years (Gupta & Larson, 1979; Rawls & Brakensiek, 1982; Tian et al., 2021). Pedotransfer functions have been used also to quantify plant available water, and for modeling water and solute movement into and through soils (Pachepsky & van Genuchten, 2011; Rawls et al., 1982). Assouline (2006) developed an empirical approach that considered the air-entry value and pore size distribution to estimate the effect of changes in the soil bulk density on the WRC expressions of Brooks and Corey (1964) and Assouline et al. (1998). In the Assouline (2006) approach, the empirical equations relating the WRC model parameters to the soil bulk density were calibrated and validated against experimental WRC data for various levels of compaction. Recently, Tian et al. (2018) developed two empirical approaches (1 and 2, respectively) to represent relationships between the van Genuchten (1980) water retention parameters (α and η) and the soil bulk density. In Approach 1, they estimated the van Genuchten–Mualem (VG) hydraulic parameters at various bulk densities using WRC data measured at a reference bulk density, and the particle size composition. In Approach 2, the VG parameters were estimated using WRC data obtained at a reference bulk density and one single WRC measurement at a different bulk density. Although Approach 2 was found to produce more reliable WRC estimates than the first approach, Approach 1 was simpler to implement than Approach 2. In a more theoretical study, Mahmoodlu et al. (2016) used the discrete element method to investigate the relative impact of compaction and particle size mixing on pore structure and the unsaturated soil hydraulic properties. They found that the VG parameter α decreased linearly with decreasing total porosity (equally, with increased soil bulk density) and pore size. However, a clear correlation between the VG parameter η and soil porosity could not be established.

Core Ideas

- We developed novel models for the water retention curve of compacted soils.
- Measured and predicted soil water retention data were in good agreement.
- The proposed models may be applied to a wide range of soil types.
- A 10–20% increase in soil bulk density reduced the soil water storage capacity by 3–49%.
- A 10–20% increase in soil bulk density reduced cumulative infiltration by 55–82%.

Unlike the analyses by Tian et al. (2018), the numerical approaches used in our work do not require a calibration process to estimating α and η. Our proposed methodology removes some of the limitations commonly encountered with direct measurements, which often are subject to much uncertainty because of generally large field-scale spatial variability in the soil hydraulic properties. This is an important practical consideration for cultivated soils, including alluvial soils (Iqbal et al., 2005; McKinion et al., 2001), and also for soils with swelling–shrinking properties such as Vertisols (Blokhuis et al., 1990; Dinka et al., 2013).

The WRC analyses presented in this study were subsequently extended to quantify the effects of compaction on water infiltration into selected arable soils. We used for this purpose the HYDRUS-1D software (Šimůnek et al., 2012), which has been employed widely for various applications related to water flow in soil. Although direct methods for quantifying the effect of compaction (and tillage) on the WRC are also available (Hill et al., 1985), they typically rely on more elaborated and time-consuming laboratory measurements (Klute, 1986; Smith & Mullins, 1991). Hence, application of numerical approaches that relate soil water retention and infiltration characteristics to soil physical properties (e.g., soil bulk density, hydraulic conductivity, and the saturated and residual water contents), which can be obtained with relatively high degrees of confidence, appears to be more practical (Farthing & Ogden, 2017; Rawls et al., 1991). Specific objectives of our work were (a) to develop numerical approaches that enable the van Genuchten (1980) hydraulic parameters to be estimated for compacted soils such that the effects of increased soil bulk density on the WRC can be determined, and (b) to extend the analysis to study water infiltration in compacted soils using HYDRUS-1D (Šimůnek et al., 2012).

2 | MATERIALS AND METHODS

2.1 | Nomenclature

Nomenclature and definitions are presented in Supplemental Table S1.

2.2 | Description of the soils and metadata used in the analyses

Criteria for selecting the soils used in our analysis from available data sources were: (a) soils must have an Ap horizon composed of coarse-, medium-, and fine-textured materials, and all soils must have their particle size distribution and soil organic carbon (SOC) content measured, (b) soils used for model validation must have WRC data at two or more bulk densities so that the effects of compaction on the soil water storage capacity can be determined, and (c) soil series selected for modeling the effect of compaction on the soil WRC and water infiltration were subject to arable cropping.

A total of nine different soil series (USDA-NRCS, 1999), spanning geographic distributions across 13 U.S. states and territories, were used (Table 1). Two of the soil series were used only for validation of the proposed WRC model, whereas three soil series were used for modeling the effects of compaction on the WRC. Data from the remaining four soil series were used for both modeling the effects of compaction on soil water retention and for validating the WRC model. The infiltration analyses were conducted for the first three soil series listed in Table 1 (bolded). The soil series used for modeling comprised a relatively wide range of soil types (textural classes). The models developed in this study were validated using water retention data measured at specific soil bulk densities (referred to in Table 1 as measured ρ_b). Bulk densities were measured as per Blake and Hartge (1986) or using the Uhland and O'Neal (1951) cores, depending upon the method reported in the original dataset. Subsequently, design bulk densities (10 and 20% increases in ρ_b relative to the lowest measured ρ_b value shown in Table 1) were used to study the effects of soil compaction on the WRC and infiltration characteristics. Design soil bulk densities are further referred to as ρ_{bc}. The 10 and 20% values represent a realistic range of bulk density increments following harvesting equipment traffic. For example, McPhee et al. (2020) and Antille et al. (2021) showed that a single pass of cotton (*Gossypium hirsutum* L.) harvesting equipment (JD7760, gross vehicle mass ≈32 Mg) on fine-textured soils (50–70% clay) increased the bulk density by between 6 and 15% relative to the soil conditions before traffic ($\rho_b \approx 1.00$–1.10 g cm^{-3}). Ansorge and Godwin (2007) and Antille et al. (2013) similarly showed that a single pass of grain harvesting equipment (CLAAS Lexion 650, gross vehicle mass ≈ 30 Mg) on medium-textured soils (~60% sand) increased the bulk density by between 16 and 25%, relative to untrafficked soil conditions ($\rho_b \approx 1.25$–1.40 g cm^{-3}). The design soil bulk densities in Table 1 hence fall within the range reported in previous studies for soils with similar textural compositions. Any reduction in traffic-induced compaction that may occur when deeper soils are considered than only the Ap horizon (Table 1) is thus captured by the design soil bulk densities used in our study.

Soil organic C (Walkley & Black, 1934) data are presented in Table 1 in terms of a range that represents minimum and maximum values reported for the series across multiple soil profiles. Soil organic C values were sourced from published data (cited in Table 1) and electronic datasets available via the Soil Resource Laboratory at the University of California at Davis (https://casoilresource.lawr.ucdavis.edu/). The relatively wide range of values in reported SOC data (up to 1.4% w/w differences between the minimum and maximum SOC contents) within some of the soil series (e.g., Decatur and Wilcox) reflected different management systems and cropping histories (e.g., soil tillage, crop type, and rotation) of those soils. Particle size distribution data (Gee & Bauder, 1986) were retrieved from the same datasets (both published and electronic) as used to source the SOC data. Mineral soil fractions are presented as the mean ± standard deviation for all surveyed profiles since particle size compositions (Ap horizon) of the individual soil series varied within a relatively narrow range.

Methods described by Richards (1949) were used to determine soil water contents at 33-kPa tension on a ceramic pressure plate apparatus, and at 200-, 500-, 900-, and 1,500-kPa

TABLE 1 Description of soils used for model validation, and for modeling the effects of compaction on water retention and infiltration

Soil series	Textural class	Ap horizon	PSD of the Ap horizon: Clay (<0.002 mm)	Silt (0.002–0.05 mm)	Sand (0.05–2.0 mm)	SOC	Measured ρ_b	Design ρ_{bc}	Geographic distribution	Land use	Source
		mm	–% (w/w) of the <2-mm mineral fraction–			% (w/w)	———g cm^{-3}———				
Soils used for model validation and modeling											
Mountview	Silt loam	0–200	16.3 ± 2.99	69.1 ± 7.07	14.6 ± 7.90	0.91–1.76	1.11, 1.24, 1.45	1.22, 1.33	TN+AL, KY	Cotton, (row, small) grains, pasture, hay, tobacco	Longwell et al. (1963)
Lexington	Silt loam	0–175	13.6 ± 4.59	71.0 ± 2.60	15.4 ± 4.51	0.64–1.10	1.43, 1.51	1.57, 1.72	TN+AR, KY, LA, MS	Cotton, (row, small) grains, pasture, hay	Longwell et al. (1963)
Grenada	Fine silt	0–125	14.3 ± 3.41	81.6 ± 3.04	4.1 ± 1.84	0.60–1.48	1.14, 1.32	1.25, 1.37	MS+AR, KY, LA, TN	Cotton, (row) grains	Longwell et al. (1963)
Dewey	Silty clay loam	0–150	30.6 ± 2.35	59.9 ± 2.33	9.5 ± <0.01	0.90–1.22	1.39, 1.52	1.53, 1.67	TN+AL, GA, KY	Row crops, (small) grains, hay, pasture	Longwell et al. (1963)
Soils used for modeling only											
Hartsells	Fine sandy loam	0–125	6.9 ± 2.48	31.6 ± 4.13	61.4 ± 4.95	0.60–1.35	1.31	1.44, 1.57	AL+AR, GA, KY, NC, OK, PA, TN	Cotton and corn, some sorghum, soybeans, and potatoes	https://casoilresource.lawr.ucdavis.edu/
Decatur	Fine silt loam	0–175	25.2 ± 4.56	60.5 ± 9.77	14.3 ± 9.49	1.07–1.96	1.37	1.51, 1.64	AL+GA, KY, TN	Soybeans, cotton, hay, corn, (small) grains, tobacco	Batchelor (1984), https://casoilresource.lawr.ucdavis.edu/
Wilcox	Very-fine clay	0–100	59.3 ± 7.41	31.6 ± 3.32	9.1 ± 4.19	1.46–2.90	1.16	1.28, 1.39	AL+AR, FL, GA, LA, MS, TN	Where cultivated: cotton, corn, and soybeans	Batchelor (1984), https://casoilresource.lawr.ucdavis.edu/
Soils used for model validation only											
Columb	Sandy loam	0–280	11.0	35.0	54.0	0.90	1.22, 1.28, 1.34	–	CA	Hay, (small) grains, orchard, row crops	Assouline (2006)
Coto	Clay	0–230	60.5 ± 9.15	9.0 ± 1.37	30.5 ± 8.12	1.62–2.44	1.06, 1.22	–	PR	Sugarcane, some pasture and food crops	Rivadeneira (1982)

Note. Particle size distribution (PSD) values are shown as means ± standard deviation ($n \geq 2$ soil profiles), except when only 1 soil profile ($n = 1$) is used; Soil organic C (SOC) values are given in in terms of their minimum–maximum range; ρ_b is measured soil bulk density used for model validation (the lowest measured value of ρ_b was for the soil without compaction) as reported at one-third bar soil water content by weight (Uhland & O'Neal, 1951 ; Blake & Hartge, 1986), and the design bulk densities (ρ_{bc}) used for modeling purposes. Geographic distribution : AL (Alabama), AR (Arkansas), CA (California), FL (Florida), GA (Georgia), KY (Kentucky), LA (Louisiana), MS (Mississippi), NC (North Carolina), OK (Oklahoma), PA (Pennsylvania), PR (Puerto Rico), and TN (Tennessee). Land use information was retrieved from http://casoilresource.lawr.ucdavis.edu/. Bolded soil series marked were used for the infiltration analyses.

tensions using a pressure membrane. Soil water retained at 60-cm tension was determined from measurements on a tension table (see Figures 2–4 in Longwell et al., 1963). For the Wilcox series, soil water contents were determined at 33-, 100-, 300-, and 1,500-kPa tensions using the same methods as for the other soils in the dataset (after Batchelor, 1984). For the Columbia and Coto series, soil water contents at saturation were measured, respectively, by Laliberte et al. (1966) who used the method described by Anat et al. (1965), and by Rivadeneira (1982) who used a porous plate connected to a water column to determine soil water retained at pressure heads between 0 and −100 cm.

The available water storage capacity (AWSC) is considered here as the difference between the amounts of water retained at 10 and 1,500 kPa, and reported on a gravimetric basis (McKenzie et al., 2002). The original data sources reported tensions in atmospheres (at 0.33, 2, 5, 9, and 15 atm) and in centimeters of water (cm H_2O) for water retained at 60 cm, instead of kilopascals (kPa). The relationship between water pressure head h (cm) and matric potential P (kPa) is $P = -10^{-5}\, h\rho_w g$ where g is gravitational acceleration ($g = 9.81$ m s^{-2}) and ρ_w is water density ($\rho_w = 1{,}000$ kg m^{-3}).

2.3 | Soil water retention analysis and model development

The VG functions were used to describe the soil water retention (WRC) and the hydraulic conductivity (K) functions (van Genuchten, 1980):

$$\theta = \begin{cases} \frac{\theta_s-\theta_r}{[1+(\alpha|h|)^\eta]^\mu} + \theta_r & \text{if } h \le 0 \\ \theta_s & \text{if } h > 0 \end{cases} \tag{1}$$

$$K = \begin{cases} K_s S_e^{\hat{L}}\left[1-\left(1-S_e^{\frac{1}{\mu}}\right)^{\mu}\right]^2 & \text{if } h \le 0 \\ K_s & \text{if } h > 0 \end{cases} \tag{2}$$

where h is the pressure head (cm), θ is the soil water content, θ_s and θ_r are the saturated and residual water contents (all in cm^3 cm^{-3}), respectively, α (cm^{-1}) and η (dimensionless) are fitting parameters that describe the shape of the water retention function, K_S is the saturated hydraulic conductivity (cm min^{-1}), $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$ is effective saturation, $\mu = 1 - \eta^{-1}$, and $\widehat{L} = 0.5$.

2.3.1 | Water retention curve parameters of noncompacted soils

Values of θ_s for the noncompacted soil condition were approximated by the total porosity of soil (ϕ, cm^3 cm^{-3}) as per Equation 3 (Blackwell et al., 1990), except for the Columbia and Coto soils, which had their θ_s measured on intact cores under laboratory conditions as discussed earlier (Laliberte et al., 1966; Rivadeneira, 1982):

$$\theta_s = \phi\left(1-P_a\right) = \left(1-\frac{\rho_b}{\rho_p}\right)\left(1-P_a\right) \tag{3}$$

where ρ_b is the soil bulk density (g cm^{-3}), ρ_p is soil particle density (2.65 g cm^{-3}; McKenzie et al., 2002), ϕ is the total porosity (cm^3 cm^{-3}) as derived from the soil bulk density using $\phi = 1 - \rho_b\rho_p^{-1}$ (Paydar & Cresswell, 1996), and P_a is the fraction of total porosity occupied by entrapped air (Bond & Collis-George, 1981). Values of P_a vary depending upon soil texture, soil structure, and fluid flow rate, with published values ranging from as little as 0.03 for clays to 0.55 for coarse sands, with most studies (albeit not all) showing more entrapped air in coarse soils (Faybishenko, 1995; Gonçalves et al., 2019; Marinas et al., 2013). Based in part on these published values, we used entrapped air values of 0.03 for fine-textured soils, 0.05 for medium-textured soils, and 0.06 for coarse-textured soils. These values of P_a are consistent with those adopted by Dalgliesh et al. (2016) to estimate the drained upper water content of soils using pedotransfer functions. The value of P_a may vary with changes in soil bulk density when a soil undergoes deformation; however, we considered P_a to be unaffected by compaction as in Assouline (2006).

Values of θ_r, α, and η were obtained by solving the following optimization problem:

$$\min_x \sum_i \left[F_i(x)\right]^2 \tag{4}$$

where

$$F = \frac{\theta - x(1)}{\theta_s - x(1)} - \left\{1+\left[x(2)\,|h|\right]^{x(3)}\right\}^{\left[\frac{1}{x(3)}-1\right]},\quad x = \left(\theta_r, \alpha, \eta\right) \tag{5}$$

such that $\theta_{r\,min} \le \theta_r \le \theta_{r\,max}$, $\alpha_{min} \le \alpha \le \alpha_{max}$, and $\eta_{min} \le \eta \le \eta_{max}$. For the optimization we used as restraining values $\theta_{r\,min} = 0.001$, $\theta_{r\,max} = 0.3$, $\alpha_{min} = 0.001\ cm^{-1}$, $\alpha_{max} = 0.9\ cm^{-1}$, $\eta_{min} = 1.0$, and $\eta_{max} = 10.0$. The MATLAB nonlinear least-square solver was used to solve the above optimization problem by applying the trust–region–reflective method (Yuan, 2015).

2.3.2 | Water retention curve parameters of compacted soils

When a soil undergoes compaction, the water retention and hydraulic conductivity curves change due to changes in the porosity and pore size distribution (Smith et al., 2001). The saturated water content of compacted soil (θ_{sc}) was calculated as follows:

$$\theta_{sc} = \theta_s \frac{\rho_p - \rho_{bc}}{\rho_p - \rho_b} \tag{6}$$

where ρ_{bc} is the bulk density of the compacted soil (g cm^{-3}).

The impact of compaction on soil pores holding water at potentials of 1,500 kPa or higher is generally negligible (Connolly et al., 2001). Data from a study on Grey Vertosols (Vertisols using the USDA-NRCS, 1999, description) showed nonsignificant differences ($P > .05$) in gravimetric water contents between compacted and noncompacted dry soils at that potential (Antille et al., 2016). Therefore, changes (increases) in the volumetric water content at 1,500 kPa due to compaction can be captured by the increased soil bulk density, as also shown by Connolly et al. (2001). The water potential at the permanent wilting point P_w was taken to be 1,500 kPa, consistent with values adopted for other arable soils from southern United States (Clower & Patrick, 1965). In view of these various studies, we assumed that the gravimetric water content (θ_{gw}) at P_w, as well as the residual gravimetric water content (θ_{gr}), remained unchanged during compaction (i.e., by the increased ρ_b). Consequently, the residual and permanent wilting-point volumetric water contents for compacted soils (θ_{rc}) can be computed as follows:

$$\theta_{rc} = \theta_r \frac{\rho_{bc}}{\rho_b} \tag{7}$$

$$\theta_{wc} = \theta_w \frac{\rho_{bc}}{\rho_b} \tag{8}$$

We used two approaches (henceforth, Approaches 1 and 2) to determine the parameters α and η of the compacted soils. In Approach 1, the values of α and η were both assumed to vary with compaction and hence were determined by solving the optimization problem described below (Equations 9 and 10). In Approach 2, the value of η was considered to be unaffected by compaction. Consequently, the value of α can be calculated in a straightforward manner.

2.3.3 | Approach 1: Determination of α and η

Given WRC information at saturation (h_s, θ_s) and the permanent wilting point (h_w, θ_w), the values of α and η for the WRC of compacted soils can be determined by solving the following optimization problem:

$$\min_x \sum_i \left[F_i(x)\right]^2 \tag{9}$$

where

$$F = \frac{\theta - \theta_{rc}}{\theta_{sc} - \theta_{rc}} - \left\{1 + \left[x(1)\,|h|\right]^{x(2)}\right\}^{\left[\frac{1}{x(2)} - 1\right]}, \quad x = (\alpha,\ \eta) \tag{10}$$

subject to the restraints $\alpha_{min} \le \alpha \le \alpha_{max}$ and $\eta_{min} \le \eta \le \eta_{max}$. The values of α_{min}, α_{max}, η_{min}, and η_{max} were the same as used for Equation 5. Unlike the optimization problem given by Equations 4 and 5, θ_{sc} and θ_{rc} are now calculated by using Equations 6 and 7, respectively. We note that the above estimation of α and η for the compacted soils becomes more reliable if additional WRC data points are available, such as by direct measurement.

2.3.4 | Approach 2: Determination of α

Our second approach assumes that the parameter η does not change with respect to compaction. This assumption was based partly on results obtained by Carsel and Parrish (1988) and our results obtained using Approach 1 as demonstrated in Section 3.1. Carsel and Parrish (1988) used multiple regression to estimate the VG parameters (θ_r, α, and η) and the saturated hydraulic conductivity (K_s) of various soil textural classes using estimates of the saturated water content (θ_s), and sand and clay contents. Their analysis was based on a very large soils database covering the twelve Soil Conservation Service textural classes. They showed that the CV for η was relatively small for all textural classes, compared with the CVs for the other hydraulic parameters (i.e., θ_s, θ_r, α, and K_s). Specifically, the CV for η varied between 3% (for silt) and 20% (for sand), generally less than 13% (except for sand being 20%), whereas the CV for K_s varied from 52% (for sand) to 453% (for silty clay), the CV for θ_s from 14% (for sandy clay) to 24% (for clay), the CV for θ_r from 6% (for sandy clay loam) to 50% (for clay), and the CV for α from 20% (for sand) to 160% (for clay), generally greater than 35% (except for sand being only 20%).

Assuming the same η, the parameter α can be estimated immediately from the permanent wilting point (1,500 kPa) of the compacted soil. Using Equation 1, the following relation is obtained:

$$\alpha_c = \frac{1}{|h_w|}\left[\left(\frac{\theta_{wc} - \theta_{rc}}{\theta_{sc} - \theta_{rc}}\right)^{-1/\mu} - 1\right]^{1/\eta} \tag{11}$$

where θ_{sc}, θ_{rc}, and θ_{wc} are calculated using Equations 6, 7, and 8, respectively.

2.4 | Effect of compaction on the hydraulic conductivity

Analyses of fluid flow and infiltration processes in compacted soils also require information on how compaction affects the

TABLE 2 Model validation: root mean square error (RMSE) and coefficient of determination (R^2) values between measured and modeled water retention curves at the design soil bulk densities (ρ_{bc}) reported in Table 1

		Modeling approach			
		Approach 1		Approach 2	
Soil series	Measured ρ_b	RMSE	R^2	RMSE	R^2
	g cm^{-3}	m^3 m^{-3}		m^3 m^{-3}	
Mountview	1.11	0.042	0.86	0.042	0.86
	1.24	0.041	0.89	0.035	0.92
	1.45	0.061	0.73	0.070	0.65
Lexington	1.43	0.017	0.99	0.017	0.99
	1.51	0.020	0.97	0.017	0.98
Grenada	1.14	0.020	0.97	0.020	0.97
	1.32	0.045	0.90	0.039	0.93
Dewey	1.39	0.016	0.94	0.016	0.94
	1.52	0.039	0.70	0.029	0.84
Columbia	1.22	0.010	1.00	0.010	1.00
	1.28	0.029	0.96	0.022	0.98
	1.34	0.051	0.86	0.040	0.92
Coto	1.06	0.006	1.00	0.006	1.00
	1.22	0.019	0.84	0.019	0.84
Avg. ± SD	–	0.030 ± 0.0169	0.90 ± 0.096	0.027 ± 0.0168	0.91 ± 0.095

Note. Modeled water retention curves were obtained using Approaches 1 and 2. SD is the standard deviation (for mean values across all soil series and bulk densities).

hydraulic conductivity. Tian et al. (2019) developed two models for estimating the saturated hydraulic conductivity (K_s) at various soil bulk densities. Their first model (Model 1) was based on the Carman–Kozeny equation (Kruczek, 2016), whereas the second model (Model 2) used the Mualem and Assouline (1989) semitheoretical model and the VG water retention function (van Genuchten, 1980). The unsaturated hydraulic conductivity (K_u) was then calculated from K_s and the WRC parameters. Results by Tian et al. (2019) showed that Model 2 produced more accurate estimates of K_u than Model 1, with Model 2 providing a better description of the WRC near saturation. Thus, we used an equation similar to Model 2 of Tian et al. (2019) to determine K_s and K_u, and to be able to account for the effects of compaction on the hydraulic conductivity and water infiltration:

$$K_s = K_{s0}\left[\frac{\left(\frac{\bar{\rho}_p-\bar{\rho}_b}{\bar{\rho}_p-1}\right)\theta_{s0}-\bar{\rho}_b\theta_{r0}}{\theta_{s0}-\theta_{r0}}\right]^{2.5}\left(\bar{\rho}_b\right)^{-7.94} \tag{12}$$

where K_{s0} is the average value of known K_s measurements at different ρ_b values, $\bar{\rho}_p = \rho_p\rho_{b0}^{-1}$, and $\bar{\rho}_b = \rho_p\rho_{b0}^{-1}$. In our study, K_{s0} was taken to be K_s of the noncompacted soils, that is at ρ_{b0}.

3 | RESULTS

3.1 | Model validation

Calculated values of the RMSE and the R^2 between measured and computed WRCs of six soils series at various soil bulk densities are shown in Table 2. Results indicate that the two models used to construct the WRC of compacted soils performed well, with Approach 2 (average RMSE ± standard deviation: 0.027 ± 0.0168 cm^3 cm^{-3}, and average R^2 ± standard deviation: .91 ± .095) performing slightly better than Approach 1 (average RMSE ± standard deviation: 0.030 ± 0.0169 cm^3 cm^{-3}, and average R^2 ± standard deviation: .90 ± .096). The WRCs of the Lexington series at different soil compaction levels using Approaches 1 and 2 are presented in Figure 1. Results for all other soil series (Mountview, Grenada, Dewey, Columbia, and Coto) are presented in Supplemental Figures S1–S5.

Our own analysis using Approach 1 indicated that η changed only slightly with compaction for all validation soils (Table 3). The CV for η varied between 0% (for Columbia sandy loam) and 2.98% (for Coto clay), whereas the CV for α varied from 0% (for Columbia sandy loam) to 14.1% (for Mountview silt loam). Since the CV for η using Approach 1 was small (less than 3%) for all of our soils, we proceeded with Approach 2 by assuming that η is not affected by compaction.

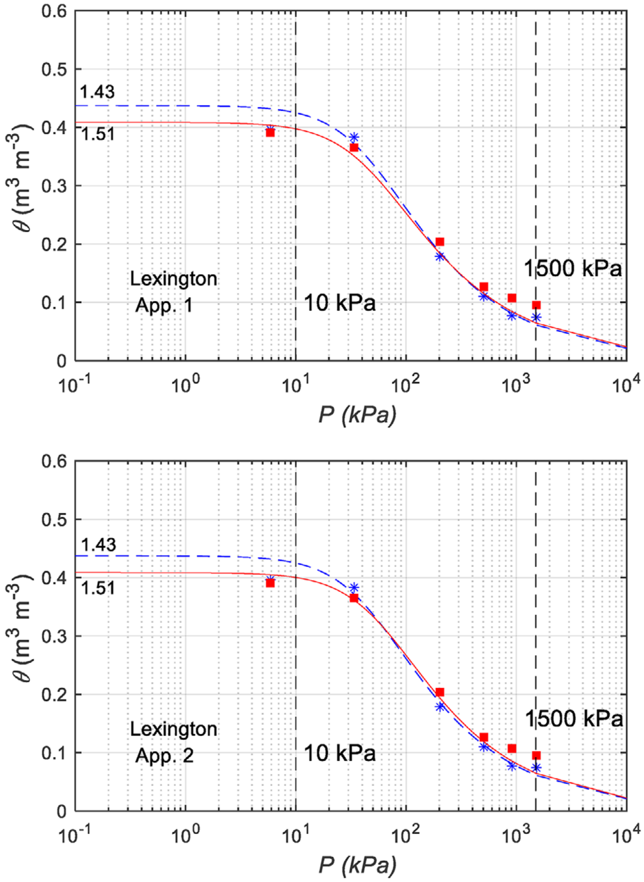

FIGURE 1 Water retention curves (WRCs) of the Lexington series with different soil bulk densities (ρ_b) as determined by Approach 1 (top) and Approach 2 (bottom). The asterisk and square symbols represent measured data at ρ_b = 1.43 and 1.51 g cm^{-3}, respectively. The dashed and solid lines represent the estimated WRCs for noncompacted and compacted soils, respectively. Vertical dotted lines at matric potentials between 10 and 1,500 kPa denote the soil water storage capacity. Definitions of variables are provided in Supplemental Table S1

Comparisons of the estimated and measured WRC data of the compacted soils actually showed that Approach 2 performed slightly better than Approach 1 (Table 2).

3.2 | Model application

Given that Approach 2 performed slightly better than Approach 1, we further focused only on applications of Approach 2 to estimating the VG-WRC parameters. Table 4 presents the estimated VG water retention parameters for both the noncompacted and compacted soil conditions. The Approach 2 parameters were used to reconstruct the WRCs for the two different compaction levels of interest.

Figures 2 and 3 show the calculated WRCs for the Lexington and Wilcox series, respectively. Results for the other soil series (Mountview, Grenada, Dewey, Hartsells, and Decatur) are shown in Supplemental Figures S6–S10. For all soils, water retention at matric potentials near saturation (larger pores) were reduced significantly with increased soil bulk density, but the compaction effects did not appear to be significant at lower matric potentials (smaller pores). Using the classification proposed by Johnson et al. (1960), the larger pores would correspond with fine (1–2 mm), medium (2–5 mm), and coarse (>5 mm) pore diameter classes. The smaller pores would correspond with micro (<0.075 mm) and very fine (0.075–1 mm) pore diameter classes.

Predicted AWSC values, expressed gravimetrically, declined significantly with increasing soil bulk densities (Figure 4). For all of the soil types and bulk densities we investigated (the latter covering ρ_b values from 1.10 to 1.80 g cm^{-3}), a linear or near-linear decrease in gravimetric AWSC with density is apparent. On average across all soils (except for Lexington and Wilcox), AWSC decreased by about 0.014 kg kg^{-1} (with standard deviation of 0.006) for every 0.1 g cm^{-3} increase in the bulk density. For Lexington and Wilcox, AWSC decreased by 0.035 and 0.056 kg kg^{-1},

TABLE 3 Statistics for the van Genuchten–Mualem (VG) water retention parameters (α and η) of Approach 1 associated with various compaction levels

	α			η		
Soil series	Mean	SD	CV	Mean	SD	CV
	cm^{-1}		%			%
Mountview	0.0579	0.0082	14.10	1.23	0.03	2.73
Lexington	0.0020	0.0000	1.96	1.56	0.02	1.42
Grenada	0.0303	0.0026	8.50	1.31	0.03	2.08
Dewey	0.1064	0.0138	12.95	1.13	0.02	1.49
Columbia	0.0091	0.0000	0.00	4.69	0.00	0.00
Coto	0.1095	0.0100	9.09	1.60	0.05	2.98
Max.	–	–	14.10	–	–	2.98
Min.	–	–	0.00	–	–	0.00

Note. Mean, SD, and CV represent the mean, standard deviation, and coefficient of variation of η values associated with various soil bulk densities. CV is the ratio of mean to SD.

TABLE 4 Estimated van Genuchten–Mualem (VG) water retention parameters and the saturated hydraulic conductivity (K_S) of soils without compaction and with two different levels of compaction using Approach 2

Soil series	Compaction level	ρ_b or ρ_{bc}	θ_r	θ_s	α	η	K_S
		g cm^{-3}	m^3 m^{-3}		cm^{-1}		cm min^{-1}
Mountview	No compaction	1.11	0.0010	0.5521	0.0654	1.27	0.690
	Low compaction	1.22	0.0011	0.5123	0.0344	1.27	0.268
	High compaction	1.33	0.0012	0.4725	0.0183	1.27	0.110
Lexington	No compaction	1.43	0.0010	0.4374	0.0020	1.58	0.069
	Low compaction	1.57	0.0011	0.3861	0.0014	1.58	0.024
	High compaction	1.72	0.0012	0.3348	0.0009	1.58	0.008
Grenada	No compaction	1.14	0.0010	0.5413	0.0321	1.33	0.213
	Low compaction	1.25	0.0011	0.5005	0.0190	1.33	0.082
	High compaction	1.37	0.0012	0.4596	0.0112	1.33	0.033
Dewey	No compaction	1.39	0.0010	0.4565	0.1161	1.14	0.618
	Low compaction	1.53	0.0011	0.4061	0.0254	1.14	0.216
	High compaction	1.67	0.0012	0.3557	0.0053	1.14	0.078
Hartsells	No compaction	1.31	0.0010	0.4753	0.0188	1.26	0.287
	Low compaction	1.44	0.0011	0.4289	0.0089	1.26	0.104
	High compaction	1.57	0.0012	0.3824	0.0041	1.26	0.039
Decatur	No compaction	1.37	0.0010	0.4637	0.0601	1.11	0.120
	Low compaction	1.51	0.0011	0.4141	0.0088	1.11	0.042
	High compaction	1.64	0.0012	0.3644	0.0012	1.11	0.015
Wilcox	No compaction	1.16	0.0010	0.5450	0.0024	1.16	N/A
	Low compaction	1.28	0.0011	0.5030	0.0008	1.16	N/A
	High compaction	1.39	0.0012	0.4600	0.0002	1.16	N/A

Note. No compaction, lowest measured bulk density (ρ_b) shown in Table 2; low and high compaction, 10 and 20% increases in soil bulk density (referred to as design densities, ρ_{bc}) relative to ρ_b. N/A, data not available; θ_r, residual water content; θ_s, saturated water content; α and η, VG parameters.

respectively, for every 0.1 g cm^{-3} increase in the bulk density, thus suggesting a relatively greater effect of compaction on their water holding capacity compared with the other soils. The Mountview and Lexington series are both silt loam soils and have similar particle size distributions but differ in their SOC contents as shown in Table 1. The effect of compaction on AWSC of the Lexington series appeared to be more significant than that of the Mountview series (Figure 4). Our calculations showed reductions in AWSC of about 8% for Mountview and 41% for Lexington when the soil bulk density increased by 20%, which may be explained by differences in their SOC contents.

3.3 | Water infiltration into soil

The VG water retention parameters of the noncompacted and compacted soils presented in Section 2.3 were used next to study the effect of compaction on ponded infiltration into a free-draining 100-cm-deep soil profile. The infiltration analysis was undertaken using HYDRUS-1D (Šimůnek et al., 2012). The water retention parameters and saturated hydraulic conductivity (K_s) used in the model simulations are listed in Table 4. Calculations assumed an initial pressure head of −800 cm, and a pressure head of 0 cm at the soil surface (ponded infiltration). The percentage decrease in cumulative infiltration (D) was calculated using

$$D = \frac{I_{c0} - I_{cc}}{I_{c0}} \times 100 \tag{13}$$

where I_{c0} and I_{cc} are the cumulative infiltrations for the noncompacted and compacted soils, respectively, at time $T = T_{\mathrm{final}}$.

Table 5 shows the impact of compaction on cumulative infiltration (I_c) at the final time (T_{final}) for the soils used in the analyses and at different soil bulk densities. The time T_{final}, taken to be 60, 360, and 120 min for Mountview, Lexington, and Grenada, respectively, corresponds to the time at which the infiltration simulations were terminated as infiltration rates became stable. Our analysis showed that 10 and 20% increases in soil bulk density, due to compaction, reduced cumulative infiltration (I_c) by 55 and 82%, respectively.

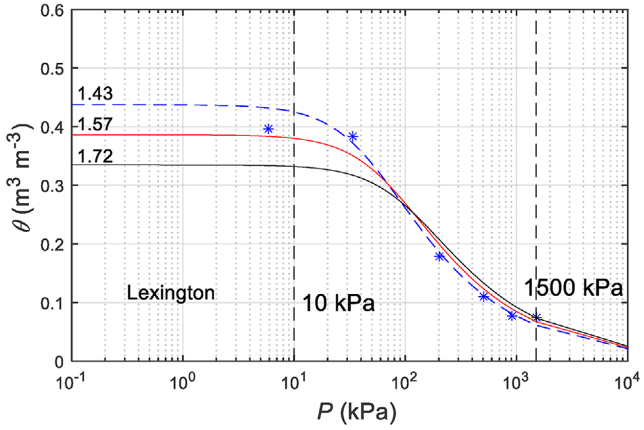

FIGURE 2 Water retention curves (WRCs) of Lexington series as determined by Approach 2 without compaction (baseline level soil bulk density, ρ_b = 1.43 g cm^{-3}) and at two different levels of compaction (ρ_b = 1.57 and 1.72 g cm^{-3}, respectively). The asterisk symbols represent measured data for the noncompacted soil condition. The dashed and the two solid lines represent the estimated WRCs for noncompacted and compacted soils, respectively. Vertical dotted lines at matric potentials between 10 and 1,500 kPa denote the soil water storage capacity. Definitions of variables are provided in Supplemental Table S1

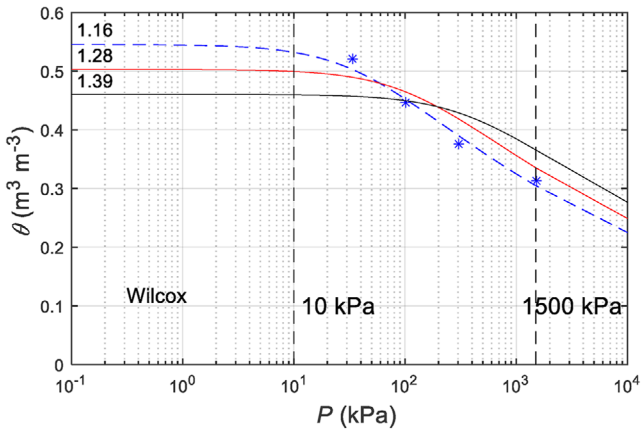

FIGURE 3 Water retention curves (WRCs) of Wilcox series as determined by Approach 2 without compaction (baseline level soil bulk density, ρ_b = 1.16 g cm^{-3}) and at two different levels of compaction (ρ_b = 1.28 and 1.39 g cm^{-3}, respectively). The asterisk symbols represent measured data for the noncompacted soil condition. The dashed and the two solid lines represent the estimated WRCs for noncompacted and compacted soils, respectively. Vertical dotted lines at matric potentials between 10 and 1,500 kPa denote the soil water storage capacity. Definitions of variables are provided in Supplemental Table S1

The effects of increased soil bulk density on cumulative infiltration are shown in Figure 5 for the Lexington series, and in Supplemental Figures S11 and S12 for the Mountview and Grenada series, respectively. Results indicate a significant reduction in infiltration as a result of compaction, consistent with other studies for different soils (Hamlett et al., 1990; Li et al., 2009). For example, for Mountview, our analysis showed that at T_{final} = 60 min, a 10% increase in soil bulk density (from 1.11 to 1.22 g cm^{-3}) reduced cumulative infiltration by about 60% (from 40.4 to 15.8 cm). Increasing the bulk density by 20% caused the cumulative infiltration at T_{final} = 60 min to decrease to less than 8 cm, a reduction of about 80%. The Lexington and Grenada soils showed similar results.

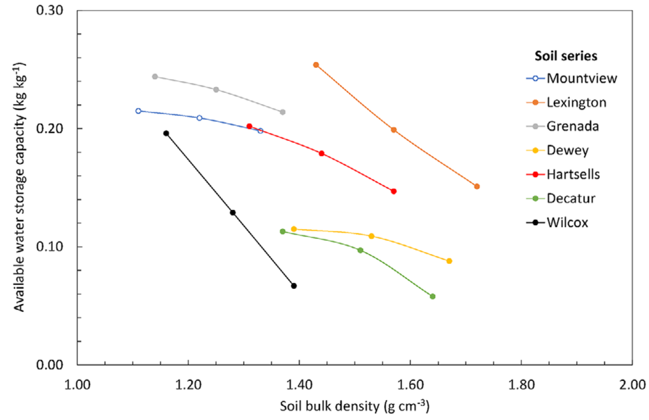

FIGURE 4 Effect of soil bulk density on available water storage capacity (expressed on a gravimetric basis) for a range of soil series, as determined from the soil water retention curves shown in Figures 2–3 and Supplemental Figures S6–S10. The available water storage capacity is considered here as the difference between the amount of water retained at matric potentials of 10 and 1,500 kPa, respectively (see also Supplemental Table S1)

4 | DISCUSSION

All of our soils showed a significant reduction in water retained between near saturation (0.01 kPa) and a matric potential of about 100 kPa. At potentials greater than 1,000 kPa, the effects of compaction became negligible. These results are consistent with those by Connolly et al. (1997), who showed that the effect of compaction on the water content at a given potential decreased progressively in the near-linear section (transition region) of the WRC. Based on experimental work by Connolly et al. (2001), Antille et al. (2016) showed that compaction had little effect on pores holding water at a potential of 1,500 kPa. This suggests a steadily increasing impact of compaction on mostly the larger pores, and supports the modeling assumptions made both in this and previous studies (Hussein et al., 2021a, 2021b; Ngo-Cong et al., 2021; Tian et al., 2018). Increased soil bulk densities tend to flatten the S-shaped WRCs, also in the absence of compaction. This reflects changes in pore size and the pore-size distribution by increasing the number of smaller pores

TABLE 5 Impact of soil compaction on cumulative infiltration (I_c) at the final time (T_{final}) for three different soil series

Soil series	Compaction level	ρ_b or ρ_{bc}	T_{final}	I_c	D
		g cm^{-3}	min	cm	%
Mountview	No compaction	1.11	60	40.37	–
	Low compaction	1.22	60	15.83	60.8
	High compaction	1.33	60	7.41	81.6
Lexington	No compaction	1.43	360	34.53	–
	Low compaction	1.57	360	15.52	55.0
	High compaction	1.72	360	7.16	79.3
Grenada	No compaction	1.14	120	26.34	–
	Low compaction	1.25	120	11.22	57.4
	High compaction	1.37	120	5.81	78.0

Note. D is the percentage decrease in cumulative infiltration I_c relative to the infiltration obtained for the uncompacted soil (bulk density, ρ_b).

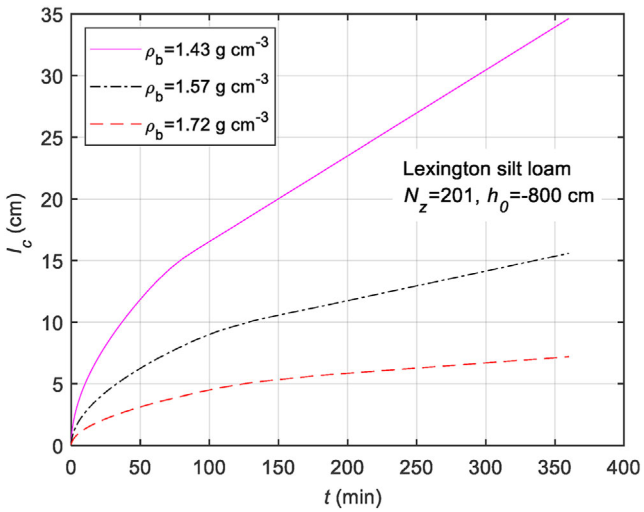

FIGURE 5 Cumulative infiltration (I_c) for Lexington series at different soil bulk densities (ρ_b) (see also Supplemental Figures S11 andS12). Definitions of variables are provided in Supplemental Table S1

(meso- and microporosity) as shown by Gupta et al. (1989) and Smith et al. (2001), among others.

Since the amount of water retained at the wilting point (1,500 kPa) is mainly determined by soil texture (Archer & Smith, 1972), flattening of the WRC and the associated decrease in AWSC is more a result of less water being retained at matric potentials near field capacity (10 kPa). The effect of increased bulk density on water retained at field capacity depends on the crossover point, being the matric potential at which the WRC of the simulated compacted and noncompacted soils cross each other, which is different for each soil type. Figures 2–3 and Supplemental Figures S6–S10 show small increases in the wilting point when expressed on a volumetric basis, especially for the more fine-textured soils in the dataset (e.g., Dewey, Decatur, and Wilcox). When the crossover occurred at low matric potentials (<10 kPa), the increased volumetric water content at field capacity appeared to be offset by the concurrent rise in the water content at the wilting point (e.g., Mountview and Grenada). Unlike Reeve et al. (1973), who reported increased available water capacities with increasing soil bulk densities, our analyses showed that the net effect of compaction reduced the AWSC values (Figure 4).

A comparison of the Mountview and Lexington soils (Figure 4), which are in the same texture group, suggests that the effect of compaction on AWSC may be partly mitigated by a higher SOC content (Table 1). Hudson (1994) showed significant (positive) correlations between SOM and the available water capacity for silt loam soils ($R^2 \approx .60$). Similar comparisons between other soils in the dataset cannot be made because they all belong to different texture groups. However, an increased SOC tends to reduce the susceptibility of a soil to compaction, the development of root growth-limiting soil bulk densities, and the Proctor density (Bennie & Krynauw, 1985; Thomas et al., 1996). Furthermore, Murphy (2015) showed that plant available water of medium-textured soils may increase by 2–3 mm per 100-mm soil depth for every unit increase in the SOM content.

The two approaches in our study showed that they can be used with confidence for a wide range of soil types (Table 2). They hence may be applied to other scenarios (e.g., cropping systems, land use, and management) to simulate the effects of changes in the soil bulk density on water retention and infiltration. A problem often encountered in agricultural systems is the need to adjust water inputs when soil hydraulic properties change dynamically during the cropping season. Such changes are governed by soil bulk density, which may increase for example following tillage or land-forming operations as soil settles with time (Meek et al., 1992). By better adjusting water inputs, soil water storage can be maximized and the risk of waterlogging and surface runoff minimized, thus improving water use efficiency. Kool et al. (2019) quantified changes in the soil bulk density after tillage and subsequently used the model of Tian et al. (2018) to investigate related changes in water retention based on previously measured dynamic soil bulk densities. Unlike the approach by Tian et al. (2018), which requires a more cumbersome calibration process to determine the van Genuchten (1980) parameters α and η, our analyses relied on either a simple optimization (Approach 1) given by Equations 9 and 10, or solving the relationship shown by Equation 11 (Approach 2). Both approaches performed satisfactorily, with Approach 2 preferred since it yielded slightly lower RMSE and higher R^2 values than Approach 1.

Increased soil water storage capacity and water retention in soil, as shown by our study when compaction is avoided (Figure 4), can translate into improved rainfall use efficiency (mainly in rainfed systems) and reduced reliance on applied water in irrigated systems (Hussein et al., 2021a, 2021b). Improved soil structural conditions and internal drainage in noncompacted soil will also reduce the risk of waterlogging and therefore possible nitrogen losses through denitrification (Ruser et al., 2006; Tullberg et al., 2018).

5 | CONCLUSIONS

Two numerical approaches were developed to determine the effects of traffic-induced compaction on the water retention curve (WRC) of a range of arable soils from southern United States. The proposed approaches satisfactorily expanded the applicability of the van Genuchten (1980) model. In Approach 1, an optimization problem was solved to enable the van Genuchten model parameters α and η to be estimated for the design bulk densities of the compacted soil, based on the WRC of the corresponding noncompacted soil. In Approach 2, the parameter η was assumed to be unaffected by changes in soil bulk density. The parameter α could then be estimated based on the water content at the permanent wilting point (1,500 kPa) of the compacted soil using the proposed Equation 11. Compared with measured data, Approach 2 yielded slightly better predictions of the WRC than Approach 1. However, both numerical approaches may be used with confidence for a wider range of scenarios than those of our study.

Modeled WRCs at the different design bulk densities (10 and 20% soil compaction levels) were combined with the HYDRUS-1D model to simulate vertical downward water infiltration into both noncompacted and compacted soils. Results confirmed the detrimental effects of (traffic) compaction on the infiltration characteristics of a range of soils, which can affect water (irrigation and rainfall) use efficiency and crop productivity. Across all soils, our analyses showed that a 10–20% increase in bulk density could reduce cumulative infiltration (I_c) at time $T = T_{final}$ (steady state) by 55–82%, and the available water storage capacity by 3–49%, depending upon soil type. Mechanization systems designed to mitigate (e.g., by using low ground pressure tires) or avoid (e.g., by implementing controlled traffic farming) soil compaction are encouraged. The models we developed make it possible to quantify the benefits of compaction avoidance in terms of improved infiltration, soil water retention, and water use efficiency, as well as provide better predictions of the overall hydrology of compacted soils.

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AUTHOR CONTRIBUTIONS

Duc Ngo-Cong: Formal analysis; Methodology; Validation; Writing-original draft. Diogenes L. Antille: Conceptualization; Data curation; Funding acquisition; Methodology; Writing-original draft. Martinus Th. van Genuchten: Methodology; Validation; Writing-review & editing. Hung Q. Nguyen: Formal analysis; Validation. Mehari Z. Tekeste: Resources; Writing-review & editing. Craig P. Baillie: Funding acquisition; Project administration; Supervision; Writing-review & editing. Richard J. Godwin: Resources; Writing-review & editing.

CONFLICT OF INTEREST

No conflicts of interest were identified by the authors.

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