Holding water with capacity to target porosity

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Abstract
Optimizing soil microbial activity requires an equal balance between water- and air-filled porosity, that is, 50% water-filled pore space (WFPS). However, many soil biological investigations report water as some fraction of water-holding capacity (WHC). This study was conducted to fill a quantitative gap between WFPS and WHC. Soil samples (n = 198) from 10 eastern U.S. states and one state in Brazil provided a wide distribution of clay (0.064–0.487 kg kg$^{-1}$) and soil organic C (SOC, 5.2–52.0 g kg$^{-1}$) concentrations (5–95% range). Gravimetric soil water content (SWC) was determined at WHC and at saturation. Both clay and SOC concentrations strongly influenced SWC; the effect of SOC was strongest and nonlinear. To achieve 50% WFPS, gravimetric SWC was 0.69 $\pm$ 0.10 times that of WHC and 0.59 $\pm$ 0.03 times that of saturation. For soil biological assays, 50% WFPS could be accurately and simply achieved with calculations using gravimetric SWC at saturation multiplied by 0.59.

1 INTRODUCTION

Soil water content and temperature are the primary environmental factors influencing soil microbial activity (Curiel Yuste et al., 2007; Moyano et al., 2012). Influence of water on microbial activity has been characterized using various measurements and indices, including matric potential, gravimetric and volumetric water content, water-holding capacity (WHC), water-filled pore space (WFPS), precipitation indices, and depth to water table (Davidson, Verchot, Cattanio, Ackerman, & Carvalho, 2000). Linn and Doran (1984) showed clearly that WFPS was an appropriate indicator of water control on soil respiratory activity on a Mollisol in Nebraska. In Ultisols in Georgia, 50% WFPS (0.50 m$^3$ m$^{-3}$) was considered appropriate to optimize both C and N mineralization (Franzluebbers, 1999).

In laboratory incubations, control over soil water content (SWC) is much greater than in the field with growing plants, solar incidence, wind, relative humidity, temperature, and precipitation patterns. Therefore, accurate control of SWC can lead to best evidence of how soil microbial activity is influenced by short- and long-term soil management activities. If not controlled, then management effects may not be accurately expressed. Despite this potential control on an important determinant of soil microbial activity to assess the effects of management, SWC is still not fully standardized during laboratory incubations. Perhaps because WFPS requires information on both soil mass and volume, it is not used universally to control SWC. Many investigators prefer to use WHC as a guide for SWC (Karhu, Mattila, Bergström, & Regina, 2011; Rao & Pathak, 1996; Xu, Tan, Wang, & Gai, 2016). However, the proportion of WHC that is ideal for soil microbial activity does not appear to be universally defined. Some

Abbreviations: SOC, soil organic carbon; SOM, soil organic matter; SWC, soil water content; WFPS, water-filled pore space; WHC, water-holding capacity.
investigators have considered SWC at 50% of WHC (Tarafdar, Meena, & Kathju, 2001; Wade et al., 2018), whereas others have used SWC at 60% of WHC (Fritze, Smolander, Levula, Kitunen, & Mäikkönen, 1994; Xu et al., 2016), and still others used SWC at > 60% of WHC (Labud, Garcia, & Hernandez, 2007; Peeples, 1974). It may also be possible that terms become intermixed in comprehensive ecosystem-level studies without adequate definition of finer details.

The objective of this study was to determine quantitative relationships among gravimetric SWC at saturation, at WHC, and at 50% WFPS from a range of soils. One hypothesis was that a constant WHC level would be related to WFPS across a diversity of soils. Another hypothesis was that soil texture and organic matter concentration would affect the amount of water retained and would be important variables in adjusting soil water-microbial activity associations.

2 MATERIALS AND METHODS

A total of 198 soil samples were collected from agricultural fields across a diversity of environments in the United States and Brazil (Table 1). Samples were from various projects involving grain crop and pasture management and represented different depth increments within the surface 30 cm of soil. Soils were selected to maximize distribution of soil texture and organic matter; for example, two depths were often selected from the same no-tillage or pasture field to obtain expected difference in soil organic C (SOC). Six samples of organic amendments with high SOC were analyzed separately and only appear in the inset of Figure 1. These samples were four oak (Quercus spp.) biochar samples, one mixed-residue yard compost, and one ground and roasted coffee bean (Coffeea arabica L.).

Total C and N were determined from soil subsamples on a Leco TruMac CN analyzer and assumed as organic since pH was acidic for all samples (5.6–6.6). Sand and clay concentrations were predicted from near infrared spectroscopy (Model 5000 with WinISI version 1.5 software, Foss North America, Inc.) of pulverized soil (ball milled for 2 min). Calibration was from 278 samples that were selected using ‘H’ statistic of 0.6. Standard error of calibration was 0.156 and 0.060 kg kg⁻¹ for sand and clay, respectively. The middle 90% of calibration observations was 0.160–0.744 kg kg⁻¹ for sand and 0.078–0.480 kg kg⁻¹ for clay. Statistical distribution of samples in this study at 5, 50, and 95 percentile limits was 0.064, 0.259, and 0.487 kg kg⁻¹, respectively, for clay and 5.2, 19.7, and 52.0 g kg⁻¹, respectively, for SOC.

Soil passing a screen with 4.75-mm openings was heaped into a cylindrical metal container with total volume of 80 ml (54 mm diam., 35 mm height). Containers had five 1-mm-diameter holes punched into the bottom. The container was tapped vigorously 10 times to allow soil to settle, and then a metal blade was used to shear off excess soil to exactly 80 ml volume. Containers of soil were dried in a forced-air oven at 55 °C for 9 h before being immersed into a pan of deionized water ~10 mm deep. Water was allowed to tick up into soil for 14 h, at which time containers were wiped of outside water and weighed immediately to calculate SWC at saturation. Containers were placed onto a paper towel, lid placed loosely on top to avoid evaporation, and allowed to drain freely for 9 h, at which time containers were weighed to calculate SWC at WHC. Containers of soil were dried in an oven at 55 °C for 3 d and then further dried at 105 °C for 16 h and mass recorded.

Density of sieved soil in the metal container was calculated as mass (variable among samples) per volume (80 ml fixed). Total porosity was derived from density, assuming particle density of 2.65 Mg m⁻³ [Total porosity = (1 – Density)/2.65]. All other calculations were derivations from soil mass at 105 °C, gravimetric SWC at saturation and at WHC, and density of soil.

Data were analyzed with SAS v. 9.4 (SAS Institute, Inc.) and plotted with SigmaPlot v. 14.0 (Systat Software, Inc.). Clay and SOC concentrations were independent variables in single and multiple regressions with soil water properties as dependent variables. Significance of variables was declared with α = .01.

3 RESULTS AND DISCUSSION

Gravimetric SWC at saturation was influenced by clay concentration (F = 60, p < .001), but more so by SOC concentration (F = 491, p < .001), as well as their interaction (F = 27, p < .001). For every 0.10 kg kg⁻¹ increase in clay, SWC at saturation increased 0.018 kg kg⁻¹ from a base of 0.266 kg kg⁻¹. For every 10 g kg⁻¹ increase in SOC, SWC at
### Table 1: Location, soil series, and taxonomy of samples selected for this investigation

| Soil taxonomy | Soil series and textural class | Location (state and county) |
|---------------|--------------------------------|-----------------------------|
| **Entisols**  | Coarse-loamy, mixed, semiactive, nonacid, thermic Aquic Udifluvents | Cartecay fSL, GA Madison |
|               | Coarse-loamy, mixed, active, nonacid, mesic Typic Udifluvents     | Comus fSL, NC Henderson     |
|               | Fine-loamy, mixed, active, nonacid, thermic Oxyaquic Udifluvents   | Congaree L, NC Catawba     |
| **Inceptisols** | Fine-loamy, mixed, active, thermic Fluvaqueptic Dystrudepts | Chewacla L, NC Rowan, NC Stanly |
|               | Loamy, mixed, mesic Lithic Dystrochrepts                           | Hollis-Charlton fSL, NH Strafford |
|               | Coarse-loamy, mixed, active, mesic Oxyaquic Dystrudepts            | Paxton fSL, MA Franklin     |
|               | Coarse-loamy, mixed, active, mesic Dystric Eutrudepts              | Spoolsville SiL, MD Frederick |
|               | Coarse-loamy, mixed, semiactive, frigid Typic Fragiaquults         | Lewbeach chL, Willowemoc chSiL, NY Delaware |
|               | Fine-loamy, mixed, superactive, nonacid, mesic Cumulic Humaquepts  | Toxaway L, NC Ashe          |
| **Alfisols**  | Fine, mixed, active/semiactive, mesic Typic Hapludalfs              | Hagerstown L, Poindexter-Wynott complex, Enott L, MD Frederick, NC Davidson, VA Mecklenburg |
|               | Fine, mixed, active, thermic Ultic Hapludalfs                      | Enon fSL, Mecklenburg CL, NC Davidson, NC Rowan |
| **Ultisols**  | Typic Rhodudalfs                                                   | Clayey, São Paulo Brazil   |
|               | Fine-loamy, mixed, semiactive, thermic Aeric Endoaquults           | Bertie fSL, NC Pasquotank   |
|               | Fine-loamy over sandy or sandy-skeletal, siliceous, subactive, thermic Typic Endoaquults | Lumbee fSL, NC Pender |
|               | Fine, kaolinitic, thermic Typic Fragiaquults                       | McColl L, NC Scotland      |
|               | Fine-loamy over sandy or sandy-skeletal, semiactive, thermic Aquic Hapludults | Johns fSL, Johns SL, NC Duplin, NC Wayne |
|               | Very-fine/fine/fine-loamy/loamy-skeletal/coarse-loamy, kaolinitic/mixed, subactive/active/semiactive, mesic/thermic Typic Hapludults | Badin chSiL, Clifftop-Nallen complex, Clifton L, Cullen CL, Glenelg L, Hartleton chSiL, Junalaska-Brassstown complex, Lansdale L, Rawlings-Rion, Rayne-Gilpin chSiL, Rhodhiss SL, Wickham LS, MD Harford, NC Alamance, NC Ashe, NC Clay, NC Davidson, NC Rockingham, NC Wake, NC Wayne, PA Lancaster, PA Northumberland, PA Somerset, WV Raleigh |
|               | Fine/fine-loamy, kaolinitic, thermic Typic Kandiudults              | Faceville fSL, Faceville LS, Georgeville, Norfolk LS, NC Nash, NC Robeson |
|               | Fine, kaolinitic, thermic Rhodic Kanhapludults                      | Lloyd CL, Lloyd L, NC Catawba, NC Rowan |

(Continues)
Table 1 (Continued)

| Soil taxonomy                                      | Soil series and textural class                                                                 | Location (state and county) | Oxisols ($n = 17$, clay = $0.483 \pm 0.020$ $\text{kg kg}^{-1}$, SOC = $12.7 \pm 4.0$ $\text{g kg}^{-1}$) |
|---------------------------------------------------|-----------------------------------------------------------------------------------------------|-----------------------------|----------------------------------------------------------------------------------|
| Fine, kaolinitic, mesic/thermic Typic              | Appling fSL, Appling SL, Cecil SCL, Cecil SL, Clifford L, Clifford SCL, Fairview SCL, Herndon L, Madison SL, Pacolet SCL, Tarrus chSiCL, Tarrus SiL | GA Oconee, GA Madison, NC Guilford, NC Iredell, NC Orange, NC Person, NC Rockingham, NC Rowan, NC Stanly, NC Surry, NC Yadkin |
| Fine/fine-loamy/fine-silty, kaolinitic/siliceous, semiactive/subactive, thermic Aeric Paleaquults | Dunbar fSL, Lynchburg fSL, Nahunta SiL | NC Brunswick, NC Halifax, NC Scotland |
| Fine-loamy, siliceous, semiactive, thermic Typic Paleaquults | Rains fSL | NC Beaufort |
| Fine-loamy, siliceous, subactive, thermic Oxyaquic Paleudults | Noboco LS | NC Scotland |
| Fine, kaolinitic, thermic Plinthic Paleudults | Varina SL | SC Dillon |
| Fine/fine-silty, kaolinitic/siliceous, subactive, thermic Typic Paleudults | Aycock vSiL, Faceville LS | NC Robeson, SC Dillon |

Note. chSiCL, channery silty clay loam; chSiL, channery silt loam; CL, clay loam; fSL, fine sandy loam; L, loam; LS, loamy sand; SCL, sandy clay loam; SiL, silt loam; SL, sandy loam; SOC, soil organic C.

saturation increased an average of 0.034 $\text{kg kg}^{-1}$. However, SWC at saturation increased an additional 0.015 $\text{kg kg}^{-1}$ for every unit product of clay and SOC. This meant that soil effectively increased in gravimetric SWC by 0.033 $\text{kg kg}^{-1}$ for every 0.10 $\text{kg kg}^{-1}$ increase in clay and by 0.049 $\text{kg kg}^{-1}$ for every 10 $\text{g kg}^{-1}$ increase in SOC. Percentage of total variation in SWC at saturation was 8% due to clay, 64% due to SOC, and 4% due to their interaction.

In a similar manner, gravimetric SWC at WHC and SWC at 50% WFPS increased with clay, SOC, and their interactions. Effects were generally of the same magnitude (although clay was not significant for SWC at WHC), and coefficients of change were lower. For every 0.10 $\text{kg kg}^{-1}$ increase in clay, SWC at WHC increased 0.005 $\text{kg kg}^{-1}$ from a base of 0.253 $\text{kg kg}^{-1}$ and SWC at 50% WFPS increased 0.008 $\text{kg kg}^{-1}$ from a base of 0.166 $\text{kg kg}^{-1}$. For every 10 $\text{g kg}^{-1}$ increase in SOC, SWC at WHC increased 0.035 $\text{kg kg}^{-1}$ and SWC at 50% WFPS increased 0.016 $\text{kg kg}^{-1}$. For both SWC at WHC and at 50% WFPS, an additional 0.010 $\text{kg kg}^{-1}$ occurred for every unit product of clay and SOC. Therefore, soils effectively increased in gravimetric SWC at WHC by 0.015 $\text{kg kg}^{-1}$ for every 0.10 $\text{kg kg}^{-1}$ increase in clay and by 0.045 $\text{kg kg}^{-1}$ for every 10 $\text{g kg}^{-1}$ increase in SOC. Realistically achieving such an increase in SOC in the surface 10 cm of soil would then lead to 4.0, 4.9, and 6.1 mm more water held at 10, 50, and 90th percentiles of soil density (0.897, 1.090, and 1.345 $\text{Mg m}^{-3}$, respectively) (i.e., 14% greater than initial condition at 25th percentile of WHC in this study).

Soil organic C had a major influence on retention of water at saturation, as well as at 50% WFPS, considered ideal for microbial activity (Figure 1). Nonlinear responses suggested that the impact of changing SOC was far greater when soils were in a depleted state than when they had “adequate” SOC of 11.6 $\text{g kg}^{-1}$ (i.e., 2% soil organic matter [SOM]). Splitting the dataset at 11.6 $\text{g kg}^{-1}$ resulted in linear regression coefficients of 0.022 and 0.005 $\text{kg SWC g}^{-1}$ at saturation in depleted and adequate SOM conditions, respectively. Coefficients were 0.016 and 0.004 $\text{kg SWC g}^{-1}$ at WHC and 0.012 and 0.003 $\text{kg SWC g}^{-1}$ at SWC at 50% WFPS. Therefore, a dramatic increase in WHC can occur by enriching SOM in depleted soils, but much less effect on soils already in adequate SOM condition. This nonlinear response was similar in nature to that of crop yield per unit change of SOC (Oldfield, Bradford, & Wood, 2019). The insets of Figure 1 indicate that large organic C inputs could lead to further improvements, but these are hypothetical until proven in the field. Organic amendments could absorb significant water as surface mulches.

Across clay and SOC variations, the fraction of WHC at 50% WFPS was $0.69 \pm 0.10$ (mean $\pm$ SD). This coefficient of variation of 14% suggests that for agricultural soils, optimum SWC for soil C and N mineralization assays would be 59–79% of WHC. However, with even lower coefficient of variation (6%), the fraction of saturation at 50% WFPS was 0.59 $\pm$ 0.03, or 56–62% of saturation. Therefore, gravimetric SWC at 56–62% of saturation would be a better
FIGURE 1  Sieved soil density (top panel) and soil water content at saturation, at water-holding capacity (WHC), and at 50% water-filled pore space (WFPS) (bottom panel) as influenced by soil organic C concentration. Note: inverted triangles are data at saturation, circles are data at WHC, and squares are data at 50% WFPS. Nonlinear regressions were of the form: soil water content = a + b × [1 − exp(−c × soil organic C)]. Coefficients were 0.21, 0.48, and 0.044 for a, b, and c, respectively, at saturation ($r^2 = 0.67, p < 0.001$); 0.20, 0.44, and 0.033 for a, b, and c, respectively, at WHC ($r^2 = 0.71, p < 0.001$); and 0.13, 0.27, and 0.042 for a, b, and c, respectively, at 50% WFPS ($r^2 = 0.65, p < 0.001$). Insets are from six pure organic amendments to illustrate that theoretical limits are lower/greater than from soils selected standard and could be used with greater confidence when conducting soil C and N mineralization assays.

Gravimetric fractions of SWC at saturation and at WHC to meet a particular WFPS level followed a linear relationship. Therefore, if WFPS level needed to be adjusted to some level other than 50% WFPS (i.e. 0.5 m$^3$ m$^{-3}$), the following equations could be used:

Fraction of saturation = 1.187 × WFPS (m$^3$ m$^{-3}$)

Fraction of WHC = 1.415 × WFPS (m$^3$ m$^{-3}$)

For example, if 60% WFPS were preferred (Doran, Mielke, & Power, 1990), then the fraction of saturation would be 0.71, instead of 0.59 at 50% WFPS.

Data from this study support a recommendation for using gravimetric SWC at 0.59 times that of saturation for determining optimum soil microbial activity (i.e., target of 50% WFPS). If in fact SWC were set at saturation, this would have been too wet for optimum C and/or N mineralization; that is, saturation was equivalent to 85 ± 4% WFPS. As well, those studies that opted for 50% of WHC as a target would have had too little water, as this was equivalent to 36 ± 5% WFPS.

Another key observation from this dataset was that the increase in SWC with incremental change in SOC in soils with depleted SOM was more consistent with results in Hudson (1994), whereas the increase in SWC with incremental change in SOC with adequate SOM was closer to results across a review of previous studies (Minasny & McBratney, 2018). This important distinction in baseline SOM condition may be a reason why both small and large changes in SWC retention can occur in response to SOC differences.

4 | CONCLUSIONS

For aerobic incubations to determine soil C and N mineralization, gravimetric SWC at 0.59 times that of saturation was ideal to target 50% WFPS. This simple approach would have achieved 47–54% WFPS in 90% of the 198 samples. Data also revealed a strong association of SWC at saturation and at WHC with SOC concentration, but in a non-linear manner. Clearly, increasing SOC from very low levels could have a dramatic impact on soil water retention (∼48%), but increasing SOC beyond an adequate condition (i.e. 2% SOM) would be moderate (∼12%).

ACKNOWLEDGMENTS

Erin Silva provided sound technical support in the laboratory. Soil samples from Maryland, Massachusetts, New Hampshire, New York, Pennsylvania, and West Virginia were provided by Sarah Goslee and Matt Sanderson. Soil samples from São Paulo, Brazil, were from collaborations with João-Paulo Rigon-Gonsiorikiewicz, Katiuça-Sueko Tanaka, Luanda Torquato-Feba, and their advisors, Carlos Crusciol and Edemar Moro.

DATA AVAILABILITY STATEMENT

Data are available at https://doi.org/10.5061/dryad.tdz08kpxj.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Franzluebbers AJ. Holding water with capacity to target porosity. Agric Environ Lett. 2020;5:e20029. https://doi.org/10.1002/ael2.20029