Effects of No-Till and Daikon Winter Crops on Surface Soil Structure and Hydrology

Isaac W. Vendig

ABSTRACT

With rising awareness of the detrimental effects of long-term tillage on agricultural soils, interest in alternative management techniques such as no-till is on the rise. Alongside this is an increased awareness of the benefits to soil provided by winter cover crops. The Daikon radish has been proposed as a winter crop to break up soil compaction and alter infiltration rates, but currently lacks adequate research. Many previous studies have sought to compare soil physical structure and hydrology of no-till soils with conventionally tilled soils but have often failed to account for the dynamic nature of a conventionally tilled soil. The goal of this study is three-fold: first, to compare the soil structure and water retention properties of a no-till soil with those of a conventionally tilled soil. Second, to assess the impact of varying the sampling date of a tilled soil with respect to the most recent tillage event, and lastly to assess the impact of Daikon radish winter cropping on surface soil structure and hydrology. The results of this study indicate that substituting a "recently disturbed" tilled soil for a "settled" tilled soil in a no-till comparison is most likely to produce substantially different results in macroporosity comparisons whereas the same substitution plays a minor or insignificant role in plant available water and microporosity comparisons. The use of a Daikon cover crop with no-till resulted in a significantly reduced pore volume in the 7.5 to 0.75 micron diameter region, possibly hinting at a deleterious effect of Daikon cover crop usage in the top 5 cm of no-till soil.

KEYWORDS

Macroporosity, microporosity, plant available water, tillage, long term experiment

INTRODUCTION

In the last century, crop breeding, increased mechanization of agriculture, and increased access to a diverse agrochemical arsenal has enabled farmers to pull more food from the surface of the earth than ever before. Although these developments have supported an exponentially growing human population fairly well on the timescale of decades, the sustainability of their use on an intergenerational timescale remains unlikely (Chan et al. 2003). Undergoing re-assessment is the agricultural practice of tillage as a means of breaking up the soil, with the goal of better root growth, better aeration, and to increase availability of soil nutrients for crops (Ussiri and Lal 2009; Brady and Weil 2002). The practice of intensive tillage is declining as a result of its destructive long-term effects on soil structure and soil health and because of increased availability of herbicide (Lal 1993; Logan 1991). No-till agriculture, a form of management that employs complete cessation of tillage, is currently being explored as a means to alleviate some negative effects of tillage such as organic matter depletion and reduced aggregate stability (Franzluebbers 2002).

Crop performance is greatly influenced by a soil's chemical composition and structure because these factors determine how much soil water can be made available to a plant. Forces of adhesion and capillary action bind water to a soil to differing degrees depending on chemical composition and pore structure (Lal and Shukla 2004). The strength by which water is bound to a soil (in units of pressure) can be measured at various states of saturation and compiled as a graph to form the water retention curve (WRC). The shape of a soil's WRC is highly consequential for crop production because it determines the amount of water a plant is able to extract from a given soil (Brady and Weil 2002). A soil's plant available water (PAW) is defined as the volumetric water content of a soil between field capacity (-33 kPa) and permanent wilting point (-1500 kPa) (Behrman et al 2016). Because of the intimate relationship between a soil's PAW and its pore structure, a management technique can alter a soil's PAW and thus influence crop production (Azooz et al 1996).

Studies comparing no-till (NT) to conventionally tilled (CT) soils commonly examine the differences between soil structures of each management technique because of the implications of soil structure for soil hydrology, root health, and aeration (Reynolds et al 2009). One way soil structure can be quantified is as a pore size distribution, a function representing the relative abundance of pores of certain size classes in a soil. The pore size distribution is derived from the

WRC using a capillary rise equation that relates a given matric potential in pascals to the equivalent pore diameter exerting that capillary force (Bhattacharyya et al 2006; Azooz et al. 1996). In addition to altering a soil's PAW by changing its pore size distribution, NT management increases freely draining macropores by increasing macro-aggregation and burrow-forming macro-faunal activity (Six et al. 2000; Kay and VandenBygaart 2002). An increase in macroporosity, here defined as the volume of porosity with equivalent pore diameter greater than 30 microns, would allow for improved soil drainage, air exchange, and better root growth (Brady and Weil 2002; Reynolds et al. 2009). While soil structure comparisons between CT and NT are vital for a determination of management impacts on soil health, the immediate effects of tillage on pore size distributions of CT systems greatly complicate such a comparison.

The pore size distribution and thus water retention characteristics of a CT soil change drastically and rapidly following tillage, making it difficult or impossible to accurately characterize the structure and hydrology of any given CT soil. Tillage operations, often occurring biannually, result in a sharp spike in macroporosity and mesoporosity meant to provide germinating plants with well drained and well aerated soils free from compaction (Sandin et al. 2017). In the weeks and months following tillage, the pore size distribution and consequently the WRC shifts as inter-aggregate spaces (macropores and mesopores) created by tillage collapse (Leij et al. 2002). The resulting pore size distribution and WRC of a CT soil are thus wave-like in nature, constantly rearranging following tillage and subsequently settling, only to be rearranged again. Most previous studies comparing CT and NT soil structure and hydrology take into account only a single time point in these CT dynamics for the comparison, often choosing it on the basis that some unspecific amount of time has passed since tillage so that the soil has been allowed to settle after disturbance (Bhattacharyya et al. 2006; Azooz et al. 1996). This static type of comparison fails to accurately portray the structure of a soil that at any point in its life might be found oscillating around two main states: "disturbed" and "settled".

While tillage is certainly a vital determinant of soil structure, the physical and biological effects of plant roots on aggregation and pore structure cannot be overlooked. It has been shown that NT systems left bare in winter have been shown to exhibit severe soil compaction, and thus it is highly beneficial for NT farms to employ some crop between periods of cultivation (Uphoff et al. 2006). The Daikon radish has been proposed as a means of relieving soil compaction because of its capacity to break through subsurface hardpans with its strong and deep taproot (Chen and

Weil 2010). The subsurface pan having been penetrated, weaker crop roots would then be able to grow into the path of old Daikon roots and extract water from otherwise unavailable deep soil water (Williams and Weil 2004). Above the hardpan, however, it is uncertain how the Daikon might affect surface soil structure and hydrology and it is indeed possible that the reduced coverage area of the Daikon root may create conditions closer to those of bare soil (Chen and Weil 2010). Very few previous no-till studies have explored the structural and hydrological effects of the use of a Daikon radish winter crop as opposed to more conventional crops with fibrous roots (Williams and Weil 2004).

In order to determine the differences in soil structure and hydrology between NT and CT systems, I will compare water retention characteristics and pore size distributions of an NT soil and those same metrics of a continuous CT system at two time points: once 1.5 weeks after tillage and again 21 weeks after tillage. A second comparison will determine the effect of varying the time elapsed since tillage of the CT soil by comparing the previous results. The following hypotheses guided this study: 1) Differences between NT and CT on the wet end of the WRC, representing the macropore volume fraction, will not be uniform across both sets of comparisons because of the dynamic nature of a CT soil, specifically with respect to macroporosity; 2) Because tillage has a limited short-term effect on pores less than 30 microns in diameter, I hypothesize that pore volume comparisons in this pore size range will not be significantly affected by the varying of CT sampling date; 3) I expect to see a shift towards greater PAW in NT plots compared to CT plots and I expect this increase to be uniform across both sets of comparisons because PAW is held by pores mostly unaffected by tillage in the short term; 4) Because the effect of the Daikon root is really intended for deep soil compaction, I don't expect the use of a Daikon cover crop to have any structural or hydrological effects within the top 5 cm of soil.

METHODS

Study site and sampling design

At the Oxford Tract, UC Berkeley (37.8762° N, 122.2673° W), the Bowles research group at the University of California, Berkeley began a 3 year long randomized-controlled experiment in July 2017 to measure interactions of two organic agricultural management techniques: Tillage (conventional tillage (CT) and no-till (NT)) and winter crop type (Daikon and broccoli). Besides the lack of tillage, the only difference between the NT treatments and the CT treatments was the rate of compost addition to both treatments. To best simulate common compost application rates for each treatment, based on local farmers' practices, NT beds received 1.5 kg • m^{-2} of compost per month whereas CT beds received 0.51 kg • m^{-2} per month. At any given time during cultivation periods, at least 8 different vegetable crops were being grown across all beds so that the cropping system could be characterized as a rotational poly-crop. The experiment was set up as a randomized complete block split plot design with tillage regime as the whole-plot factor and cover crop type as the sub-plot factor. With 4 replicates, the entire experiment consisted of 16 beds, each 30.48 meters in length and 1 meter wide. The soil under cultivation is a Tierra Alfisol according to the USDA-NCSS soil survey data (O'Geen 2018**)** and had been under CT management for at least two decades before the commencement of the experiment. Prior soil testing has determined its composition to be clay-loam: 42% sand, 24% silt, 34% clay with 4.1% soil organic matter (A&L Western Laboratories, unpublished data).

To compare the structural and hydrological properties of the NT beds to those of the CT beds, I sampled the NT beds once, 15 months after conversion from CT, and sampled the CT beds twice: once 21 weeks after the last tillage event [CT (21)] and then again 1.5 weeks after the last tillage event [CT (1.5)]. I divided each bed into 3 equal sub-parcels on a diagram, assigned numbers (1, 2, and 3) to each parcel, and then randomly sampled one of these sub-parcels. This was done to avoid the possibility of any soil gradients on the plot systematically affecting measurements. CT soil cores were collected once after weeks of settling and then collected again from the same locations immediately following autumn tillage on October 3rd, 2018. Sampling dates for water retention curves are displayed in Table 1 for reference.

Table 1. Sampling timeframe. Tillage group labels, sampling dates, and time since last tillage of each group. Groups assigned the same bed label letter were sampled from the same beds.

Tillage Group	**Sampling Date**	**Time Since Tillage**	**Bed Label**
CT (1.5)	Oct 13, 2018	1.5 Weeks	a
CT (21)	Sep 22, 2018	21 Weeks	a
NT	Oct 4, 2018	15 Months	b

Development of water retention curves

To develop WRCs, I collected intact 250-milliliter soil cores from each of the selected sites, sampling from the top of the soil and extending 5 centimeters down into the soil column. On NT beds with recent compost additions, I brushed aside loose compost to access intact soil. To gather points on the wet end of the curve (0 kPa to -100 kPa) I analyzed the soil cores using an evaporation technique in conjunction with an instrument employing two mini precision tensiometers (Hyprop 2, Meter Group, https://www.metergroup.com/?q=hyprop; Bogie et al 2018). For this procedure, I saturated each core in a bath of manually degassed water for 36 hours using capillary rise and then I connected each to the Hyprop tensiometer and allowed them to dry for roughly 6 days, until cavitation within the tensiometer was reached.

I analyzed water retention points on the dry end of the curve (1 MPa to 100 MPa) using a WP4C dewpoint potentiometer. For this procedure, I saturated 2-gram subsamples from each core and continually measured their water potentials as they dried until the potentiometer gave a reading of 1 MPa. I then recorded 6 potentiometer readings for each subsample as they dried from 1 MPa to 100 MPa along with their respective weights. When samples had dried out to 100 MPa, they were oven dried at 105° C for 36 hours and re-weighed to determine gravimetric water content and were subsequently plotted alongside the Hyprop points using bulk density measurements from intact cores to convert to volumetric water content. Using the Hyprop Fit software, the combined water retention points were fitted to constrained bimodal Van Genuchten curves (Meter Group 2011; Durner 1994). This WRC model was chosen on the basis of minimized root mean square error as compared to other common models.

Pore size distributions

To develop pore size distributions for each site, I manipulated WRCs using a common conversion formula. I calculated pore size distributions from WRCs using the equation $EPD = \frac{4\sigma\cos\alpha}{\rho g h}$ where σ is the surface tension of the water (72.8 mN m^{-1} at 25° C), α is the angle of the meniscus (assumed to be zero), ρ is the density of water (.998, g cm^{-3}), g is gravitational acceleration (980 cm s^{-2}), h is the matric pressure (cm water) and EPD is the equivalent pore diameter in micrometers (Reynolds 2009). I divided the pore sizes into 4 size classes: 30 microns to measured saturation (macroporosity), 30-7.5 microns, 0.75-0.02 microns, and less than 0.02 microns in a method similar to that employed by Bhattacharyya et al. (2006). Each class, representing a percentage of total soil volume, was compared first between NT and CT (1.5) and then between NT and CT (21) to test for significant differences in pore size distributions.

Plant available water calculation

PAW was calculated as the difference between water contents at field capacity (-33 kPa) and permanent wilting point (-1500 kPa) as modeled using the constrained bimodal Van Genuchten curves (Durner 1994).

Statistical analysis

I compared PAW, macroporosity, and all pore size intervals using 2-way split plot ANOVAs with "tillage treatment" as a whole-plot factor and "winter crop type" as a sub-plot factor. For the NT to CT (1.5) comparison, the whole-plot factor contained two levels: NT and CT (1.5). For the NT to CT (21) comparison, the whole-plot factor also contained two levels: NT and CT (21). For both comparisons, the sub-plot factor contained two levels: Daikon winter crop and broccoli winter crop. I considered both main effects and interaction effects for each comparison. I only considered p-values less than 0.05 significant, but also reported marginally significant ($0.05 > p > 0.10$) effects. I subsequently separated all groupings with significant ANOVA effects ($p < 0.05$) using Tukey's HSD test (alpha= 0.05). Split plot ANOVAs and HSD tests were conducted using the R package "Agricolae" (R Core Team 2018).

I tested homogeneity of variance and normality of residuals for every model to confirm that ANOVA assumptions were met. I tested data for homoscedasticity using the Levene test in the R package "Cars" with alpha equals 0.05 (R Core Team 2018). I natural log transformed all heteroscedastic data to maintain homogeneity of variance and the two cases in which this transformation still did not result in homoscedastic data were noted in the results section. I confirmed Normality of residuals using the Shapiro-Wilk normality test in R with alpha = 0.05 (R Core Team 2018).

RESULTS

Water retention curves

The most substantial difference between curves can be seen in the gap between the CT (21) and CT (1.5) curves in the top left portion of the graph corresponding to the macropore fraction (Figure 1).

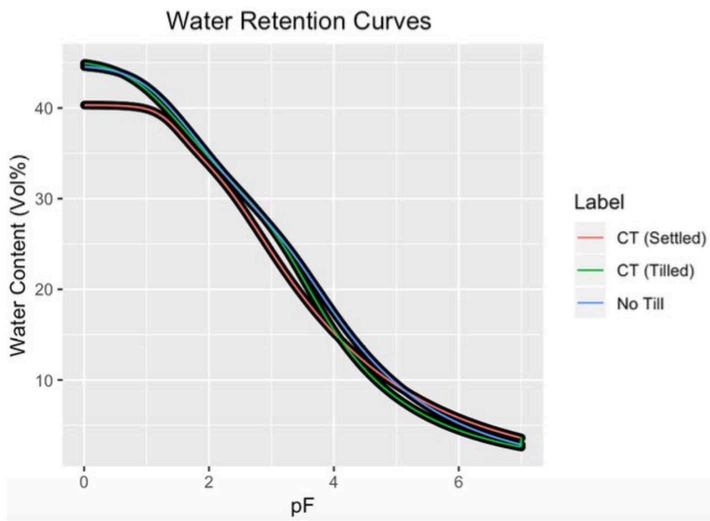

Figure 1. Average water retention curves of tillage groups. Averaged water retention curves for each tillage group (n=8 for each curve). "Settled" CT soils correspond to CT (21) while "Tilled" CT soils correspond to CT (1.5). The greatest difference between the curves is visible in the top left (macropore) portion of the graph.

Pore size distribution

In the analysis of the main effect of tillage, the two macropore fraction (30 micron diameter and greater) ANOVAs produced results that contradicted one another in both direction of difference and significance level (Table 2). On the contrary, in the 0.75 to 0.02 micron fraction, a noteworthy similarity in the main effect of tillage across both sets of comparisons was evident, with similar directions of difference and significance levels. Although no main effects of winter crop variation (Daikon vs broccoli) were found to be significant, one significant interaction effect was found in the 7.5 to 0.75 micron diameter range.

Main Effects of Tillage

Table 2. Main effects of tillage. Mean volumetric water content percentages of each interval grouped by tillage treatment and the corresponding ANOVA results for main effects of tillage. Table (a) displays the NT to CT (1.5) comparisons while table (b) displays the results of the NT to CT (21) comparisons. Two marginally significant main effects (•) and one significant main effect (*) occurred. Contradicting results are evident in the macropore (30+ micron diameter) fraction while the 0.75 to 0.02 micron fraction shows notable similarities across both comparisons.

a)

Pore Size Interval	NT (Vol %)	CT (1.5) (Vol %)	F Value	P Value
30+ Microns	9.49%	11.87%	9.99	0.0508•
30 to 7.5 Microns	4.37%	4.55%	0.60	0.49
7.5 to 0.75 Microns	8.45%	9.95%	2.79	0.19
0.75 to 0.02 Microns	13.53%	12.46%	8.42	0.06•
0.02 Microns and Less	7.66%	7.35%	2.85	0.19

b)

Pore Size Interval	NT (Vol %)	CT (21) (Vol %)	F Value	P Value
30+ Microns	9.49%	8.65%	0.74	0.45
30 to 7.5 Microns	4.37%	4.20%	4.08	0.13
7.5 to 0.75 Microns	13.53%	9.50%	1.95	0.26
0.75 to 0.02 Microns	13.53%	11.44%	19.57	0.021*
0.02 Microns and Less	7.66%	8.43%	0.0054	0.95

CT macropore volume in the NT to CT (1.5) comparison was numerically greater than that of the NT soil. Though these means were not technically significantly different ($p > 0.05$), a strong trend verging on significance is evident. When the same comparison was made with the “settled” CT (21) soil, however, the CT macropore volume was found to be numerically (though not statistically) lower than that of the NT (Figure 2).

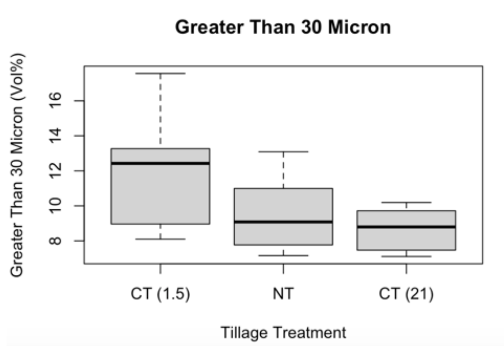

Figure 2. Macroporosity box plots. Box plots of macropore (30+ microns) volume percentages grouped by tillage type. NT to CT macropore comparisons produce contradictory results when CT (1.5) is substituted for CT (21).

NT soils had greater volumetric pore space in the pore diameter range of 0.75 to 0.02 microns in both the NT to CT (1.5) and NT to CT (21) comparisons (13.56% to 12.46% and 11.44% respectively) (Fig. 3). In addition to this similarity in direction of difference, both comparisons showed similar (but not equivalent) levels of significance. In the NT to CT (1.5) comparison, Levene's test indicated that variances were unequal when grouped by tillage treatment, $F = 5.96$, $p = 0.029$. Data were natural log transformed to correct this but were still heteroscedastic when transformed, $F = 4.96$, $p = 0.043$.

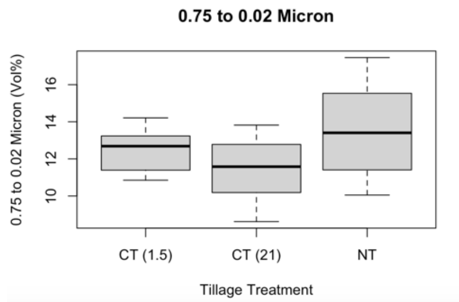

Figure 3. NT microporosity in the 0.75 to 0.02 micron range. Volumetric pore space of NT soils was greater in both CT comparisons in the 0.75 to 0.02 micron diameter range. Significance levels were similar (but not equivalent) across both comparisons.

Winter Crop Main Effects

No main effects of winter crop variation on any pore size range were significant (Table 3).

Table 3. Winter crop main effects. Mean volume percentages within respective pore size intervals separated by winter crop type. Table (a) corresponds to the NT to CT (1.5) comparison while table (b) displays results of the NT to CT (21) comparison. No significant main effects of Daikon vs broccoli winter crops were evident in either comparison.

a)

Pore Size Interval	**Daikon (Vol %)**	**Broccoli (Vol %)**	**F Value**	**P Value**
30+ Microns	10.15%	11.16%	1.75	0.23
30 to 7.5 Microns	4.35%	4.58%	0.15	0.71
7.5 to 0.75 Microns	8.97%	9.46%	1.91	0.21
0.75 to 0.02 Microns	13.93%	12.12%	2.94	0.14
0.02 Microns and Less	7.96%	8.21%	0.91	0.38

b)

Pore Size Interval	**Daikon (Vol %)**	**Broccoli (Vol %)**	**F Value**	**P Value**
30+ Microns	9.28%	8.84%	0.30	0.60
30 to 7.5 Microns	4.28%	4.29%	0.004	0.99
7.5 to 0.75 Microns	8.41%	9.57%	2.32	0.18
0.75 to 0.02 Microns	13.64%	11.39%	3.66	0.10
0.02 Microns and Less	8.49%	8.47%	0.01	0.91

Interaction Effects

One marginally significant interaction effect and one significant interaction effect occurred (Table 4).

Table 4. Interaction effects. Mean volume percentages within respective pore size intervals separated into interaction groups with ANOVA results. Table (a) displays values for the NT to CT (1.5) comparison and table (b) displays values for the NT to CT (21) comparison. One marginally significant interaction effect (•) and one significant interaction effect (*) occurred, both in the NT to CT (1.5) comparison.

a)

Pore Size Interval	**NT - Daikon (Vol %)**	**NT-Broccoli (Vol %)**	**CT (1.5) - Daikon (Vol %)**	**CT (1.5) - Broccoli (Vol %)**	**F - Value**	**P -Value**
30+ Microns	9.83%	9.11%	10.48%	13.21%	5.13	0.06•
30 to 7.5 Microns	4.62%	4.13%	4.08%	5.03%	1.50	0.27
7.5 to 0.75 Microns	7.59%	9.34%	10.36%	9.57%	12.84	0.01*
0.75 to 0.02 Microns	15.35%	11.78%	12.51%	12.57%	2.97	0.14
0.02 Microns and Less	8.42%	8.73%	6.95%	7.70%	0.16	0.71

b)

Pore Size Interval	**NT - Daikon (Vol %)**	**NT-Broccoli (Vol %)**	**CT (21) - Daikon (Vol %)**	**CT (21) - Broccoli (Vol %)**	**F - Value**	**P -Value**
30+ Microns	9.83%	9.11%	8.75%	8.56%	0.10	0.76
30 to 7.5 Microns	4.62%	4.13%	3.95%	4.46%	0.95	0.36
7.5 to 0.75 Microns	7.59%	9.34%	9.24%	9.79%	0.64	0.45
0.75 to 0.02 Microns	15.35%	11.78%	11.95%	11.00%	1.23	0.31
0.02 Microns and Less	8.42%	8.73%	8.57%	8.22%	0.50	0.51

The interaction effect in the 7.5 to 0.75 micron diameter range was found to be significant in the NT to CT (1.5) ANOVA, $F(1, 6) = 6.41$, $p = 0.01$. Means were subsequently separated by Tukey's HSD test (alpha = 0.05) and the NT-Daikon group was determined to be significantly lower than the other 3 groups (Figure 4).

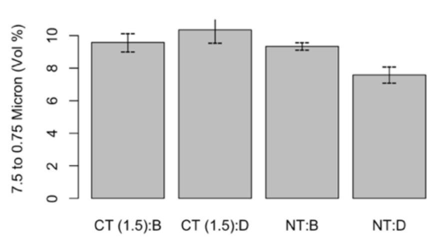

Figure 4. Interaction effect in the 7.5 to 0.75 micron range. Bar graph displaying mean volume percentages of each interaction group in the 7.5 to 0.75 micron diameter range with standard error bars affixed on top. The NT-Daikon group contained significantly less pore volume in this range than the other 3 groups.

The marginally significant interaction effect in the macropore range of the NT to CT (1.5) comparison was not separated by Tukey's HSD test because significance at $p < 0.05$ was taken as a prerequisite to mean separation. As such, it is not possible to tell which groups differed from one another at $p < 0.10$, but the CT groups appear to form a distinct block with values numerically greater than the NT groups.

Plant available water

No PAW measurements were significantly different from one another in either NT to CT (1.5) or NT to CT (21) comparison (Tables 5 and 6 respectively). Levene's test indicated that variances were unequal in the NT to CT (21) PAW comparison when grouped by tillage treatment, $F = 5.17$, $p = 0.039$. Values were natural log transformed to correct this but were still unable to be made homoscedastic, $F = 4.89$, $p = 0.044$. These means were not significantly different when natural log transformed $F(1, 3) = 0.13$, $p = 0.75$.

In the NT to CT (1.5) comparison, one marginally significant interaction effect occurred in which the NT-Daikon PAW was numerically lowest out of all four (Table 5c). Also notable in this marginally significant interaction is a numerical ordering according to tillage group, with the two NT means being least and the two CT (1.5) means numerically greater.

Table 5. ANOVA results of NT to CT (1.5) PAW comparisons. Mean PAWs and main effects of tillage (a), mean PAWs and main effects of winter crop variation (b), and mean PAWs of interaction groups and corresponding interaction effects (c). (•) denotes marginal significance.

a)

	NT	**CT (1.5)**	**F Value**	**P Value**
PAW (Vol %)	14.83%	16.56%	2.16	0.23

b)

	Daikon	**Broccoli**	**F Value**	**P Value**
PAW (Vol %)	15.79%	15.59%	0.15	0.71

c)

	NT–Daikon	**NT–Broccoli**	**CT (1.5) – Daikon**	**CT (1.5) – Broccoli**	**F Value**	**P Value**
PAW (Vol %)	14.39%	15.27%	17.19%	15.92%	4.61	0.075•

Table 6. ANOVA results of NT to CT (21) PAW comparisons. Mean PAWs and main effects of tillage (a), mean PAWs and main effects of winter crop variation (b), and mean PAWs of interaction groups and corresponding interaction effects (c).

a)

	NT	CT (21)	F Value	P Value
PAW (Vol %)	14.83%	15.35%	0.13	0.75

b)

	Daikon	Broccoli	F Value	P Value
PAW (Vol %)	14.93%	15.37%	0.33	0.59

c)

	NT-Daikon	NT-Broccoli	CT (21) - Daikon	CT (21) - Broccoli	F - Value	P - Value
PAW (Vol %)	14.39	15.27%	15.23%	15.47%	0.038	0.85

DISCUSSION

The goal of this study was to determine the effect of 15 months of NT agriculture on soil structure and hydrology by comparing NT soils to CT soils at two timepoints since the last tillage of a CT soil. Through use of this dual comparison, it is possible to first examine the methodological implications of the dynamic CT soil structure by identifying incongruencies in results across each comparison. By identifying those results that stayed constant across both sets of comparisons, it is then possible to not only determine those aspects of soil structure and hydrology that are unaffected by the regular rearrangement of the CT soil structure, but also to determine reliable differences in NT and CT soils owing to their respective management regimes. In addition to the primary question of methodology and the secondary question of tillage regime effects, this research also sought to determine the effects of Daikon winter crop usage on soil structure and hydrology versus fibrous rooted winter crops like broccoli. With a more reliable methodology, more information on NT versus CT, and information on Daikon usage in conjunction with NT, farmers may be able to determine the most suitable set of management techniques for the health of their soils.

Macroporosity

The dynamic macropore structure of a CT soil complicates structural and hydrological comparisons between CT and NT soils and makes it difficult to assess differences in soil health between the two management techniques. Soils lacking in adequate macroporosity can result in severely reduced crop yields because of the importance of macropore space for soil aeration and healthy root growth (Brady and Weil 2002). As has been noted in many studies, the most substantial immediate effect of tillage on soil structure is to elevate structural (macropore) pore space by agitation of the soil structure (Leij et al 2002; Sandin et al 2017). This elevated macropore space is evident in the NT to CT (1.5) comparison in which the mean CT macropore space was found to be (marginally) greater than that of the NT. Over the course of weeks to months following tillage, this macropore space subsequently declines as the soil settles. Evidence of this settling is apparent in the NT to CT (21) macropore comparison, in which the CT macropore space showed no significant difference from that of the NT and was in fact numerically lower. As such, the macropore space of a CT soil at any given time might be found in a highly elevated state, a reduced state, or somewhere in between depending on the proximity of the most recent tillage event.

Many previous NT studies over-simplify the NT to CT comparison with respect to macropore space by only taking into account one time point in the dynamic CT timeframe. This time point is often alluded to as being sufficiently removed from the most recent tillage as to be free from disturbance and may be 4 weeks after tillage, 28 weeks after tillage, or may not even be specified (Azooz et al 1996; Bhattacharyya et al 2006; Alvarez and Steinbach 2009). The macropore volume data illustrate the importance of considering both "disturbed" and "settled" tilled soils in an NT to CT comparison as one CT time point might result in differing or even opposing results if substituted for the other. Furthermore, a decision to consider only "settled" CT soils misrepresents CT soil macroporosity, suggesting that the norm for a CT soil is its "settled" state when in fact the point of tillage is to continually shift a CT soil into a "disturbed" state. Had this study been restricted to a comparison between only NT and CT (1.5) or only NT and CT (21), differing and possibly conflicting results would have been obtained and, alone, neither would accurately depict the dynamic nature of CT macropore structure.

Microporosity

A shift towards greater microporosity in the 0.75 to 0.02 micron pore fraction evident in both sets of NT to CT comparisons has mixed implications for the ability of NT to store plant available water. This increase in NT microporosity is not uncommon in previous studies and may be the result of the compaction of micropores shifting intra-aggregate pore size distributions towards smaller sizes, though no significant compaction was otherwise evident (Reichert et al 2016). Some of the porosity within this fraction holds water available to plants, but any water held within pores less than 0.2 microns in diameter is inaccessible (Brady and Weil 2002). If NT porosity shifts towards pores holding water too tightly bound for usage by crops without a corresponding increase in overall porosity to offset it, this greater microporosity may come at the expense of PAW. The numerically (though not significantly) decreased PAW I found in NT soils compared to both CT soils may hint at such a deleterious shift, but no conclusive evidence of such a trend in PAW can be found in this study.

Plant available water

The effects of management regime on PAW were likely non-significant in both comparisons because of the limited effects of NT on pores holding plant available water. A dominant mechanism by which NT is believed to alter soil structure is that of increased macro-aggregate formation and stability (Six et al 2000). Through increased aggregation via organic binding agents, inter-aggregate pore space of NT soils is elevated relative to CT soils. This process, in addition to pore formation by earthworm activity, creates pores that are likely too large to be filled at field capacity, the lower boundary of PAW, and are thus unable to influence PAW. If, as is suggested in previous literature, the NT soils under consideration did indeed have greater macro-aggregate formation and stability than the CT soils, the effect of this macro-aggregation on pores holding PAW was too modest to alter PAW significantly (Six et al 2000). On the contrary, the numerically lower PAW of NT soils compared to CT soils at both time points may even suggest a reduction in porosity containing PAW under NT after 15 months of conversion due to shifts in intra-aggregate porosity.

Both PAW comparisons (NT to CT (1.5) and NT to CT (21)) yielded identical results because PAW is held mostly by pores outside of the range of porosity immediately affected by tillage. Plant available water is soil water held between a suction of -33 kPa and -1500 kPa, corresponding to pores with diameters of 8.85 microns and .2 microns respectively (Lal and Shukla 2004). Because the immediate effect of tillage is mainly on structural macropore space and PAW is mostly composed of textural micropore space, PAWs are unlikely to be dramatically different when a CT soil is sampled 1.5 weeks after tillage versus 21 weeks after tillage (Brady and Weil 2002; Leij et al 2002). As such, it is unlikely to make a difference whether NT soils are compared to tilled soils immediately after tillage or compared to tilled soils after months of settling when considering PAW.

Winter crop effects

Although the strong taproot of a Daikon may provide structural and hydrological benefits to soils at the depth of a hardpan or claypan, its low root abundance in the top soil may have negative effects on pore volumes at a 5 cm depth. In a study comparing taproot cover crops with fibrous rooted cover crops, Chen and Weil (2010) found Daikon roots to be less numerous than fibrous rooted cover crop species in the top layer of soil (5-10 cm), a finding consistent with the morphology of this plant. A highly reduced root density likely created conditions closer to NT plots lacking winter crops, which can be more compacted than heavily tilled soils (Uphoff et al 2006). The significantly lower porosity of the NT-Daikon group in the 7.5 to 0.75 micron fraction is thus attributable to the reduced root density of the Daikon compared to a broccoli cover crop in conjunction with NT's propensity for compaction. As this pore size fraction is a key component of PAW, the use of a Daikon cover crop with NT may in time reduce PAW in the top 5 cm of soil compared to a fibrous rooted cover crop, though no conclusive evidence of such a PAW reduction is evident in the data collected. However, any detriments of a potential topsoil PAW reduction may be outweighed if the Daikon root is successful in providing crops with access to water below the hardpan or increasing deep percolation.

This interaction effect was likely significant in only the NT to CT (1.5) comparison because the recent tillage had the effect of separating the CT groups more distinctly. A similar numerical ordering of means is found in the CT (21) interaction group comparison in this pore size range, with the NT-Daikon porosity being least of all four groups.

LIMITATIONS AND FUTURE DIRECTIONS

The relatively short duration and small sample size of this experiment likely limited the resolution of the results. Many no-till studies last a decade or more because of the slow-acting nature of soil processes such as organic matter build-up and aggregation (Peigne et al 2017; Mitchel et al 2017). In another decade, more substantial and dependable differences in soil structure and hydrology might be discernable. In addition, increasing sample sizes by sampling each plot twice would likely increase homoscedasticity of data. Two pore size interval comparisons in this study lacked homoscedasticity and were not made sufficiently homoscedastic even when natural log transformed. With greater resources and more time, this study would be improved and a more concrete pattern could be discernable with respect to all physical characteristics measured.

The contradictory results obtained in the macropore fraction of the two NT to CT comparisons highlight a substantial methodological concern for analyses of soil structure and hydrology. In the future, the effects of NT on macro and microporosity and their respective effects on crop health will hopefully be more easily assessed with a slightly modified frame of comparison. By comparing NT structural characteristics to those of CT in both "disturbed" and "settled" states, a less biased comparison of the benefits and detriments of each respective management technique can be made. Specifically, the immediate effects of tillage on CT macroporosity and related hydrological characteristics might be incorporated into future study designs by considering the "disturbed" state of a CT soil as an inherent characteristic of it and consequently including it in any comparison.

The effects of a Daikon cover crop used in conjunction with NT warrant further study. After 15 months, only one season of cover cropping had passed, but in time the effects of a Daikon cover crop might be more pronounced and a clearer pattern more evident. Additionally, if NT plots with Daikon cover crops are indeed more prone to compaction in a critical pore size interval for PAW, further study is necessary to determine the effects of this compaction on PAW after more time has passed. Furthermore, a drought stress tolerance test or a yield comparison experiment might provide evidence on the relative availability of water if there really is a tradeoff between surface soil PAW and deep-water access with Daikon usage. A penetrometer test may also provide more information on the effects of Daikon usage through the depth of a hardpan, where its effect is mainly intended.

Broader implications

In comparing the physical and hydrological characteristics of an NT soil to those of a CT soil, it is most essential to consider the time elapsed since the last tillage of a CT soil when examining metrics associated with macroporosity. Changes in macropore structure upon conversion to NT have significant implications for soil aeration and root growth but the highly variable nature of CT macroporosity greatly complicates any CT to NT comparison (Drewry 2001; Chan 2003). Of equal importance for research purposes is that pore structure comparisons of pores less than 30 microns in diameter as well as PAW comparisons are very little affected by the time elapsed since CT tillage. Lastly, the reduced average root density of a Daikon cover crop may have negative impacts on topsoil porosity when used with NT, a finding which warrants further study.

Changes in PAW previously documented in long term NT studies may require more than 15 months to manifest if they are to manifest at all. As it stands, there is no indication that after 15 months of NT a preferable shift in pore size distribution can be expected. The significant (and marginally significant) increase of NT microporosity in the 0.75 to 0.02 micron range is unlikely to be beneficial for crop production unless that microporosity is able to retain plant available water, a condition for which I found no evidence. With respect to this hydrological data alone, the CT soil 1.5 weeks after tillage is likely to result in the most favorable crop production due to its increased macroporosity compared to NT 15 months after conversion. Other soil suitability metrics not assessed in this study, such as changes in organic matter content, aggregate stability, and many others, could potentially provide evidence to the contrary but would require further study.

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