Soil properties following reforestation or afforestation of marginal cropland

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Abstract

Aims Reforestation or afforestation of marginal agricultural lands offers opportunities to sequester soil organic carbon (SOC), improve the quality of degraded soils, and provide ecosystem services. The objectives of this study were to identify the extent and distribution of marginally productive cropland in the state of Iowa and to quantify the changes in SOC and relevant soil properties following tree planting.

Methods A geographic information system (GIS) analysis was used to identify 1.05 million ha of marginal cropland within the state. Soil samples were collected from four locations with (<51 yr-old) forest plantations and adjacent crop fields. Soil samples were analyzed for SOC, total nitrogen (TN), pH, cation exchange capacity (CEC), ammonium acetate-extractable K, Ca, Mg, and Na, and particle size.

Results The forested soils had 30.0±5.1 % (mean ±standard error) more SOC than the tilled cropland. The average annual change in SOC following tree planting was estimated to be 0.56±0.05 Mg C ha^{-1} yr^{-1}. Differences were observed in several soil properties but strong correlations with SOC content were only observed for bulk density and extractable Ca.

Conclusions These results indicate that within 5 decades of tree planting on former cropland or pasture there was consistently and significantly greater SOC in soil beneath the trees.

Abbreviations

C	Carbon
CEC	Cation exchange capacity
CSR	Corn suitability rating
GIS	Geographic information system
HEL	Highly erodible land
ISPAID	Iowa Soil Properties and Interpretations Database
NT	No-till
SOC	Soil organic carbon
TN	Total nitrogen

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Introduction

Reforestation and afforestation are often considered foremost practices for sequestering carbon (C) as a

component of climate change mitigation strategies. Although global assessments have shown that planting trees has limited potential to offset increasing atmospheric carbon dioxide concentrations (Vitousek 1991; Nilsson and Schopfhouser 1995; Lal 2001, 2005), there remains strong interest in increasing the amount of forested land area for multiple reasons, both environmental and economic. In primarily agricultural regions, C sequestration through forest restoration or expansion has a significant food security implication as taking land out of crop production reduces the food production potential (Fissore et al. 2010). To avoid such losses in food production, tree plantings must either provide a food source themselves such as fruit or nut production or provide some ecosystem services such as C sequestration, enhanced hydrology, or improved water quality to compensate for increasing intensification of production practices on the remaining crop land. Forest ecosystems do offer great potential to improve soil quality of degraded or marginal lands by reducing soil disturbance and providing perennial ground cover, thereby providing multiple ecosystem services (Van Schoenholtz et al. 2000; Moussavou Boussougou et al. 2010). In particular, the potential to increase soil organic matter content is of great interest as organic matter is a critical soil quality feature associated with enhanced C and nutrient cycling, healthy soil fauna, optimal soil structure, and improved infiltration and soil water holding capacity (Hudson 1994; Kay 1997; Loveland and Webb 2003; Teepe et al. 2003).

Planting trees on soils previously managed for crop or forage production can affect many soil properties primarily through fundamental changes in organic matter and nutrient cycling. In forest systems, aboveground litter inputs represent a larger percentage of the total organic inputs to the soil than in cropped and grassland systems, where the primary organic input is often the decomposition of roots (Pettapiece 1969; Anderson 1987; Gale and Cambardella 2000). For this reason, former agricultural soils that are planted to trees are likely to develop an organic-rich surface layer that may also contain nutrients extracted from deep soil layers and deposited on the surface through litterfall.

Paul et al. (2002) reviewed global data on changes in soil C following afforestation. They found that soil organic carbon (SOC) often decreased during the first 5 year after tree planting and suggested it was likely due to activities associated with tree establishment. They concluded mechanical soil disturbance such as

mounding, ripping, and cultivation during site preparation for planting and lack of significant plant growth and thus low C input as the main factors leading to SOC loss during this interval. Accumulation of C following the initial decrease occurs as annual C inputs from primary production exceed C lost via decomposition. The calculated time for a new equilibrium between inputs and decomposition to be reached ranged from 10 to more than 60 years depending on site, climate, and species. Laganière et al. (2010) conducted a meta-analysis of 33 recent publications on afforestation and concluded that the main factors affecting SOC restoration are previous land use, tree species, soil clay content, disturbance (plowing, mounding, trenching and/or mechanical tree planting), and climate. They found greater SOC accumulation under broadleaf species and in soils with >33 % clay content where clay content has been related to SOC stabilization through structural protection or the formation of colloidal- or mineral-humus complexes (Hassink 1997; Rasmussen et al. 2007). Morris et al. (2007) also reported greater SOC accumulation in deciduous forests (0.35 Mg C ha^{-1} yr^{-1}) as compared to coniferous forests (0.26 Mg C ha^{-1} yr^{-1}) in Michigan and found C accumulation to be strongly correlated with exchangeable soil Ca. Paul et al. (2003) found SOC sequestration following afforestation at several Midwestern U.S. sites was related to soil Ca, Mg, and K. Also, these and other studies suggest that increases in SOC following tree planting are greater in former cropland and in more nutrient rich soils versus grassland (Vesterdal et al. 2002; Poeplau et al. 2011). Several factors influenced by tree species and soil properties have been found to affect the rate and degree of SOC changes following tree establishment on former agricultural lands.

The objectives of this study were to: 1) identify the amount and spatial distribution of marginally productive cropland in the state of Iowa, and 2) quantify the changes in SOC and relevant soil properties following tree planting by analyzing soil samples from already afforested/reforested areas and adjacent cropped areas representative of these marginal lands.

Materials and methods

Marginal lands analysis

A statewide geographic information system (GIS) analysis was completed to identify the extent and

distribution of vulnerable, low-productivity soils that had formed under forest vegetation, hereafter referred to as "marginal lands" for row crop production. The Iowa Soil Properties and Interpretations Database (ISPAID, http://extension.agron.iastate.edu/soils/SSDS_maps.html) was used to identify soils formed under forest (NATIVEVEG class=F), having a corn suitability rating (CSR) less than the county average, and designated as highly erodible land (HEL). The analysis was limited to soils that formed under forest cover to assess the potential ecosystem benefits of restoring these soils to their natural cover. The CSR is a productivity index that provides a relative ranking of all soils mapped in Iowa regarding their potential for row crop production (Miller et al. 2006). The HEL designation is given if the soil is classified in Land Capability Classes 4, 6, 7, or 8, which have severe limitations for arable crop production (Soil Survey Staff 2001) or would have excessive erosion if cropped (Miller et al. 2006). Individual state-wide raster datasets (1-ha resolution) were generated to represent both the native forest soils and the HEL. To identify soils with low CSR, rasterized soil map unit CSR values were compared to a county-mean CSR raster (1-ha resolution) generated from the ISPAID database. The marginal lands classification resulted from a spatial overlay operation identifying those soils that were common to all three input rasters: native forest soils, HEL soils, and soils with a CSR less than the county mean.

Soil sampling

Sampling locations were identified to provide a representative range of characteristics and meet most, if not all, of the marginal land criteria. Four sampling locations were selected that provided a range of soils, tree species, cropping practices, land use history, and properties that met or approached each of the marginal land criteria (Table 1). The Allamakee location was within the Yellow River State Forest and included an eastern white pine (*Pinus strobus*) plantation, a more recent eastern black walnut (*Juglans nigra*) plantation, mature native (undisturbed) hardwoods, and a cropped field. The Allamakee location has ridge and valley topography as it is located in the Paleozoic Plateau of northeastern Iowa that was unglaciated by the last North American continental ice sheet. The Clayton location was a former field planted to hardwoods in

1992 and an adjacent field that has continued to be cultivated. The Fayette silt loam soil (fine-silty, mixed, superactive, mesic Typic Hapludalfs) present at these two locations is the most common forest-derived soil in Iowa representing 34.9 % (51,000 ha) of all forest-derived soils within the state (ISPAID database). Trees were planted into former cultivated crop fields at both of these locations.

The Jefferson site consisted of a pasture with sparse native hardwoods that was planted to hardwoods in 1984. The adjacent field was cultivated but had been in grass from 1993 to 2003 when it was returned to row crop production. This site is mapped as a Pershing silt loam (fine, smectitic, mesic Vertic Epiaqualfs), which is listed as a transition soil in the ISPAID database as the category for soils formed under oak savannah. The Sac location was chosen to represent a prairie-derived soil (Galva silty clay loam, fine-silty, mixed, superactive, mesic Typic Hapludolls) of the Loess Hills of western Iowa. This location offered an opportunity to provide increased geographic representation and assess the effects of afforestation with softwood species under lower rainfall and in a deep loess soil. This site included a closed canopy (white pine) and a more open canopy (Scotch pine—*Pinus sylvestris*, with some hardwoods) having a grass understory. One adjacent field was tilled but another field was under long-term no-till (NT). The NT field was sampled in two locations immediately adjacent to the white pine (NT Crop W) and the Scotch pine (NT Crop E). As for the Jefferson site, the trees were planted into grazed pasture at the Sac site.

All of the soils are located on uplands and formed in loess overlaying glacial till (Galva and Pershing) or bedrock (Fayette). The Fayette and Galva soils are well-drained with mixed mineralogy as a result of their formation in glacial till and loess. The Pershing soil is moderately well drained and somewhat poorly drained with smectitic mineralogy due to a greater proportion of montmorillonite in the clay fraction.

Limited information is available on tree planting and site management at the measurement locations. In general, the locations received minimal weed control and no fertilization or thinning. Initial low planting density and/or tree mortality resulted in low stand density and significant grass cover (principally smooth brome—*Bromus inermis*) at some locations, especially for the Scotch pine at the Sac location. The white pine at the Allamakee location were planted at the highest

Table 1 Summary of field locations. Precipitation and temperature data are 30-yr normals from the nearest weather station (National Oceanic and Atmospheric Administration 2002). Sand, silt, and clay content are averages for 0–30 cm depth

Location	Latitude & longitude	Elevation (m)	Mean annual Precip. (mm)	Mean annual Temp. (°C)	Previous land Use	Tree species	Tree age (yrs)	Tree density (# ha^{-1})	Crops &Tillage	Soil (USDA Classification)	Sand (%)	Silt (%)	Clay (%)
Allamakee	43 ° 10' 35.7" N 91 ° 10' 53.6" W	302	871	8.2	Crop	Eastern white pine (*Pinus strobus*)	51	3000	Corn/soybean/oats/ alfalfa/(*Zea mays* L *Glycine max*, *Avena sativa* L., *Medicago sativa* L.) No-till	Fayette silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs)	4.4	72.8	22.8
						Eastern black walnut (*Juglans nigra*)	15	1300					
						Native hardwood (*Quercus* spp., *Carya* spp., and *Acer* spp.)	uneven	170					
Clayton	42 ° 39' 5.3" N 91 ° 21' 31.0" W	228	867	8.0	Crop	Northern red oak (*Quercus rubra*)	17	2400	Corn/soybean	Fayette silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs)	4.8	71.0	24.2
						Ash (*Fraxinus* spp.)			Tilled				
Jefferson	40 ° 59' 15.0" N 92 ° 5' 13.3" W	348	928	10.7	Pasture	White oak (*Quercus alba*) Shagbark hickory (*Carya ovata*)	22	1600	Corn/soybean Tilled	Pershing silt loam (fine, smectitic, mesic Vertic Epiaqualfs)	3.5	75.5	21.0
Sac	42 ° 26' 12.7" N 95 ° 9' 21.8" W	400	838	8.0	Pasture	Eastern white pine	35	1000	Corn/soybean	Galva silty clay loam (fine-silty, mixed, superactive, mesic Typic Hapludolls)	3.8	60.2	36.0
						Scotch pine (*Pinus sylvestris*)	32	600	Tilled and no-till				

density (3,000 trees per ha) with the existing stand density at other locations ranging from 600 to 2,400 trees/ha. Some tree inventory data were available for the Sac site where the white pine averaged 14.2 m in height and 25.3 cm diameter at breast height (DBH) and the Scotch pine averaged 6.9 m in height and 20.3 cm DBH. Understory vegetation ranged from no understory for the Sac white pine, primarily smooth brome grass for the Sac Scotch pine, Clayton, and Jefferson sites, and a mixture of forbs and woody shrubs for the white pine and eastern black walnut at the Allamakee location.

At each location, all soil samples were collected within a single soil map unit. The portions of the map unit that were forested and cultivated were delineated and then divided into 5 m-square sampling polygons. Five of these polygons under each land use were then randomly selected for sampling and their location identified using a global positioning system (GPS). Five soil samples were taken in each of the five polygons selected (center of polygon and 2 m in each cardinal direction) by hand with a 3.2 cm-diameter x 30 cm-long split-tube probe (Clements Associates, Inc., Newton, IA). Each sample was composed of duplicate cores collected after the surface litter or crop residue had been removed. The cores were sectioned into 0–10, 10–20, and 20–30 cm depth increments in the field and placed in plastic bags. All samples were collected following crop harvest in October to December 2006. This stratified random sampling design resulted in a total of 25 samples for each land use at each location.

Soil analysis

The soil samples were weighed and a subsample removed and dried for 24 h at 105°C to determine field soil water content and bulk density. The remaining field-moist sample was passed through an 8-mm sieve, roots removed, and a ~100 g subsample passed through a 2-mm sieve. All soil samples were then air-dried. A ~15 g sample of the air dry 2-mm fraction was placed on a roller mill (Bailey Mfg., Inc., Norwalk, IA) for 12 h to create a fine powder for total C and total nitrogen (TN) analysis by dry combustion (Fison NA 15000 Elemental Analyzer,[1] ThermoQuest

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[1] Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Corp., Austin, TX). An effervescence test was used to determine if any inorganic soil carbon (carbonates) was present. No carbonates were detected in any sample so total C values were used for SOC. Equivalent soil mass correction was completed prior to calculation of SOC mass storage (g m^{-2}) following Ellert et al. (2002) and Ellert and Bettany (1995). The heaviest soil sample for a layer within each land use was used as the reference soil mass for that layer. A thickness layer adjustment (T_{adj}) was used to bring all samples to an equivalent soil mass:

$$T_{adj} = (SM_{ref} - SM_{ori})/\rho_{bbe} \qquad (1)$$

where SM_{ref} and SM_{ori} are the reference and original soil mass of the individual depth increment to be adjusted, respectively, and ρ_{bbe} is the bulk density of the soil-depth increment beneath the depth increment to be adjusted. Bulk density beneath the deepest sampling layer was assumed to be similar to bulk density of the deepest soil depth increment. Mass (M) of SOC was calculated for each individual soil depth increment (0–10, 10–20, and 20–30 cm):

$$M = SOC\ content \times \rho_b \times (T_o + T_{adj}) \qquad (2)$$

where ρ_b is the bulk density and T_o is soil layer thickness.

Samples of the air dry 2 mm-sieved soil were used to determine pH in water (1:1 paste, Thomas 1996), pH in SMP buffer solution (Watson and Brown 1998),, and ammonium acetate extractable K, Ca, Mg, and Na (Warncke and Brown 1998). Concentrations of elements in soil extracts were determined using an inductively coupled plasma atomic emission spectrophotometer (Thermo Jarrell Ash 61E, Thermo Elemental, Franklin, MA). Estimates of cation exchange capacity (CEC) were obtained from the ammonium acetate extractable K, Ca, Mg, and Na concentrations (Warncke and Brown 1998). Particle size distribution (pipet method, Gee and Or 2002) was determined on a composite sample of all five soil samples from the same polygon. For sites with samples from multiple land uses (Allamakee and Sac), single-Factor ANOVA at $P=0.05$ was used to test for significant differences in soil properties. Two-sample T-tests were used at the other locations (Clayton and Jefferson).

Results

Marginal lands

The spatial distribution of marginal soils and the sampling locations are illustrated in Fig. 1. Of the 14.6 million ha of land in Iowa, 1.05 million ha or 7.2 % of the state land area was identified as marginal using the CSR, HEL, and native forest cover criteria. Using 2004 National Agricultural Statistics Service data (http://www.nass.usda.gov/research/Cropland/metadata/metadata_ia04.htm), 64 % of this marginal land was still under agricultural land use (row crops, small grains, and pasture). By comparison, for the entire state of Iowa, 89 % of the land area is currently under agricultural land use.

SOC and TN with depth

The surface 0 to 10 cm layer of soil beneath planted trees had a significantly greater SOC concentration than tilled soils at all locations (Fig. 2). Differences among land uses for the 10–20 and especially 20–30 cm layers were smaller and not always statistically significant. Soils beneath trees had on average 59.2 ± 15.5 %, 11.8 ± 7.5 %, and 29.4 ± 14.0 % (mean±standard error) higher SOC concentration for the 0–10, 10–20, and 20–30 cm layers, respectively when compared to the tilled soil at each site. For the entire 30 cm surface layer, only the walnut planting at the Allamakee location did not have a significantly higher SOC concentration than the tilled soils. At the Sac location,

both NT soils also had a significantly greater SOC concentration than the tilled cropland with SOC concentrations in the top 30 cm not significantly different from the Scotch or white pine soils. Over the full 30 cm layer, soils beneath the trees at all locations had a 36.4 ± 10.7 % higher SOC concentration when compared to the tilled soils.

Relationships among land uses and with depth for SOC on a mass basis (g m^{-2}) followed many similar patterns as for SOC concentration (Fig. 2) but with some differences due to variation in soil bulk densities among land uses (Fig. 3). At each location except Sac, significantly greater amounts of SOC were observed in the 0–30 cm layer of the forested soils. At the Sac location, SOC contents beneath the white and Scotch pine were not always significantly different from the NT fields (NT Crop E and NT Crop W) but all had significantly more SOC than the tilled cropland. At each location cropped soils had lower SOC than forested soils in the 0–10 cm layer with the exception of the Sac location where the NT Crop E soil had significantly more SOC than under scotch pine. Differences were less distinct for the 10–20 and 20–30 cm layers likely due to mixing during tillage operations of the cropped soils and stratification of SOC beneath the litter layer of the forested soils. Tillage of the cropped soils involved non-inversion (i.e. not moldboard plow) implements (chisel plow, disk, and field cultivator). At the Allamakee location, there was a consistent trend in SOC with time after tree planting (Walnut<White Pine<Native), especially for the 0–10 cm layer. The

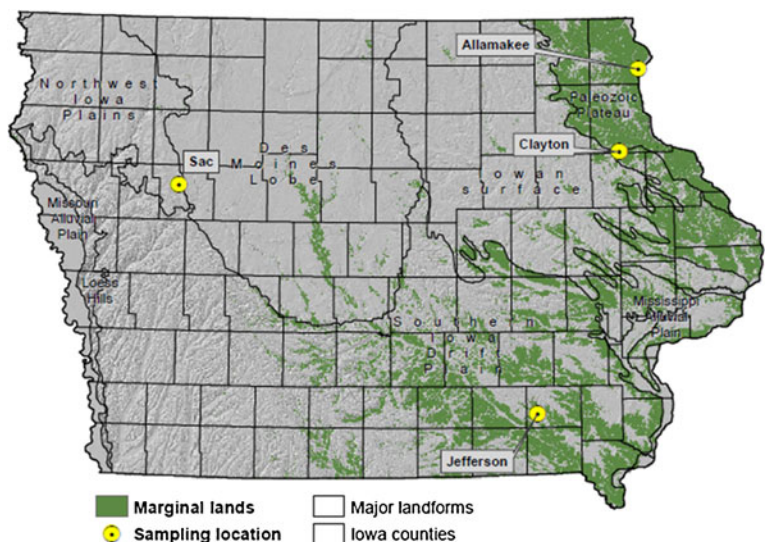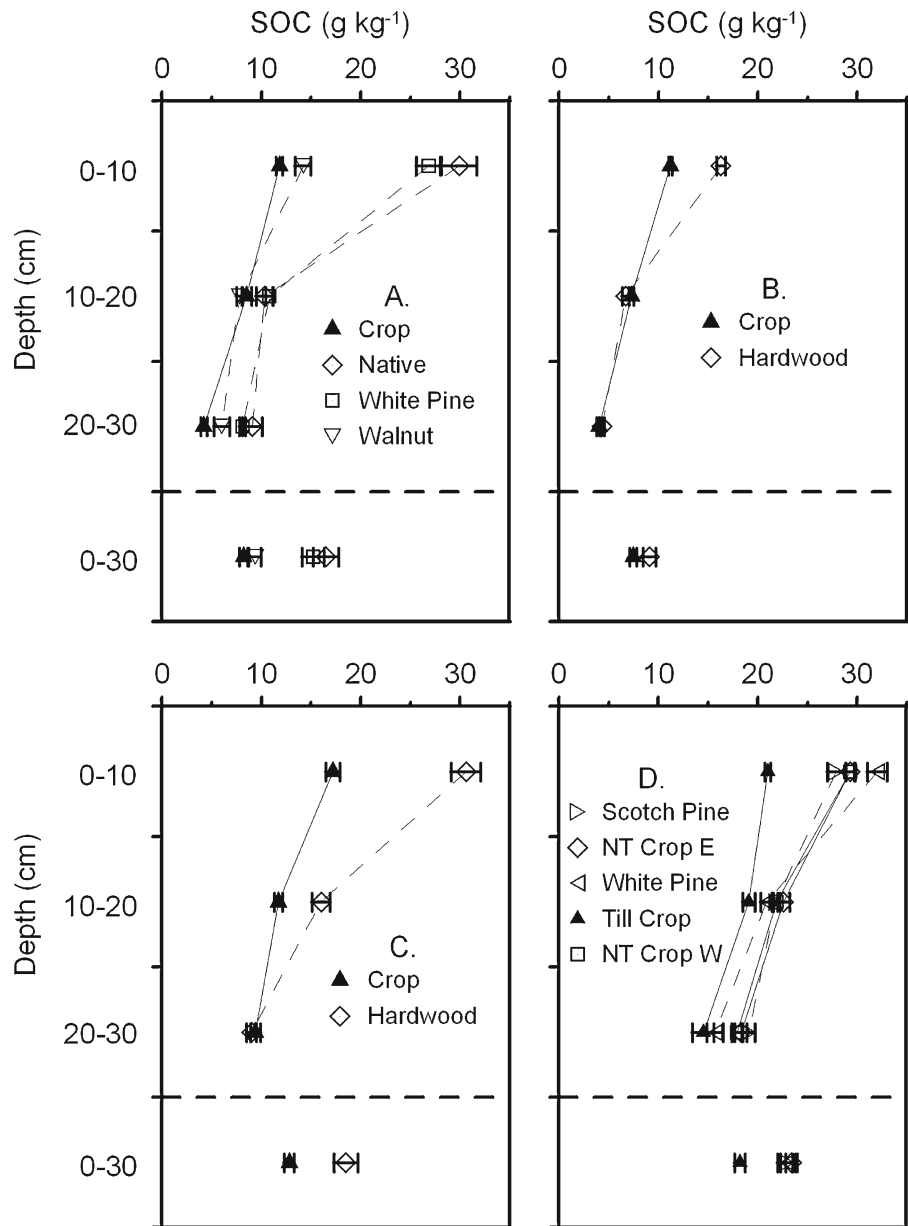**Fig. 1** Spatial distribution of marginal lands and sampling locations

Fig. 2 Soil organic carbon (SOC) concentration with depth for (**a**) Allamakee, (**b**) Clayton, (**c**) Jefferson, and (**d**) Sac. The 0–30 cm data are the means of the three separate layers. Error bars are one standard error


soil in the native forest had the greatest SOC content for the 0–10 and 20–30 cm depth increments and overall, SOC amounts were Native=White Pine>Walnut>Crop. For all locations, forest soils had 30.0± 5.1 % greater SOC on a mass basis as compared to the tilled cropland soils.

Trends in TN content followed very closely with those for SOC content (Fig. 4). There were only minor differences from the relationships among land uses observed for SOC including no significant differences in the 10–20 and 20–30 cm layers at Allamakee. As

for SOC, there were higher TN contents in the 0–10 cm layer and generally more pronounced stratification in the forested soils. Overall, 0–30 cm TN contents followed the pattern of Sac>Jefferson>Allamakee>Clayton with values ranging from a high of 305 gm^{-2} for Sac NT Crop W to a low of 150 gm^{-2} for Clayton Crop. For the 0–30 cm average SOC values, the pattern was very similar, Sac>Allamakee~Jefferson>Clayton with a range from 3,317 gm^{-2} for Sac NT Crop E to 1,200 gm^{-2} for Clayton Crop. The C/N ratio for the 0–30 cm layer was greater for

Fig. 3 Soil organic carbon (SOC) content with depth for (**a**) Allamakee, (**b**) Clayton, (**c**) Jefferson, and (**d**) Sac.. The 0–30 cm data are the means of the three separate layers. Error bars are one standard error
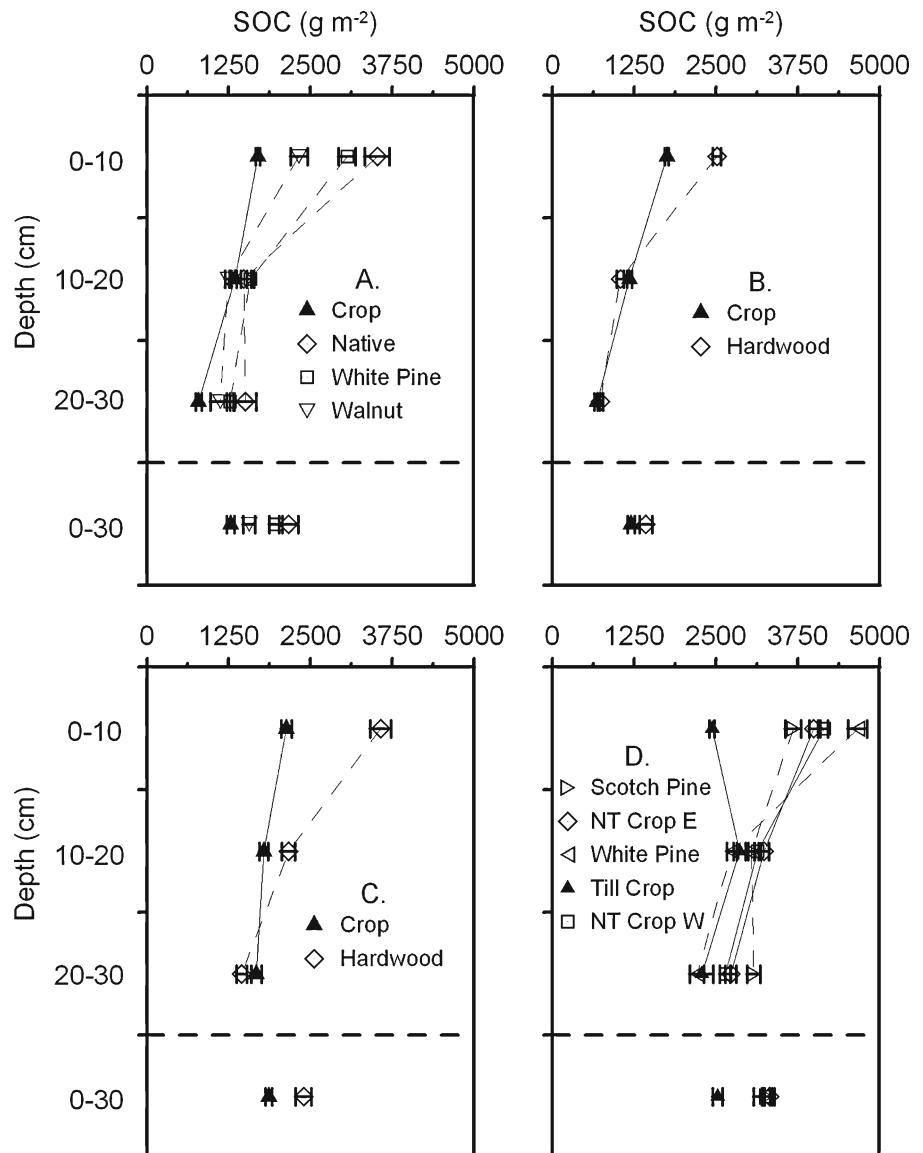

forested soils at each location and statistically greater for all locations except Clayton (data not shown). Values ranged from 11.9 for Sac White Pine to 7.4 for Allamakee Crop. Average C/N ratios by location were 11.2, 10.0, 9.0, and 7.9 for Sac, Jefferson, Allamakee, and Clayton, respectively.

An estimate of the average annual change in SOC in afforested and reforested sites are presented in Fig. 5. These data points were calculated by subtracting the average SOC concentration for the tilled crop soils from the afforested or reforested soils for each layer, dividing by the number of years since tree planting, and then summing the values for the three

layers. This estimate assumes that the SOC in the cropped fields has not changed significantly since the trees were planted, i.e. these soils were near SOC equilibrium. An additional assumption for the Sac and Jefferson locations is that the grazed pastures into which the trees were planted and the adjacent cropped fields had the same SOC levels at the time of tree planting. This second assumption is more tenuous but pastures in Iowa are routinely overgrazed and non-fertilized; management practices that could result in SOC levels comparable with adjacent tilled fields (Skinner 2008). Cropping practices have not changed significantly at the Allamakee, Clayton, and Sac
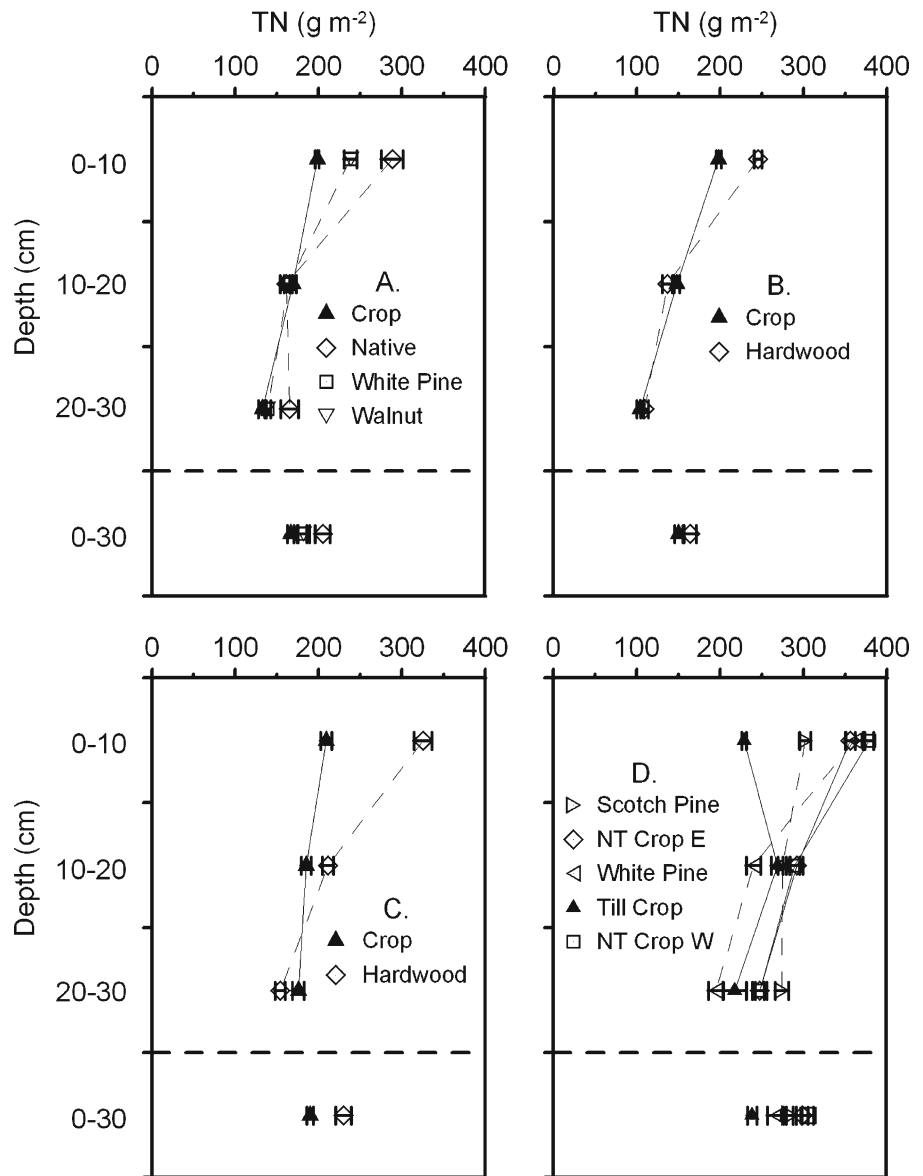
locations since tree planting. The cropped soil at the Jefferson site had been in grass for 10 years prior to 2003 although any SOC accrual due to lack of tillage (the grass was not grazed or fertilized) during this period may have been lost during the 4 year of cropping prior to soil sampling (Reicosky 1997). The rate of SOC increase averaged 0.56 Mg C ha^{-1} yr^{-1} ranging from a minimum of 0.40 to a maximum of 0.72 Mg C ha^{-1} yr^{-1} for the Allamakee white pine and the Jefferson mixed hardwood locations, respectively. The relative rates of change range from 2.0 % yr^{-1} for Allamakee white pine to 5.9 %yr^{-1} for

Clayton mixed hardwood with an overall average annual change in SOC of 4.2 %yr^{-1} for all locations.

Other soil properties

Selected soil properties relevant to the observed trends in SOC and TN are summarized in Table 2. Average pH values were all acidic with the minimum and maximum values for any layer both observed at the Sac location with 5.57 for the 10–20 cm layer beneath white pine and 6.55 and 6.59 for the two NT soils. Higher values were observed at the Clayton and
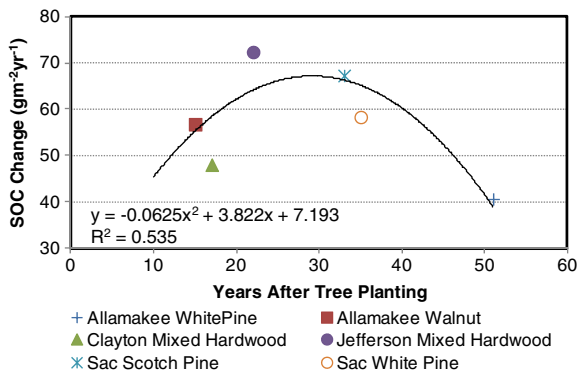
Fig. 5 Average annual increase in soil organic carbon (SOC) for the 0–30 cm layer with time after tree planting assuming that the cropped SOC was at equilibrium

Jefferson locations with the Clayton forest soil pH 0.24 units greater than the cropped soil pH. There was lower pH beneath the white pine at the Allamakee location but not as great a difference as for Sac. Generally lower bulk densities were observed for forested soils and in surface layers. Ammonium acetate- extractable Ca had less consistent results. Only small differences in extractable Ca were observed between forested and cropped soils at the Allamakee, Clayton and Jefferson locations. At the Sac location soils beneath both pine species had greater Ca than the cropped soils through all layers, lacking statistical significance only for the white pine at 20–30 cm.

Trends in CEC were also variable with notably higher values for the Sac location, which were approximately 10 cmol kg^{-1} greater than the other three locations. This may be attributable to clay content as the Galva soil at the Sac location had 27–45 % clay while the other locations ranged only from 15% to 34 %. The highest CEC was observed for the Sac white pine, which also had the lowest pH. Overall, there were only modest differences in particle size among samples from the four locations. The Fayette and Pershing soils had 15% to 34 % clay, 60% to 81 % silt, and 2% to 11 % sand. The Galva soil had comparable amount of sand (2% to 14 %) but somewhat more clay (27% to 45 %) and less silt (53–66 %).

Correlations between SOC and various soil properties including pH, bulk density, nutrients, CEC, and particle size were investigated to ascertain any functional relationships. In many instances, only weak or inconsistent correlations were revealed. The soil properties with the most consistent and strongest correlations with SOC were bulk density (Fig. 6) and

extractable Ca (Fig. 7). The relationship between SOC and bulk density, especially for the 0–10 cm layers for most locations and land uses, illustrates the commonly observed finding of lower bulk density and higher SOC in surface layers in both forested and cultivated soils. Some sorting of data points by layer and land use occurs at all locations but is perhaps most evident at the Sac location as the tilled crop soils display consistently low SOC at similar bulk densities. Higher Ca concentrations in the surface soil layers beneath pine forests are to be expected due to higher Ca concentrations in coniferous leaf litter (Millar 1974). This was observed in this study at the Sac location but not for the white pine at the Allamakee location.

Discussion

Approximately 15 % of Iowa was under forest (primarily deciduous) vegetation at the time of European settlement beginning around 1840 (Anderson 1996). The majority of land within the state had tall grass prairie vegetation and a small amount of oak savannah, which was often the transitional zone between prairie and forest. The native forest areas were concentrated in the Paleozoic Plateau of the northeastern part of the state and in larger river valleys in the eastern half of the state. Although no direct evidence is available for the specific sampling locations of this study, the Allamakee, Clayton, and Jefferson sites were probably cleared for cultivation and/or grazing by 1860. As European settlement generally progressed from east to west across the state, the Sac site would have come under cultivation about one decade later (Ross 1951). Therefore, the cropped fields at each sampling location had been under continuous cultivation and/or grazing for approximately 140 years.

If the requirement of forest as native vegetation is removed from the marginal land criteria, then over 3 times as many hectares (3.7 million ha or 25.3 % of the state land area) meet the remaining two criteria (HEL and CSR less than county average). Regarding the CSR criteria, each county would of course have significant area with below-county average CSR. The area of HEL is predominantly in regions of the state with steeper topography including the unglaciated Paleozoic Plateau in the northeast, Loess Hills in the west, and Southern Iowa Drift Plain. Very little marginal land was identified in the Northwest Iowa Plains and Des Moines Lobe

Table 2 Summary of selected soil properties for cropped and forested plots at each of the four Iowa sampling locations

	Depth (cm)	Allamakee				Clayton		Jefferson		Sac				
		Crop	Black Walnut	White Pine	Native Hardwood	Crop	Mixed Hardwood	Crop	Mixed Hardwood	Tilled Crop	No-till Crop E	No-till Crop W	Scotch Pine	White Pine
pH	0–10	5.59c [H]	6.29a	6.14b	6.24ab	6.07***	6.49***	6.49	6.49	6.00b	6.59a	6.55a	6.00b	5.75c
	10–20	6.00b	6.33a	5.83b	5.98b	6.13*	6.39*	6.30	6.30	6.13b	6.21ab	6.29a	5.74c	5.57d
	20–30	6.28a	6.23a	5.85b	5.76b	6.00	6.11	6.08	6.10	6.37a	6.20b	6.33a	5.82c	5.64d
	0–30	6.00b	6.28a	5.94b	6.00b	6.07***	6.33***	6.29	6.30	6.17b	6.33a	6.39a	5.85c	5.65d
Bulk density (g cm^{-3})	0–10	1.24a	1.30a	1.02b	1.01b	1.42***	1.32***	1.05*	0.95*	1.06c	1.17b	1.25a	1.21ab	1.03c
	10–20	1.46a	1.47a	1.24b	1.29b	1.52***	1.44***	1.39***	1.17***	1.33ab	1.32b	1.36a	1.26c	1.15d
	20–30	1.64a	1.59a	1.38b	1.43b	1.59	1.58	1.47	1.40	1.41a	1.38ab	1.37b	1.36b	1.28c
	0–30	1.45a	1.45a	1.21b	1.24b	1.51**	1.45**	1.30***	1.25***	1.27b	1.29ab	1.33a	1.28b	1.15c
Calcium (mg kg^{-1})	0–10	197a	195a	165b	175b	194	189	205	195	134b	128b	127b	173a	179a
	10–20	172	167	159	169	175	167	199	183	120b	123b	125b	165a	163a
	20–30	155b	167a	152b	169a	172	163	209	194	109c	112c	115bc	138a	120b
	0–30	174a	177a	158b	171a	180*	173*	204*	190*	121b	121b	122b	158a	154a
CEC cmol kg^{-1}	0–10	12.6c	13.9b	16.2a	17.0a	13.6	13.8	15.0*	17.2*	27.2b	25.0c	26.3b	26.8b	30.4a
	10–20	11.3b	12.6ab	13.6a	13.0a	13.7	14.5	14.6	14.6	27.2bc	26.4c	27.4b	27.7b	30.2a
	20–30	13.3	13.9	14.5	15.2	15.7*	17.5*	17.8**	13.3**	25.9c	26.2bc	26.6bc	27.0b	29.0a
	0–30	12.4c	13.5b	14.8a	15.0a	14.3*	15.2*	15.8	15.0	26.8b	25.9b	26.8b	27.1b	29.8a

[H] Means for land uses within each depth increment at Allamakee or Sac locations followed by the same letter are not significantly different as determined by a Fisher's Protected Least Significant Difference (P>0.05). Means for land uses within each depth increment at the Clayton and Jefferson locations were significantly different at P>0.05 (*), P>0.01 (**), or P>0.001 (***) as determined by a two-sample T-test

Fig. 6 Soil organic carbon content (SOC) vs. bulk density (BD) by layer for for (**a**) Allamakee, (**b**) Clayton, (**c**) Jefferson, and (**d**) Sac.. Also shown is the best fit regression line for all data at each location
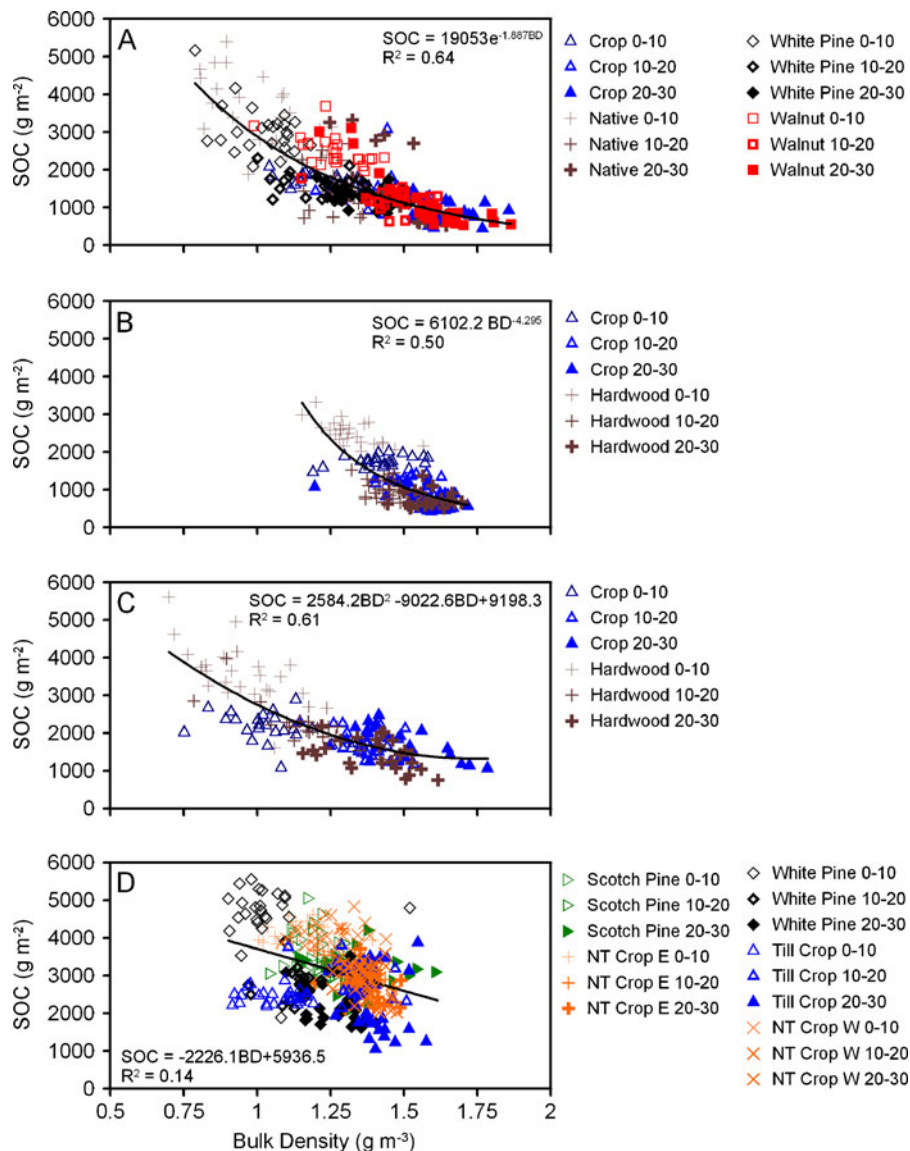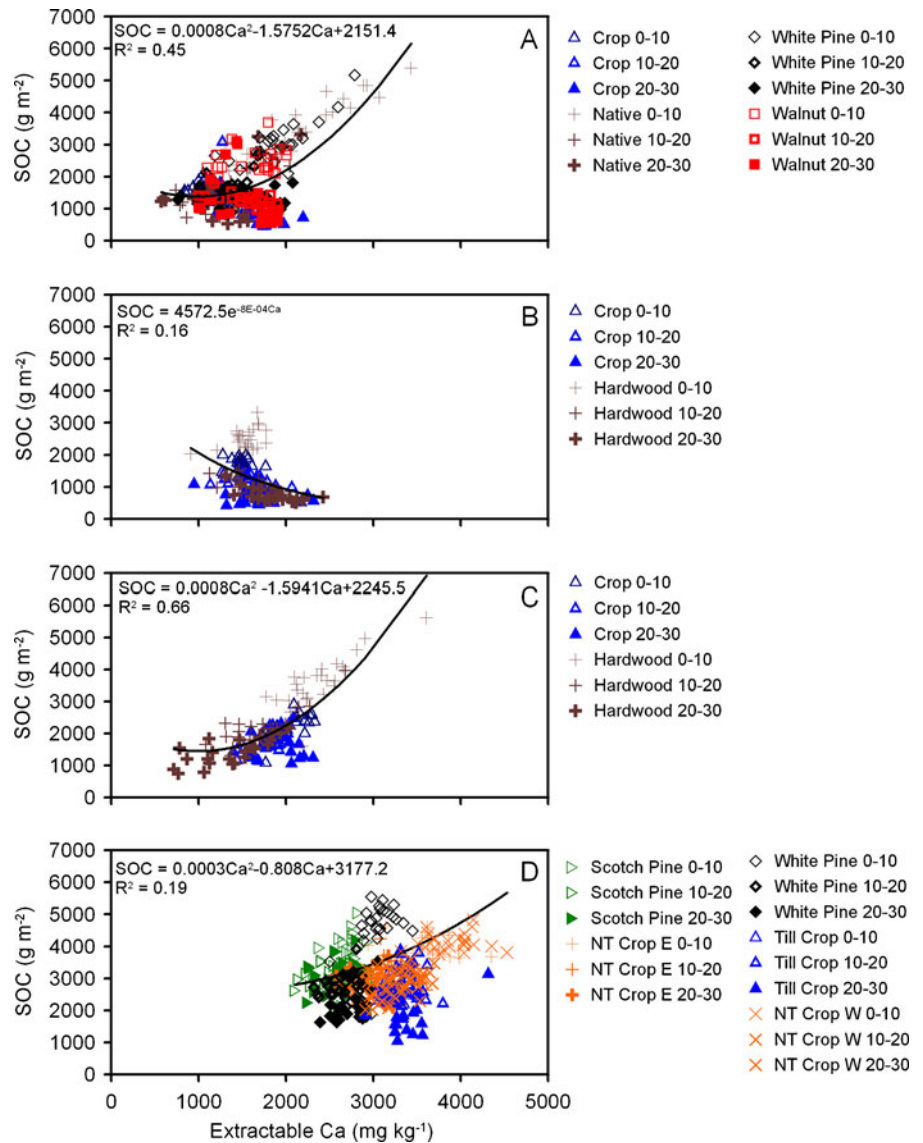

regions due to the lack of native forest cover and/or HEL.

The trend of SOC change with time after tree planting shown in Fig. 5 is consistent with current understanding of SOC changes following a change in land use (Post and Kwon 2000). Depending on soil conditions at the time of tree planting, SOC can decrease for several years after planting possibly due to several factors including site disturbance, soil erosion, and low C inputs from the young vegetation (Paul et al. 2002). After this initial SOC depletion phase, SOC begins to slowly accumulate with increasing tree growth and C inputs, soil biophysical quality improvement, and as C cycling mechanisms adjust to the new

inputs and temperature and moisture regimes. The rate of incorporation of organic C into SOC increases for a period depending on climate and site conditions but this is likely to occur for only a limited period in temperate settings (Post and Kwon 2000). The incorporation rate begins slowing again as the SOC level approaches saturation or a new equilibrium for the site conditions is established (soil, climate, organic inputs, and fertility).

The average annual SOC change estimate of 0.56 Mg C ha^{-1} yr^{-1} for the surface 30 cm of soil is reasonable when compared with the values reported by Post and Kwon (2000). They reported and average increase of 0.34 Mg C ha^{-1} yr^{-1} with a range from small decreases in cool temperate pine plantings to 3.0 Mg C

Fig. 7 Soil organic carbon content (SOC) vs. ammonium acetate- extractable calcium (Ca) by layer for for (**a**) Allamakee, (**b**) Clayton, (**c**) Jefferson, and (**d**) Sac.. Also shown is the best fit regression line for all data at each location

$SOC = 0.0008Ca^2 - 1.5752Ca + 2151.4$
$R^2 = 0.45$

△ Crop 0-10   ◇ White Pine 0-10
△ Crop 10-20   ◆ White Pine 10-20
▲ Crop 20-30   ◆ White Pine 20-30
+ Native 0-10   □ Walnut 0-10
+ Native 10-20   □ Walnut 10-20
+ Native 20-30   ■ Walnut 20-30

$SOC = 4572.5e^{-8E-04Ca}$
$R^2 = 0.16$

△ Crop 0-10
△ Crop 10-20
▲ Crop 20-30
+ Hardwood 0-10
+ Hardwood 10-20
+ Hardwood 20-30

$SOC = 0.0008Ca^2 - 1.5941Ca + 2245.5$
$R^2 = 0.66$

△ Crop 0-10
△ Crop 10-20
▲ Crop 20-30
+ Hardwood 0-10
+ Hardwood 10-20
+ Hardwood 20-30

$SOC = 0.0003Ca^2 - 0.808Ca + 3177.2$
$R^2 = 0.19$

▷ Scotch Pine 0-10   ◇ White Pine 0-10
▷ Scotch Pine 10-20   ◆ White Pine 10-20
▶ Scotch Pine 20-30   ◆ White Pine 20-30
+ NT Crop E 0-10   △ Till Crop 0-10
+ NT Crop E 10-20   △ Till Crop 10-20
+ NT Crop E 20-30   ▲ Till Crop 20-30
                      ✕ NT Crop W 0-10
                      ✕ NT Crop W 10-20
                      ✕ NT Crop W 20-30

ha^{-1} yr^{-1} increases in wet subtropical plantings. In a review of several Midwestern U.S. sites, Paul et al. (2003) found SOC changes after tree planting of −0.07 to 0.55 Mg C ha^{-1} yr^{-1} for deciduous plantings and −0.85 to 0.58 Mg C ha^{-1} yr^{-1} for coniferous plantings. The average SOC accumulation rates in this study were nearly identical for the coniferous and deciduous plantings (0.55 ±0.08 and 0.56±0.09 Mg C ha^{-1} yr^{-1}, respectively). However, any tree species effect may have been obscured by the different previous land use (crop vs. pasture) and time since planting (average 39.7 and 18.0 years. for coniferous and deciduous plantings, respectively) in addition to the differences in soil characteristics among locations. Ney et al. (2002) used statewide soils and forest databases to estimate C storage and fluxes of Iowa forests including the change in SOC in the surface 30 cm for the period from 1974 to 1990. They estimated that in 1990 Iowa forest lands contained 114 million Mg of C with 60.7 % of the C in the surface 30 cm of soil. Their estimated annual rate of SOC change was an increase of 0.79 Mg C ha^{-1} yr^{-1}, which is approximately 38 % greater than the average SOC accrual rate found in this study.

In another Midwestern study, an estimated SOC change of 0.11 Mg C ha^{-1} yr^{-1} was found for the surface 15 cm beneath a 35 yr-old eastern red cedar (*Juniperus virginiana*)—Scotch pine shelterbelt in eastern Nebraska (Sauer et al. 2007). Hernandez-Ramirez et

al. (2011) used stable C isotope techniques on soil samples from the Nebraska study and the white pine soil at the Sac location of this study to discern the source of SOC beneath the trees. Source-partitioning analysis showed that 53.9 and 47.1 % of the SOC in the 7.5- and 10-cm surface layers at the Nebraska and Sac locations, respectively, was tree-derived with mean residence times of 45 and 55 years. This result further strengthens the validity of estimates presented in Fig. 5 as it indicates a significant amount of the SOC for the Sac white pine, which was planted into pasture, was tree-derived and thus accumulated during the 30+ years since afforestation. The difference in SOC for the Sac white pine and tilled crop soils was 694 $g\,m^{-2}$, which is consistent with the source partitioning analysis that found 24.7 % (795 $g\,m^{-2}$) of the Sac white pine SOC was tree-derived.

The calculated rates or C accrual in forested soils in this study ranged from 0.40 to 0.72 Mg C ha^{-1} yr^{-1}. When comparing the NT fields with the tilled crop field at the Sac location, the estimated SOC accumulation is 2.37±0.014 Mg C ha^{-1} yr^{-1}. By comparison, West and Post (2002), in a review of global literature on tillage and crop rotation effects on SOC sequestration, concluded that a change from conventional tillage to NT (excluding wheat-fallow systems) can sequester on average 0.57±0.14 Mg C ha^{-1} yr^{-1}. On marginal soils in Iowa it seems reasonable that SOC increases following tree planting would be less than SOC increases following conversion from tilled to NT crop production. Cropped fields receive annual N additions either through symbiotic N fixation (legumes such as soybean or alfalfa) or application of N fertilizer (typically 100 to 150 kg N ha^{-1} for corn production). The wider C/N ratios for forested soils in this study, (9.7 vs. 8.9 for cropped soils) are consistent with N-limited decomposition of woody biomass with high lignin content and high C/N ratios (Mellillo et al. 1989). The deposition of such slowly decomposing biomass on the soil surface in forests leads to the development of a litter layer, the C content of which was not measured in this study. Sauer et al. (2007) measured the mass and C content of the litter layer beneath 35 year-old red cedar and scotch pine in Nebraska and found that it contained approximately 1/3 as much C as the surface 15 cm of soil. This pool of C could be given credit in C sequestration analyses thereby improving the comparison of afforestation vs. conversion to no-tillage. Very low C/N ratios for the 10–20 and 20–30 cm layers of the cropped Fayette soils at the Allamakee and Clayton locations

(5.9 to 7.9) may be due to a legacy of significant erosion at these sites exposing subsurface horizons with extremely low SOC. Annual N additions to these cropped soils likely enhance rapid and more complete decomposition of the available organic inputs from the crop residues.

Greater cation (Al, Ca, Mg, K, and Na) concentration in the soil solution has been found to increase the sorption of some organic molecules onto clay surfaces thereby enhancing organic matter stabilization (Sollins et al. 1996). High Ca levels in the cropped fields at Sac may be the result of recent aglime (crushed calcite or dolomite) applications to raise the soil pH for optimal crop production. Only a narrow range of Ca concentration was observed at the Clayton location with a much greater range at the Jefferson site and significantly higher Ca in the 0–10 cm layer under the hardwood forest. Aside from Ca content, accumulation of SOC beneath planted forests in this study was not strongly correlated with soil properties previously found to be related to SOC increases (e.g. clay content). However, none of these relationships are universal. For instance, Laganière et al. (2010) reported that soils with >33 % clay have a greater ability to sequester SOC while Poeplau et al. (2011) found that the rate of SOC change decreased with clay content. Oades (1988) noted that clay content is often correlated with other factors, such as soil moisture and CEC that affect plant biomass productivity. These interactions further complicate the interpretation of clay content-SOC relationships.

Even though the locations chosen in this study were intended to represent marginal soils of Iowa, soils in the state are in general of a very high quality when compared to other temperate regions. Soil properties that affected SOC accumulation in other regions were not found limiting at the locations sampled in this study.

At four locations representing marginal agricultural lands in Iowa, the surface 30-cm layer of forested soils had on average 30.0±5.1 % greater SOC than adjacent cultivated crop soils. Estimates of SOC increase with time ranged from 0.40 to 0.72 Mg C ha^{-1} yr^{-1} for these locations that had trees ranging in age from 17 to 51 years. These rates of C accrual are comparable to other studies of tree planting on agricultural lands in temperate regions. If C in the litter layer and in the above- and belowground biomass (Vesterdal et al. 2002; Morris et al. 2007) is also considered, afforestation or reforestation of marginal cropland would be an even more effective means for sequestering carbon.

Planting trees on lands marginal for crop production also resulted in a marked decrease in soil bulk density with no adverse changes in soil pH, CEC, or soil nutrient content. The overall results suggest that conversion of marginal agricultural lands to forest will likely improve general soil quality and has potential to enhance related ecosystem services associated with water quality and availability, nutrient cycling, biodiversity, and C storage. These ecosystem services may be critical to overall environmental quality if increasing intensification of production practices on the available higher quality farmland continues to meet global food demands. Characterizing these ecosystem benefits is a key aspect of such land use conversion and is an important element for characterizing the potential benefits of forested lands in agricultural areas (Schoeneberger 2009; Sauer and Hernandez-Ramirez 2011).

Afforestation and reforestation are also viewed as having great potential for positive impact on cellulosic bioenergy production and energy diversification with significant environmental and economic implications. However, caution must again be exercised to avoid loss of food production potential. Only the most degraded or vulnerable soils should be considered for tree planting and agroforestry practices that include food production (i.e. fruit and nut trees and forest farming) should be encouraged. With time, soil quality of the reforested lands may improve enough to enable these formerly marginal agricultural lands to return to arable cropping or forage production at a higher level of productivity.

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