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RESEARCH ARTICLE

Soil nitrogen conservation with continuous no-till management

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Abstract Tillage management is an important regulator of organic matter decomposition and N mineralization in agroecosystems. Tillage has resulted in the loss of considerable organic N from surface soils. There is potential to rebuild and conserve substantial amounts of soil N where no-till management is implemented in crop production systems. The objectives of our research were to measure N conservation rate with continuous no-till management of grain cropping systems and evaluate its impact on mineralizable and inorganic soil N. Samples were collected from 63 sites in production fields using a rotation of corn (*Zea mays* L.)—wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.)—double-crop soybean (*Glysine max* L.) across three soil series [Bojac (Coarse-loamy, mixed, semiactive, thermic Typic Hapludults), Altavista (Fine-loamy, mixed semiactive, thermic Aquic Hapludults), and Kempsville (Fine-loamy, siliceous, subactive, thermic Typic Hapludults)] with a history of continuous no-till that ranged from 0 to 14 yrs. Thirty-two of the sites had a history of biosolids application. Soil cores were collected at each site from 0–2.5, 2.5–7.5 and 7.5–15 cm and analyzed for total N, Illinois soil N test-N (ISNT-N), and [NH_4 + NO_3]-N. A history of biosolids application increased the concentration of total soil N by 154 ± 66.8 mg N kg^{-1} (310 ± 140 kg N ha^{-1}) but did not increase ISNT-N in the surface 0 – 15 cm. Continuous no-till increased the concentration of total soil N by 9.98 mg N kg^{-1} $year^{-1}$ (22.2 ± 21.2 kg N ha^{-1} $year^{-1}$) and ISNT-N by 1.68 mg N kg^{-1} $year^{-1}$ in the surface 0–15 cm. The implementation of continuous no-till management in this cropping system has resulted in conservation of soil N.

Keywords No-till · N Cycling · N-Use efficiency · Biosolids

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Introduction

Due to conservation awareness, improved technology, and increased fuel costs, no-till management has been implemented on a significant portion of U.S. cropland. In 2004, about 23% of U.S cropland was managed no-till (CTIC 2004). In Virginia, approximately 35% of annual crop production land was managed using no-till (CTIC 2004). Continuous no-till management can have a significant influence on soil organic N cycling (Franzluebbers et al. 1994a; Kristensen et al. 2000)

and fertilizer N use efficiency (Martens and Dick 2003; Meisinger et al. 1985).

Nitrogen is among the most important nutrients required for the production of world food supplies. Currently, as much as 40% of the world's protein supply is estimated to be derived from fertilizer N; by 2050 it is expected to be about 60% (Smil 2001). Nitrogen use efficiency is paramount to both agronomic viability and environmental health. The primary objective of N applications to cropland by the agricultural producer is to increase yield with a subsequent economic return from the capital invested. In order to maximize profit, N needs must be accurately determined to allow producers to meet yield goals with economically acceptable capital investments. Excessive N applications are undesirable from an economic standpoint. The negative environmental ramifications of unnecessary N applications, such as the potential for contamination of ground water and hypoxia in surface waters, are also widely recognized (Follett and Hatfield 2001).

Nitrogen use efficiency has been defined using a number of factors of input and recovery (e.g., Moll et al. 1982; Raun and Johnson 1999; Semenov et al. 2007). Here, we have adapted our definition of N use efficiency of a cropping system from Cassman et al. (2002) as the proportion of applied N recovered in the harvested crop, contained in recycled crop residues, and incorporated into soil organic matter (SOM). The N not recovered in these pools is lost from the system and contributes to the reactive N load in the environment external to the cropping system. Thus, N use efficiency of a cropping system may be increased through greater crop uptake recovery of applied N, by decreasing N lost from SOM, or both.

Soil tillage is one of the oldest known management tools for mining soil organic nutrient reserves to enhance crop growth (Martens 2001). A number of tillage dependent factors influence the rate of SOM decomposition in agronomic cropping systems. With tillage, soil organic matter becomes more evenly distributed within the plow layer. Residues left on the soil surface with no-till management experiences frequent wetting and drying while residues that are incorporated with tillage are buffered against extremes in moisture conditions thus favoring microbial activity. This may be the greatest factor leading to SOM decomposition in tilled soils (Franzluebbers 2004). Tillage also aerates soil, creating a more oxidative environment. Removal of residues from the surface exposes more soil to solar radiation, decreases soil albedo, and results in higher soil temperatures.

No-till management has received a great deal of attention for its potential to sequester C and offset anthropogenic CO_2 emissions (Follett 2001; Franzluebbers 2005; Paustian et al. 1997; Uri 2001; West and Marland 2002; West and Post 2002). Any management practice that changes soil organic C will also influence soil organic N since the C/N ratio of stable SOM has a relatively narrow range ($\sim$10:1–12:1). There is potential to conserve a substantial amount of soil organic N with no-till management. Franzluebbers (2004) used meta-analysis to estimate the rate of total soil N conservation with no-till management compared to shallow tillage and found that total soil N was increased by an average rate of 28 kg N ha^{-1} $year^{-1}$ ($n = 26$) under no-till.

Increased tillage intensity decreases the soils capacity to immobilize and conserve mineral N (Carter and Rennie 1984; Follett and Schimel 1989). Follett and Schimel (1989) observed that after 16 years of cultivation, total N in the surface 10 cm of soil had decreased by 27%, 32%, and 50% of native sod in no-till, stubble-mulch, and plow treatments, respectively. Pierce and Fortin (1997) found similar results in Michigan comparing no-till to conventional till treatments that had been in place for 11 years. Carter and Rennie (1984) found immobilization of fertilizer N in no-till soils into microbial biomass mainly in the surface 5 cm and less from 5 to 10 cm. By immobilizing N at the soil surface, soil N cycling with no-till management is slower but may be more efficient (House et al. 1984).

A portion of the additional N retained as SOM in no-till soils may potentially become available for crops (Franzluebbers et al. 1994a; Wienhold and Halvorson 1999). Franzluebbers et al. (1994a) found that mineralizable N was an average of 45% greater in soils treated no-till for 9 years in Texas compared to those that were disk tilled. In a spring wheat-winter wheat-sunflower crop rotation Wienhold and Halvorson (1999) observed that N mineralization in the surface 5 cm of soil treated no-till was 112% and 143% greater than those cultivated using minimal (sweep plow) or conventional tillage (chisel plow and a double disk), respectively.

A soil based approach that attempts to quantify organic N turnover could improve the precision of

fertilizer N recommendations and increase N use efficiency (Mulvaney et al. 2005). A number of chemical methods have been proposed for estimating soil N availability (Bundy and Meisinger 1994; Stevenson and Cole 1999). Soil test methods designed to estimate potentially mineralizable N have been based on an empirical approach, and their use has been limited due to poor correlations with seasonal N mineralization and crop N uptake (Khan et al. 2001a; Stevenson and Cole 1999). The Illinois soil N test (ISNT) was developed by Khan et al. (2001b) as a simple soil assay to estimate mineralizable soil N and predict reduced response to N-fertilization. The ISNT uses direct alkaline hydrolysis to estimate hydrolysable amino sugar-N, a labile fraction of total soil N. Khan et al (2001a) found that ISNT values were well correlated with hydrolysable amino sugar-N (r =0.91) and used the assay to successfully identify soils in Illinois that were non-responsive to fertilizer-N. They found a wide range of N-test values for both responsive and non-responsive sites and suggested the possibility of using the soil test to quantitatively determine fertilizer N rates in conjunction with expected yield goals. The ISNT has also been found to provide useful data in other regions of the U.S. Klapwyk and Ketterings (2006) were able to identify non-responsive corn silage fields on dairy farms in New York using the ISNT. Williams et al. (2007) successfully predicted the economic optimum N rate (EONR) for corn grown on well- ($r^2 = 0.87$) or poorly—($r^2 = 0.78$) drained soils in North Carolina. Sharifi et al. (2007) found that the ISNT was highly correlated ($r = 0.72$) with N mineralization during a 24 week aerobic incubation period of 153 soils that were collected from existing field experiments extending across four Canadian provinces and into Maine, USA.

The ISNT has not proven useful in all regions or cropping systems. For example, working in Iowa, Barker et al. (2006) found no relationship between the ISNT and relative corn grain yield, corn response to fertilizer N, or EONR. The soils used in their study had relatively high levels of hydrolysable NH_4-N relative to amino sugar-N and the authors suggested that this may partially explain the poor performance of the ISNT. Marriott and Wander (2006) used the assay to compare labile soil N in conventional and organic cropping systems and found that the ISNT was not a sensitive index of labile N. The ISNT fraction was not preferentially enriched by organic management and its response was similar to that of total soil C and N. For these reasons it is not likely that the assay will be adopted as a universal soil N test. Rather, its use will be limited to regions and applications were the assay has proven useful. To our knowledge, the assay has not been tested for its ability to detect changes in soil N with no-till management.

Little research has been conducted to investigate N conservation in long-term no-till soils, particularly in the Mid-Atlantic Coastal Plain. Quantification of organic N cycling in no-till soils may improve the precision of fertilizer N recommendations and increase N use efficiency. The most common crop rotations in the middle coastal plain of Virginia is corn—wheat or barley—double-crop soybean. Corn and soybean have been planted no-till on most farms since at least the early to mid 1980's; however, on many farms some tillage is conducted prior to planting small grain (i.e., wheat or barley). Many no-till fields are also periodically tilled to alleviate soil compaction, control difficult weeds, incorporate organic amendments (i.e., biosolids) or remove tire ruts left by harvesting equipment. The objectives of this research were to measure N conservation rate with continuous no-till management of grain cropping systems and evaluate its impact on ISNT- and inorganic- N content.

Materials and methods

Sampling locations

Sixty-three grain crop production fields were selected across three soil series in the Virginia coastal plain with a history of continuous no-till management ranging from 0 to 14 years (Table 1). Fields were located within the geographic region 37°41 N–37°17 N and 77°40 W–77°12 W. Average annual temperature of the region is 14°C and precipitation is 112 cm year^{-1}. The three soils series, Bojac (Coarse-loamy, mixed, semiactive, thermic Typic Hapludults), Altavista (Fine-loamy, mixed semiactive, thermic Aquic Hapludults), and Kempsville (Fine-loamy, siliceous, subactive, thermic Typic Hapludults), represent a significant portion of the land area used for crop production in the region. All but eight sites were in a corn—wheat or barley—double-crop soybean rotation. The eight sites that did not have a small grain (wheat or barley) in rotation grew full season soybeans.

Thirty-two of the sites had a history of biosolids application. All fields with a history of biosolids received the most recent application 4 or 5 years prior to the sampling date.

Sampling and analysis

Fields were sampled in 2005 or 2006 shortly following corn harvest except locations 10, 30, and 49 which were tilled following corn harvest in preparation for small grain planting. These locations were not sampled until 3 months following tillage to allow for soil conditions to stabilize. Five soil samples where collected from each location along a 100 m transect using 5 cm dia. soil cores split into 0–2.5 cm, 2.5–7.5 cm and 7.5–15 cm depth increments. The shallow sampling depth was chosen since the predominant form of tillage in the region is shallow double-disking and typically does not incorporate residues deeper than 10 cm. This was confirmed at multiple locations by excavating miniature soil pits following tillage operations. Intact soil cores were sealed in plastic wrap and stored on ice immediately following collection. On returning to the lab the cores were separated by layer, the soil removed and rapidly air-dried. Bulk density was determined on each core at each depth increment by obtaining an air-dry weight for each core and oven drying (105°C) a subsample to determine moisture content. Following bulk density measurements, air-dried soil samples were ground and sieved (2 mm). For chemical analysis, composite samples were made for each sampling layer by thoroughly mixing equal volume sub samples from each core.

Total soil C and N levels were determined in duplicate by dry combustion using a VarioMax CNS macro elemental analyzer[1] (Elementar, New Jersey). The concentration of ISNT-N was determined using the procedures described in Technical Note 02-01 (University of Illinois at Urbana Champaign [UIUC], 2004) and Khan et al. (1997). Briefly, 1 g of soil was treated with 10 ml of 2 M NaOH in a 473-ml wide-mouth Ball® jar, and heated for 5 hrs at 50°C on a hotplate to liberate [NH_4^++amino sugar]—N as gaseous NH_3 which was collected in a 4% w/v H_3BO_3 solution. The [NH_4^++amino sugar]—N was subsequently determined by acidimetric titration with standardized 0.01 M H_2SO_4 using a Radiometer TIM 900 Titration Manager and ABU901 autoburette (Radiometer Analytical S.A., Lyon, France). Soil NH_4-N and NO_3-N were extracted with 2 M KCl for one hour on a reciprocating shaker and determined colorimetrically using a QuickChem Automated Ion Analyzer (Lachat Instruments, Milwaukee, WI). There is very little vermiculite or illite in the surface 15 cm of the course textured soils we investigated; thus, we did not analyze for fixed NH_4-N.

Data analysis

Total soil C and N, ISNT-N, NO_3-N, NH_4-N and bulk density were calculated for 0–7.5 cm and 0–15 cm depths using depth weighted summation. The depth weighted concentration of total soil N, ISNT-N and [NO_3 + NH_4]-N for 0–2.5, 0–7.5 and 0–15 cm at each of the 63 locations sampled are listed in Table 2. Bulk density and total soil C data are reported elsewhere (Spargo et al. 2008). Analysis of variance was performed using PROC GLM of SAS with duration of continuous no-till (dNT) treated as a continuous quantitative variable, biosolids as a dummy variable, and soil series as a class variable (SAS Institute 2002). Sites with a history of biosolids application were assigned a value of 1 for the biosolids effect and sites with no history of biosolids application a value of 0. For model building, marginal sums of squares (type III) were used to test significance of main effects and interactions. When biosolids and soil series were not significant at the $P < 0.05$ level they were dropped from the model. When soil series was significant, *t*-tests were used to determine which of the soil series contributed ($P < 0.05$) to the model. Parameter estimates and confidence intervals were calculated using the SOLUTION and CLPARM commands in SAS, respectively.

Results and discussion

Total soil N

Soil C may become limiting in tilled systems, increasing N mineralization and limiting N immobilization (Follett and Schimel 1989). The elimination of tillage generally results in slower residue decomposition and a

[1] Trade and company names are given for the reader's benefit and do not imply endorsement or preferential treatment of any product by Virginia Tech, the USDA, or the Colonial Soil and Water Conservation District.

Table 1 Sampling location site descriptions

Site	Soil series[a]	Crop rotation[b]	History of biosolids application	Duration continuous no-till	Tillage type last applied[c]
1	Altavista	C-SG/DCB	No	1	DD
2	Altavista	C-SG/DCB	No	3	DD
3	Altavista	C-FSB	No	5	DD
4	Altavista	C-SG/DCB	No	6	DD
5	Altavista	C-SG/DCB	No	6	DD
6	Altavista	C-FSB	No	6	DD
7	Altavista	C-SG/DCB	No	7	DD
8	Altavista	C-SG/DCB	No	7	DD
9	Altavista	C-SG/DCB	No	8	DD
10	Altavista	C-SG/DCB	No	8	DD
11	Altavista	C-SG/DCB	No	13	DD
12	Altavista	C-SG/DCB	No	14	DD
13	Altavista	C-SG/DCB	No	14	DD
14	Altavista	C-SG/DCB	Yes	0	DD
15	Altavista	C-SG/DCB	Yes	2	DD
16	Altavista	C-SG/DCB	Yes	2	DD
17	Altavista	C-SG/DCB	Yes	4	DD
18	Altavista	C-SG/DCB	Yes	4	DD
19	Altavista	C-SG/DCB	Yes	5	DD
20	Altavista	C-SG/DCB	Yes	8	DD
21	Altavista	C-SG/DCB	Yes	8	DD
22	Altavista	C-SG/DCB	Yes	8	DD
23	Altavista	C-SG/DCB	Yes	8	DD
24	Altavista	C-SG/DCB	Yes	9	DD
25	Bojac	C-FSB	No	5	DD
26	Bojac	C-FSB	No	5	DD
27	Bojac	C-SG/DCB	No	8	DD
28	Bojac	C-SG/DCB	No	8	DD
29	Bojac	C-SG/DCB	No	8	DD
30	Bojac	C-SG/DCB	Yes	0	DD
31	Bojac	C-SG/DCB	Yes	2	MB/DD
32	Bojac	C-SG/DCB	Yes	2	DD
33	Bojac	C-SG/DCB	Yes	2	DD
34	Bojac	C-SG/DCB	Yes	3	DD
35	Bojac	C-SG/DCB	Yes	6	DD
36	Bojac	C-SG/DCB	Yes	8	DD
37	Bojac	C-SG/DCB	Yes	8	DD
38	Bojac	C-SG/DCB	Yes	8	DD
39	Bojac	C-SG/DCB	Yes	8	DD
40	Bojac	C-SG/DCB	Yes	9	DD
41	Emporia	C-SG/DCB	No	0	DD
42	Emporia	C-SG/DCB	No	2	MB/DD
43	Emporia	C-FSB	No	4	DD
44	Emporia	C-FSB	No	4	DD
45	Emporia	C-FSB	No	4	DD
46	Emporia	C-FSB	No	4	DD
47	Emporia	C-SG/DCB	No	5	DD
48	Emporia	C-SG/DCB	No	6	DD
49	Emporia	C-SG/DCB	No	8	DD
50	Emporia	C-SG/DCB	No	8	DD
51	Emporia	C-SG/DCB	No	11	DD

Table 1 continued

Site	Soil series[a]	Crop rotation[b]	History of biosolids application	Duration continuous no-till	Tillage type last applied[c]
52	Emporia	C-SG/DCB	No	11	DD
53	Emporia	C-SG/DCB	No	11	DD
54	Emporia	C-SG/DCB	Yes	3	Ch
55	Emporia	C-SG/DCB	Yes	3	Ch
56	Emporia	C-SG/DCB	Yes	4	Ch
57	Emporia	C-SG/DCB	Yes	5	Ch
58	Emporia	C-SG/DCB	Yes	9	DD
59	Emporia	C-SG/DCB	Yes	9	DD
60	Emporia	C-SG/DCB	Yes	9	DD
61	Emporia	C-SG/DCB	Yes	9	DD
62	Emporia	C-SG/DCB	Yes	9	DD
63	Emporia	C-SG/DCB	Yes	14	DD

[a] Bojac (Coarse-loamy, mixed, semiactive, thermic Typic Hapludults), Altavista (Fine-loamy, mixed semiactive, thermic Aquic Hapludults), and Kempsville (Fine-loamy, siliceous, subactive, thermic Typic Hapludults)

[b] Corn (*Zea mays* L.), C; small grain [wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.)], SG; double-crop soybean (*Glysine max* L.), DCB; and full season soybean, FSB

[c] Double disk, DD; mould-board plow, MB; chisel plow, Ch

net increase in SOM thus, continuous no-till management is expected to conserve soil N (Martens 2001). Analysis of variance and parameter estimates for the effects of dNT, biosolids and soil series on the concentration of total soil N are summarized in Table 3. Concentration of total soil N increased significantly with dNT at the 0–2.5, 0–7.5, and 0–15 cm depths. Continuous no-till management increased the concentration of soil N by 50, 28, and 10 mg N kg^{-1} $year^{-1}$ at the 0–2.5, 0–7.5, and 0–15 cm depths, respectively. The higher rate of increase near the surface is indicative of the stratification of SOM with the elimination of tillage (Franzluebbers 2002; Spargo et al. 2008). Tillage practices affect N immobilization processes in soil due to residue placement. The stratification of SOM near the soil surface is more similar to natural systems rather than the complete mixing that results from tillage (Follett and Peterson 1988; Franzluebbers 2002). The accumulation of crop residues near the soil surface stratifies microbial activity and conserves more soil N (Schomberg and Jones 1999).

Biosolids also had a significant effect on the concentration of total soil N. There was an interaction between dNT and biosolids at the 0–2.5 cm depth. The concentration of soil N increased faster where biosolids were applied with dNT (51 mg N kg^{-1} $year^{-1}$) since organic N added with biosolids not incorporated by tillage accumulated at the soil surface. The interaction between dNT and biosolids was not significant at 0–7.5 or 0–15 cm but biosolids did have a significant effect on the concentration of total soil N. Biosolids increased the concentration of total N by 232 and 154 mg N kg^{-1} at 0–7.5 and 0–15 cm, respectively. We expected to find an interaction between biosolids application and dNT in the 0–7.5 cm and 0–15 cm depth. This would have suggested that biosolids derived soil organic N mineralized at a slower rate under continuous no-till management. Interpretation of these results are complicated by the fact that all fields with a history of biosolids received an application 4–5 years prior to the sampling and several of these locations were tilled following application (i.e., 10–15, 30–34, and 51–54) while others were not.

Soil series had a significant effect on total soil N concentration at 0–7.5 and 0–15 cm but not at 0–2.5 cm. The Bojac soil series had 168 and 142 mg total soil N kg^{-1} less than the other two soil series at the 0–7.5 and 0–15 cm depths, respectively. The Bojac has a much coarser texture than either the Altavista or Emporia soils. Soils with higher clay content typically have higher SOM (Nichols 1984). This is due, in part, to the formation of SOM—clay mineral complexes and aggregates that protect SOM from microbial oxidation (Wiseman and Puttmann 2006). In addition, the coarse textured Bojac soil series has much lower water holding capacity and, with more rapid depletion of available soil water, it has a lower biomass productive capacity than the Altavista or Emporia soils. Since crop yields are typically lower, the amount of crop residues returned to the soil each season is reduced, resulting in lower SOM contents (Follett 2001; Lal et al. 1999).

Table 2 Depth weighted concentration of total soil N, Illinois soil N test-N (ISNT-N), and KCl extractable [NO_3 + NH_4]-N from each of the sampling sites

Site	Total N, g kg^{-1a}			ISNT-N, mg kg^{-1b}			[NO_3 + NH_4]-N, mg kg^{-1c}		
	0–2.5 cm	0–7.5 cm	0–15 cm	0–2.5 cm	0–7.5 cm	0–15 cm	0–2.5 cm	0–7.5 cm	0–15 cm
1	0.725	0.652	0.585	141	132	121	10.2	8.3	6.8
2	0.797	0.603	0.553	149	126	117	14.7	10.1	7.5
3	0.960	0.833	0.810	130	120	114	16.5	16.2	16.3
4	0.892	0.663	0.541	140	104	90.7	45.4	31.2	27.4
5	1.17	0.956	0.802	158	145	127	26.0	20.1	18.2
6	1.04	0.712	0.543	126	96.0	77.1	19.8	20.4	17.8
7	0.939	0.644	0.483	163	123	103	8.3	6.0	5.0
8	1.51	1.09	0.850	209	167	140	8.7	7.0	6.4
9	1.16	0.811	0.634	154	117	97.8	22.4	18.5	15.5
10	1.16	0.837	0.676	178	139	119	12.8	8.6	6.6
11	1.53	1.05	0.810	247	174	139	21.6	15.3	12.1
12	1.16	0.695	0.520	169	118	94.0	19.1	13.3	10.2
13	1.57	1.03	0.818	209	157	135	21.3	14.7	11.6
14	0.928	0.939	0.838	135	133	121	12.2	9.8	8.0
15	1.09	1.03	0.871	141	138	118	24.9	23.5	23.7
16	1.08	0.957	0.803	132	122	107	31.3	24.6	19.5
17	1.12	0.796	0.633	185	147	127	17.7	13.7	10.9
18	1.12	0.827	0.676	181	148	129	7.6	6.4	5.4
19	1.07	0.789	0.676	189	146	138	14.3	10.5	9.4
20	2.31	1.37	0.963	271	177	128	31.9	23.4	18.7
21	2.40	1.44	1.08	288	201	160	25.5	19.2	17.3
22	1.71	1.18	0.880	209	165	131	22.2	18.8	17.2
23	1.47	1.06	0.817	187	148	122	40.3	26.7	20.7
24	1.41	1.03	0.774	199	149	115	15.7	14.4	9.7
25	0.922	0.637	0.513	119	84.8	69.0	50.1	30.9	24.8
26	1.09	0.735	0.545	129	97.3	76.0	48.9	33.9	25.5
27	1.06	0.639	0.467	131	90.0	71.1	36.5	20.6	18.2
28	1.17	0.698	0.502	168	122	102	14.6	9.6	7.3
29	0.980	0.591	0.425	128	102	89.0	15.1	13.4	9.2
30	0.638	0.643	0.557	89.9	88.7	78.6	8.1	8.0	6.4
31	0.876	0.623	0.522	89.8	62.7	56.9	18.7	16.4	15.6
32	0.996	0.840	0.726	140	125	109	54.9	39.8	31.9
33	0.942	0.795	0.660	129	118	97.6	25.8	20.1	16.9
34	0.988	0.821	0.733	104	90.2	84.6	23.5	19.5	17.7
35	1.02	0.763	0.623	194	144	127	18.1	14.2	9.8
36	1.50	0.944	0.628	188	113	77.5	91.6	44.6	29.6
37	1.21	0.745	0.538	143	103	72.6	38.0	25.3	20.8
38	1.41	0.977	0.737	150	105	86.5	43.7	27.7	22.2
39	1.83	1.24	0.889	191	136	102	26.9	19.5	16.0
40	1.58	1.12	0.779	197	149	110	10.4	7.2	5.4
41	0.699	0.689	0.611	112	119	110	8.2	7.0	6.9
42	0.940	0.802	0.628	166	150	124	9.8	7.1	6.1

Table 2 continued

Site	Total N, g kg^{-1}[a]			ISNT-N, mg kg^{-1}[b]			[NO_3 + NH_4]-N, mg kg^{-1}[c]		
	0–2.5 cm	0–7.5 cm	0–15 cm	0–2.5 cm	0–7.5 cm	0–15 cm	0–2.5 cm	0–7.5 cm	0–15 cm
43	0.920	0.765	0.595	115	101	82.8	17.3	17.0	15.5
44	1.14	0.923	0.758	165	139	123	25.9	19.8	17.7
45	0.962	0.803	0.683	139	121	105	15.4	15.3	14.7
46	0.742	0.606	0.499	111	89.3	75.1	17.0	13.1	12.5
47	0.957	0.742	0.621	176	145	127	13.8	12.1	10.2
48	1.18	1.02	0.822	159	136	111	27.7	23.1	20.2
49	1.21	0.954	0.749	197	159	137	10.8	8.7	8.3
50	1.28	0.933	0.706	206	165	131	9.7	7.1	5.5
51	1.20	0.950	0.726	180	152	127	17.7	12.4	8.9
52	1.44	1.09	0.820	224	189	156	17.2	12.7	10.9
53	1.10	0.796	0.608	157	132	110	11.7	6.8	4.8
54	1.06	0.920	0.795	126	112	101	23.3	20.2	17.9
55	1.35	1.09	0.843	135	113	87.7	20.7	16.7	15.4
56	1.27	1.00	0.790	158	121	96.7	31.5	23.9	20.0
57	1.25	1.00	0.780	224	182	149	16.3	12.9	9.7
58	0.882	0.725	0.581	154	133	111	21.4	16.9	12.2
59	1.21	0.933	0.669	214	171	131	15.7	14.9	12.0
60	1.54	1.34	1.08	225	203	174	18.4	15.2	12.2
61	1.06	0.828	0.595	157	138	110	18.5	16.0	11.4
62	1.27	0.860	0.613	192	142	111	16.3	12.9	9.5
63	3.09	1.81	1.18	383	226	147	30.7	20.3	18.7
Mean	1.21	0.895	0.702	169	134	111	22.7	16.9	14.0

[a] Total soil N was determined by dry combustion using a VarioMax CNS macro elemental analyzer (Elementar, New Jersey)

[b] ISNT-N was determined using the procedures described in Technical Note 02-01 (University of Illinois at Urbana Champaign [UIUC], 2004) and Khan et al. (1997)

[c] Soil [NH_4 + NO_3]-N were extracted with 2 M KCl and determined colorimetrically using a QuickChem Automated ion analyzer (Lachat Instruments, Milwaukee, WI)

In order to estimate the mass of total N conserved we used bulk density to calculate N on an areal basis (kg N ha^{-1}). Analysis of variance and parameter estimates for the effects of dNT, biosolids and soil series on the mass of total soil N at the 0–2.5, 0–7.5 and 7.5–15 cm depths are summarized in Table 4. The overall trends for changes in the mass of total N with depth were similar to changes in the concentration of total N; however, dNT had no significant effect on the mass of total N at the 0–15 cm depth. This is surprising considering dNT did significantly increase the concentration of total N at the 0–15 cm depth. The only way this would be possible is if bulk density increased with dNT. Our previous analysis of the data indicated that bulk density was decreased with dNT at 0–2.5 cm and unaffected at both 0–7.5 and 0–15 cm (Spargo et al. 2008). The lack of a significant relationship between dNT and the mass of soil N in the 0–15 cm may simply be due to variance introduced by including bulk density in the calculation. An alternative method to estimate the conservation rate of total soil N on an areal basis with continuous no-till is to use the average bulk density for all locations at the 0–15 cm depth which we determined to be 1.48 Mg m^{-3}. Using this value and the conservation rate of 9.98 ± 9.56 mg N kg^{-1} year^{-1} for the 0–15 cm depth from Table 3 we estimate a conservation rate on an areal basis of 22.2 ± 21.2 kg N ha^{-1} year^{-1} with continuous no-till management. This is similar to the average N conservation rate of 28 kg N ha^{-1} year^{-1} with no-till reported by Franzluebbers (2004).

Table 3 Analysis of variance and parameter estimates for the effects of duration of continuous no-till management (dNT), biosolids application and soil series on the depth weighted concentration of total soil N at the 0–2.5, 0–7.5, and 0–15 cm depth

0–2.5 cm Depth

Source	df	Sum of squares[a]	F Value	Pr > F
Model	2	5.53×10^6	34.9	<0.0001
dNT	1	3.48×10^6	43.9	<0.0001
dNT × biosolids	1	2.06×10^6	26.0	<0.0001
Error	60	4.75×10^6		
Total	62	10.3×10^6		

Parameter	Estimate (mg kg^{-1})	Standard error (mg kg^{-1})	±95% CI (mg kg^{-1})
Intercept	741	74.9	150
dNT	50.3	11.0	22.0
dNT × biosolids	50.8	9.97	20.0

0–7.5 cm Depth

Source	df	Sum of squares	F Value	Pr > F
Model	4	1.44×10^6	12.1	<0.0001
dNT	1	5.08×10^5	17.1	0.0001
Biosolids	1	6.48×10^5	21.8	<0.0001
Soil series	2	2.81×10^5	4.72	0.013
Error	58	1.73×10^6		
Total	62	3.17×10^6		

Parameter	Estimate (mg kg^{-1})	Standard error (mg kg^{-1})	±95% CI (mg kg^{-1})
Intercept	882.	59.3	119.
dNT	28.4	6.46	12.9
Biosolids	232	44.8	89.8
Soil series[b]			
Bojac	−168	57.5	115

0–15 cm Depth

Source	df	Sum of squares	F Value	Pr > F
Model	4	5.54×10^5	8.47	<0.0001
dNT	1	6.19×10^4	3.79	0.041
Biosolids	1	2.57×10^5	15.7	0.0002
Soil series	2	2.35×10^5	7.20	0.0016
Error	58	9.49×10^5		
Total	62	1.50×10^6		

Parameter	Estimate (mg kg^{-1})	Standard error (mg kg^{-1})	±95% CI (mg kg^{-1})
Intercept	596	44.9	90.4
dNT	9.98	4.79	9.56
Biosolids	154	33.2	66.8
Soil series			
Bojac	−142	42.6	85.3

[a] Main effect sum of squares are Type I

[b] Individual soil series were evaluated using t-test to determine significance (not shown)

Table 4 Analysis of variance and parameter estimates for the effects of duration of continuous no-till management (dNT), biosolids application and soil series on the depth weighted mass of total soil N at the 0–2.5, 0–7.5, and 0–15 cm depth

0–2.5 cm Depth				
Source	df	Sum of squares[a]	F value	Pr > F
Model	2	2.89×10^5	24.9	<0.0001
dNT	1	1.38×10^5	23.9	<0.0001
dNT × biosolids	1	1.51×10^5	26.0	<0.0001
Error	60	3.47×10^5		
Total	62	6.36×10^5		
Parameter	Estimate (kg ha^{-1})	Standard error (kg ha^{-1})	±95% CI (kg ha^{-1})	
Intercept	260	20.3	40.2	
dNT	8.70	2.98	5.96	
dNT × biosolids	13.7	2.70	5.37	
0–7.5 cm Depth				
Source	df	Sum of squares	F value	Pr > F
Model	4	1.08×10^6	10.5	<0.0001
dNT	1	2.37×10^5	9.15	0.0037
Biosolids	1	5.52×10^5	21.4	<0.0001
Soil series	2	2.95×10^5	5.70	0.0055
Error	58	1.50×10^6		
Total	62	2.58×10^6		
Parameter	Estimate (kg ha^{-1})	Standard error (kg ha^{-1})	±95% CI (kg ha^{-1})	
Intercept	943	55.3	111	
dNT	19.7	6.01	12.0	
Biosolids	216	41.7	83.8	
Soil series[b]				
Bojac	−178	53.6	107	
0–15 cm Depth				
Source	df	Sum of squares	F value	Pr > F
Model	4	2.24×10^6	7.74	<0.0001
dNT	1	4.45×10^4	0.63	0.43
Biosolids	1	9.94×10^5	13.74	0.0007
Soil series	2	1.20×10^6	8.29	0.0005
Error	58	4.19×10^6		
Total	62	6.43×10^6		
Parameter	Estimate (kg ha^{-1})	Standard error (kg ha^{-1})	±95% CI (kg ha^{-1})	
Intercept	1396	94.5	189	
dNT	8.90	10.1	20.1	
Biosolids	310	69.7	140	
Soil series				
Bojac	−334	89.6	180	

[a] Main effect sum of squares are Type I

[b] Individual soil series were evaluated using *t*-test to determine significance (not shown)

We also examined the effect of dNT, biosolids, and soil series on the soil C:N ratio. The C:N ratio was unaffected at the 0–2.5 cm depth and increased at the 2.5–7.5 and 7.5–15 cm depths by continuous no-till management (Fig. 1). We expected the C:N ratio to increase with continuous no-till management due to the accumulation of high C:N ratio particulate organic matter with the elimination of tillage (Diekow et al. 2005; Pikul et al. 2007; Wander and Bidart 2000). It is interesting that the accumulation of crop residues at the soil surface with continuous no-till management did not increase the C:N ratio at the 0–2.5 cm depth but increased it at depth. Crozier and King (1993) found that the C:N ratio of above ground corn shoot residue (42:1) and fine roots (33:1) were lower than below ground shoot residue (118:1) and coarse roots (78:1). Without tillage to evenly distribute corn residues through the plow layer, this would be expected to lead to stratification with lower C:N residues near the surface. In addition, Franzluebbers (1994b) suggested that repeated wetting and drying, such as occurs at the soil surface, leads to an accumulation of organic N which may be due to the accumulation of microbial resistant N compounds in crop residues. This would also lead to accumulation of lower C:N residues at the soil surface than at depth. Neither biosolids nor soil series had a significant influence on the C:N ratio at any depth.

Illinois soil N test and inorganic N

The concentration of ISNT-N followed a similar trend as total soil N. Analysis of variance and parameter estimates for the effects of dNT, biosolids and soil series on the concentration of ISNT-N are summarized in Table 5. The concentration of ISNT-N increased significantly with dNT at the 0–2.5, 0–7.5, and 0–15 cm depths. Continuous no-till management increased the concentration of ISNT-N by 6.63, 4.12, and 1.68 mg ISNT-N kg^{-1} $year^{-1}$ at the 0–2.5, 0–7.5, and 0–15 cm depths, respectively.

There was a significant interaction between dNT and biosolids at the 0–2.5 cm depth but not at the 0–7.5 or 0–15 cm depths. The concentration of ISNT-N increased faster with dNT where biosolids were applied. The interaction between dNT and biosolids was not significant at 0–7.5 or 0–15 cm and the additive effect of biosolids was only significant at 0–7.5 cm. Biosolids increased the concentration of ISNT–N by 20 mg N kg^{-1} at 0–7.5 cm. It is interesting that sites with a history of biosolids did not have a significantly higher concentration of ISNT-N at 0–15 cm but did have greater total N.

Soil series also had a significant effect on ISNT – N concentration at 0–2.5, 0–7.5 and 0–15 cm. The Bojac soil series had 29.0, 38.0 and 29.2 mg N kg^{-1} less than the other two soil series at the 0 – 2.5, 0 – 7.5 and 0 – 15 cm depths, respectively. The reasons that the coarse-textured Bojac soil has lower concentrations of ISNT – N are likely similar to those previously discussed for total N.

We also considered the effect of dNT, biosolids, and soil series on ratio of ISNT-N to total N (data not shown). The only factor that had a significant influence was biosolids ($P = 0.004$). The ratio of ISNT-N to total N was 0.15 where biosolids had been applied compared to 0.17 where it had not. This may indicate that the application of biosolids increases the concentration of recalcitrant organic soil N.

It appears that ISNT-N was no more sensitive to management than total N. For example, at 0–15 cm both models explained 37% of the variability in total N and ISNT-N (as indicated by GLM Type I sum of squares). In a comparison of labile SOM between organic and conventional farming systems Marriott and Wander found ISNT-N to be highly correlated ($r = 0.98$) with total soil N and suggested this indicated ISNT-N may extract some recalcitrant forms of soil N. We also found significant correlation between ISNT-N and total soil N at the 0–2.5, 2.5–7.5, and 7.5–15 cm depths but the relationship was not as strong ($r = 0.83$, 0.62, and 0.53, respectively; Fig. 2) as that found by Marriott and Wander (2006). Further, the fraction of total N extracted by the ISNT was significantly different ($P < 0.05$) at each of the sampling depths. The percentage of total N extracted by the ISNT was 13.6, 15.6, and 17.0% at the 0–2.5, 2.5–7.5, and 7.5–15 cm depths, respectively. The frequent drying and rewetting of surface-placed residues reduces N mineralization from plant residues (Varco et al. 1993) and may increase the resistance of certain N compounds to microbial decomposition (Franzluebbers et al. 1994b). Future work involving more detailed soil N fractionation will need to be done on these soils in order to elucidate this trend and determine potential agronomic and environmental implications.

Concentrations of NO_3- and NH_4-N were unaffected by tillage or biosolids history. The concentration of inorganic soil N is dependent on

Table 5 Analysis of variance and parameter estimates for the effects of duration of continuous no-till management (dNT), biosolids application and soil series on the depth weighted concentration of Illinois soil N test-N at the 0–2.5, 0–7.5, and 0–15 cm depth

0 – 2.5 cm Depth

Source	df	Sum of squares[a]	F value	Pr > F
Model	1	9.19×10^4	22.9	<0.0001
dNT	1	6.06×10^4	60.2	<0.0001
dNT × biosolids	1	1.87×10^4	18.6	<0.0001
Soil series	2	1.26×10^4	6.28	<0.0034
Error	58	5.84×10^4		
Total	62	1.50×10^5		

Parameter	Estimate (mg kg^{-1})	Standard error (mg kg^{-1})	± 95% CI (mg kg^{-1})
Intercept	116	10.3	20.5
dNT	6.63	1.26	2.52
dNT × biosolids	5.43	1.14	2.28
Soil series			
Bojac	−29.0	10.4	20.8

0–7.5 cm Depth

Source	df	Sum of squares	F value	Pr > F
Model	3	3.12×10^4	15.3	<0.0001
dNT	1	3.32×10^3	26.3	<0.0001
Biosolids	1	2.93×10^3	5.73	0.02
Soil series	2	1.48×10^4	14.5	<0.0001
Error	58	2.97×10^4		
Total	62	6.09×10^4		

Parameter	Estimate (mg kg^{-1})	Standard error (mg kg^{-1})	±95% CI (mg kg^{-1})
Intercept	129	7.77	15.3
dNT	4.12	0.846	1.70
Biosolids	20.0	5.87	11.7
Soil series[b]			
Bojac	−38.0	7.54	15.1

0–15 cm Depth

Source	df	Sum of squares	F value	Pr > F
Model	3	1.37×10^4	11.5	<0.0001
dNT	1	3.32×10^3	8.40	0.005
Soil series	2	1.03×10^4	13.1	<0.0001
Error	59	2.33×10^4		
Total	62	3.70×10^4		

Parameter	Estimate (mg kg^{-1})	Standard error (mg kg^{-1})	±95% CI (mg kg^{-1})
Intercept	108	6.41	12.8
dNT	1.68	0.739	1.45
Soil series			
Bojac	−29.2	6.51	13.0

[a] Main effect sum of squares are Type I

[b] Individual soil series were evaluated using t-test to determine significance (not shown)

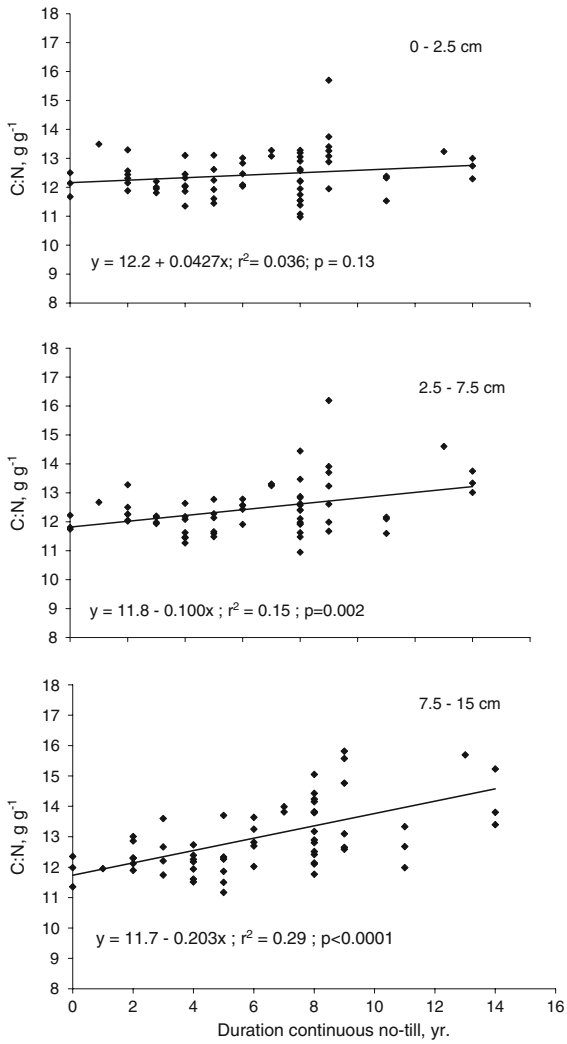

Fig. 1 Relationship between the C:N ratio at 0–2.5, 2.5–7.5 and 7.5–15 cm sampling depths and the duration of continuous no-till

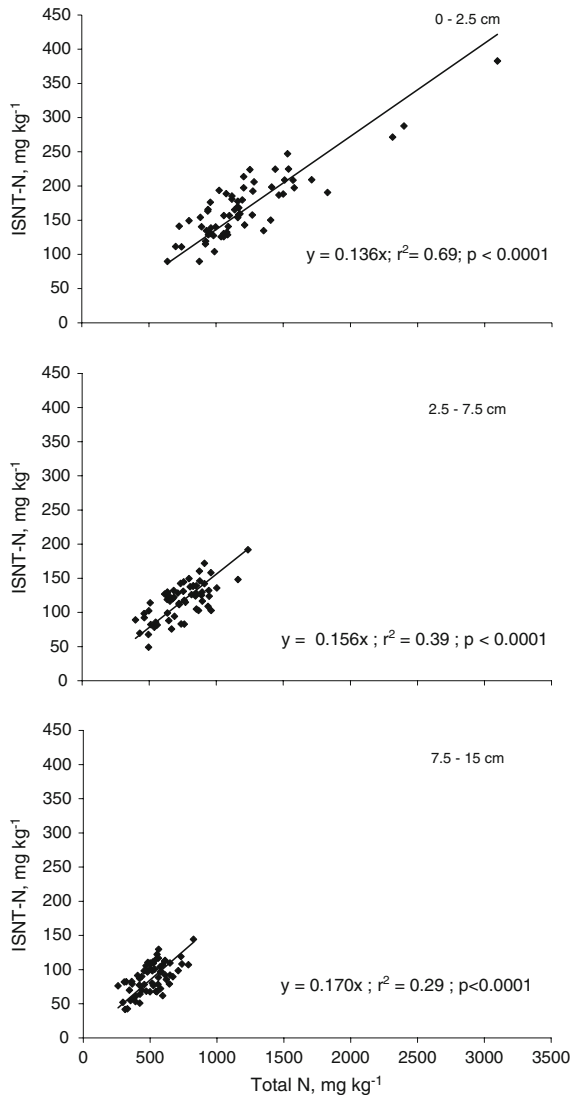

Fig. 2 Relationship between the concentration of ISNT-N and the concentration of total N at the 0–2.5, 2.5–7.5 and 7.5–15 cm sampling depths

numerous N-cycle processes (Stevenson and Cole 1999) and the sensitivity of inorganic soil N to management practices may be limited by its temporal and spatial variability. The concentration of NO_3-N was significantly greater ($P < 0.05$) at the surface 0–2.5 cm (16.8 mg N kg^{-1}) than 2.5–7.5 cm (9.5 mg N kg^{-1}) and 7.5–15 cm (7.2 mg N kg^{-1}). The concentration of NH_4-N was also significantly greater ($P < 0.05$) at the surface 0–2.5 cm (5.9 mg N kg^{-1}) than 2.5–7.5 cm (4.5 mg N kg^{-1}) and 7.5–15 cm (3.9 mg N kg^{-1}). Soil series had a significant affect on the concentration of soil NO_3-N but not NH_4-N. The Bojac soil series had 12.6 ($P = 0.0008$), 6.01 ($P = 0.003$) and 3.91 ($P = 0.01$) mg NO_3-N kg^{-1} more than the Altavista and Emporia soils at 0–2.5, 0–7.5 and 0–15 cm depths, respectively (data not shown). The higher concentration of NO_3-N in the coarse-textured Bojac soils is of particular concern since leaching losses are more likely to occur from these excessively well drained soils.

Conclusions

Continuous no-till is an effective management practice in the Virginia middle coastal plain to conserve soil N.

We found that the implementation of continuous no-till on farms previously using rotational or intermittent tillage resulted in the conservation of 22.2 ± 21.2 kg N ha^{-1} $year^{-1}$ (0–15 cm). These data provide a quantitative estimate of the N conservation rate within the surface 15 cm for the region based upon on-farm observations. Our observed rate is similar to the average N conservation rate of 28 kg N ha^{-1} $year^{-1}$ ($n = 26$) with no-till reported by Franzluebbers (2004). The conservation of soil N with continuous no-till management indicates improved N use efficiency of the cropping system.

It is important to recognize that a substantial portion of the soil N conserved with continuous no-till management can become rapidly available and potentially lost from the system when intermittent tillage is used as a modifier to address perceived soil compaction, remove ruts, control weeds or incorporate residues (Pierce and Fortin 1997). Therefore, the use of periodic or intermittent tillage of no-till cropping systems should only be practiced when absolutely necessary. When intermittent tillage is used, it should be synchronized with cropping to maximize the capture of mineralized soil N by growing vegetation.

A portion of the additional N retained as SOM in no-till soils may potentially become available for crops (Franzluebbers et al. 1994a; Wienhold and Halvorson 1999). A soil based approach that quantifies organic N turnover may be necessary to improve the precision of fertilizer N recommendations in these systems. The ISNT has shown promise in some regions in certain cropping systems to predict N-mineralization (Sharifi et al. 2007) and a concomitant reduction in fertilizer N needs (Khan et al. 2001b; Klapwyk and Ketterings 2006; Mulvaney et al. 2005; Williams et al. 2007) but has failed in others (Barker et al. 2006). Future work will need to determine if the ISNT is an effective assay for the prediction of soil N availability in the corn-wheat-double crop soybean cropping system of the middle coastal plain of Virginia.

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References

Barker DW, Sawyer JE, Al-Kaisi MM, Lundvall JR (2006) Assessment of the amino sugar-nitrogen test on Iowa soils: II. field correlation and calibration. Agron J 98:1352–1358. doi:10.2134/agronj2006.0034

Bundy LG, Meisinger JJ (1994) Nitrogen availability indices. In: Weaver RW, Angle JS, Bottomley P, Bezdicek D, Smith S, Tabatabai A, Wollum A (eds) Methods of soil analysis. Part 2. SSSA, Madison, WI, pp 951–984

Carter MR, Rennie DA (1984) Dynamics of soil microbial biomass N under zero and shallow tillage for spring wheat, using N-15 urea. Plant Soil 76:157–164. doi:10.1007/BF02205576

Cassman KG, Dobermann A, Walters DT (2002) Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31:132–140. doi:10.1639/0044-7447(2002)031[0132:ANUEAN]2.0.CO;2

Crozier CR, King LD (1993) Corn root dry-matter and nitrogen distribution as determined by sampling multiple soil cores around individual plants. Commun Soil Sci Plant Anal 24:1127–1138

CTIC (2004) Conservation technology information center. National crop residue management survey http://www.conservationinformation.org/index.asp?site=1&action=crm_results. Cited 2 July 2008

Diekow J, Mielniczuk J, Knicker H, Bayer C, Dick DP, Kogel-Knabner I (2005) Carbon and nitrogen stocks in physical fractions of a subtropical acrisol as influenced by long-term no-till cropping systems and N fertilisation. Plant Soil 268:319–328. doi:10.1007/s11104-004-0330-4

Follett RF (2001) Soil management concepts and carbon sequestration in cropland soils. Soil Tillage Res 61:77–92. doi:10.1016/S0167-1987(01)00180-5

Follett RF, Hatfield JL (eds) (2001) Nitrogen in the environment: sources, problems, and management. Elsevier, London

Follett RF, Peterson GA (1988) Surface soil nutrient distribution as affected by wheat-fallow tillage systems. Soil Sci Soc Am J 52:141–147

Follett RF, Schimel DS (1989) Effect of tillage practices on microbial biomass dynamics. Soil Sci Soc Am J 53:1091–1096

Franzluebbers AJ (2002) Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res 66:95–106. doi:10.1016/S0167-1987(02)00018-1

Franzluebbers AJ (2004) Tillage and residue management effects on soil organic matter. In: Magdoff FR, Weil RR (eds) Soil organic matter in sustainable agriculture. CRC Press, Boca Raton, FL, pp 227–268

Franzluebbers AJ (2005) Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. Soil Tillage Res 83:120–147. doi:10.1016/j.still.2005.02.012

Franzluebbers AJ, Hons FM, Zuberer DA (1994a) Long-term changes in soil carbon and nitrogen pools in wheat management-systems. Soil Sci Soc Am J 58:1639–1645

Franzluebbers K, Weaver RW, Juo AS, Franzluebbers AJ (1994b) Carbon and nitrogen mineralization from cowpea plants part decomposing in moist and in repeatedly dried

and wetted soil. Soil Biol Biochem 26:1379–1387. doi:10.1016/0038-0717(94)90221-6

House GJ, Stinner BR, Crossley DA, Odum EP, Langdale GW (1984) Nitrogen cycling in conventional and no-tillage agroecosystems in the southern piedmont. J Soil Water Conserv 39:194–200

Institute SAS (2002) SAS/Statistical user's guide, 6.03rd edn. SAS Institute Inc., Cary, NC

Khan SA, Mulvaney RL, Mulvaney CS (1997) Accelerated diffusion methods for inorganic-nitrogen analysis of soil extracts and water. Soil Sci Soc Am J 61:936–942

Khan SA, Mulvaney RL, Hoeft RG (2001a) A simple soil test for detecting sites that are nonresponsive to nitrogen fertilization. Soil Sci Soc Am J 65:1751–1760

Khan SA, Mulvaney RL, Hoeft RG (2001b) A simple soil test for detecting sites that are nonresponsive to nitrogen fertilization. Soil Sci Soc Am J 65:1751–1760

Klapwyk JH, Ketterings QM (2006) Soil tests for predicting corn response to nitrogen fertilizer in New York. Agron J 98:675–681. doi:10.2134/agronj2005.0241

Kristensen HL, McCarty GW, Meisinger JJ (2000) Effects of soil structure disturbance on mineralization of organic soil nitrogen. Soil Sci Soc Am J 64:371–378

Lal R, Follett RF, Kimble J, Cole CV (1999) Managing U.S. cropland to sequester carbon in soil. J Soil Water Conserv 54:374–381

Marriott EE, Wander MM (2006) Total and labile soil organic matter in organic and conventional farming systems. Soil Sci Soc Am J 70:950–959. doi:10.2136/sssaj2005.0241

Martens DA (2001) Nitrogen cycling under different soil management systems. Adv Agron 70:143–192. doi:10.1016/S0065-2113(01)70005-3

Martens DA, Dick W (2003) Recovery of fertilizer nitrogen from continuous corn soils under contrasting tillage management. Biol Fertil Soils 38:144–153. doi:10.1007/s00374-003-0645-y

Meisinger JJ, Bandel VA, Stanford G, Legg JO (1985) Nitrogen-utilization of corn under minimal tillage and moldboard plow tillage 1: 4-year results using labeled N-fertilizer on an Atlantic coastal-plain soil. Agron J 77:602–611

Moll RH, Kamprath EJ, Jackson WA (1982) Analysis and interpretation of factors which contribute to efficiency of nitrogen-utilization. Agron J 74:562–564

Mulvaney RL, Khan SA, Ellsworth TR (2005) Need for a soil-based approach in managing nitrogen fertilizers for profitable corn production. Soil Sci Soc Am J 70:172–182. doi:10.2136/sssaj2005.0034

Nichols JD (1984) Relation of organic-carbon to soil properties and climate in the Southern Great Plains. Soil Sci Soc Am J 48:1382–1384

Paustian K, Collins HP, Paul EA (1997) Management controls on soil carbon. In: Paul EA, Paustian K, Elliot ET, Cole CV (eds) Soil organic matter in temperate ecosystems: Long-term experiments in North America. CRC Press, Boca Raton, FL, pp 15–49

Pierce FJ, Fortin MC (1997) Long-term tillage and periodic plowing of a no-tilled soil in Michigan: impacts, yield, and soil organic matter. In: Paul EA, Paustian K, Elliot ET, Cole CV (eds) Soil organic matter in temperate ecosystems: long-term experiments in North America. CRC Press, Boca Raton, FL, pp 141–149

Pikul JL, Osborne S, Ellsbury M, Riedell W (2007) Particulate organic matter and water-stable aggregation of soil under contrasting management. Soil Sci Soc Am J 71:766–776. doi:10.2136/sssaj2005.0334

Raun WR, Johnson GV (1999) Improving nitrogen use efficiency for cereal production. Agron J 91:357–363

Schomberg HH, Jones OR (1999) Carbon and nitrogen conservation in dryland tillage and cropping systems. Soil Sci Soc Am J 63:1359–1366

Semenov MA, Jamieson PD, Martre P (2007) Deconvoluting nitrogen use efficiency in wheat: a simulation study. Eur J Agron 26:283–294. doi:10.1016/j.eja.2006.10.009

Sharifi M, Zebarth BJ, Burton DL, Grant CA, Cooper JM (2007) Evaluation of some indices of potentially mineralizable nitrogen in soil. Soil Sci Soc Am J 71:1233–1239. doi:10.2136/sssaj2006.0265

Smil V (2001) Enriching the Earth; Fritz Haber, Carl Bosch and the transformation of world food production. MIT Press, Cambridge

Spargo JS, Alley MM, Follett RF, Wallace JV (2008) Soil carbon sequestration with continuous no-till management of grain cropping systems in the Virginia Coastal Plain. Soil Tillage Res (in press)

Stevenson FJ, Cole MA (1999) Cycles of soil: carbon, nitrogen phosphorus, sulfur, micronutrients, 2nd edn. Wiley, Inc., New York

UCUI (2004) The Illinois soil nitrogen test for amino sugar-N: estimation of potentially mineralizable soil N and ^{15}N, No. 02–01, Rev. f. ^{15}N analysis service. University of Illinois, Urabana-Champaign

Uri ND (2001) Conservation practices in US agriculture and their impact on carbon sequestration. Environ Monit Assess 70:323–344. doi:10.1023/A:1010735510641

Varco JJ, Frye WW, Smith MS, Mackown CT (1993) Tillage effects on legume deomposition and transformation of legume and fertilizer N-15. Soil Sci Soc Am J 57:750–756

Wander MM, Bidart MG (2000) Tillage practice influences on the physical protection, bioavailability and composition of particulate organic matter. Biol Fertil Soils 32:360–367. doi:10.1007/s003740000260

West TO, Marland G (2002) A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agric Ecosyst Environ 91:217–232. doi:10.1016/S0167-8809(01)00233-X

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci Soc Am J 66:1930–1946

Wienhold BJ, Halvorson AD (1999) Nitrogen mineralization responses to cropping, tillage, and nitrogen rate in the Northern Great Plains. Soil Sci Soc Am J 63:192–196

Williams JD, Crozier CR, White JG, Heiniger RW, Sripada RP, Crouse DA (2007) Illinois soil nitrogen test predicts Southeastern U.S. corn economic optimum nitrogen rates. Soil Sci Soc Am J 71:735–744. doi:10.2136/sssaj2006.0135

Wiseman CL, Puttmann W (2006) Interactions between mineral phases in the preservation of soil organic matter. Geoderma 134:109–118. doi:10.1016/j.geoderma.2005.09.001