CHAPTER 3

Cropland Management in the Eastern United States for Improved Soil Organic Carbon Sequestration

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CHAPTER OUTLINE

Abbreviations: CT, conventional tillage; NT, no-till; SOC, soil organic carbon

INTRODUCTION

The eastern United States (Figure 3.1) is a very diverse region with respect to geography, soils, and climate. This diversity leads to the production of a wide range of crops using numerous management practices and variable potentials to increase soil organic C (SOC) sequestration (defined here as the accumulation of SOC in response to changing management). The largest extent of cropland lies on Atlantic and Gulf Coastal Plains and Piedmont of the southeastern and mid-Atlantic states; however, portions of the Appalachian Plateau, Ridge and Valley, and New England physiographic provinces are also used for crop production.

The eastern U.S. has a long history of crop production. Prior to the arrival of European settlers in the 17th and 18th centuries, Native Americans produced crops such as corn (*Zea mays*),

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beans (genus *Phaseolus*), and squash (genus *Cucurbita*) in small clearings and established new fields when older fields became depleted. With European colonization, settlers expanded the area under cultivation by clearing forests and established intensive cultivation of cash crops such as corn, cotton (*Gossypium* L.), tobacco (*Nicotina* L.), rice (*Oryzal* L.), indigo (*Indigofera tintoria*), and timber production. Continuous cultivation of fields coupled with poor land stewardship resulted in rapid depletion in nutrients, accelerated soil erosion, and an eventual decline in crop productivity (Busscher et al., 2010). This type of management was commonly practiced because there was always more land available for farming. Unfortunately, it took another century for farmers to be made aware that land availability was limited and that the soil needed good stewardship to replenish nutrients and reduce erosion losses (Bennett and Chapline, 1928). Because of a more favorable climate, the intensification of agriculture and depletion of soil resources was greatest in the southeastern and mid-Atlantic states. However, past soil erosion also degraded productivity of soils throughout the northeastern U.S.

For almost two centuries, fields in the eastern U.S. were prepared for row crop production using some form of conventional tillage (CT, plowing and/or disking). These tillage operations invert topsoil and incorporate crop residue, a practice that is well known to hasten its microbial oxidation and loss from the SOC pool (Reicosky et al., 1995; Hunt et al., 1996). This has been a serious concern because SOC declines in sandy soils of the coastal plains can result in poor soil physical conditions for plant growth (Busscher et al., 1987), low water storage capacities (Peele et al., 1970; Campbell et al., 1974), and reduced capacity of soils to retain nutrients (Pierzynski et al., 2000) and herbicides (Novak et al., 1996). In addition to tilling the soil using conventional practices, SOC declines in the

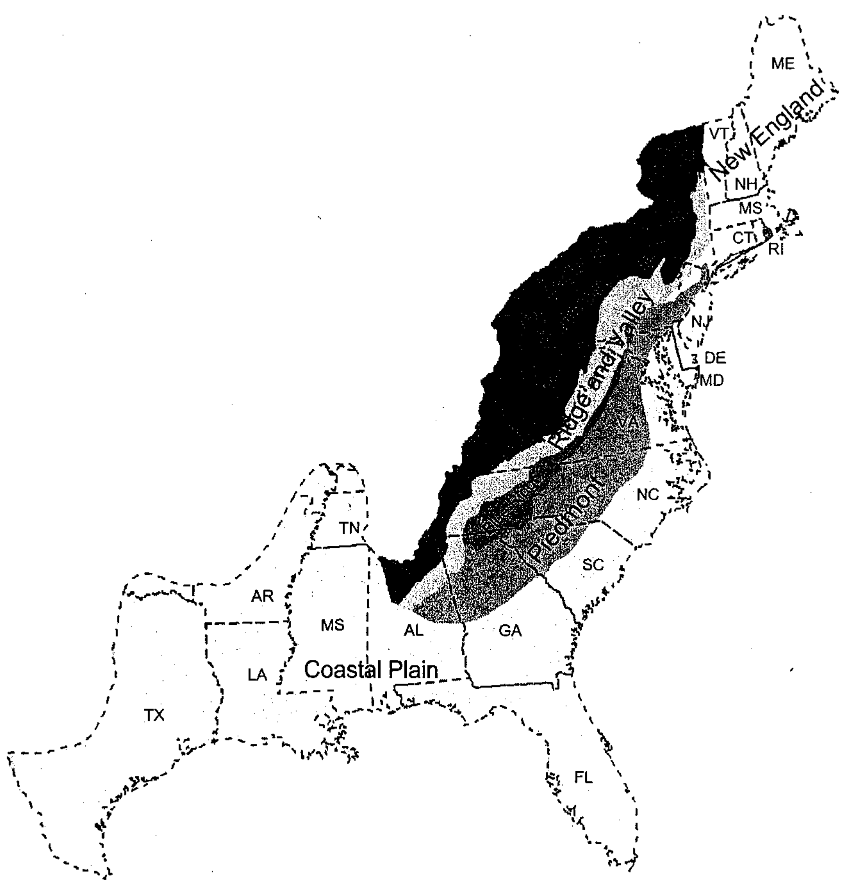

FIGURE 3.1
Physiographic provinces of the Eastern United States.

southeastern U.S. have been made worse in many areas by long-term cotton monoculture because cotton returns small amounts of crop residue to the soil (Causarano et al., 2006; Novak et al., 2009). Other crops such as corn, soybean (*Glycine max* L.), or wheat (*Triticum* L.) can supply more crop residues (>3.1 t/ha) to the soil (Hunt and Matheny, 1993; Karlen et al., 1987); unfortunately, more crop residues may not translate into higher SOC contents especially when soils are tilled using conventional practices (Parton and Schimel, 1987; Wang et al., 2000).

Increased awareness and adoption of conservation measures since the mid-20th century have helped to control erosion and restore productivity of soils throughout the eastern U.S. The adoption of conservation tillage, which involves minimal surface tillage, leaves crop residues to accumulate at the soil surface. The unincorporated crop residues decompose more slowly when compared to soils under traditional tillage operations (Reicosky and Lindstrom, 1993; Lal and Kimble, 1997; Paustian et al., 2000; Bauer et al., 2006). The use of additional management practices such as cover cropping, manure application, and improved crop rotations can also help to reduce soil losses and increase retention of soil organic matter. This chapter will address current crop production management practices and their impact on SOC dynamics in the eastern U.S. and analyze potential for additional SOC sequestration.

GEOGRAPHIC REGIONS OF THE EASTERN U.S

The Coastal Plain is an expansive geophysical province that extends from southern New Jersey along the Atlantic coast through the coast of the Gulf of Mexico to southeastern Texas (Figure 3.1), with cropland comprising about 15% of the total land area in the region (USDA, 2006). The Coastal Plain was formed through a series of sea level rises and recessions and subsequent depressional and erosional forces (Siple, 1967). The landscape is relatively flat and typified by scarps and terraces resulting from changes in ocean level, deposition of sediments, and river dissection over time. The elevation ranges from sea level to about 150 m (Daniels et al., 1999). Ultisols are the dominant Coastal Plain soil order. Stable coastal surfaces developed aged soils that included an eluvial (E) horizon, weathered clays (Daniels et al., 1967a), and a reddened argillic B horizon (Daniels et al., 1967b). Because of the extreme age, abundant rainfall, and humid climate, many of the Ultisols have a high degree of weathering leading to low pH (unless limed), highly weathered clay (Shaw et al., 2004; Novak et al., 2009), low cation exchange capacity (<2 to 4 $cmol_c\ kg^{-1}$; Kleiss, 1994), and low SOC content (0.2 to 0.8 $g\ kg^{-1}$; Hunt et al., 1982; Novak et al., 2009). Coastal Plains sandy soils also commonly have a restrictive subsurface hard layer (Mullins, 2000; Chartres et al., 1990) that can limit root penetration (Busscher et al., 2001). Average precipitation is 1000–1500 $mm\ yr^{-1}$ (increasing north to south), with maximum rainfall in mid-summer in the eastern portion and winter and spring in the west. Average temperatures range from 13 to 20°C (increasing north to south), with the average number of frost-free days ranging from 200 to 305 (USDA, 2006).

The Piedmont extends from the Appalachian Mountains to the Coastal Plain, ranging from Alabama to southeastern Pennsylvania (Figure 3.1). Cropland accounts for 8% of the Southern Piedmont Major Land Resource Area (MLRA) and 28% of Northern Piedmont MLRA (USDA, 2006). The Piedmont can be extensively hilly and contain soils that formed in unstable positions where soil profile expression has been limited (i.e. Inceptisols, Entisols). In more stable positions, such as on gently rolling topography, soils are older and will show more soil profile development (Alfisols and Ultisols). Piedmont soils are often formed from residuum or alluvium along streams and rivers (Daniels et al., 1999) leading to textures that vary from fine-clayey to coarse. Profile horizonation sequences of Piedmont soils are highly variable. Profiles can be composed of kaolinitic, mixed, and smectitic clays and depending on age are low in base saturation due to leaching from the rock parent

TABLE 3.1 Land Area (Hectares) in the Eastern United States Planted to Major Row Crops Reported in the 2007 Census of Agriculture (USDA-National Agricultural Statistic Service). Sugarcane was Produced on 164,200 ha in Louisiana and 153,328 ha in Florida. The Total Land Area in all States Planted to these Crops was 14,620,640 ha

State	Corn (grain)	Corn (silage)	Soybeans	Cotton	Small grains	Rice	All vegetables	Peanuts	Grain sorghum	Tobacco	State total
Alabama	112,048	11,016	72,768	154,939	41,014	NR	7,433	64,162	2,360	NR	465,739
Arkansas	236,775	1,887	1,141,889	346,036	284,760	536,767	5,637	NR	87,655	NR	2,641,406
Connecticut	1,443	24,147	119	NR†	3,220	NR	4,167	NR	NR	1,267	34,363
Delaware	75,090	6,353	62,997	NR	35,167	NR	14,179	NR	132	NR	193,919
Florida	13,736	27,005	4,887	32,421	25,486	4,603	91,059	48,048	539	421	248,205
Georgia	181,848	38,657	113,489	403,553	120,432	NR	48,196	210,081	18,101	7,286	1,141,643
Louisiana	292,567	4,087	240,495	135,191	87,774	152,613	7,601	NR	99,381	NR	1,019,708
Maine	1,325	23,516	310	NR	18,205	NR	27,006	NR	NR	NR	70,362
Maryland	186,355	63,979	156,575	NR	83,541	NR	13,024	NR	1,982	171	505,628
Massachusetts	985	13,895	100	NR	NR	NR	6,302	NR	NR	536	21,818
Mississippi	353,815	11,900	579,589	265,701	134,910	74,897	12,438	NR	47,345	NR	1,480,596
New Hampshire	92	12,640	NR	NR	NR	NR	1,366	NR	NR	NR	14,097
New Jersey	33,030	11,528	32,083	NR	134,908	NR	20,510	NR	249	NR	232,307
New York	223,410	507,568	80,909	NR	66,269	NR	64,859	NR	290	NR	943,305
N. Carolina	390,998	56,886	559,221	213,054	224,033	NR	47,398	36,057	3,497	68,884	1,600,028
Pennsylvania	397,205	429,139	174,576	NR	116,122	NR	22,192	NR	1,278	3,194	1,143,706
Rhode Island	17	1,653	NR	NR	NR	NR	964	NR	NR	NR	2,634
S. Carolina	150,886	13,392	179,197	64,110	64,032	NR	10,453	22,814	2,428	8,134	515,446
Tennessee	316,146	52,565	395,284	204,143	104,447	937	11,650	NR	4,093	8,144	1,300,617
Vermont	2,174	87,403	814	NR	279	NR	1,156	NR	NR	NR	91,827
Virginia	162,433	126,295	198,610	23,993	96,571	NR	10,637	8,761	NR	8,457	635,758
Crop total	3,132,377	1,525,511	3,993,913	1,843,142	1,641,171	769,817	428,228	389,923	269,331	106,493	

†NR, None reported

materials (Daniels et al., 1999). The average precipitation is 940–1525 mm yr^{-1} (increasing north to south). Average temperatures range from 9 to 18°C (also increasing north to south), with the average number of frost-free days ranging from 185 to 275 (USDA, 2006).

The Appalachian Ridge and Valleys extend from northern Alabama through central Pennsylvania (Figure 3.1). Parallel ridges of limestone, shale, and sandstone are separated by narrow to moderately wide valleys that range from nearly level to rolling hills. Soils are typically shallow on ridges, but can be deep and productive in larger valleys. Valley soils are classified as Inceptisols, Alfisols, and Ultisols with loamy or clayey textures and drainage typically ranging from excessively drained to moderately well drained. Croplands occupy approximately 15% of the Ridge and Valley landscape. Average precipitation is 800–1300 mm yr^{-1}, with maximum precipitation from late winter to early summer. Average temperatures are 11–17°C in the southern portion and 7–14°C in the north, with an average of 205 frost-free days in the south and 180 days in the north (USDA, 2006).

Much of northern Pennsylvania and New York lies on the glaciated Appalachian Plateau (Figure 3.1). Soils are primarily formed from glacial till and outwash (April et al., 1986). Soils that formed on semi-stable plateaus are classified as Inceptisols or Alfisols, with loamy texture. These soils range from shallow to moderately deep with drainage ranging from well to very poorly drained. Soils in the outwash areas are classified as Entisols, Inceptisols, or Spodosols, and can be well to excessively well drained especially if the texture is dominated by sands (April et al., 1986). Cropland is typically found on broad plateau tops which are nearly level to moderately sloping and dissected by narrow, steep-walled valleys. Approximately 17% of the land area on the Appalachian Plateau is used for crop production (USDA, 2006). It should be noted that the large amount of rock material on the till surface and in the profile of glacial soils make agricultural production difficult; extremely rocky lands are left for forestry production. Average precipitation is 760–1200 mm y^{-1}, with a large portion as snowfall. The average temperature is 4–10°C, with an average of 165 frost-free days per year (USDA, 2006).

The New England physiographic province (Figure 3.1) comprises the northern-most portion of the eastern United States and is a portion of the Appalachian Highlands. Over 80% of New England is mountainous and forested, with less than 4% of the land used for crop production. The greatest portion of the cultivated land is on gently rolling uplands and coastal lowlands. The dominant cultivated soils are Entisols and Inceptisols formed from glacial till and outwash. The average precipitation is 850–1400 mm y^{-1}. The average temperature is 6–12°C in the southern portion of the region and 4–9°C in the north, with an average of 190 frost-free days in the south decreasing to 160 days in the north portion of the region.

CROPLAND MANAGEMENT IN THE EASTERN U.S.

The 2007 Census of Agriculture (USDA-NASS, 2007) provided the most recent state-by-state listing of land area devoted to the production of major crops (Table 3.1). Corn is the most commonly grown crop throughout the eastern U.S., with approximately 4.6 and 1.5 Mha grown for grain and silage, respectively. A majority of the corn is harvested for grain in the mid-Atlantic and southeastern states, while much of the corn in the northeastern states (generally grown in rotation with multiple years of alfalfa) is harvested for silage. Soybean is the second most widely grown crop in the eastern U.S. (approximately 4 Mha) and accounted for the greatest cropland area in several states (Arkansas, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia). Cotton production in the southeastern states accounted for approximately 1 Mha. Approximately 1.6 Mha were used for small grain production throughout the region. Other major crops included rice (770,000 ha),

TABLE 3.2 Use of Conservation Tillage for Major Crops in Eastern U.S. States where Data are Available[†]

Crop/state	Hectares planted	Conservation tillage[‡]	Reduced tillage[§]	Conventional tillage[¶]	No-till[#]	No-till with >30% residue cover
		percent of hectares			percent of hectares	
Corn (2005)						
Georgia	109,102	59	9	31	32	29
New York	399,941	8	8	84	2	2
North Carolina	303,027	60	11	29	57	54
Pennsylvania	545,393	43	25	32	41	40
Cotton (2007)						
Alabama	161,622	48	21	30	40	35
Arkansas	347,529	12	5	83	9	9
Georgia	416,086	41	16	43	38	27
Louisiana	135,428	7	7	87	5	5
Mississippi	266,673	19	3	78	20	19
North Carolina	202,019	56	15	29	57	46
South Carolina	72,753	47	11	41	48	45
Tennessee	208,024	65	17	17	80	65
Soybeans (2006)						
Arkansas	1,249,220	26	8	66	15	14
Louisiana	351,480	32	12	56	26	25
Mississippi	674,680	41	14	46	35	35
North Carolina	553,480	60	31	10	73	55
Tennessee	463,687	83	5	12	74	72
Virginia	210,080	93	3	4	82	81

[†]Source: Horowitz et al. (2010).
[‡]>30% residue cover on soil surface.
[§]15–30% residue cover on soil surface.
[¶]<15% residue cover on soil surface.
[#]Defined as no-inversion tillage or other mechanical disturbance of the soil.

peanut (*Arachis hypogea* L.) (390,000 ha), sugarcane (*Saccharium officinarum* L.) (318,000 ha), grain sorghum (*Sorghum bicolor* Moench) (270,000 ha), and tobacco (106,000 ha). A wide range of vegetables, including potato (*Solanum tuberosum* L.), are also grown throughout the eastern states, with production of all vegetables accounting for approximately 430,000 ha.

No-till and other conservation tillage (>30% residue cover) and reduced tillage (15–30% residue cover) are used to varying extents within eastern states. While annual data for tillage practices for all major crops in each state are not available, the USDA-Economic Research Service estimates (Horowitz et al., 2010) are available for selected states in years that survey data were obtained for a specific crop (Table 3.2). For corn (last estimated in 2005), conservation tillage usage was as high as 60% in North Carolina and as low as 2% in New York. The low rate of adoption of conservation tillage in New York and the New England states has been attributed to slower warming of soils under residue cover and subsequent impacts on crop establishment in the spring (P. Salon, personal communication). Estimates of tillage usage for cotton production in 2007 (Table 3.2) also indicate large differences among states. Conservation tillage was used on approximately 60% of the acreage in North Carolina and Tennessee and only 10% of the land in Arkansas and Louisiana. Soybean production with conservation tillage (estimated in 2006) ranged from as much as 93% of the acreage in Virginia to 26% in Arkansas.

Poultry, dairy, swine, and beef production are important throughout the eastern U.S., and land application of manure from confined animal operations is a significant C input to soils on many farms throughout the region (Table 3.3). North Carolina, New York, and Pennsylvania produce the greatest quantities of manure in the region (approximately 900,000 Mg C y^{-1}, each, in 1997). With the exception of Connecticut and Vermont, annual statewide manure C production would be $\leq$0.6 Mg C ha^{-1} on available cropland assuming uniform distribution (which does not occur), even in the states with the greatest manure production (Table 3.3). Since only a portion of the manure C will be resistant to degradation and contribute to the formation of stable organic matter in soil, the quantities of manure produced limits the total impact of manure application on C sequestration throughout states within the region. However, ample manure is available for land application in areas with concentrated livestock production and can contribute substantially to SOC sequestration. Application of manure at a rate sufficient to provide the N requirement for a corn crop (145–180 kg N ha^{-1}) typically requires 50,000–80,000 L ha^{-1} of liquid dairy or swine manure, 15–25 Mg of beef manure ha^{-1}, or 2–4 Mg ha^{-1} of chicken litter [fresh weight basis, Penn State University Agronomy Factsheet 55 (online at http://cropsoil.psu.edu/extension/facts/agfact55.pdf)]. Assuming that manure solids and any included bedding materials are 40% C, these application rates represent a C addition to soil of 1.0–1.6 Mg C ha^{-1} for liquid dairy manure (assuming 5% dry matter), 1.8–3.0 Mg C ha^{-1} for beef manure (assuming 30% dry matter), 1.25–2.0 Mg C ha^{-1} for swine slurry (assuming 2.5% dry matter), and 0.3–0.5 Mg C ha^{-1} with poultry litter (assuming 34% dry matter).

Cover crops are used throughout the eastern U.S. to reduce soil erosion and nutrient losses, and they contribute biomass that can potentially lead to greater sequestration of C in soils. The use of cover crops can be especially beneficial following crops that leave limited quantities of residues on the soil surface (i.e. soybean, cotton, and corn harvested for silage). However, comprehensive data on the extent of eastern U.S. cropland planted to cover crops and the type of cover crop used are not available. A recent program in Maryland, as part of that state's efforts to improve water quality in the Chesapeake Bay, has provided financial incentives to farms planting winter cover crops. This resulted in the planting of a state record 161,066 ha of winter cover crops in the fall of 2010 (Maryland Department of Agriculture, 2010).

SYNTHESIS OF PUBLISHED FINDINGS

Results of Previously Reported Research

An earlier review (Franzluebbers, 2005) addressing SOC sequestration potential for cropland in the southeastern U.S. indicated that cropland management had a variable impact on SOC storage. For 96 comparisons at 22 locations with 5 to15 years of NT, an average of 0.41 $\pm$ 0.46 Mg SOC ha^{-1} yr^{-1} (mean $\pm$ standard deviation) was sequestered in response to the use of NT compared to CT. With an additional 51 comparisons of SOC on conventional and conservation-tillage cropland in the region, SOC sequestration rate was revised to 0.45 $\pm$ 0.04 Mg C ha^{-1} yr^{-1} (mean $\pm$ standard error) at a sampling depth of 20 $\pm$ 1 cm and 11 $\pm$ 1 y of duration (Franzluebbers, 2010). Soil organic C sequestration rate in studies with cover crops (0.55 $\pm$ 0.06 Mg C ha^{-1} y^{-1}, n = 87), summarized by Franzluebbers (2005), was greater than without cover crops (0.30 $\pm$ 0.05 Mg C ha^{-1} y^{-1}, n = 60). Impacts of manure application on SOC sequestration reported in Franzluebbers (2005) were unclear, with an average increase of 0.26 $\pm$ 2.15 Mg SOC ha^{-1} yr^{-1} with manure (19 comparisons). When only manure application studies longer than 2 years were considered (7 studies), manure additions increased the SOC sequestration rate by 0.72 $\pm$ 0.67 Mg ha^{-1} yr^{-1}. In contrast, an estimated SOC sequestration rate of −0.07 $\pm$ 0.27 Mg ha^{-1} yr^{-1} with conversion from CT to NT was reported for the northeastern U.S. and eastern Canada by Franzluebbers and Follett (2005).

TABLE 3.3 Manure Production from Confined livestock Operations Including Dairy and Beef Cattle, Swine, and Poultry, and Cropland Available for Manure Application in Eastern U.S. States in 1997

State	Number of animal units[†]				Manure production ($Mg\ yr^{-1}$)[‡]				Total manure C ($Mg\ yr^{-1}$)[§]	Cropland available for application (ha)[†,¶]	$Mg\ C\ ha^{-1}$
	Dairy	Beef	Swine	Poultry	Dairy	Beef	Swine	Poultry			
Alabama	14,428	1,283	20,816	379,305	253,933	13,728	258,118	1,327,568	202,645	838,969	0.24
Arkansas	31,795	117,970	125,331	641,716	559,592	1,262,279	1,554,104	2,246,006	533,522	3,331,393	0.16
Connecticut	33,956	7,942	450	16,952	597,626	84,979	5,580	59,332	47,131	11,075	4.26
Delaware	10,077	2,184	4,566	86,875	177,355	23,369	56,618	304,063	54,482	211,256	0.26
Florida	109,078	10,392	3,811	90,306	1,919,773	111,194	47,256	316,071	149,990	270,159	0.56
Georgia	93,134	9,802	71,243	466,868	1,639,158	104,881	883,413	1,634,038	341,764	1,476,675	0.23
Louisiana	43,691	3,650	2,383	57,003	768,962	39,055	29,549	199,511	69,676	1,419,030	0.05
Maine	43,979	9,114	569	23,826	774,030	97,520	7,056	83,391	60,423	149,940	0.40
Maryland	92,809	23,577	9,955	121,458	1,633,438	252,274	123,442	425,103	170,442	611,128	0.28
Massachusetts	28,773	5,395	1,693	3,167	506,405	57,727	20,993	11,085	33,414	53,594	0.62
Mississippi	36,723	75,933	47,036	236,545	646,325	812,483	583,246	827,908	259,781	1,793,075	0.14
N. Hampshire	21,160	3,878	416	1,121	372,416	41,495	5,158	3,924	23,554	38,971	0.60
New Jersey	19,485	4,492	2,549	NR	342,936	48,064	31,608	—	23,240	159,297	0.15
New York	765,239	148,410	9,116	20,686	13,468,206	1,587,987	113,038	72,401	850,496	1,433,114	0.59
N. Carolina	62,491	4,706	1,433,278	66,1202	1,099,842	50,354	17,772,647	2,314,207	942,292	1,869,291	0.50
Pennsylvania	674,726	122,717	141,342	227,680	11,875,178	1,313,072	1,752,641	796,880	892,037	1,659,145	0.54
Rhode Island	2,437	353	323	307	42,891	3,777	4,005	1,075	2,786	4,875	0.57
S. Carolina	19,451	3,324	38,923	174,990	342,338	35,567	482,645	612,465	119,440	730,141	0.16
Tennessee	89,128	127,355	39,635	53,340	1,568,653	1,362,699	491,474	186,690	279,936	1,736,549	0.16
Vermont	200,663	42,050	231	1,217	3,531,669	449,935	2,864	4,260	224,183	199,068	1.13
Virginia	98,503	112,014	50,577	291,627	1,733,653	1,198,550	627,155	1,020,695	385,925	1,088,989	0.35

[†] *Source: Kellogg et al. (2000).*
[‡] *Assuming 17.6, 10.7, 12.4, and 3.5 metric tons manure per animal unit per year for milk cows (as excreted, no bedding), beef heifers (excreted manure plus bedding), hogs for slaughter (excreted manure with in-barn dilution, no-bedding), and broiler chickens (including bedding) (adapted from 2011 Pennsylvania Agronomy Guide).*
[§] *Assuming manure and bedding solids are 40% C, and dry matter content of dairy, beef, swine, and poultry manure are 12, 30, 8, and 34%, respectively (adapted from 2011 Pennsylvania Agronomy Guide).*
[¶] *Includes land used for production of 24 crops including all those widely grown in the eastern U.S.*

However, because data for the northeastern U.S. were not available, that estimate was derived only from research conducted in eastern Canada (Gregorich et al., 2005)

Recent Information from the Southeastern U.S.

Recent studies reporting SOC changes in response to adoption of NT in the southeastern U.S. croplands (Table 3.4) are consistent with the previous estimate for the region (Franzluebbers, 2005). For 37 comparisons of CT and NT with an average duration of 9 years, the SOC sequestration rate was 0.58 ± 0.71 Mg C ha^{-1} y^{-1}(mean $\pm$ standard deviation). Because initial SOC masses were not always reported, sequestration rates were calculated as the difference in SOC mass between NT and CT at the final sampling divided by the duration of the conservation practice. The variation in sequestration among sites may be a reflection of differences in the capacities of individual soils to protect and retain organic matter, but is also likely influenced by crop species and management as well as variability in experimental design including factors such as length of experiment, sampling depth, and numbers of samples obtained.

Soil organic C sequestration rates determined from two extensive field surveys were consistent with rates estimated by Franzluebbers (2005). When sampling 63 sites to 15 cm depths on the Coastal Plain of Virginia, Spargo et al. (2008) showed a positive sequestration of 0.31 ± 0.28 Mg SOC ha^{-1} yr^{-1} (mean $\pm$ standard deviation) with NT. Half of the sites studied had histories of biosolid application. The sequestration rate with NT for fields receiving biosolids was 0.48 ± 0.34 Mg SOC ha^{-1} yr^{-1}, while the rate for fields without biosolid application was 0.11 ± 0.35 Mg SOC ha^{-1} yr^{-1}. An on-farm study with 87 sites across the Piedmont and Coastal Plains of Alabama, Georgia, North Carolina, South Carolina, and Virginia (Causarano et al., 2008) showed an average sequestration rate of 0.52 ± 0.59 Mg C ha^{-1} yr^{-1} with no distinct differences among states or geophysical province. Average SOC mass in the upper 20 cm of soil was 38.9, 27.9, and 22.2 Mg SOC ha^{-1} in pasture, NT, and CT, respectively. Management explained 41.6% of the variation in SOC, while surface horizon clay content explained 5.2%, and mean annual precipitation accounted for only 1% of the variation.

Soil C accumulation with conservation tillage systems that employ some tillage, but retain >30% surface cover, has been studied to a lesser extent than with strict NT. Novak et al. (2009) measured SOC content in a comparison of disk tillage (2 passes, 15 cm deep) with conservation tillage (paratill subsoiling to 40 cm deep and NT planting) across a field in the South Carolina Coastal Plain that was under a cotton/corn rotation. Sampling soils by depth across the field (Figure 3.2) showed that 8 years of conservation tillage led to a 49% increase in SOC in the 0–3 cm depth (1.0 Mg ha^{-1}, significant at $P \leq 0.05$). On the other hand, SOC contents in 3–15 cm depth declined under conservation tillage by 26% (2.8 Mg ha^{-1}, significant at $P \leq 0.05$). While data indicate that minimal residue incorporation into soil with conservation tillage induced SOC stratification, the mixing of crop residues with disk tillage resulted in little change between initial and final SOC contents in either depth increment. A statistically significant reduction in SOC contents in the subsurface (20–25 cm) with NT in Minnesota has also been reported (Dolan et al., 2006).

A limited number of other reports for conservation tillage systems in the southeast have shown net SOC accumulation. A comparison of CT, NT, NT planting with paratill (subsoiling to 40–50 cm) and paratill with disking conducted on the Alabama Coastal Plain (Siri-Prieto et al., 2007) indicated that using both NT and NT with paratill increased SOC concentration in the 0–5 cm depth by approximately 20% over 3 years (no significant change with CT and paratill with disking). However, in the 5–10 cm depth, SOC concentrations for the paratill with NT planting treatment increased slightly over initial SOC concentration while concentration did not change with time when NT was used. When CT, NT, and strip-till (subsoiled to 35 cm in 30 cm-wide strip) were compared in Georgia, Sainju et al. (2006)

TABLE 3.4 Soil C Sequestration from Recent (since 2005) Southeastern US Comparing Tillage or Combinations of Tillage, Cover Crop, and/or Nutrient Source (Adapted from Franzluebbers, 2010)

Location	Soil series or taxonomic group	Duration (years)	Depth (cm)	Crop rotation[‡]	Organic waste	SOC CT	SOC NT	Reference
						Mg ha^{-1}		
Belle Mina, AL	Decatur SiL[†]	10	20	CO/RY-CO-CN/RY[§]	none	37.4	40.1	Sainju et al., 2008
Belle Mina, AL	Decatur SiL	10	20	CO/RY-CO-CN/RY[§]	poultry litter	43.7	43.7	Sainju et al.,2008
Headland, AL	Dothan LS	3	20	CO/RY-PN/O	none	21.6	23.3	Siri-Prieto et al., 2007
Shorter, AL	Typic and Aquic Paleudults (LS)	2.5	30	CO/BO+RY-CN/WL+CC	none	23.5	26.2	Terra et al., 2005
Shorter, AL	Typic and Aquic Paleudults (LS)	2.5	30	CO/BO+RY-CN/WL+CC	dairy manure	29.1	32.6	Terra et al., 2005
AL (Coastal Plain)	Kandiudults/Haploxeralfs (LS)	13.3	20	CO/RY-PN/RY	none	18.0	20.1	Causarano et al., 2008
AL (Piedmont)	Kanhapludults (SCL)	10	20	CO	none	19.6	25.4	Causarano et al., 2008
Bartow, GA	Dothan SL	2	15	CO/RY[§]	none	17.6	19.3	Sainju et al., 2007
Tifton, GA	Tifton LS	2	15	CO/RY-CO/RY-PN/RY[§]	none	17.7	17.0	Sainju et al., 2007
Fort Valley, GA	Dothan SL	7	30	CO-GS	none	21.4	24.2	Sainju et al., 2006
Fort Valley, GA	Dothan SL	7	30	CO/RY-GS/RY	none	22.6	27.2	Sainju et al., 2006
Fort Valley, GA	Dothan SL	7	30	CO/HV-GS/HV	none	23.1	26.7	Sainju et al., 2006
Fort Valley, GA	Dothan SL	7	30	CO/RY+HV-GS/RY+HV	none	23.9	27.9	Sainju et al., 2006
Watkinsville, GA	Cecil SL/SCL	7	20	CO/RY-CN/RY-ML/RY-GS/RY-SB/CC-CN/CC	poultry litter	27.1	32.7	Franzluebbers et al, 2007
Watkinsville, GA	Cecil SL/SCL	3	30	GS/RY (ungrazed)	none	40.6	51.6	Franzluebbers and Studemann, 2008
Watkinsville, GA	Cecil SL/SCL	3	30	GS/RY (grazed)	From grazing cattle	46.5	49.5	Franzluebbers and Studemann, 2008
Watkinsville, GA	Cecil SL/SCL	3	30	WW/ML (ungrazed)	none	45.6	45.1	Franzluebbers and Studemann, 2008
Watkinsville, GA	Cecil SL/SCL	3	30	WW/ML (grazed)	From grazing cattle	42.8	46.6	Franzluebbers and Studemann, 2008

GA (Coastal Plain)	Plinthic Kaniudlts (LS)	15.3	20	CO-PN/WW-SB/RY	none	16.7	21.5	Causarano et al., 2008
GA (Piedmont)	Kanhapludults (SL)	8.3	20	GS/WW-SB-CO/O	none	26.7	27.5	Causarano et al., 2008
Harmony, NC	Fairview SCL/ Braddock L	7	20	CN/BL (silage)	Dairy manure	33.5	36.6	Franzluebbers and Brock, 2007
Harmony, NC	Fairview SCL/ Braddock L	7	20	CN/RY (silage)	Dairy manure	33.5	33.1	Franzluebbers and Brock, 2007
Harmony, NC	Fairview SCL/ Braddock L	7	20	CN/BL-SG/RY (silage)	Dairy manure	33.5	39.1	Franzluebbers and Brock, 2007
NC (Coastal Plain)	Quartzsamments/ Kandiudults (LS)	7.5	20	CO-CO/RY-SB/WW	none	18.2	33.6	Causarano et al., 2008
NC (Piedmont)	Kanhapludults (SCL)	12.7	20	PN/WW-CO/WW-SB/ CC	none	25.0	32.6	Causarano et al., 2008
Florence, SC	Norfolk LS	25	7.6	CO-WW/SB-CO	none	10.1	20.3	Bauer et al., 2006
Florence, SC	Norfolk LS	24	15	CO-WW/SB-CO	none	20.6	31.4	Novak et al., 2007
SC (Coastal Plain)	Kaniudults/ Kanhapludults (LS)	16	20	CO-SB	none	24.8	25.3	Causarano et al., 2008
SC (Piedmont)	Typic Kanhapludults (SCL)	14.7	20	CO-SB/WW-ML	none	22.2	26.5	Causarano et al., 2008
VA (Coastal Plain)	Altavista SL	14	15	CO-WW/SB	none	15.9	21.9	Spargo et al., 2008
VA (Coastal Plain)	Altavista SL	9	15	CO-WW/SB	biosolids	20.2	22.9	Spargo et al. , 2008
VA (Coastal Plain)	Bojac LfS	3	15	CO-WW/SB	none	14.1	13.3	Spargo et al. , 2008
VA (Coastal Plain)	Bojac LfS	9	15	CO-WW/SB	biosolids	16.7	19.1	Spargo et al. , 2008
VA (Coastal Plain)	Emporia LfS	11	15	CO-WW/SB	none	17.2	19.3	Spargo et al. , 2008
VA (Coastal Plain)	Emporia LfS	11	15	CO-WW/SB	biosolids	20.2	29.9	Spargo et al. , 2008
VA (Coastal Plain)	Hapludults (SL)	13.3	20	CO-WW/SB	none	20.4	31.4	Causarano et al., 2008
VA (Piedmont)	Kanhapludults/ Kandiudults (L)	9	20	SB-CO/WW	none	27.7	29.9	Causarano et al., 2008
Mean ± std. dev.		8.8 ± 5.6	21 ± 6			25.4± 9.4	29.6± 9.4	

†Soil texture abbreviations: LfS, loamy fine sand; LS, loamy sand; S, sand; SCL, sandy clay loam; SL, sandy loam; SiL, silt loam.
‡Crop abbreviations: BL, barley; BO, black oat; CC, crimson clover; CN, corn; CO, cotton; FR, forage radish; GS, grain sorghum; HV, hairy vetch; ML, millet; O, oats; PN, peanut; RY, annual rye grass; SB, soybean; SG, small grain (wheat or barley); WL, white lupine; WW, winter wheat.
§Mean includes treatments both with and without rye cover crop, because no significant effect on SOC of using cover crop.

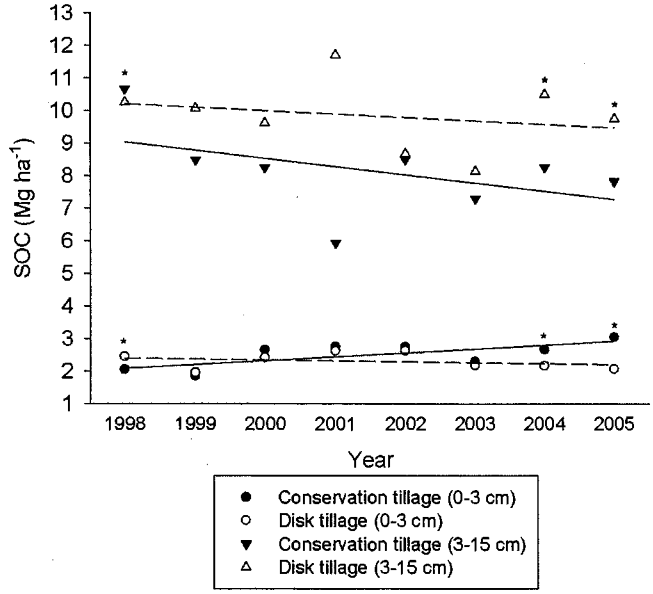

FIGURE 3.2

Median SOC contents (n = 50) in topsoil after 8 years of conservation and disk tillage under a corn/cotton rotation at Florence, South Carolina, indicated SOC gains in the upper 3 cm were offset by declining content in the 3–15 cm depth. Linear regression lines indicate the trend in SOC with time within each depth (solid lines for conservation tillage, dashed lines for disk tillage). The symbol (*) indicates that the tillage treatments are significantly different ($P \leq 0.05$, Mann-Whitney rank sum test) within a depth increment for a given year. (Adapted from Novak et al., 2009.)

observed similar rates of SOC gain with strip-till and NT (0.61 ±0.47 vs. 0.54 Mg ha^{-1} y^{-1}) compared to CT. In a separate study in Alabama, Sainju et al. (2007) found that, when inorganic fertilizers were used, mulch till (rotary harrowing to 5–7 cm) led to an increase of 4.0 Mg SOC ha^{-1} over 10 years, while NT resulted in an increase of 1.5 Mg SOC ha^{-1} and 1.2 Mg SOC ha^{-1} was lost with CT (moldboard plow/disk/field cultivator). However, when the fertility source was poultry litter the 10-year increase in SOC was similar for the three tillage systems (4–5 Mg ha^{-1}).

While winter cover crops were used in a large number of the studies cited in Table 3.4, only three studies included comparisons to no-cover crop controls. Sainju et al. (2006) reported that rye (*Secale cereal* L.), hairy vetch (*Vicia villosa*) and rye/vetch mixtures as cover crops led to greater SOC in both CT and NT in a study conducted in Georgia. Hairy vetch/rye mixtures resulted in the greatest increase. In CT, SOC increased by about 0.8, 1.6, and 2.4 Mg ha^{-1}, relative to using no cover crop, with rye, hairy vetch, and the mixture during the 7-year study. In NT, SOC was 2.4, 1.9, and 2.6 Mg ha^{-1} greater than the control for rye, vetch, and the mixture. Conversely, cover crop use did not affect SOC mass in studies conducted in Alabama (Sainju et al., 2008) and Georgia (Sainju et al., 2007) despite significant increases in biomass inputs.

The impact of applying manures and other organic amendment on SOC sequestration remains unclear, but data suggest there may be an interaction between NT use and manure addition. Biosolid applications on the Virginia Coastal Plain (Spargo et al., 2008) resulted in greater SOC accumulations in the upper 15 cm compared to unamended fields with both CT and NT (3.3 ± 0.9 and 5.8 ± 4.8 Mg ha^{-1} for CT and NT). Sainju et al. (2008) found that poultry litter application over a 10-year period added approximately 0.3 Mg SOC ha^{-1} yr^{-1} to the upper 20 cm with NT, mulch till, and CT. Watts et al. (2010) reported that the combination of NT and poultry litter application (sufficient to supply 170 kg N ha^{-1} in corn or 45 kg P ha^{-1} in soybean) for 14 years to continuous corn and continuous soybean in northeastern Alabama increased SOC concentration in the 0–5 cm depth by 170 and 104%. The use of NT with inorganic fertilizer increased SOC contents in the 0–5 cm depth by 110% with corn, but did not affect SOC in soybean. With CT, poultry litter application increased SOC in corn plots by 40% but did not affect SOC concentration when applied to soybean plots. Neither NT nor poultry litter impacted SOC concentration in the 5–10 or 10–20 cm depth. Adeli et al. (2007) also observed an apparent interaction of NT and poultry litter application on SOC sequestration in cotton fields on two farms in central Mississippi that had soils with similar texture and initial organic matter concentrations. On the farm using NT, 0.6 Mg SOC ha^{-1} yr^{-1} was sequestered in the upper 15 cm with annual application of 4.5 Mg ha^{-1} of broiler litter and as much as 1.6 Mg SOC ha^{-1} yr^{-1} added with 6.5 Mg ha^{-1} litter and supplemental inorganic N. Soil organic C on the farm using CT was unchanged by broiler litter applications.

A limited number of studies from the southern U.S. have documented soil quality improvement in response to greater accumulation of SOC with the adoption of conservation practices. In their survey of sites across Coastal Plain and Piedmont of several states, Causarano et al. (2008) observed greater aggregate stability and a greater proportion of larger soil aggregates with NT than with CT, suggesting improved soil structure, aeration, and resistance to erosion. They also found a close correlation between total SOC, microbial biomass C, and potentially mineralized C, suggesting enhanced microbial activity and nutrient cycling with increasing SOC. Franzluebbers and Stuedemann (2008) also observed 2–3-fold increases in microbial biomass and potentially mineralized C with NT compared to CT.

Northeastern U.S.

Reports of management impacts on SOC sequestration in northeastern U.S. croplands are very limited, and findings from replicated plot studies that have been specifically designed to follow soil C dynamics are not available. In an on-farm study, Dell et al. (2008) sampled soils from a common series (Hagerstown silt loam) on several farms in the State College, PA, area where CT and NT had been used with silage corn/alfalfa rotations, with and without rye cover crops. They found an average of 51% greater mineral-associated C in the upper 5 cm of fields where NT had been used, but they observed similar accumulations in the 5–10 cm depths and upper Bt horizons of all fields. The difference in mineral-associated and particulate soil C between NT and CT fields suggested a sequestration rate of about 0.5 Mg ha^{-1} yr^{-1} with NT. However, the study used neither repeated measurements nor comparison of paired fields, and a true measure of sequestration was not determined. There was no detectable effect of cover crop usage, possibly because of the reported poor establishment of rye in many years due to unfavorable weather. In a long-term plot study (25 years) conducted near State College, PA, Duiker and Beegle (2006) reported soil organic matter (SOM) concentrations, determined by loss on ignition, that were 72 and 32% greater in the upper 25 cm with NT compared to moldboard plow/disk and chisel/disk systems. Concentration of SOM was very similar in the 5–10 and 10–15 cm depths of NT and moldboard plowed soils, but SOM was 10 to 20% greater in the 5–10 and 10–15 cm layer with chisel tillage compared to either NT or moldboard tillage.

Blanco-Canqui and Lal (2008) and Chatterjee and Lal (2009) reported paired comparisons of CT and NT on several farms throughout Pennsylvania, along with farms in Ohio and Kentucky. They generally observed greater SOC concentration in the upper 10 cm of soil with NT compared to CT and estimated SOC sequestration rates to a 60 cm depth for NT ranging from −2.95 to 4.94 Mg ha^{-1} y^{-1}, but no statistically significant differences ($P \leq 0.05$) could be detected between CT and NT for the entire 60 cm soil profiles on any of the farms. However, Kravchenko and Robertson (2011) showed that the amount of replication reported by Blanco-Canqui and Lal (2008) provided low statistical power and was insufficient to support hypothesis testing. The probability of verifying an SOC change of 10% was ≤10% in all depth increments and the probably of verifying even a 100% change in SOC was only about 50% in the 50–60 cm depth. Kravchenko and Robertson (2011) stressed caution when drawing conclusions about whole-profile SOC changes in cases where high variability at deeper depth masks the identification of significant changes near the soil surface.

Detection of statistically significant impacts of cropland management on SOC sequestration is complicated by the measurement error resulting from spatial variation in SOC concentrations and is dependent on adequate sampling replication (Kravchenko and Robertson, 2011). In the uneven and sloping terrain of the Piedmont, Ridge and Valley, Appalachian Plateau, and New England Uplands, SOC can vary greatly over even short distances. Dell and Sharpley (2006) observed a high degree of spatial variation in SOC concentration in the surface soils (0–5 cm) across a small watershed in the Ridge and Valley Province of central Pennsylvania. Using geostatistical analysis, they determined that soil sampling was required at 10 m or closer intervals to adequately capture the range of spatial variation within fields in that landscape. Observed coefficients of variation for individual fields, sampled at 30 m intervals, indicated that 2- to 5-fold more samples were needed to statically verify changes in SOC that were less than 10% of the original mean.

CARBON SEQUESTRATION POTENTIAL IN THE REGION

Southeastern U.S.

Available data for the southeastern U.S. indicates that, on average, adoption of NT can be expected to sequester approximately 0.5 Mg SOC ha^{-1} yr^{-1} for 10 to 20 years after the elimination of tillage. However, deviation in estimated sequestration rates is sufficiently wide to include some systems where no net accumulation of SOC is achieved, as well as soils with substantially greater sequestration. Data are not sufficient to estimate sequestration rates for conservation tillage systems that utilize some tillage, especially considering the wide range of field operations that are used. Estimates of sequestration potential with the use of cover crops and manure application are also difficult to determine because of high variability among studies and the wide range of practices used.

Northeastern U.S.

Soil carbon sequestration potential in the northeastern U.S. is difficult to estimate because of sparse data availability. Limited on-farm data from Pennsylvania showed greater SOC accumulations near the surface in NT fields compared to adjacent CT fields, but sampling has not been extensive enough to support calculation of SOC sequestration rates. Moreover, data are not available to accurately estimate impacts of manure application or cover crop use on SOC in the region. No-till or other high residue conservation tillage methods have not been widely adopted in New York and the New England states, contributing to the scarcity of data for the northeast.

Research Needs

While conversion to NT or use of cover crops is generally expected to result in increased SOC near the surface, management impacts on SOC below the upper few cm of soil are not as well established. Both sampling depth and sample numbers must be carefully addressed, especially with diverse soil types, in future studies in order to provide sound information about management impacts on SOC below the upper few cm of the soil profile and to correctly estimate whole-profile SOC accumulations. While there has been controversy over appropriate sampling depth (Baker et al., 2007), VandenBygaart et al. (2011) evaluated data from several sites across Canada and determined that sampling to 30 cm was appropriate for capturing SOC changes. Given rooting depths of commonly grown crops, sampling to 30 cm also appears appropriate in the eastern U.S. Adequate replication can become increasingly more important with increasing depth in the soil profile, because SOC concentration decreases and spatial variability tends to increase. Therefore, large sample numbers may be needed to provide adequate statistical power to evaluate SOC stocks (Kravchenko and Robertson, 2011). Lack of statistically significant effects of management practices on SOC accumulations have led to conclusions that the practices have no effect. However, Kravchenko and Robertson (2011) point out the possibility of committing Type II statistical errors (concluding no difference when differences are present) when sample numbers are low and statistical power is limited.

A limited number of studies, such as Novak et al. (2009), have reported that increases in SOC near the surface with the adoption of NT or other conservation tillage practices can be offset by statistically significant reductions in SOC lower in the soil profile. A better knowledge of the extent and cause of these atypical responses is needed to strengthen estimates of SOC sequestration in cropland soils. Longer-term studies are needed to determine if SOC reductions observed in subsurface layers are short-term responses to changing management or if they are sustained over time.

In general, much more information is needed to adequately estimate the potential for increased SOC sequestration in the northeastern U.S. One limitation to increasing SOC stocks in croplands of New York and the New England states is little adoption of NT. Research and education efforts are needed to identify and promote high residue/low disturbance production methods that are appropriate for the region. Strip-till and related practices have been successful in Canada where, like the northeastern U.S., cool spring time soil temperatures are seen as problematic with conventional NT (Vyn and Raimbault, 1992).

Use of cover crops is generally expected to increase SOC, but impacts of cover crop species and management remain poorly defined. Mixtures of cover crops may have a greater impact on SOC than monocultures, but additional research is needed at a greater number of locations with a wider range of cover crop species and management practices.

Application of organic amendments can have a significant impact on SOC levels, but the relationship between manure management practices and sequestration has not been extensively studied in all regions of the eastern U.S. and with a complete range of organic materials. Manure management guidelines have changed in recent years to address water quality impairment, most notably in the Chesapeake Bay watershed, but it is not known if those changes have impacted the sequestration of C added with manures. Manure injection is one technology that offers promise for reducing nutrient transport to surface waters, but research is needed to determine if it has an impact on the sequestration of manure C in soil.

Vegetables are grown on ~0.5 Mha throughout the eastern U.S., but little is known about how management and utilization of conservation practices can impact SOC sequestration in those systems. Sugarcane and rice are additional crops that are grown extensively in portions of the region, with limited information concerning sequestration potential. However, more is known about SOC losses through subsidence in the southern regions where sugarcane is grown than is known about rebuilding SOC levels.

Improvements in soil quality and productivity resulting from practices that sequester SOC merit greater consideration. Additionally, a better understanding of the impact of reducing erosion, and subsequent soil organic matter losses from the field, on regional C budgets is needed.

CONCLUSIONS AND RECOMMENDATIONS

Topography, soil resources, climate, crops, and production methods vary greatly across the eastern U.S., and these factors make estimation of SOC sequestration potential complex. Recent data from the southeastern U.S. has generally been consistent with previously published sequestration rates following adoption of conservation practices in the region (0.41 ± 0.46 Mg SOC ha^{-1} y^{-1}; Franzluebbers, 2005). This range would encompass the limited number of systems where no net gain in SOC occurs. While reductions in SOC at depth with conservation tillage do not appear to be the norm, further research is needed to define the cause, extent, and impact of this phenomenon on regional and national SOC sequestration estimates. To avoid ambiguous results and potentially misleading conclusions, sampling from ongoing and future SOC monitoring should be obtained to a depth of at least 30 cm and replication from all sampling depths should be sufficient to provide adequate power for conclusive statistical testing. In general, much more information is needed to predict SOC sequestration potential with conservation practices in the northeastern U.S.

Reducing soil erosion remains the primary benefit of conservation tillage and NT, regardless of the potential for SOC sequestration with these practices. Controlling erosion and subsequent redistribution of SOC is essential to maintain productivity of soil resources. Sequestration of SOC and mitigation of climate change are valuable "side" benefits of NT and other conservation tillage systems, but even in situations where conservation practices do not result in a net gain in SOC, agronomic and environmental benefits of controlling soil erosion remain compelling reasons for the use of the practices.

The combined use of NT and cover crops and the applications of manures or other C-rich organic amendments to a broader land base represent the best potential for increased SOC sequestration in eastern U.S. cropland soils. The greatest sequestration is likely to be achieved by conversion of marginally productive croplands to perennial vegetation (see Chapter 5) or, based on recent reports, by the use of recalcitrant biochars to increase SOC sequestration (Spokas, 2010; Novak and Busscher, 2011).

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