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Soil physical properties and water dynamics under contrasting management regimes at the Morrow Plots

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ABSTRACT

This study investigated changes in soil physical quality and water dynamics arising from continuous cropping at the Morrow Plots, the oldest agricultural experiment in North America. The objectives were to examine the effects of continuous cultivation on soil water retention and determine the optimum water content for tillage (θ_{OPT}) in a prime agricultural soil. Soil samples collected at 0–5, 5–10, and 10–15 cm depths were used to measure bulk density and water retention using the HyProp 2 and WP4-T Dewpoint Potentiometer. Soil organic carbon (SOC) and soil penetration resistance (PR) were measured to a depth of 15 cm. The soil water retention data were fitted with the Dexter double exponential and van Genuchten models. Neither model consistently fitted all the water retention data across the different management practices. The corn-oat-hay (COH) rotation generally reduced soil bulk density within the 0–15 cm depth by an average of 9 % and PR by 21 % compared to the continuous corn (CC) treatment. The COH rotation slightly increased topsoil water-holding capacity (0–15 cm), although trends varied with fertility regimes. The θ_{OPT} for the COH and CC estimated by the van Genuchten model was generally wetter than the water content at field capacity (θ_{FC}). In contrast, the θ_{OPT} estimated by the Dexter model was slightly drier than θ_{FC}. Despite limitations due to the lack of true replicates and the small sample size at the Morrow Plots, this research underscores the long-term impact of crop rotation on soil hydraulic properties in prime agricultural soils.

1. Introduction

Soil water retention (SWR) is a crucial hydraulic property of soils that controls essential processes including the transport of solutes and nutrients, leaching, runoff, numerous water-energy interactions, and greenhouse gas emissions (Assouline et al., 1998; Ket et al., 2018). It is fundamental for soil productivity and soil health because it is critical for crop development and growth, and determines the availability of moisture to soil biota (Panagea et al., 2021). Soil water content also affects soil workability, which considers the ease with which soil can be worked during seedbed preparation to reduce the risk of damage to soil structure (Obour et al., 2017, 2019).

In temperate rainfed regions, climate variability, particularly increased spring precipitation, has significantly affected the management of agricultural fields and narrowed the window for soil tillage and planting (Grady et al., 2021). This affects soil workability and the optimum water content for tillage (θ_{OPT}). Soil workability refers to the ease with which soils can be worked without damaging their structure (Obour et al., 2017, 2019). The θ_{OPT} represents the water content at which soils can be tilled to achieve optimal seedbed structures for crop establishment (Dexter and Birkas, 2004). These variables can inform the timing of field traffic which can have adverse effects on soil physical quality when heavy machinery is used under wet conditions. This reduces soil porosity and degrades soil structure, and thus, reduces crop productivity and yield. A recent meta-analysis suggests that yield reductions associated with increased soil compaction range from 6–34 % in cereal and soybean crops (Obour and Ugarte, 2021). Quantitative information about soil water retention can provide valuable information for scheduling cultural practices such as tillage operations to prevent the risk of traffic-induced soil structural degradation (Obour and Ugarte,

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2021). Also, information on soil water retention can be useful for hydrological modeling and developing decision support systems for crop selection, water management, and flood control (Liang et al., 2016; Magyar et al., 2023).

Soil water retention is highly influenced by soil texture, structure, and soil organic matter (SOM), among other properties (Huang et al., 2016). Water storage and movement are governed primarily by pore size distribution (PSD), which defines the relative abundance of each pore size in a representative volume of soil (Nimmo, 2004). Both intra-and inter-pedal pores are important to soil water retention and soil workability. Soil macropores (>75 μm) control the movement of water within the soil under saturated conditions, while mesopores (30–75 μm) are crucial to water retention for plant uptake (Jongerius, 1957). The relationships between SWR and other soil properties such as PSD, SOM, and texture have been described by numerous models (e.g., Jensen et al., 2019; Panagea et al., 2021). Most models are uni-modal expressions, which implicitly assume a single peak of pore volume at a given tube equivalent pore size (Dexter et al., 2008; Jensen et al., 2019). Uni-modal water retention models such as the van Genuchten (hereafter noted as the vanG model) can introduce errors when estimating the water content of soils with more than a single peak of PSD, which is common in topsoils and well-structured soils (Jensen et al., 2019). Dual or bi-modal models have been developed to better describe hydraulic movement in temperate topsoils and well-structured soils (Regelink et al., 2015). Such soils commonly have textural porosity derived from the pore space among individual soil mineral particles and structural porosity derived from the pore space between micro-aggregates. The double-exponential model (hereafter called the Dex model) proposed by Dexter et al. (2008) is more appropriate for describing the PSD of soils with two peaks representing textural and structural pores. Accordingly, we expected the Dex model to provide better estimates of soil water characteristics in the Morrow Plots than the vanG model.

The Morrow Plots, established in 1876 at the University of Illinois, are the oldest experimental agricultural fields in the United States and among the longest running in the world. These plots have provided valuable data on soil fertility, crop rotation, and the long-term impacts of agricultural practices on soil health. The dominant soil in the area, Flanagan silt loam (Aquic Argiudoll) (Darmody and Peck, 1996), has a high water retention capacity due to its high clay content, particularly montmorillonite minerals, which swell and shrink in response to moisture changes (Velde and Peck, 2002). Given these mineral properties, management practices including crop rotations, organic amendments, or tillage practices, could significantly influence the soil's hydraulic dynamics. However, it remains unclear how significant changes in SOM (Aref and Wander, 1998; Nafziger and Dunker, 2011) in the Morrow Plots soils, resulting from long-term crop rotation and fertility regimes, might affect SWR and the ability of uni- and bi-modal water retention models to describe these changes. The objective of this study was to evaluate the impact of over 140 years of crop rotation and fertility regimes on soil water retention characteristics and the optimum water content for tillage.

2. Materials and methods

2.1. Description of the study site

This study was carried out at the Morrow Plots located at the University of Illinois (40.1043° N, 88.2261° W) campus. Samples were taken in April 2018 from the continuous corn (CC), and corn-oat-hay (COH) rotation before incorporation of the hay crop. Hay crops include alfalfa (*Medicago sativa* L.) and red clovers (*Trifolium pratense* L.). The fertilizer treatments investigated were unamended (U), nitrogen, phosphorus, and potassium applied to formerly unamended plots (UNPK) and manure (M). For a complete field plot layout see Aref and Wander (1998). Amounts and timing of fertility inputs have been updated to represent commonly used management practices since the establishment in 1876 and management details are available in Aref and Wander (1998). Recent changes include the transition from moldboard plowing to chisel plowing in 1989 and an increase in seeding density in 2013. The soil has an average clay content of 24 %, 71 % silt, and 5 % sand in the Ap horizon (0–20 cm) (Soil Survey Staff, 2023).

Two intact soil core subsamples per treatment plot were collected from selected combinations (COH+U, COH+UNPK, COH+M, CC+U, CC+UNPK, and CC+M) to represent the greatest contrast in soil properties. Soil samples were collected at soil depths of 0–5, 5–10, and 10–15 cm. Intact soil cores were collected with steel rings that have an inner volume of 250 cm^3 (diameter = 8 cm, height = 5 cm). A composite of five bulk soil samples was collected adjacent to the intact cores using a 2.54 cm probe to 0–15 cm depth. The samples were used to determine SOC concentrations. At each sampling point, triplicate soil penetration resistance (PR) measurements were taken to 15 cm depth using a dynamic cone penetrometer (SF-10, Gilson, OH, USA). The number of strikes required to drive a cone with a 20.3-mm-diameter base into the soil by dropping a 2-kg hammer 40 cm to contact a strike plate was recorded following the recommendations in Herrick and Jones (2002).

In the laboratory, the soil moisture retention curve at the wet end (pF< 3.6) was measured on each intact soil core using a HyProp 2 arrangement (METER Group, Inc., WA, USA). The soil cores were fully saturated with DI water for 4–7 days before being assembled with the fully vacuumed HyProp 2 unit. Tensio-shafts were inserted to two depths (3.1 cm and 5.6 cm) to measure the gradient of hydraulic properties within the soil matrix. The average reading between the two tensiometers was assumed to represent the center of the sample (METER, 2015). The sample-HyProp 2 apparatus was placed on a Kern EG 2200–2NM balance (EG 2200–2NM, Kern & Sohn, Balingen, Germany) connected to a Windows PC for automatic monitoring of soil moisture change over time (METER, 2015). The HyProp 2 measurements were terminated after the tensiometer reading dropped below air pressure. Two subsamples of about 10 g were taken from the bottom, middle, and top sections of the soil core for measurement of soil water content at the wilting point (pF4.2) using a WP4-T Dewpoint Potentiometer (Scanlon et al., 2002). The subsamples were taken from three sections of each soil core ensuring that the gradient of soil moisture status in the core was accounted for. The remaining HyProp sample and the subsamples were oven-dried for 24 h at 105 °C to determine water content. The bulk density of each soil core was calculated as the oven-dried soil mass, comprising the oven-dry mass of the six subsamples and the oven-dry mass of the remaining HyProp sample divided by the sample volume. The total porosity was calculated from bulk density and an assumed particle density of 2.65 Mg m^{-3}.

To determine SOC, the bulk soil samples were air-dried, ground, and sieved to 2 mm before quantifying SOC using dry combustion in a Micro Vario Elemental Combustion System (Elementar Americas, Ronkonkoma, NY, USA) (Skjemstad and Baldock, 2008).

2.2. Soil water retention

Gravimetric water content (θ_g) at pF 0, 1, 1.5, 1.8, 2.0, 2.5, 2.8, 3.0, 3.5, 4.0, and 4.2 was estimated from the HyProp 2 data and the WP4 measurements by a linear interpolation function in Microsoft Excel. Volumetric water content at the selected matric potentials was computed by multiplying the θ_g at a given matric potential by the soil bulk density.

The PSD of the soil at a given matric potential was estimated from the water retention measurements using the capillary equation which was re-written and used in Startsev and McNabb (2001):

$$d = -3000/\psi \tag{1}$$

where d is the equivalent cylindrical tube diameter (μm) and Ψ is the soil matric potential (hPa). Plant available water (PAW) at 0–5, 5–10, and 10–15 cm depth were calculated as the difference between soil water content at field capacity (θ_{FC}) and permanent wilting point (PWP)

Table 1
Mean and standard deviations for soil organic carbon concentration, bulk density and penetration resistance (PR) at the Morrow Plots based on rotation and fertility regimes.

Treatment	Soil organic carbon (g/kg)	Bulk density (Mg m^{-3})			PR (# strikes)
	0–15 cm depth	0–5 cm depth	5–10 cm depth	10–15 cm depth	0–15 cm depth
Means for rotation					
COH	25.8 ± 2.9	1.33 ± 0.13	1.33 ± 0.07	1.39 ± 0.08	8.00 ± 1.73
CC	16.7 ± 1.3	1.42 ± 0.05	1.50 ± 0.05	1.54 ± 0.13	9.70 ± 0.58
Means for fertility regimes					
U	20.3 ± 5.7	1.36 ± 0.07	1.40 ± 0.12	1.40 ± 0.14	9.50 ± 0.71
UNPK	19.9 ± 3.4	1.42 ± 0.05	1.45 ± 0.07	1.52 ± 0.11	9.50 ± 0.71
M	23.4 ± 6.8	1.33 ± 0.17	1.39 ± 0.14	1.47 ± 0.15	7.50 ± 2.12

Continuous corn (CC), and corn-oat-hay (COH) rotation and fertilizer treatments: unamended (U), Nitrogen, phosphorus, and potassium applied to formerly unamended plots (UNPK) and manure (M), and ± indicates standard deviations of the mean.

(de Melo et al., 2023). Here θ_{FC} was taken as water content at pF 1.8 and PWP as the soil water content at pF 4.2. The soil water holding capacity (WHC) was derived from PAW and it was computed by integrating soil water content for the three depths (n):

$$WHC = \sum_{h=1}^{n} (PAW_h * D_h) \tag{2}$$

where Dh is the thickness (in mm) of the soil horizon (Stoorvogel et al., 2019).

2.3. Fitting data to water retention models

The water retention data were fitted to the Dex model (Dexter et al., 2008):

$$\theta = C + A_1 e^{(-h/h_1)} + A_2 e^{(-h/h_2)} \tag{3}$$

where C is the asymptote of the equation, A_1 and A_2 are the amounts of textural and structural pore space, and h_1 and h_2 are characteristics of the pore water suctions at the textural and structural pores, respectively. The parameters of the Dex model were obtained by nonlinear regression analysis to obtain the smallest residual sum of squares. The PSD was obtained by differentiating Eq. [3] with respect to matric potential using a differential function (Jensen et al., 2019):

$$\frac{d\theta}{d(\log_{10}h)} = -\frac{A_1}{h_1} e^{(-h/h_1)} h \ln 10 - \frac{A_2}{h_2} e^{(-h/h_2)} h \ln 10 \tag{4}$$

The water retention data were also fitted with the van Genuchten (1980) equation as:

$$\theta = (\theta_{SAT} - \theta_{RES})[1 + (\alpha h)^n]^{-m} + \theta_{RES} \tag{5}$$

where θs_{AT} is the water content at saturation obtained from the water retention curve, θ_{RES} is the residual water content, which was assumed to be zero (Dexter et al., 2008), h is the soil matric potential, α is a scaling factor for h, and n and m are parameters that control the shape of the curve. Values of a and n were obtained using the curve-fitting program, RETC (van Genuchten et al., 1991). The van Genuchten equation was fitted with the Mualem restriction ($m=1-1/n$) (Mualem, 1976) to prevent over-parameterization. To estimate PSD predicted by the vanG model, Eq. [5] was differentiated with respect to matric potential using a differential function Equation (Jensen et al., 2019):

$$\frac{d\theta}{d(\log_{10}h)} = (\theta_{SAT} - \theta_{RES})\left\{\alpha n(\alpha h)^{n-1}(-m)[1 + (\alpha h)^n]^{-m-1}\right\} h \ln 10 \tag{6}$$

2.4. Optimum water content for tillage

The θ_{OPT} was estimated using the two soil water retention models investigated. Using the vanG model, θ_{OPT} was estimated as the water content at the inflection point (θ_{INFL}) (Dexter and Bird, 2001):

$$\theta_{INFL} = \theta_{SAT}\left[1 + \frac{1}{1 - 1/n}\right]^{1-1/n} \tag{7}$$

For the Dex model, θ_{OPT} was estimated as the local minimum of the PSD between the peaks of the textural and structural pore space (Dexter and Richard, 2009).

The Akaike's Information Criterion (AIC) is useful for comparing models with a differing number of parameters (Akaike, 1974). The goodness of fit for the vanG model and the Dex models was quantified in terms of values of AIC and the root mean squared error (RMSE) as:

$$AIC = 2K + Nin\left(\frac{RSS}{N}\right) \tag{8}$$

$$RMSE = \sqrt{\frac{1}{N}\sum (\theta_{meas} - \theta_{fitted})^2} \tag{9}$$

where K is the number of adjustable model parameters, N is the number of matric potentials fitted to the model and RSS is the residual sum of squares. When two models are compared, a smaller AIC or RMSE implies a better model. Simple regression analyses were performed to examine how soil bulk density is related to the amount of textural pore space (A_1) and structural pore space (A_2).

2.5. Data analysis

The Morrow Plots were designed before the general recognition of the need for thoughtful experimental design that included randomization and replication as implied in Yetes (1964) and Aref and Wander (1998). Consequently, evaluation of treatment effect sizes and interactions is not feasible in this study given the low statistical power rendered by the current treatment arrangement. Given the described limitations, the Morrow Plots lack true replication needed for optimal statistical comparison of treatment effects and interactions of the variables investigated (crop rotation, fertility amendments, and crop rotation × fertility amendment), plots within the rotation and fertility strips were used as replicates in separate analyses to derive means and standard deviations by each management factor. The greater proportion of the discussion in this study reflects general patterns rather than observed statistical significance. Finally, simple linear regression analyses were performed to understand relationships between measured soil variables.

3. Results

3.1. Soil organic carbon

Soil organic carbon at the 0–15 cm depth was 54 % more concentrated in the COH than in CC treatments (25.8 vs. 16.7 g/kg). The SOC content was 17 % greater in the M (23.4 g/kg) than in the UNPK (19.9 g/kg) and 15 % greater than in the U (20.4 g/kg) plots.

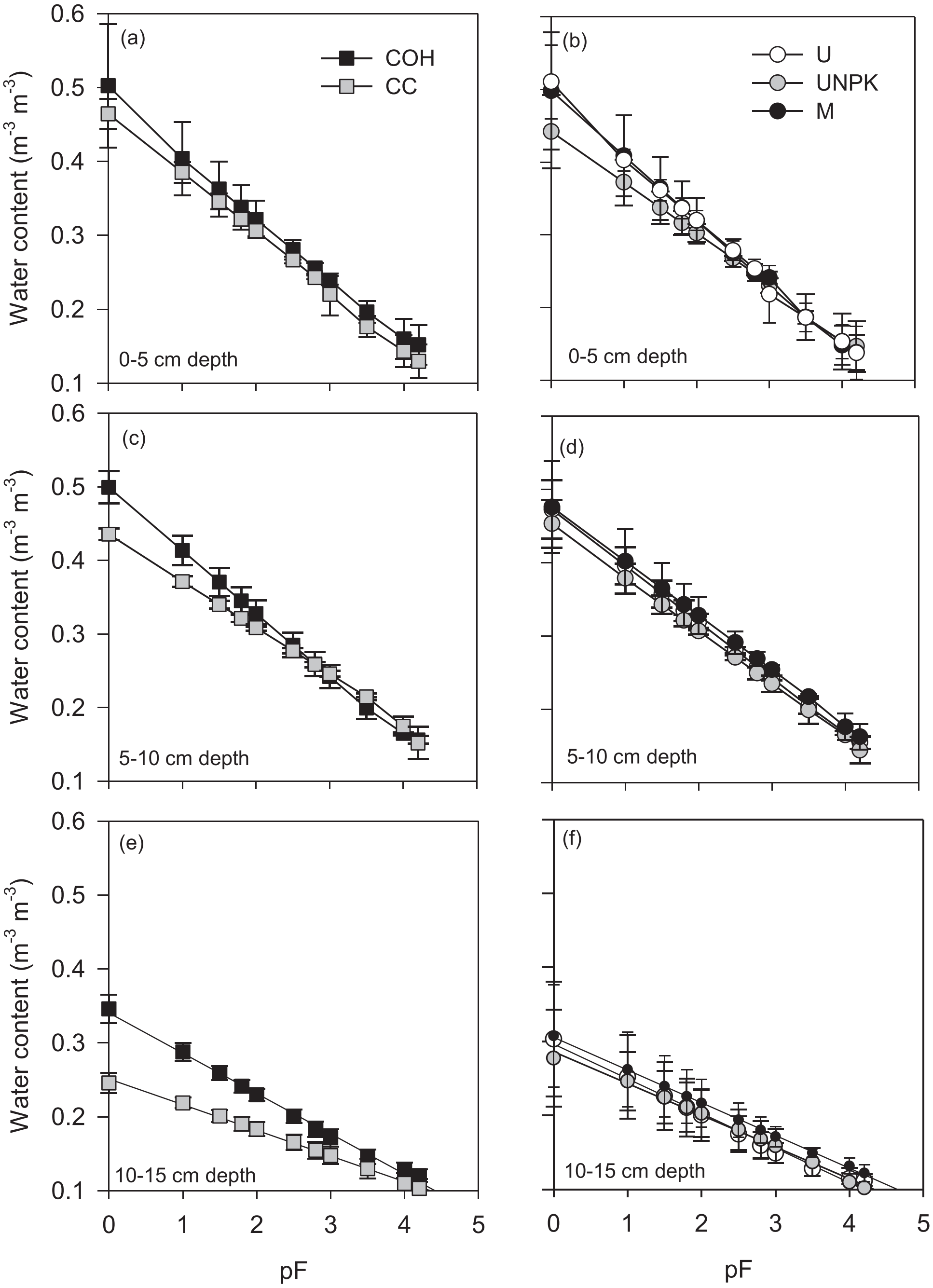

Fig. 1. Estimated water content (volumetric) at given matric potentials for the investigated treatments average for crop rotation (a, c and e) and fertilization (b, d and f) at 0–5, 5–10 and 10–15 cm depth. Unamended (U), Nitrogen, phosphorus, and potassium applied to formerly unamended plots (UNPK) and manure (M) plots. Error bars indicate standard deviations of the mean.

3.2. *Soil bulk density, soil water retention, and pore size distribution*

Soil bulk density was consistently lower in the COH compared to the CC soil with average values of 1.35 and 1.49 Mg m^{-3} for the 0–15 cm depth. Bulk density values were greater at the 5–10 and 10–15 cm than in the 0–5 cm samples (Table 1). Soil bulk density for the CC treatment at 5–10 and 10–15 cm depth was 13 % and 11 % greater than their counterparts in the COH rotation. The magnitude of change in bulk density at 0–15 cm depth was less prominent for fertility regimes which ranked UNPK>M>U with average values of 1.46, 1.40, and 1.39, respectively. Soil penetration resistance values generally followed trends in bulk density. Fewer strikes were needed in the COH treatment to penetrate the 15 cm depth. This was 21 % fewer strikes than what was required in the CC plots. Soil PR was 27 % lower in the M treatment than in the U and UNPK treatments (Table 1).

Soil water retention measured using the HyProp 2 and WP4-T Dewpoint Potentiometer suggests COH soil water retention tended to be higher than that of the CC soils at all depths investigated, and differences among treatments decreased at more negative matric potentials (Fig. 1). The effects of the fertility regimes on soil water retention were less pronounced, with slight reductions in the UNPK treatment observed in comparison to the other treatments. Table 2 suggests that θ_{FC} is greater in the COH at the 5–10 and 5–10 cm depths. There was only a slight increase in PWP, PAW, and WHC in the COH rotation and trends varied among depths. Mean estimates for θ_{FC}, PWP and WHC across fertility treatments were similar.

Table 2
Means and standard deviation for field capacity (θ_{FC}), permanent wilting point (PWP), plant available water (PAW), and water holding capacity (WHC) at different depths determine using the HyProp 2 and WP4-T Dewpoint potentiometer.

	θ_{FC} (m^3 m^{-3})				PWP (m^3 m^{-3})				PAW (m^3 m^{-3})	WHC (mm)
	0–5 cm	5–10 cm	10–15 cm	Avg. 0–15 cm	0–5 cm	5–10 cm	10–15 cm	Avg. 0–15 cm	Avg. 0–15 cm	0–15 cm
Means for rotation +/- one standard deviation of the mean										
COH	0.35 ± 0.02	0.34 ± 0.02	0.33 ± 0.01	0.34 ± 0.02	0.16 ± 0.04	0.16 ± 0.01	0.17 ± 0.01	0.16 ± 0.02	0.18 ± 0.03	81.80 ± 9.19
CC	0.33 ± 0.02	0.32 ± 0.02	0.31 ± 0.02	0.32 ± 0.02	0.13 ± 0.02	0.15 ± 0.03	0.17 ± 0.02	0.15 ± 0.03	0.17 ± 0.07	73.00 ± 9.80
Means for fertility regimes +/- one standard deviation of the mean										
U	0.33 ± 0.01	0.33 ± 0.02	0.31 ± 0.02	0.33 ± 0.02	0.14 ± 0.03	0.15 ± 0.03	0.16 ± 0.01	0.15 ± 0.02	0.17 ± 0.06	77.92 ± 4.13
UNPK	0.34 ± 0.02	0.32 ± 0.02	0.32 ± 0.02	0.33 ± 0.02	0.15 ± 0.05	0.14 ± 0.02	0.16 ± 0.02	0.15 ± 0.03	0.18 ± 0.03	77.36 ± 7.46
M	0.34 ± 0.03	0.34 ± 0.02	0.33 ± 0.02	0.34 ± 0.03	0.14 ± 0.02	0.16 ± 0.02	0.18 ± 0.01	0.16 ± 0.03	0.18 ± 0.04	79.24 ± 15.74

Continuous corn (CC), and corn-oat-hay (COH) rotation and fertilizer treatments: unamended (U), Nitrogen, phosphorus, and potassium applied to formerly unamended plots (UNPK) and manure (M).

The COH soils contained a greater proportion of both macro and mesopores (30–100 μm) than CC soils across all depths. Macroporosity (>100 μm) was 6, 36, and 66 % greater in 0–5, 5–10 and 10–15 cm depths, respectively in the COH than CC rotations. Mesopore content for the COH was 6, 34, and 40 % greater than the volume in the CC soils at 0–5, 5–10, and 10–15 cm depths respectively. Fertility treatments had less effect on the volume of meso- and macropores at the investigated depths except for the 0–5 cm depth, where the fractions of meso- and macropores in the M treatment were marginally higher than those found in the U and UNPK treatments (Fig. 2).

3.3. Model fit

The PSD values obtained by differentiating the water retention data fitted with the Dex and the vanG models are presented in Tables 3 and 4. The AIC and RMSE values reveal variability in the vanG and Dex model fit with the water retention data. For example, for water retention data for the CC treatment at 0–5 cm depth, the absolute value of AIC for the Dex model (-96) was greater than that produced by the vanG model (-86) suggesting a lower model parsimony in the vanG model; however, potentially poorer model performance was suggested by its RMSE of 0.017 which was greater than that produced by the Dex model (0.009). The saturated water content (θ_{SAT}) of the soil predicted by the vanG model marginally differed between the COH and CC soil, and the M compared to the U and UNPK treatments. Similar trends showing marginal variations were observed for fitting shape parameters of the soil water retention curve, namely α, n, and m (Table 3).

3.4. Relating bulk density to textural and structural pores

The A_1 and A_2 parameters are highly influenced by soil densification; therefore, a simple linear regression analysis was performed to investigate the relationship between soil bulk density and the A_1 and A_2 parameters of the Dex model (Figs. 3a and 3b). There was a negative relationship between bulk density and structural pores (the A_2 parameter) at 0–5 and 5–10 cm depths. Surprisingly, bulk density was strongly and inversely related to textural pores (the A_1 parameter) at the 0–5 cm depth, which explained 68 % of the A_1 variance probably due to freeze-thaw in this layer.

3.5. Optimum soil water content for tillage

The θ_{OPT}, estimated as the local minimum by the Dex model (θ_{OPTDex}) or as the water content at the inflection point by the vanG model (θ_{INFL}), is shown in Table 5. The COH had higher θ_{FC}, θ_{INFL}, and θ_{OPTDex} than the CC treatment at all depths except for θ_{INFL} at the 0–5 cm depth where values were similar (Table 5). Soil θ_{INFL} declined with depth and tended to be higher at all depths in the M treatment than in the UNPK and U treatments. At 5–10 cm depth, θ_{INFL} in the M (0.27 kg kg^{-1}) and UNPK (0.22 kg kg^{-1}) were both higher than the U treatment (0.26 kg kg^{-1}). Table 5 indicates that the θ_{OPT} in the rotation and fertility regimes determined by the vanG and the Dex models differed. In general, the vanG θ_{INFL}, which estimates θ_{OPT}, was generally wetter than θ_{FC} and the opposite was true for that estimated by the Dex's θ_{OPTDex}.

4. Discussion

4.1. Common metrics

The relationships between commonly used soil metrics, soil management, and plant productivity are generally understood. For example, plant root growth can be restricted when bulk density exceeds critical values of 1.47 Mg m^{-3} in clay, 1.75 Mg m^{-3} in silt, and 1.80 Mg m^{-3} in loam and sandy soils (Arshad et al., 1996). Similarly, root growth can be slowed down by soils with PRs exceeding 2 MPa and completely impeded by PR ≥ 3 MPa (Bengough et al., 2011; Dexter, 2004). Observations at the Morrow Plots showed that even after almost a century and a half, the bulk density values in the COH and CC plots were below the critical limits. In general, the benefits of diversified crop rotation to soil quality are loosely tied to the incorporation of manures and plant residues that increase SOC. Reduced bulk density and PR in the Morrow Plots can readily be tied to SOC levels that are 54 % higher in the COH than in CC plots. Additions of crop residues and manure can reduce soil bulk density and PR due to improvements in structure and the dilution effect of lighter organic materials mixing with high-density soil mineral fractions (Ozlu and Kumar, 2018; Ozlu et al., 2019). While the influence of fertility is less clear, bulk density was greatest in the inorganically fertilized UNPK plots relative to both the U and M plots and, soil PR was reduced in the M plots where SOC contents were greatest.

4.2. Water retention data

The water retention characteristics of the Morrow Plots soils provide additional insights into how management alters soil hydraulic properties which are of increasing interest due to the challenges posed by climate change. The larger proportion of mesopores observed in the COH treatment using soil water retention curves resulted in greater θ_{FC}, PWP, and WHC than present in the CC soils. Soil θ_{FC}, PWP, and WHC were also greater in the M than U or UNPK plots. While differences in pore size abundance were relatively small, differences exerted notable influences

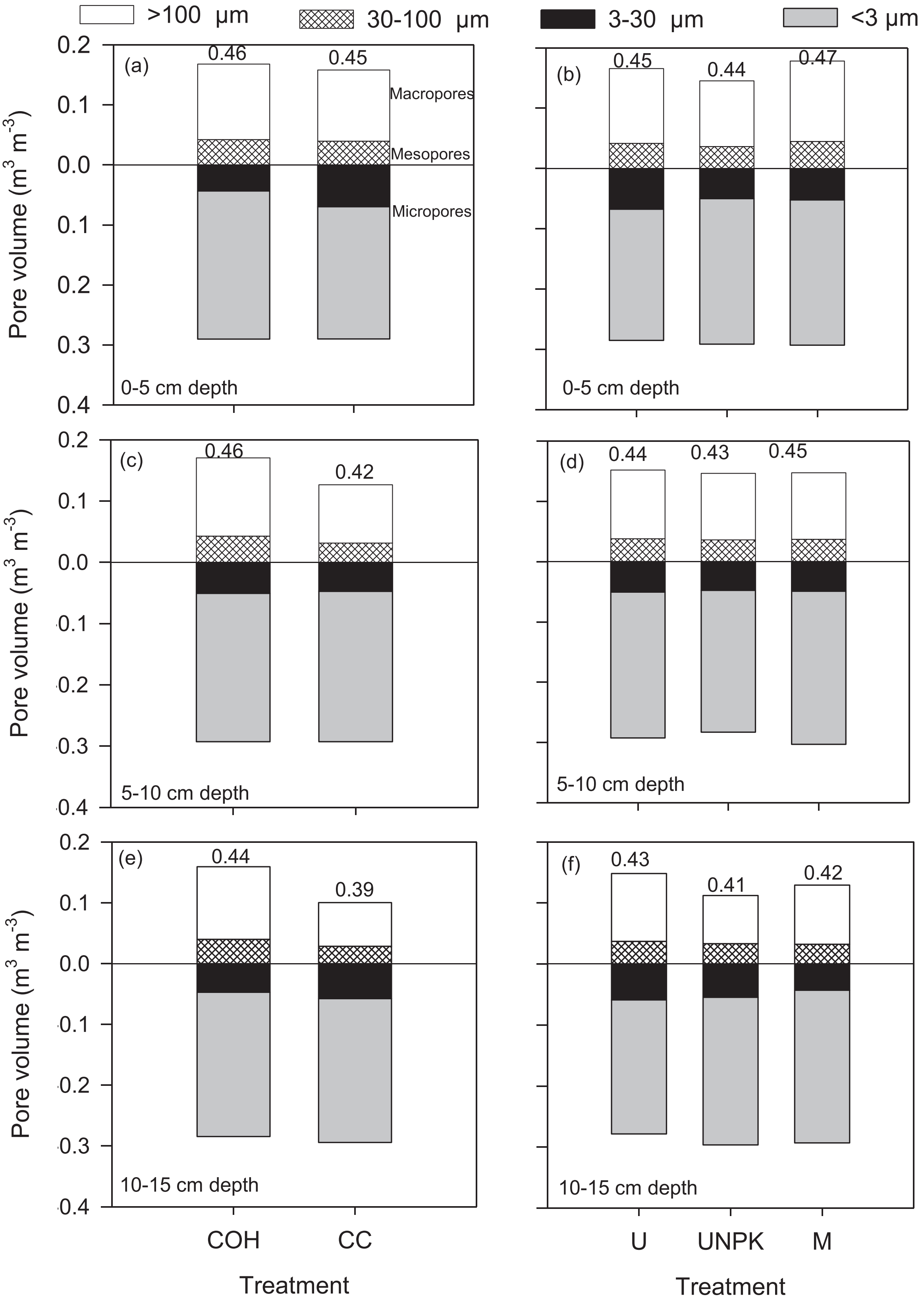

Fig. 2. Fractions of pores of selected size classes as derived from the soil water retention measurements across cropping system (a and c) and fertilization (b and d) at 0–5, 5–10, and 10–15 cm depth. The values on top of bars are total pore volumes. Continuous corn (CC), and corn-oat-hay (COH) rotation and fertilizer treatments: unamended (U), Nitrogen, phosphorus, and potassium applied to formerly unamended plots (UNPK) and manure (M). The zero-lines separate macro-pores (pores >100 µm) and meso-pores (pores 30–100 µm) and from micropores (pores <30 µm).

Table 3
Estimated van Genuchten soil water retention parameters at 0–5, 5–10 and 10–15 cm depths.

Treatment	Depth (cm)	θ_{SAT}	θ_{RES}	α	n	m	AIC	RMSE
	0–5							
Mean for rotation +/-								
COH		0.38 ± 0.08	0	0.25 ± 0.05	1.13 ± 0.04	0.12 ± 0.03	−103.83	0.007
CC		0.33 ± 0.03	0	0.16 ± 0.06	1.16 ± 0.04	0.14 ± 0.03	−86.13	0.017
Means for fertility regimes +/-								
U		0.36 ± 0.03	0	0.22 ± 0.04	1.14 ± 0.01	0.13 ± 0.01	−99.30	0.008
UNPK		0.33 ± 0.03	0	0.20 ± 0.12	1.14 ± 0.04	0.12 ± 0.03	−99.55	0.011
M		0.39 ± 0.10	0	0.21 ± 0.03	1.17 ± 0.05	0.15 ± 0.04	−86.10	0.019
	5–10							
Mean for rotation +/-								
COH		0.38 ± 0.04	0	0.26 ± 0.05	1.13 ± 0.02	0.12 ± 0.01	−105.03	0.006
CC		0.28 ± 0.02	0	0.23 ± 0.09	1.11 ± 0.02	0.10 ± 0.01	−103.93	0.007
Means for fertility regimes								
U		0.34 ± 0.06	0	0.24 ± 0.05	1.13 ± 0.02	0.12 ± 0.02	−104.70	0.006
UNPK		0.30 ± 0.03	0	0.25 ± 0.11	1.13 ± 0.01	0.12 ± 0.01	−104.55	0.008
M		0.35 ± 0.07	0	0.25 ± 0.04	1.12 ± 0.02	0.11 ± 0.02	−104.20	0.007
	10–15							
Mean for rotation +/-								
COH		0.35 ± 0.05	0	1.15 ± 0.06	0.13 ± 0.07	0.20 ± 0.05	−98.13	0.02
CC		0.28 ± 0.07	0	0.73 ± 0.16	0.06 ± 0.57	0.40 ± 0.05	−118.33	0.00
Means for fertility regimes								
U		0.34 ± 0.07	0	0.88 ± 0.18	0.11 ± 0.59	0.67 ± 0.09	−103.29	0.02
UNPK		0.28 ± 0.05	0	0.84 ± 0.13	0.08 ± 0.56	0.04 ± 0.09	−108.00	0.00
M		0.31 ± 0.08	0	1.10 ± 0.07	0.09 ± 0.02	0.18 ± 0.02	−113.39	0.00

θs_{AT} is the water content at saturation obtained from the water retention curve, θ_{RES} is the residual water content, AIC (Akaike's Information Criterion), RMSE (Root mean square error), α, n and m are the fitting shape parameters of the soil water retention curve. Continuous corn (CC), and corn-oat-hay (COH) rotation and fertilizer treatments: unamended (U), Nitrogen, phosphorus, and potassium applied to formerly unamended plots (UNPK) and manure (M). Mean values are followed by one standard deviation of the mean.

Table 4
Estimated Dexter Double Exponential Equation parameters at 0–5, 5–10, 10–15 cm depths.

Treatment	Depth	C	A_1	h_1	A_2	h_2	AIC	RMSE
	cm	$m^3 m^{-3}$	$m^3 m^{-3}$	hPa	$m^3 m^{-3}$	hPa	-	-
	0–5							
Mean for rotation								
COH		0.17 ± 0.02	0.17 ± 0.05	1289.83 ± 10.93	0.15 ± 0.04	18.57 ± 1.98	−96.43	0.009
CC		0.14 ± 0.01	0.17 ± 0.04	1532.00 ± 850.53	0.14 ± 0.01	19.73 ± 8.18	−95.63	0.009
Means for fertility regimes								
U		0.16 ± 0.02	0.19 ± 0.01	1005.80 ± 114.70	0.15 ± 0.01	15.15 ± 1.71	−95.80	0.010
UNPK		0.17 ± 0.03	0.16 ± 0.04	1453.85 ± 85.71	0.14 ± 0.02	19.55 ± 3.29	−99.40	0.008
M		0.15 ± 0.01	0.18 ± 0.06	1773.10 ± 953.08	0.17 ± 0.04	22.75 ± 8.17	−92.90	0.011
	5–10							
Mean for rotation								
COH		0.17 ± 0.01	0.17 ± 0.02	1303.03 ± 496.02	0.15 ± 0.02	19.10 ± 4.76	−96.90	0.009
CC		0.14 ± 0.02	0.17 ± 0.01	4979.07 ± 1392.22	0.12 ± 0.01	28.67 ± 10.26	−101.67	0.007
Means for fertility regimes								
U		0.17 ± 0.03	0.16 ± 0.03	2092.15 ± 1664.52	0.14 ± 0.02	24.40 ± 11.74	−98.90	0.008
UNPK		0.12 ± 0.02	0.20 ± 0.01	5529.15 ± 129.89	0.13 ± 0.01	23.35 ± 1.05	−101.75	0.007
M		0.18 ± 0.00	0.15 ± 0.04	1801.85 ± 204.22	0.15 ± 0.03	23.90 ± 2.15	−97.20	0.009
	10–15							
Mean for rotation								
COH		0.18 ± 0.02	0.16 ± 0.02	1183.20 ± 503.77	0.14 ± 0.02	18.08 ± 4.46	−101.32	0.006
CC		0.11 ± 0.01	0.08 ± 0.00	2040.05 ± 2493.69	0.07 ± 0.00	24.36 ± 25.27	−113.39	0.004
Means for fertility regimes								
U		0.12 ± 0.01	0.11 ± 0.03	633.85 ± 276.43	0.10 ± 0.03	11.22 ± 1.87	−107.57	0.005
UNPK		0.12 ± 0.03	0.10 ± 0.02	1831.18 ± 1272.09	0.09 ± 0.02	28.74 ± 26.67	−109.42	0.005
M		0.19 ± 0.02	0.14 ± 0.03	2369.85 ± 2575.52	0.12 ± 0.03	23.71 ± 13.70	−105.07	0.005

C is the asymptote of the equation, A_1 and A_2 are the amounts of textural and structural pore space, and h_1 and h_2 are characteristics of the pore water suction at the textural and structural pores, respectively, and RMSE (Root mean square error). Continuous corn (CC), and corn-oat-hay (COH) rotation and fertilizer treatments: unamended (U), Nitrogen, phosphorus, and potassium applied to formerly unamended plots (UNPK) and manure (M). Mean values are followed by one standard deviation of the mean.

on water retention characteristics (Rabot et al., 2018) that likely contribute to consistently higher maize yields achieved in the COH rotation.

Additional information about soil management and structure interactions may be provided by models. As stated earlier, some authors have argued that the Dex model can better describe water retention in well-structured soils with bi-modal pores than the vanG model (Dexter et al., 2008; Ding et al., 2016; Jensen et al., 2019). In the present study, the model statistics (AIC and RMSE) did not indicate that either model had a superior ability to consistently describe the water retention curve of the Morrow Plots. Nevertheless, from the perspective of tillage-induced soil structural deformation, the θ_{OPT} estimated by the Dex model in the Morrow Plots was generally slightly drier than θ_{FC}, whereas the θ_{OPT} estimated by the vanG model was generally wetter

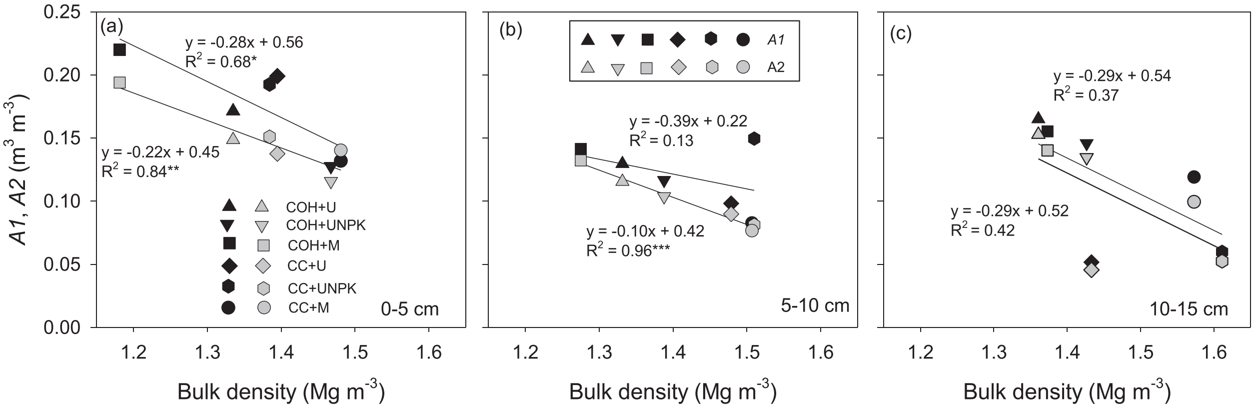

Fig. 3. Textural porosity (A_1) and structural porosity (A_2) as a function of bulk density for the investigated treatments at 0–5, 5–10 and 10–15 cm depth. *$p < 0.05$; * * $p < 0.01$; * ** $p < 0.001$. Continuous corn (CC), and corn-oat-hay (COH) rotation and fertilizer treatments: unamended (U), Nitrogen, phosphorus, and potassium applied to formerly unamended plots (UNPK) and manure (M).

Table 5
Water content at field capacity and the optimum water content for tillage estimated by the van Genuchten Equation (vanG) and the Dexter Double Exponential Equation (Dex) at 0–5, 5–10 and 10–15 cm depths.

Treatment	θ_{FC}	θ_{INFL}	θ_{OPTDex}	θ_{FC}	θ_{INFL}	θ_{OPTDex}	θ_{FC}	θ_{INFL}	θ_{OPTDex}
	kg kg^{-1}								
		0–5 cm depth			5–10 cm depth		10–15 cm depth		
Mean for rotation									
COH	0.26 ± 0.04	0.29 ± 0.06	0.25 ± 0.03	0.26 ± 0.03	0.28 ± 0.04	0.24 ± 0.01	0.24 ± 0.01	0.26 ± 0.01	0.23 ± 0.01
CC	0.23 ± 0.02	0.29 ± 0.02	0.21 ± 0.01	0.21 ± 0.01	0.22 ± 0.01	0.19 ± 0.01	0.19 ± 0.01	0.20 ± 0.02	0.17 ± 0.01
Means for fertility regimes									
U	0.25 ± 0.02	0.27 ± 0.01	0.24 ± 0.03	0.24 ± 0.03	0.26 ± 0.04	0.22 ± 0.04	0.21 ± 0.04	0.23 ± 0.04	0.20 ± 0.05
UNPK	0.24 ± 0.01	0.24 ± 0.00	0.22 ± 0.01	0.22 ± 0.01	0.22 ± 0.01	0.21 ± 0.02	0.21 ± 0.02	0.22 ± 0.04	0.19 ± 0.03
M	0.26 ± 0.05	0.35 ± 0.05	0.23 ± 0.05	0.25 ± 0.04	0.27 ± 0.04	0.22 ± 0.03	0.23 ± 0.03	0.24 ± 0.03	0.22 ± 0.03

θ_{FC} (Water content at field capacity), θ_{INFL} (Water content at inflection point) estimated by van Genuchten equation, and θ_{OPTDex} (Optimum water content estimated by Dexter double exponential function). Continuous corn (CC), and corn-oat-hay (COH) rotation and fertilizer treatments: unamended (U), Nitrogen, phosphorus, and potassium applied to formerly unamended plots (UNPK) and manure (M). Mean values are followed by one one standard deviation of the mean.

than θ_{FC} (Table 5). Tillage when the soil is wetter than θ_{OPT} can damage soil increasing the risks of soil compaction as well as the production of undesirable seedbed structures dominated by a greater number of large clods that hinder crop establishment (Dexter and Birkas, 2004; Obour et al., 2017). The θ_{OPT} was greater under the M treatment than either the U or UNPK treatments. Increases in the θ_{OPT} of the COH and M soils and associated increases in structural pore spaces (A_2), were consistent with the findings showing that management practices that decrease soil bulk density tend to increase A_2 of soils (Dexter et al., 2008) and benefit productivity (Obour et al., 2018).

4.3. Practical implication of findings

Long-term field trials provide critical insights into the impact of crop rotations and fertility regimes on soil physical quality (Johnston and Poulton, 2018). In the Morrow Plots, no single model (neither the Dex nor the vanG) was consistently superior in describing the water retention curves across different crop rotations and fertility regimes. This discrepancy observed in the model fits highlights the complexity of soil water retention modeling and suggests that no ‘one-size-fits-all’ model exists for all soil types and management practices. Overall, the findings emphasize that management practices that reduce bulk density and improve soil structure, such as crop rotation and organic amendments can enhance soil water retention and availability. These practices are critical for maintaining long-term soil fertility and ensuring sustainable crop production.

5. Conclusions

Both the van Genuchten and Dexter double exponential models demonstrated that the inclusion of COH in the Morrow Plots generally increased soil water content at pF0 – 4.2 and the optimum water content for tillage (θ_{OPT}) at soil depths of 0–5, 5–10 and 10–15 cm compared to soils under continuous corn (CC) cropping. The incorporation of animal manure tended to decrease soil bulk density and reduce soil penetration resistance at the Morrow Plots compared to the UNPK fertilization. Regarding model performance, statistical evaluations (AIC and RMSE) did not reveal a consistent trend indicating a superior model fit across rotation, fertility regimes, and soil depths in the Morrow Plots. Notably, the van Genuchten model typically estimated a wetter θ_{OPT} compared to field capacity (θ_{FC}), suggesting that the Dexter model may offer a more accurate representation of soil water retention characteristics in these Plots. We acknowledge the constraints on the lack of true replication at the Morrow Plots. Even so, the long history (i.e. >140 years) of continuous cropping and diverse management regimes of the Morrow Plots makes it a valuable resource for understanding the trends and impact of various long-term agricultural strategies. Also, collecting soil samples from different depths at the Morrow Plots has proven valuable in providing a more comprehensive understanding of how long-term management practices influence soil physical quality, especially soil water retention and θ_{OPT} under different crop rotations and fertility management regimes.

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CRediT authorship contribution statement

Peter B. Obour: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yushu Xia:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Carmen M. Ugarte:** Writing – review & editing, Supervision, Resources, Funding acquisition, Formal analysis, Conceptualization. **Tony Grift:** Writing – review & editing, Resources, Funding acquisition. **Michelle M. Wander:** Writing – review & editing, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors report no declarations of interest.

Data availability

Data will be made available on request.

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