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Soil physical properties of agricultural systems in a large-scale study

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ABSTRACT

The extent to which findings from small-scale field studies can be used to make agricultural recommendations or management decisions is a concern because of natural influential processes that occur only at a large-scale. A large-scale field study was conducted to determine the effects of agricultural management systems on soil physical properties, including their spatial and temporal variations. Three replicates of the systems were based on soil type in an area that had been intensively mapped and were established in 1998 at the Center for Environmental Farming Systems, Goldsboro, NC. Agricultural management systems include five treatments which were best management practices (BMP: with subplots conventional tillage – BCT and no-tillage – BNT), organic crop production (OCP), integrated crop–animal (ICA), plantation forestry-woodlot (PFW), and abandoned-field succession (AFS). Soil physical properties of bulk density (Db), saturated hydraulic conductivity (Ksat), field capacity (FC), saturated water content (SWC), total porosity (TP), micro- and macroporosity (MicP, MacP), and water stable aggregation (WSA) were measured in multiple years within the period 1999–2007. The experimental methods successfully produced data with acceptable levels of variability, discernable soil property differences between systems, and unambiguous relationships between soil properties. Blocking areas with large portions of a diagnostic soil maintained the homogeneity of experimental plots and produced acceptable error terms in statistical procedures. The sampling scheme used prevented sample collection in previously sampled areas. Tilled systems BCT and OCP did not differ in soil physical properties and their properties remained rather constant with time. The BNT, PFW and AFS systems had similar properties with higher Db, lower TP, higher MicP and higher FC than tilled systems. The ICA sub-treatments developed a post-grazing higher Db, lower TP and lower MacP.

1. Introduction

In scaling-up of small agricultural experiments, results are assumed to be valid despite influential natural processes that occur only at a large-scale; e.g., overland flow and/or rill erosion. Fewer assumptions would be required if the appropriate scaling is considered when building experimental designs. Experiments that are designed to be spatially and temporally large represent commercial management and inferences drawn can be directly related to management information needs. In addition, long-term assessments are important because temporal effects and variations will determine management decisions.

A survey conducted by Van Es et al. (2007) showed that about 97% of field experiments use the Randomized Complete Block Design (RCBD). The RCBD is successful in large-scale field experimentation when within block homogeneity is achieved. Sources of variability used as the basis for blocking are identified, and blocks are delineated in the landscape with sizes, shapes and orientations that accommodate treatments and minimize within block variability. The RCBD has been implemented in large-scale experiments with repeated success (Pierce and Gray, 2006; Monserud, 2002; Fleming et al., 2007).

In addition to minimizing within block variability, another critical design goal of large-scale experiments is to develop an effective plot sampling scheme. For each experimental variable, sampling units, sample size and number, and sampling methods need to be determined. When choosing sampling techniques, the most important criterion is minimization of sampling error (DE Gruijter, 2002).

Abbreviations: BMP, best management practices; BCT, best management practice conventional tillage sub-treatment; BNT, best management practice no-tillage sub-treatment; OCP, organic crop production; ICA, integrated crop–animal; PFW, plantation forestry woodlot; AFS, abandoned-field succession; Db, bulk density; Ksat, saturated hydraulic conductivity; FC, field capacity; SWC, saturated water content; TP, total porosity; MicP, microporosity; MacP, macroporosity; WSA, water stable aggregation; RCBD, randomized complete block design; CEFS, Center for Environmental Farming Systems; FSRU, Farming Systems Research Unit.

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The objective of this paper is two-fold: first, we describe the set-up of a large-scale farming systems study established in 1998 at the Center for Environmental Farming Systems (CEFS) (www.CEFS.ncsu.edu) near Goldsboro, NC. Set-up includes soil mapping, delineation of experimental plots and replications, treatment implementation methods, plot sampling techniques, and data collection. Second, we analyzed soil physical data and discuss results for the various management systems, including spatial and temporal variations. This information will help agricultural scientists develop effective large-scale experiments.

2. Materials and methods

Our experiment, hereafter referred to as the Farming Systems Research Unit (FSRU), was designed to study long-term approaches that integrate a broad range of factors involved in agricultural systems. A major goal of the FSRU was to provide the empirical framework to address landscape-scale issues that impact the long-term sustainability of North Carolina's agriculture. The experiment was located on an 8-ha site intensively mapped based on soil type and subdivided into three blocks (Fig. 1). Three experimental blocks were delineated to enclose one of the two dominant soil types identified as diagnostic soils: Wickham sandy loam (fine, loamy, mixed, thermic Typic Hapludult) or Tarboro loamy sand (mixed, thermic Typic Udipsamment). Each block was subdivided into five main plots to accommodate five management systems: best management practices (BMP's), organic crop production (OCP), integrated crop–animal (ICA), plantation forestry-woodlot (PFW), and abandoned-field succession (AFS). Some main plots were subdivided to accommodate sub-treatments. Experimental plots ranged in size from 1.2 to 3.6 ha.

The vegetation grown in each system is listed in Table 1. The two sub-treatments under the BMP system were conventional tillage (BCT) and no-tillage (BNT). These sub-treatments represent predominant farming practices used by growers in eastern North Carolina and other regions of the South Atlantic Coastal Plain. Practices within each BMP sub-treatment included small-grain crops, short rotations, and pesticides when economically justified. The OCP system was divided into four sub-treatments designed to assess four strategies of transition from conventional to organic crop production. Data from one of the sub-treatments are presented in this paper. The ICA sub-treatments CA1, CA2 and CA3, represented three entry points of a 15-year rotation. Pasture species that were used in ICA included the warm-season perennial grasses switch grass (*Panicum virgatum*), eastern gamagrass (*Tripsacum dactyloides*), indiangrass (*Sorghastrum nutans*), and cool-season annuals such as rye (*Secale cereale*) and ryegrass (*Lolium multiflorum*). When in pasture, the subplots were stocked with dairy steers or beef heifers (*Bos taurus*), goats (*Capra hircus*), swine (*Sus scrofa domesticus*) or poultry (*Gallus* spp.). The PFW used conventional silvicultural practices and sub-treatments are tree species of cherrybark oak (*Quercus falcate* var. *padgodefolia*), bald cypress (*Taxodium distichum*), green ash (*Fraxinus pennsylvanica* var. *lanceolata*), and longleaf pine (*Pinus palustris*). Results from the cherrybark oak sub-treatment are presented in this paper. The AFS system represented a standard (control) for the study of farming environmental impacts. These plots were "abandoned"; i.e., they were not managed throughout the study.

In September 1998, all experimental plots were chisel plowed to the 20 cm depth, disked, and planted to rye (*S. cereale* L.). System implementation began in the spring of 1999 after rye harvest. At this time, five sampling areas within each subplot were selected using random distances perpendicular to a transverse line, and restricted within the diagnostic soil (Fig. 1). To identify each sampling area, the starting point on and the distance from the transverse line were chosen at random. The sampling area center

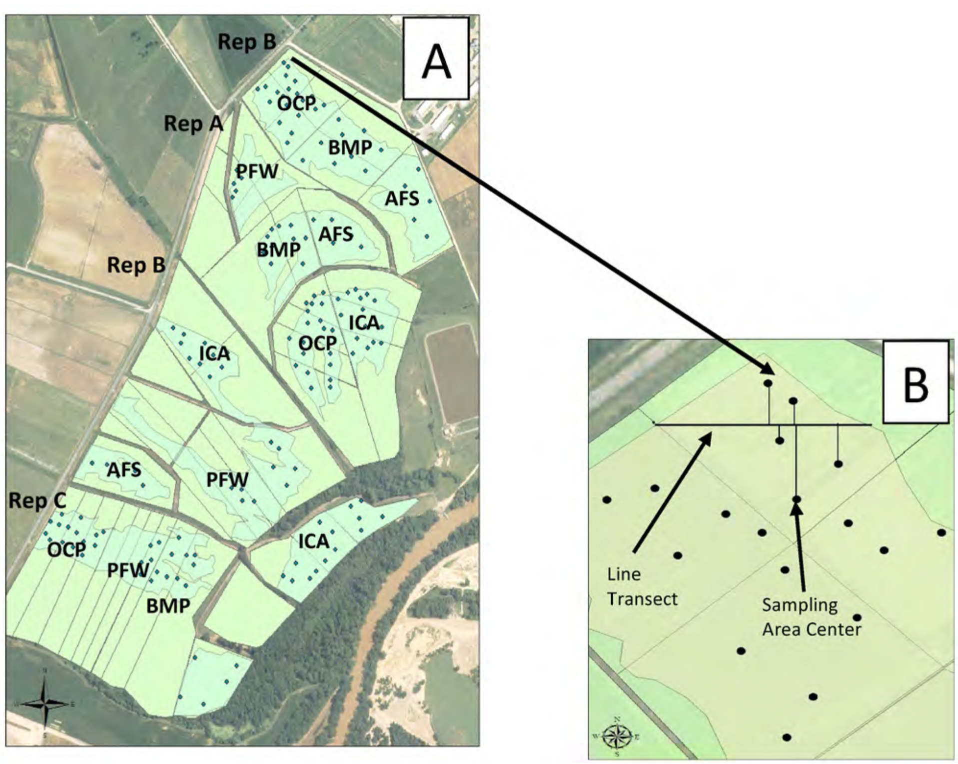

Fig. 1. Experimental layout of the Farming Systems Research Unit at the Center for Environmental Farming Systems, Goldsboro, NC. The experiment (A) is a randomized complete block with three replications. Five sampling areas were randomly chosen within each experimental plot (B). Systems are: BMP = best management practices; OCP = organic crop production; ICA = integrated crop/animal; PFW = plantation-forestry woodlot; AFS = abandoned-field succession.

Table 1
Vegetation grown in each system from 1999 to 2007 at the Farming Systems Research Unit at the Center for Environmental Farming Systems, Goldsboro, NC.

Year	BMP's[a]			ICA				
	BCT	BNT	OCP	CA1	CA2	CA3	PFW	AFS
1999	Corn		Soybeans	Pasture[c]	Corn	Soybeans	Black walnut	Abandoned field
2000	Peanuts		Potatoes[b]	Pasture[c]	Soybeans	Potatoes[b]		
2001	Cotton		Cabbage	Pasture[c]	Cotton	Soybeans		
2002	Corn		Corn	Pasture[c]	Corn	Cotton		
2003	Peanuts		Soybeans	Pasture[c]	Peanuts	Corn		
2004	Corn		Corn	Pasture[c]	Potatoes[b]	Peanuts		
2005	Corn		Corn	Corn	Pasture[c]	Sorghum		
2006	Sorghum		Soybeans	Sorghum	Pasture[c]	Sorghum		
2007	Soybeans		Soybeans	Soybeans	Pasture[c]	Soybeans		

[a] Systems: OCP = organic crop production; BCT = best management practice conventional tillage sub-treatment; BNT = best management practice no-tillage sub-treatment; AFS = abandoned-field succession; CA1, CA2, CA3 = integrated crop–animal (ICA) sub-treatments; PFW = plantation forestry woodlot.
[b] Sweet potatoes.
[c] Mixture of native, warm-season grasses – switchgrass (*Panicum virgatum*), big bluestem (*Andropogon geradii*), eastern gamagrass (*Tripsum dactyloides*), cool-season tall fescue (*Festuca arundinacea*).

was physically marked and geo-referenced using a Trimble® (Sunnyvale, CA) global positioning system (GPS) unit and stored on a geographic information system (GIS) database to ensure that the same area was marked each sampling year.

The sampling scheme had 28 sample points around the sampling area center (Fig. 2). On each sampling event, the randomly chosen sample point was flagged using a SUUNTO® (Vantaa, Finland) bearing compass. A person would stand over the sampling area center and direct another person to the predetermined sample point. The other person would pull a 1 m, 3 m, or 5 m long rope while being directed in an arc to the sample point. Once flagged, soil samples were collected from no more than 1-m away from the sample point.

Using this sampling method, we collected samples for soil physical property measurements of bulk density, saturated hydraulic conductivity, field capacity, saturated water content, total porosity, micro- and macroporosity, aggregate stability and particle size analysis. All properties but aggregate stability and particle size analysis were measured from undisturbed 7.6-cm deep by 7.6-cm diameter soil cores that were collected from the surface in each sample point. Cores, trimmed to size and capped to prevent spillage, were immediately stored at 4 °C, for a time not exceeding 1 month, before being processed. Each soil core was placed in a separate pressure chamber (Dane and Hopmans, 2002) and slowly water-saturated; saturation

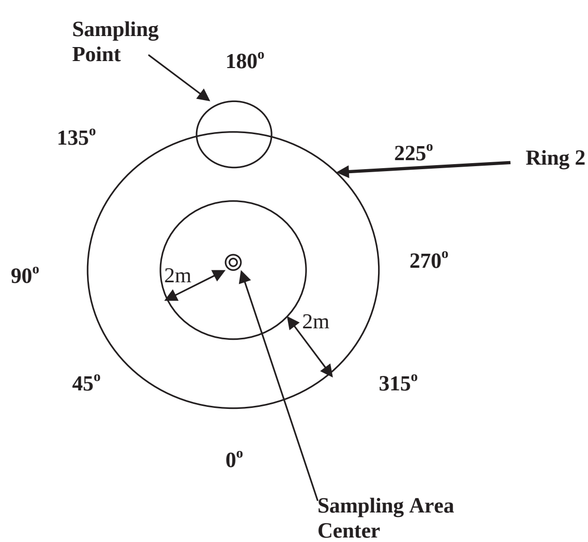

Fig. 2. The sampling scheme used at each of the five plot sampling areas. The delineated sampling point in the figure (ring no. 2, 180°) is one of 28 possible sampling points produced by this scheme.

and field capacity water contents were determined at soil water pressures of 0 kPa and −10 kPa, respectively. Soil macroporosity, the soil volume fraction of large pores unable to retain water by capillary action, was determined as the difference of water holding capacities between saturation and field capacity.

After desorption at −10 kPa, the soil cores were removed from the pressure chamber and re-saturated for measurement of saturated hydraulic conductivity using the constant head soil core method (Reynolds et al., 2002). After this, the cores were oven-dried at 105 °C to determine bulk density (Grossman and Reinsch, 2002). Grab samples collected adjacent to soil-core sampled areas were air-dried and crushed to pass a 2 mm sieve and particle density was measured with the pycnometer method (Flint and Flint, 2002). The average particle density of 840 soil samples (8 subplots × 5 sampling points × 3 replications × 8 years) was 2.62 g/cm^3 with a standard deviation of 0.12 g/cm^3. Using the bulk density and particle density data, the soil total porosity was determined, which was used to determine the soil microporosity by subtraction; i.e., soil total porosity minus soil macroporosity.

Sampling for soil aggregate stability was done separately from other soil properties. Soil aggregates of size 2.00–4.75 mm in diameter were obtained from samples collected from the upper 7.5 cm at each sample point. The stability of these aggregates was measured using the wet-sieving procedure described by Nimmo and Perkins (2002). Briefly, 50 g of air-dried aggregates were evenly distributed on a 2.00 mm sieve to form a single layer and were oscillated 25 times in deionized water for 1 min. Aggregates that remained in the sieve were oven-dried and weighed. The weight fraction of aggregates remaining on the sieve, relative to the initial aggregate weight of 50 g, was the water stable aggregation (WSA) measurement.

Each data collection year, all soil properties were measured from an unused randomly chosen point within each sampling area. For all properties except aggregate stability, samples were first collected on March 13, 1999 immediately after rye harvest for a measurement of baseline data. Samples were collected annually until 2003 (Table 2) and lastly in 2007. Sampling was done in the fall after harvest to avoid recent disturbance from tillage. Because soil usually settles quickly after tillage, we assumed that fall samples would best represent growing-season soil conditions. This would also allow for better detection of long-term changes in soil physical conditions. However, samples for measurement of WSA were collected on March 1, 1999 (baseline), November 1, 1999, March 14, 2001, May 22, 2002, May 30, 2003 and June 28, 2007.

All data were analyzed using statistical analysis systems (Statistical Analysis Systems Institute, 2001) and the General Linear Models (GLM) procedure for a modified split–split plot analysis of variance having system as main plot factor, subplots

Table 2
Tillage and sampling dates in the organic crop production system (OCP), the BMP conventional tillage (BCT), and the three integrated crop/animal sub-treatments (CA1, CA2, CA3).

OCP	BCT	CA1	CA2	CA3
13 March baseline soil samples	13 March baseline soil samples	13 March baseline soil samples	13 March baseline soil samples	13 March baseline soil samples
1999				
Crop: *soybeans* 25 March chisel 6 May chisel & disk 20 May disk 24 June cultivate 9 July cultivate **04 November soil samples**	*Crop*: *corn* 31 March chisel & disk 06 April disk 6 May cultivate 13 September harvest **04 November soil samples**	*Crop*: *pasture* 01 April chisel & disk **04 November soil samples**	*Crop*: *corn* 01 April chisel & disk 06 May cultivate **04 November soil samples** 29 November disk	*Crop*: *soybeans* 06 May chisel & disk 07 June cultivate 25 June cultivate **04 November soil samples** 30 November disk
2000				
Crop: *potatoes* 15 May bedded 18 July cultivate **11 November soil samples** 18 October disk	*Crop*: *peanuts* 06 April chisel & disk 05 May disk 20 October peanut dig **11 November soil samples**	*Crop*: *pasture* **11 November soil samples**	*Crop*: *no-till soybeans* **11 November soil samples**	*Crop*: *potatoes* 04 April chisel & disk 24 April disk 15 May bedded 11 July cultivate 16 October disk **11 November soil samples**
2001				
Crop: *cabbage* 11 April chisel & disk 10 May cultivate 18 May cultivate 06 September disk **15 October soil samples**	*Crop*: *cotton* 20 March chisel 16 April disk 27 April disk 20 June cultivate **15 October soil samples** 25 October disk	*Crop*: *pasture* 15 October soil samples	*Crop*: *cotton* 28 March disk 16 April chisel & disk 27 April disk 20 June cultivate **15 October soil samples** 25 October disk	*Crop*: *no-till soybeans* **15 October soil samples**
2002				
Crop: *corn* 07 March chisel & disk 02 April chisel & disk **19 September soil samples** 07 October disk 18 October disk	*Crop*: *corn* 02 April disk **19 September soil samples** 08 October disk	*Crop*: *pasture* 19 September soil samples	*Crop*: *corn* 09 April disk 19 May cultivate **19 September soil samples** 04 November chisel & disk	*Crop*: *cotton* 08 May strip till **19 September soil samples** 28 October disk 04 November chisel & disk
2003				
Crop: *soybeans* 16 April disk 29 April disk 10 June disk 24 June cultivate 01 July cultivate **01 October soil samples**	*Crop*: *peanuts* 29 April disk 20 May disk 22 May bedded 25 June cultivate **01 October soil samples** 13 October peanut dig 14 November disk	*Crop*: *pasture* Pasture **01 October soil samples**	*Crop*: *peanuts* 21 April disk 5 May disk 21 May bedded 25 June cultivate **01 October soil samples** 20 October dig peanuts 13 November disk	*Crop*: *no-till corn* **01 October soil samples**
2007				
Crop: *soybeans* June 27 strip tillage 10 July cultivate 21 July cultivate 10 August disk 24 October disk **16 November soil samples**	*Crop*: *soybeans* 18 June disk **16 November soil samples**	*Crop*: *no-till soybeans* **16 November soil samples**	*Crop*: *pasture* **16 November soil samples**	*Crop*: *no-till soybeans* **16 November soil samples**

Note: Sampling dates are listed in bold format.

nested within systems [subplot (system)] as subplot factor, and year of measurement as sub-subplot factor. The SAS LSMEANS procedure and PDIFF option were used to determine *p*-values ($p > t$ for Ho: mean *i*th = mean *j*th) for preplanned comparisons. Preplanned comparisons were based on FSRU hypotheses that no short or long-term effects will be found between the following systems: (1) BCT, BNT, and OCP; (2) AFS versus BCT, BNT and OCP; (3) AFS versus PFW; (4) ICA sub-treatments CA1, CA2 and CA3. Statistical tests were interpreted at the 5% probability level.

3. Results and discussion

3.1. Data analysis

The analysis of variance of 1999 baseline soil property data showed no significant system or sub-treatment effects. Box-and-whiskers plots (Fig. 3) were made on a per replication basis because the replication effect was significant in the ANOVA. The plots revealed a symmetric distribution for all properties except for the Ksat data: its distribution was skewed toward values lower than 0.5 cm/h in replications A and B and lower than 0.05 cm/h in replication C. It is known that this variable possesses an asymmetrical distribution (Parkin et al., 1988, 1990; Parkin and Robinson, 1992). Some studies tested various transformations with the objective of normalizing these data (Mesquita et al., 2002); the best transformation was the lognormal probability density function. Based on this, we conducted the analysis of variance on log-transformed Ksat data. All other properties were analyzed without transformation.

Results from the ANOVA of all soil properties with probability values (p) for factors [system, sub-treatment (system) and year] and factor interactions are presented in Table 3. All properties had

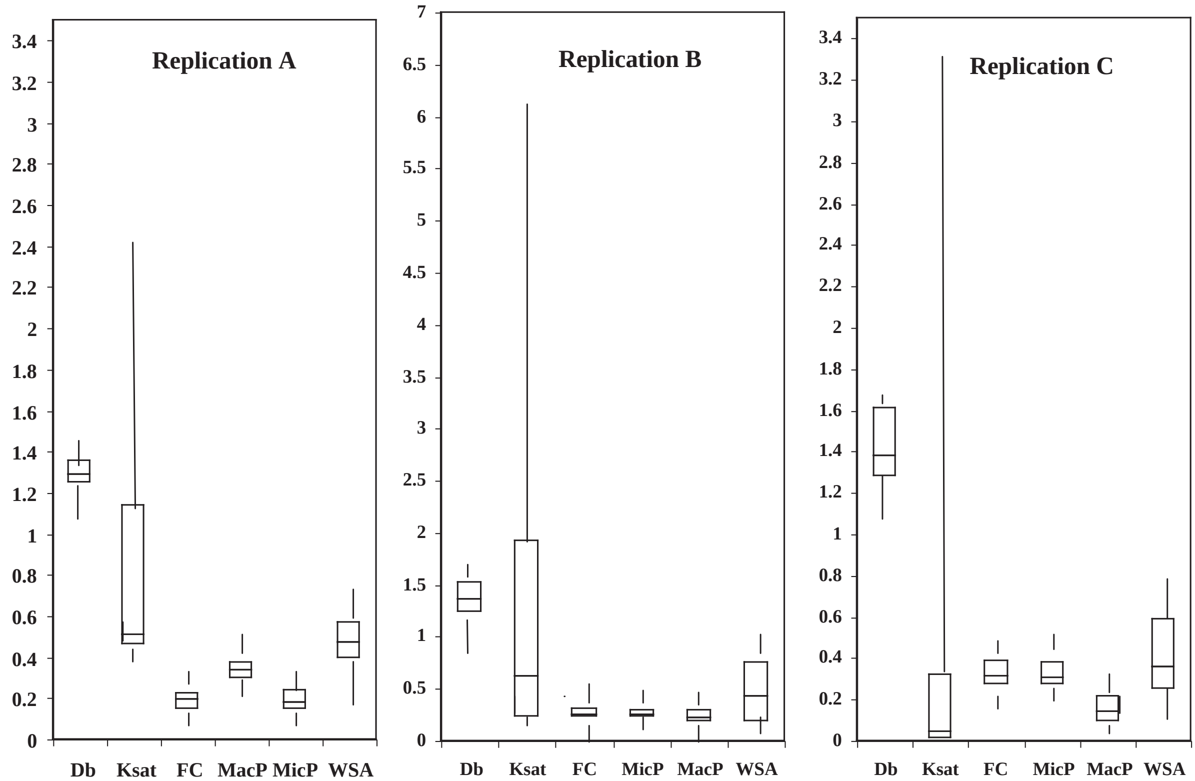

Fig. 3. Box-and-whiskers plots of the soil physical properties measured on March 1999 (baseline data). Properties are: Db = bulk density (g/cm^3); Ksat = saturated hydraulic conductivity (cm/h); FC = field capacity (cm^3/cm^3); MicP = microporosity (cm^3/cm^3); MacP = macroporosity (cm^3/cm^3); WSA = percent water stable aggregation.

significant ($p < 0.05$) system × year and/or sub-treatment (system) × year interaction except for Ksat. Differences in Ksat were only found between years. The highest coefficient of variation was obtained with log-transformed Ksat (68.1%). Water stable aggregation (WSA) had the second highest coefficient (31.7%) and coefficients for the other four properties were less than 15.0%. The magnitude of these coefficients was typical of those obtained in small-scale field studies (Cassel et al., 1995; Wagger and Denton, 1989).

3.2. Bulk density

Beginning with baseline values, bulk density (Db) increased in the untilled AFS and BNT systems and decreased in the tilled OCP and BCT systems (Fig. 4). These changes occurred within the first two years of the study. In the untilled systems, Db increased from an average baseline value of 1.36 g/cm^3 reaching a maximum value in 2000 and remaining at about 1.45 g/cm^3 on the average until 2003. In 2007, the Db in BNT was found to be significantly higher at 1.50 g/cm^3 than that in AFS at 1.40 g cm^3; a difference likely due to the presence of vehicular traffic in BNT. In the tilled OCP and BCT systems, Db fluctuated around a mean of 1.31 g/cm^3 from 2000 to 2007.

Bulk density in the ICA sub-treatments also varied in response to tillage. It increased with time in CA1 during pasture years (1999–2003). The highest value of 1.60 g/cm^3 was obtained in 2003 for the system that was continuously in pasture; this density has been found to restrict rooting in these coarse textured soils (Vepraskas, 1988). The lowest value after the beginning of the experiment of 1.41 g/cm^3 was obtained in 2007, a non-pasture year. Sub-treatments CA1 and CA2 showed slight decreases on years the soil was tilled and slight increases in years when the soil was not tilled. The CA2 sub-treatment was converted to pasture in 2005, and by 2007 it had developed a Db of 1.58 g/cm^3.

Bulk density in the PFW system increased from the baseline value during the first study year and remained at 1.45 g/cm^3 on the average until 2007. No differences were found at each sampling date between PFW and AFS. There was no vehicular traffic on these two systems therefore bulk density increased by the settling and consolidation of soil from natural processes.

Table 3
Results from the analysis of variance of soil physical properties.

Source of variation	Soil property[a]					
	Db	lnKsat	FC	MacP	MicP	WSA
Replication	0.9489	0.2743	0.0009	<0.0001	0.0004	0.1381
System	0.3315	0.9909	0.4572	0.1392	0.7133	0.0253
Subplot (system)	<0.0001	0.3314	0.2167	0.0010	0.0352	0.1248
Year	0.0013	<0.0001	0.0005	<0.0001	<0.0001	<0.0001
System × year	<0.0001	0.5142	0.1811	0.0003	0.0274	<0.0001
Subplot (system) × year	<0.0001	0.3192	0.0074	0.0005	0.7070	<0.0001
CV (%)	3.6	68.1	9.4	14.8	9.2	31.7

[a] Db = bulk density; lnKsat = lognormal saturated hydraulic conductivity; FC = field capacity; MacP = macroporosity; MicP = microporosity; WSA = water stable aggregation.

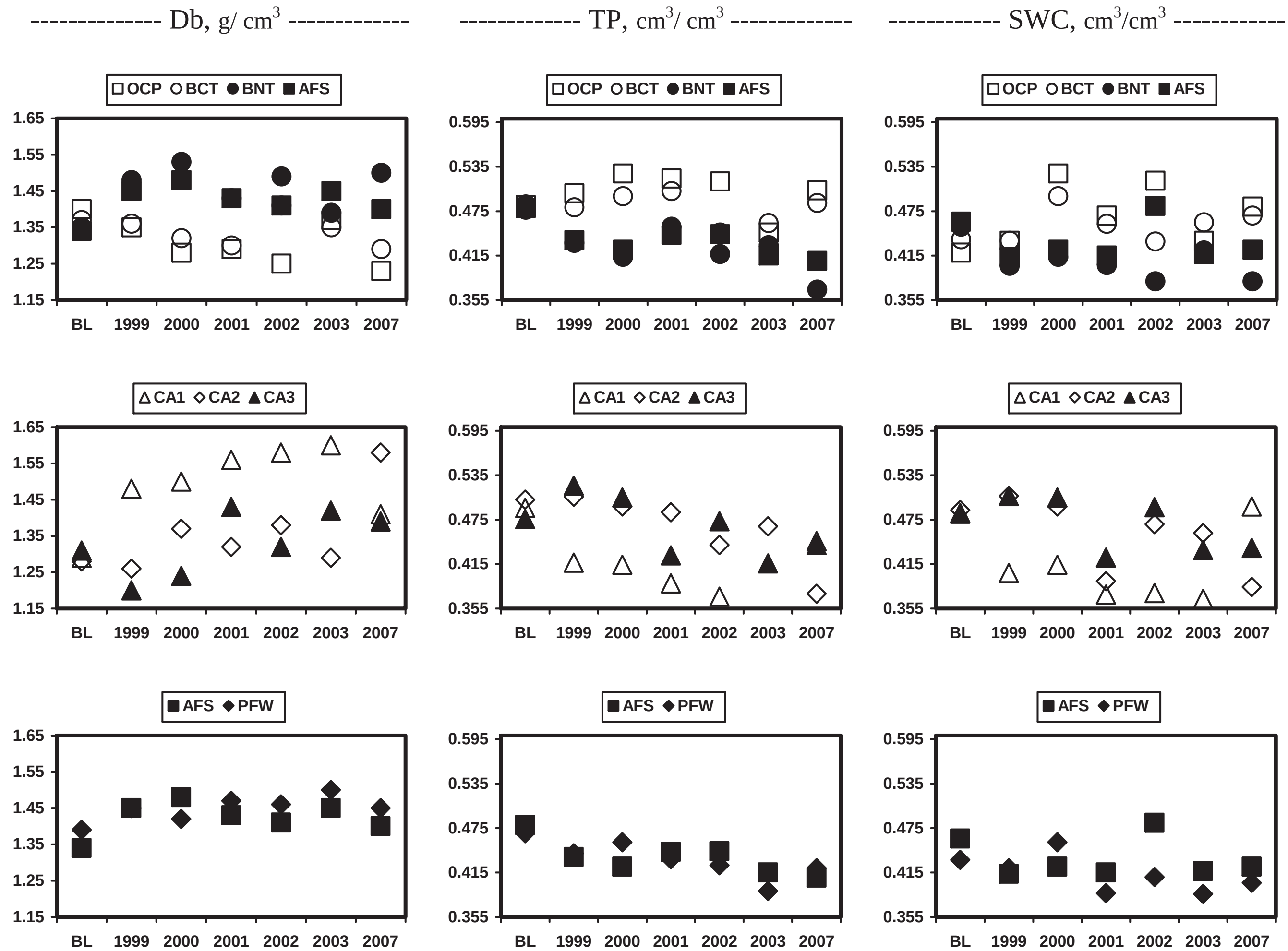

Fig. 4. Bulk density (Db), total porosity (TP) and saturated soil water content (SWC) measurements made on March 1999 (baseline data), after crop harvest each fall until 2003, and in 2007. Systems: OCP = organic crop production; BCT = best management practice conventional tillage sub-treatment; BNT = best management practice no-tillage sub-treatment; AFS = abandoned-field succession; CA1, CA2, CA3 = integrated crop–animal (ICA) sub-treatments; PFW = plantation forestry woodlot.

3.3. Porosity and pore-size distribution

The saturated water content data produced similar values and trends in porosity when compared to the total porosity data generated using bulk density and particle density parameters (Fig. 4). The linear regression function of these two measurements is presented in Fig. 5. A *t*-test on the response statistic of 0.78 cm^3/cm^3 against a value of 1 cm^3/cm^3 was highly significant ($p > t = 0.0001$). Hence, the estimates of porosity using the saturated water content data are on the average 22% lower than those using estimates of porosity using the particle density and bulk density data. However, the saturated water content data can be used as an estimate of soil porosity especially if the goals are to test for treatment differences and/or monitor temporal change.

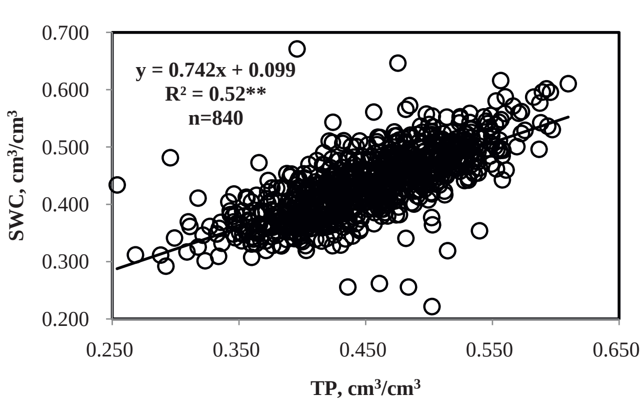

Fig. 5. Regression of saturated water content (SWC) as a function of total porosity (TP) using all the data collected throughout the study.

As expected, total porosity increased or remained high with tillage (Fig. 4). The highest porosity values were found in OCP and BCT. All other systems showed a decreasing time trend from baseline values to 2007. In 2007, BNT and CA2 had the lowest porosity (0.370 cm^3/cm^3) and OCP and BCT had the highest porosity (0.494 cm^3/cm^3).

Tillage affected macroporosity but not microporosity. For example, macroporosity was greater in OCP, and BCT than in the untilled BNT and AFS systems but no significant differences existed in microporosity (Fig. 6). The same trend was evident when comparing the tilled CA2 and CA3 sub-treatments to the untilled CA1 sub-treatment. Systems BNT and AFS had the same macroporosity except for 2007 where it was significantly higher ($p > 0.0001$) in AFS. When collecting the 2007 soil cores, we observed an abundance of channels or large pores in AFS that had originated from root decay. The substantial root turnover from a sizeable plant population of grasses and bushes with massive root systems seems to be a major source of macroporosity in AFS.

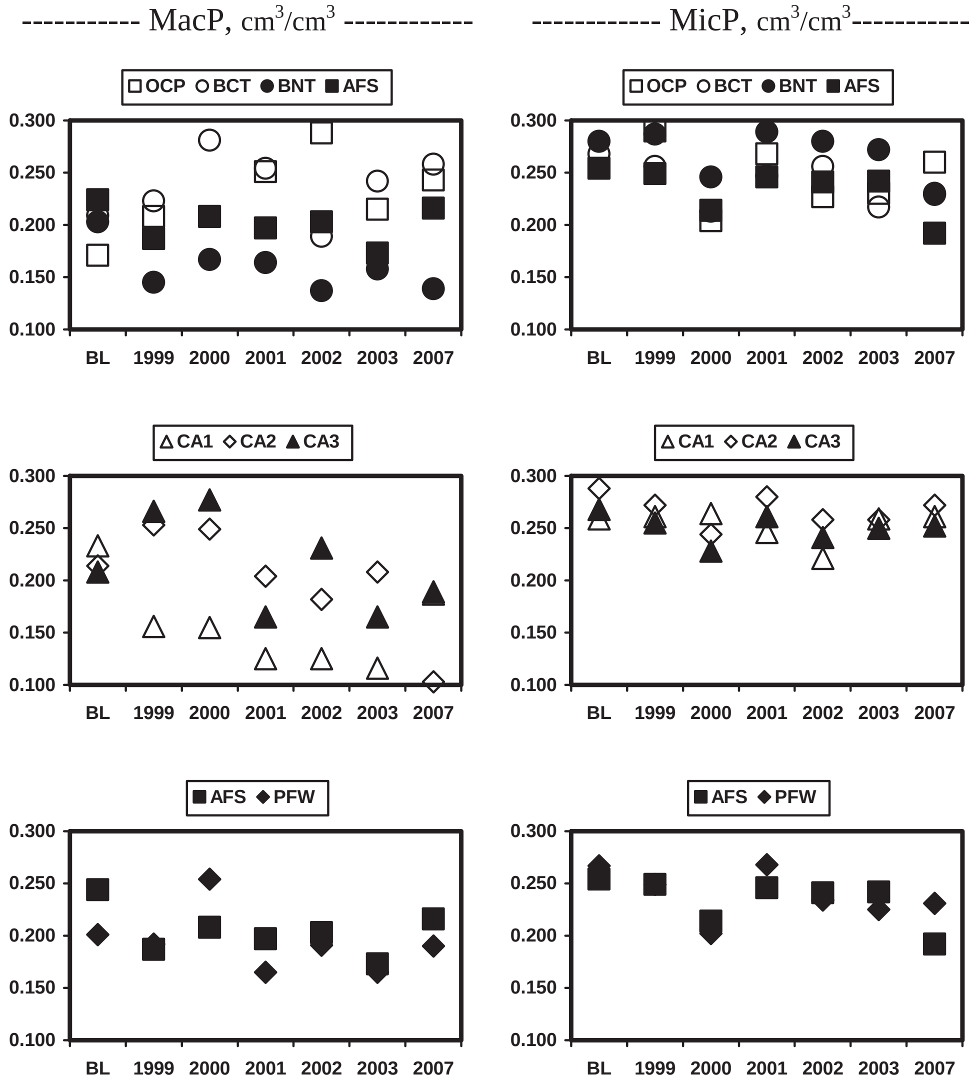

Fig. 6. Macroporosity (MacP) and microporosity (MicP) measurements made on March 1999 (baseline data), after crop harvest each fall until 2003, and in 2007. Systems: OCP = organic crop production; BCT = best management practice conventional tillage sub-treatment; BNT = best management practice no-tillage sub-treatment; AFS = abandoned-field succession; CA1, CA2, CA3 = integrated crop–animal (ICA) sub-treatments; PFW = plantation forestry woodlot.

Tilled systems had about equal volumes of macro and micropores but untilled systems had more microporosity than macroporosity. The regression function between these two variables did not differ when using the BNT data versus the BCT data. The resulting relationship after pooling the BNT and BCT data is illustrated in Fig. 7. Micropore volume was more abundant in the untilled BNT while the tilled BCT had more macropore volume. The regression function indicates a 37.4% decrease in microporosity with a unit increase in macroporosity. It is likely that tillage increases the macroporosity of the soil in part at the expense of capillary pore volume.

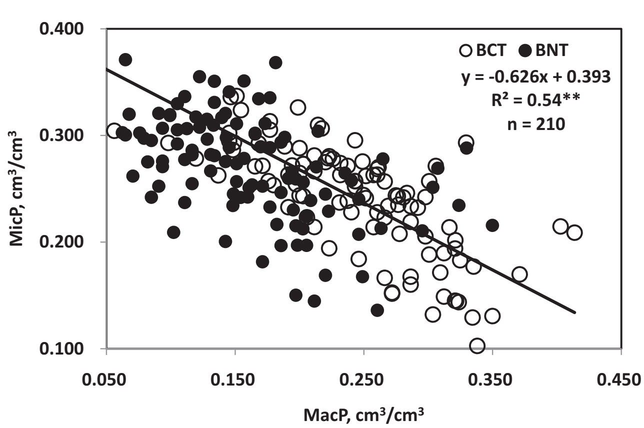

Fig. 7. Relationship between microporosity (MicP) and macroporosity (MacP) using data from best management practices conventional tillage (BCT, opened circles) and no-tillage (BNT, closed circles).

As illustrated in Fig. 6, each year except for 2007 more microporosity was found in BNT than in OCP and BCT. Surprisingly, the microporosity in AFS was significantly ($p < 0.05$) lower than that of BNT. We cannot fully explain this effect except for the possibility that much of the micropore space in AFS may have been occupied by small roots. As mentioned earlier, we observed AFS cores with substantial root mass compared to many almost rootless BNT soil cores. Grass roots were also abundant in PFW soil cores and as shown in Fig. 6, PFW and AFS had equal microporosities.

3.4. Field capacity and saturated hydraulic conductivity

On most occasions field capacity was found to be lower in systems with tillage (Fig. 8). This was expected since these systems have lower microporosity and therefore less ability to retain water against gravitational drainage. As illustrated in Fig. 9, no relationship existed between field capacity and total

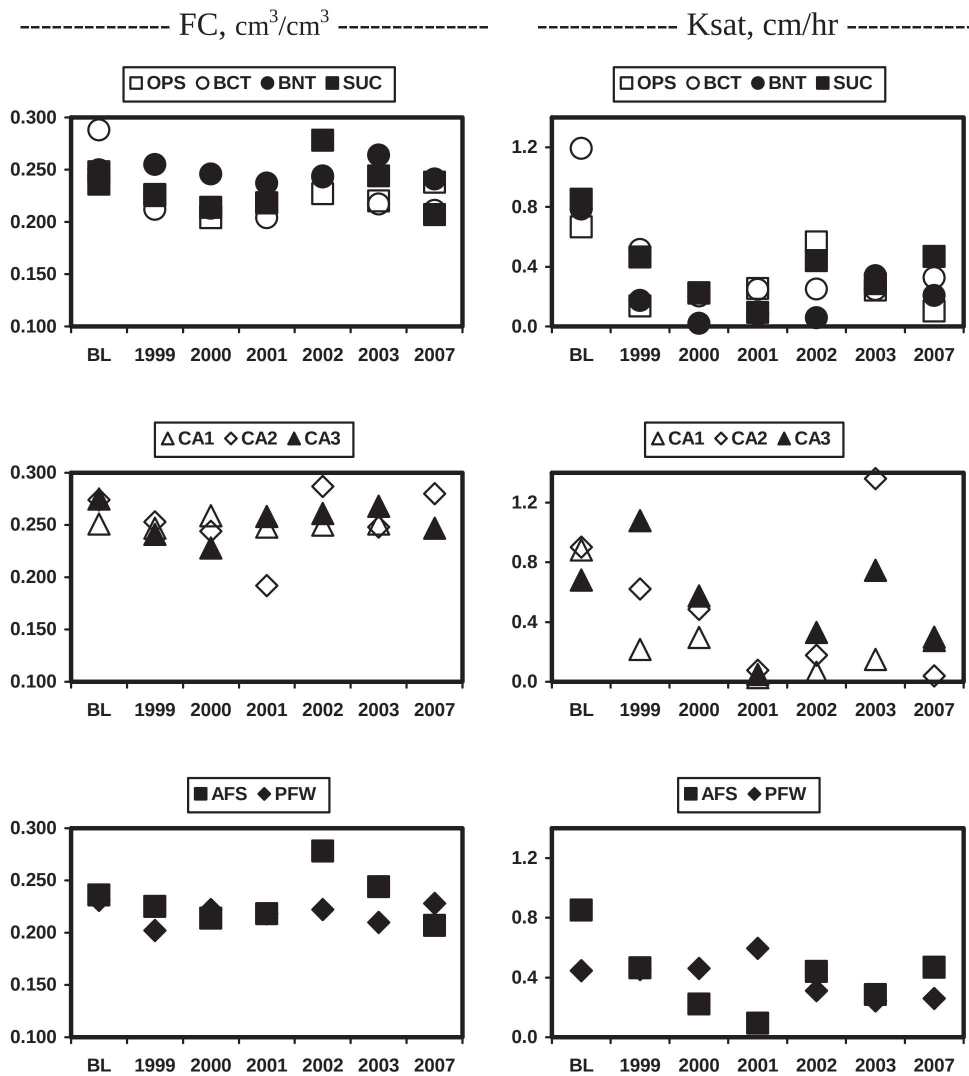

Fig. 8. Field capacity (FC) and saturated hydraulic conductivity (Ksat) measurements made on March 1999 (baseline data), after crop harvest each fall until 2003, and in 2007. Systems: OCP = organic crop production; BCT = best management practice conventional tillage sub-treatment; BNT = best management practice no-tillage sub-treatment; AFS = abandoned-field succession; CA1, CA2, CA3 = integrated crop–animal (ICA) sub-treatments; PFW = plantation forestry woodlot.

porosity but a strong relationship exists when the macropore space is excluded and field capacity is regressed against microporosity (Fig. 9), as expected because microporosity holds available water.

The lack of statistical differences in hydraulic conductivity (Fig. 8) between systems may be related to the high variability of the data. Even under a lognormal transformation the ANOVA produced a fairly large error (CV = 68.1%). However, some years tilled systems showed higher numerical means of Ksat (Fig. 8), or fluctuations in Ksat were observed when alternating tillage among years; e.g., CA2 and CA3 from 2000 to 2003 (Fig. 8).

Scattergram plots (not shown) of Ksat against each soil property revealed a well defined relationship with macroporosity and Db. The analysis searching for the best regression of Ksat as a function of these two properties generated exponential equations (Fig. 10).

Typical Ksat values for loamy sand and sandy loam textural classes have been found to be in the 0.24–0.07 cm/min range (Leij et al., 1996). The Ksat range in this study was 0.46–0.02 cm/min. Under the regression functions of Fig. 10, a Ksat of 0.07 cm/min, the low extreme value reported by Leij et al. (1996), corresponds to a Db value of 1.44 g/cm^3 and a macroporosity of 0.180 cm^3/cm^3. These or similar values of Db and macroporosity were found in untilled systems. For example, in BNT and AFS, Db was 1.45 g/cm^3 on the average and macroporosity 0.174 cm^3/cm^3 (Fig. 6). In the ICA system, Ksat was very low in the pastured CA1 sub-treatment where by 2003 the Db was 1.6 g/cm^3 and macroporosity 0.116 cm^3/cm^3. In PFW, Db remained through the years at about 1.46 g/cm^3 and macroporosity 0.194 cm^3/cm^3. In conclusion, the ability of the matrix of these soils to conduct water seems lowest when the Db is1.44 g/cm^3 or higher and/or the macroporosity 0.180 cm^3/cm^3 or lower.

3.5. Aggregate stability

Significant differences were found in aggregate stability between systems with air-dry aggregates (Fig. 11) but not with field-moist or rewetted aggregates (data not shown). The largest differences were observed in 2003 and 2007 where the untilled CA1 (pasture), BNT and AFS at times had twice the amount of stable aggregates than the tilled OCP and BCT systems. The significant differences observed among air-dry samples may be attributed to soluble organic compounds such as carbohydrates that serve as cementing agents under dry conditions and are rendered ineffective under moist conditions. Haynes and Swift (1990) found a

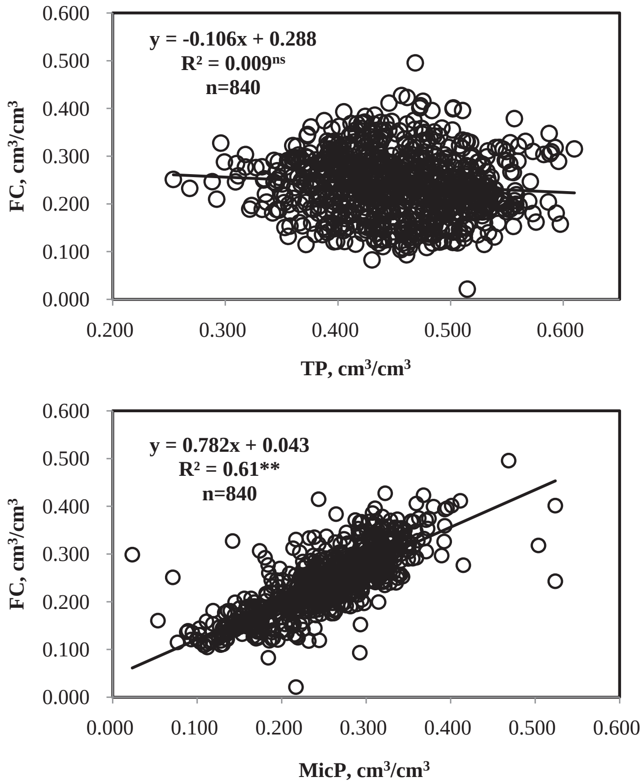

Fig. 9. Regression of field capacity (FC) as a function of total porosity (TP) (upper figure) and microporosity (MicP) (lower figure) using all the data collected throughout the study.

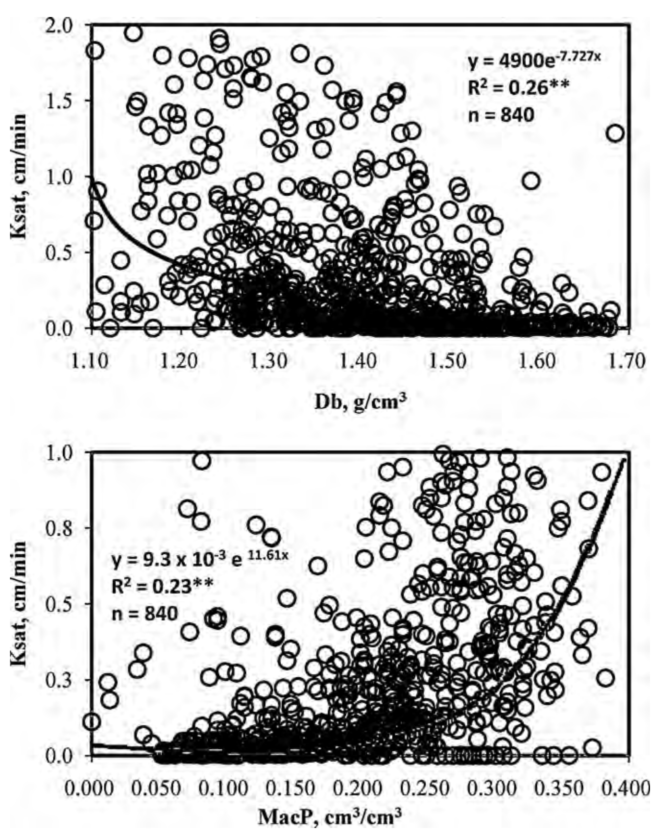

Fig. 10. Regression of saturated hydraulic conductivity (Ksat) as a function of bulk density (Db) (upper graph) and macroporosity (MacP) (lower graph) using all the data collected throughout the study.

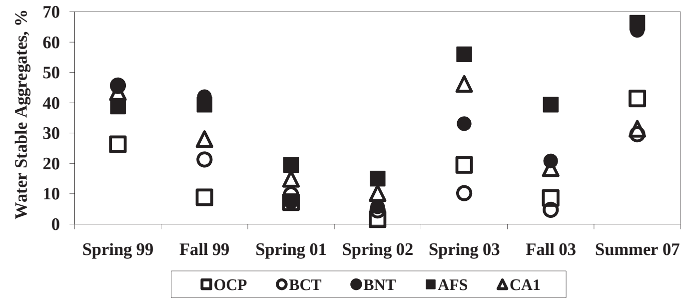

Fig. 11. Water stable aggregates (aggregate stability) in systems organic crop production (OCP), best management practice conventional tillage (BCT), best management practice no-tillage (BNT), abandoned-field succession (AFS), and the CA1 subsystem of the integrated crop/animal system (ICA).

strong correlation between aggregate stability and water-extractable carbohydrate content. In their study, air-drying aggregates having a high content of these carbohydrates increased their stability considerably. They found a larger content of these carbohydrates in highly stable aggregates of long-term pasture systems and a low content in the less stable aggregates of long-term tilled land. In addition to carbohydrates, polysaccharides from bacteria or fungi and root mucilage are vital soil constituents and play an integral role in the cementation of soil aggregates (Andrade et al., 1998). We believe that the untilled BNT, AFS and CA1 systems had a higher concentration of the aforesaid binding agents near the soil surface than the tilled OCP and BCT systems. Conversely, the action of tillage in OCP and BCT not only destroy and weaken aggregates but also will not allow these compounds to increase in concentration at the soil surface.

Temporal differences in aggregate stability may be confounded by operator-to-operator variability associated with the measurement procedure and we therefore hesitate to make definite conclusions of the observed changes. We are uncertain of the decrease in the first three years in all systems and especially in OCP, BNT and CA1 where various organic matter sources nourish the soil surface and an increase in stability is expected. The only plausible explanation is that the inundation of the entire research area caused by hurricane Floyd in September 1999 had an impact on soil conditions. Notice that the first post-baseline samples were collected immediately after Floyd in November (Table 2) and these samples show a decrease in stability relative to baseline samples (Fig. 11). The effects of short-term flooding on soil solution chemistry and the consequential decrease in soil aggregation has been recently documented in a study by De-Campos et al. (2009). They found that tilled soils were more sensitive to the adverse effects of flooding than untilled ones and they reported a 21% decrease in tilled soil aggregate stability. In our study, decreases in aggregate stability from baseline values in 1999–2002 values were 30 and 40% respectively for untilled and tilled systems.

4. Conclusions

4.1. Experimental methods

The experimental methods successfully produced data with acceptable levels of variability, discernable soil property differences between systems and unambiguous relationships between soil properties. Blocking areas with large portions of a diagnostic soil maintained the homogeneity of experimental units (plots) and produced acceptable error terms in the statistical procedures used. Finding a plot sampling point was quick and easy with GPS technology. The sampling scheme used produced multiple sampling locations within a sampling point preventing the collection of samples in previously sampled areas.

4.2. Soil physical conditions

The tilled systems OCP and BCT did not differ in soil physical properties and each soil property remained rather constant with time. Relative to these two systems, BNT developed higher bulk density, and a lower total porosity and macroporosity, but a higher capillary porosity (microporosity) and water retention capacity (field capacity). The AFS and BNT systems had similar properties except for somewhat smaller macroporosity and larger microporosity in BNT. In general, the BNT system closer resembles the AFS system than OCP and BCT.

The integrated CA1 sub-treatment developed a higher bulk density and lower total porosity and macroporosity than CA2 and CA3 sub-treatments. These differences occurred within the first study year. It is evident that in a grazed pastured system like CA1 compaction impacts soil physical conditions rather quickly; the effect of compaction on increased bulk density and reduced porosity is also seen when CA2 is converted to pasture from 2003 onwards. The fact that microporosity did not differ between sub-treatments indicates that the decrease in total porosity is due to the loss of macroporosity; i.e., micropores are not being formed as macropores become smaller in size by the compaction effect.

Soil properties in PFW and AFS were basically the same and they differed little with time. Both systems displayed a slight increase in bulk density and slight decrease in porosity. All other properties remained fairly constant with time relative to baseline values.

References

Andrade, G., Mihara, K.L., Linderman, R.G., Bethlenfalvay, G.J., 1998. Soil aggregation status and rhizobacteria in the mycorrhizosphere. Plant Soil 2002, 89–96.

Cassel, D.K., Raczkowski, C.W., Denton, H.P., 1995. Tillage effects on corn production and soil physical conditions. Soil Sci. Soc. Am. J. 59, 1436–1443.

Dane, J.H., Hopmans, J.W., 2002. Water retention and storage. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. SSSA, Madison, WI, pp. 671–720.

De-Campos, A.B., Mamedov, A.I., Huang, C., 2009. Short-term reducing conditions decrease soil aggregation. Soil Sci. Soc. Am. J. 73, 550–559.

Fleming, M.M.S., Stucky, J.M., Brownie, C., 2007. Effects and importance of soil wetness and neighbor vegetation on *Solidago verna* M.A. Curtis ex Torrey & A. Gray (spring-flowering goldenrod) [Asteraceae] transplant survivorship and growth. Castanea 72 (4), 205–213.

Flint, A.L., Flint, L.E., 2002. Particle density. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. SSSA, Madison, WI, pp. 229–240.

Grossman, R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. SSSA, Madison, WI, pp. 201–225.

Haynes, R.J., Swift, R.S., 1990. Stability of soil aggregates in relation to organic constituents and soil water content. J. Soil Sci. 41, 73–83.

DE Gruijter, J.J., 2002. Sampling. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. SSSA, Madison, WI, pp. 45–79.

Leij, F.J., Alves, W.J., van Genuchten, M.Th., Williams, J.R., 1996. The UNSODA unsaturated soil hydraulic database. In: Version 1.0. Report IAG-DW 12933934, National Risk Management Research Laboratory, Office of Research and Developments, USEPA, Cincinnati, OH.

Mesquita, M.G.B., Moraes, S.O., Corrente, J.E., 2002. More adequate probability distributions to represent the saturated soil hydraulic conductivity. Sci. Agric. 59 (4), 789–793.

Monserud, R.A., 2002. Large-scale experiments in the moist maritime forests of the Pacific Northwest. Landsc. Urban Plan. 59 (3), 159–180.

Nimmo, J.R., Perkins, K.S., 2002. Agreegate stability and size distribution. In: Methods of Soil Analysis. Part 4, SSSA, Madison, WI, pp. 317–327.

Parkin, T.B., Chester, S.T., Robinson, J.A., 1990. Calculating confidence intervals for the mean of a lognormal distributed variables. Soil Sci. Soc. Am. J. 54, 321–326.

Parkin, T.B., Meisinger, J.J., Chester, S.T., Starr, J.L., Robinson, J.A., 1988. Evaluation of statistical estimation methods for lognormal distributed variables. Soil Sci. Soc. Am. J. 52, 323–329.

Parkin, T.B., Robinson, J.A., 1992. Analysis of lognormal data. Adv. Soil Sci. 20, 193–235.

Pierce, C.M.F., Gray, M.E., 2006. Western corn rootworm, *Diabrotica virgifera virgifera* LeConte (Coleoptera Chrysomelidae), oviposition: a variant's response to maize phenology. Environ. Entomol. 35 (2), 423–434.

Reynolds, W.D., Elrick, D.E., Youngs, E.G., Amoozegar, A., Booltink, H.W.G., 2002. Saturated and field-saturated water flow parameters. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. SSSA, Madison, WI, pp. 797–878.

Statistical Analysis Systems Institute, 2001. SAS User's Guide: Statistics, Version 9.2. SAS Institute, Inc., Cary, NC.

Van Es, H.M., Gomes, C.P., Sellman, M., Van Es, C.L., 2007. Spatially-balanced complete block designs for field experiments. Geoderma 140, 346–352.

Vepraskas, M.J., 1988. Bulk density values diagnostic of restricted root growth in coarse-textured soils. Soil Sci. Soc. Am. J. 52, 1117–1121.

Wagger, M.G., Denton, H.P., 1989. Influence of cover crop and wheel-traffic on soil physical properties in continuous no-till corn. Soil Sci. Soc. Am. J. 53, 1206–1210.