

Carbon Sources and Dynamics in Afforested and Cultivated Corn Belt Soils

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Afforestation of degraded cropland can sequester atmospheric C; however, source partitioning and turnover of soil organic C (SOC) in such ecosystems are not well documented. This study assessed SOC dynamics in two 35-yr-old, coniferous afforestation sites (i.e., a forest plantation situated in northwestern Iowa on a silty clay loam soil and a shelterbelt situated in eastern Nebraska on a silt loam soil) and the adjacent agricultural fields. Soil samples were collected at both sites to determine SOC and total N concentrations and stable C isotope ratios ($\delta^{13}\text{C}$, natural abundance) in both whole soil and the fine particulate organic matter (POM) fraction (53–500 μm size). In these fine-textured soils, afforestation of cropland performed through either shelterbelt or forest plantation caused substantial increases in surface SOC storage compared with conventionally tilled cropping systems ($\geq 57\%$; $P < 0.05$); this confirms the direct benefits of tree planting on SOC sequestration. Relative to cropped soils, afforested soils exhibited a more depleted $\delta^{13}\text{C}$ signature (-17 vs. -22%), indicating a shift in C sources. Source-partitioning assessment revealed that tree-derived C contributed roughly half of the SOC found directly beneath the trees. The C-enriched afforested surface soils exhibited SOC turnover rates of 0.018 to 0.022 yr^{-1} and mean residence times of 55 to 45 yr. Fine POM in afforested surface soils accounted for a large proportion (21%) of the existing SOC, 79% being derived from tree inputs. This supports the role of POM as a significant sink for recently sequestered SOC in these ecosystems.

Abbreviations: MRT, mean residence time; POM, particulate organic matter; SOC, soil organic carbon; SOM, soil organic matter; TN, total nitrogen.

Soils can act as a net sink of atmospheric C (Lal et al., 1998; Collins et al., 1999; Follett, 2001), creating opportunities for mitigation of global climate change effects. Additionally, concomitant increases in in situ quantities of soil organic matter (SOM) can enhance soil structure, soil biology, and overall ecosystem resiliency (Follett, 2001; Marriott and Wander, 2006; Jastrow et al., 2007). The relative effects of land-management choice, basic underlying principles, and associated ecophysical factors governing accretion of SOC in cropping systems have been documented in the literature (as reviewed by Paustian et al., 2000; Six et al., 2002; Hutchinson et al., 2007; Jastrow et al., 2007); however, little information is available about the comparative effects of afforestation vs. cropping systems on SOC accrual and storage (Vesterdal et al., 2002; Martens et al., 2003).

The influential role of plant species on SOC sequestration is increasingly being recognized. The U.S. Corn Belt landscape is dominated by corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] cultivation. These two crops cover 74% of the total Corn Belt land surface (National Agricultural Statistics Service, 2009). Abundant knowledge is currently available about the comparative effects of these common cropping systems on SOC accrual (Omonode et al., 2006; Angers and Eriksen-Hamel, 2008; Russell et al., 2009). Cessation of tillage operations in these cropping systems is typically considered as a strategic management option for increasing SOC sequestration (Angers and Eriksen-Hamel, 2008; Purakayastha et al., 2008; Follett et al., 2009). The beneficial effects of both undisturbed (Russell et al., 2005; Kucharik, 2007) and restored (Jastrow et al., 1998; Omonode and Vyn, 2006; Hernandez-

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Ramirez et al., 2009) native prairie vegetation on enhanced SOC sequestration relative to conventionally tilled fields are also well established. Few studies, however, have examined the practice of tree planting in degraded cropland as a means for SOC accretion (Garten, 2002; Vesterdal et al., 2002; Sauer et al., 2007). After assessing a mature shelterbelt in Nebraska, Sauer et al. (2007) reported the overall relative advantages of afforestation over continuous cultivation for SOC accrual. Likewise, evaluating two locations in Ohio, Bronick and Lal (2005) found consistently enhanced SOC concentrations in forest vs. cropland soils. Although the available studies support the beneficial role of trees in SOC sequestration, information regarding SOC dynamics and turnover is still lacking in the literature.

With the aim of attaining insights into SOC dynamics, data on conventional SOC inventories need to be supplemented with information about incorporation and stabilization of newly added C material into SOC as well as SOC allocation into labile and recalcitrant SOM pools. This critical understanding of SOC transformation and retention processes can, in part, be acquired through the examination of SOM fractions (Christensen, 2001; Olk and Gregorich, 2006). The POM fraction represents a relatively rapidly decomposable SOM pool (Cambardella and Elliott, 1992; Buyanovsky et al., 1994; Balesdent et al., 1998; Wander, 2004) that can effectively reveal short-term responses of SOC dynamics to land-management change (Tiessen and Stewart, 1983; Chan, 2001; Mirsky et al., 2008; Hernandez-Ramirez et al., 2009). To date, however, few studies have evaluated land-use changes such as tree establishment in degraded cropland using POM fractionation (Garten, 2002; Bronick and Lal, 2005). An even further enhanced understanding of SOC turnover and dynamics can be achieved if quantification of SOM fractions is combined with C source assessment (Cambardella and Elliott, 1992; Stewart et al., 2008). Using stable isotope composition methods, both McPherson et al. (1993) and Bekele and Hudnall (2003) effectively discriminated the tree-C contribution to SOC in forest-prairie transitions. Nonetheless, little information is currently available on SOC source partitioning and turnover rates focusing on afforested ecosystems (forest plantation and shelterbelt) in prairie-derived soils, and therefore, studies are needed to acquire this information.

Earlier studies consistently supported the ability of soil to sequester C in afforested temperate ecosystems, but they also indicated a limited understanding of the underlying mechanisms for SOC accretion in afforested soils. A systematic approach to effectively enhance this knowledge base is needed and should include side-by-side on-farm assessments. Studies by Ellert and Gregorich (1996), Carter et al. (1998), Wander and Bollero (1999), Marriott and Wander (2006), and Causarano et al. (2008) have used preexisting, selected field locations to represent a variety of cropping, forest, and pasture systems within a given region. These studies have successfully identified beneficial effects of tillage cessation and organic amendments on SOC stocks; however, similar studies have not been commonly undertaken to characterize afforested soils. It can be hypothesized that afforestation increases SOC stocks relative to conventional cropping systems. Thus,

the objective of our study was to assess the impacts of contrasting land-management conversion such as different afforestation and cultivation practices on SOC dynamics and sequestration by examining SOC accretion, plant-C sources, turnover parameters, and SOC and plant-C allocations into the POM fraction in two selected field sites within the western U.S. Corn Belt.

MATERIALS AND METHODS

Site Description and Sample Collection

Mead Site

This study was conducted within the U.S. Corn Belt at two field sites (Mead and Sac). The Mead site is located at the University of Nebraska-Lincoln Agricultural Research and Development Center (41°9' N, 96°29' W, 356-m elevation). The soil series is a Tomek silt loam (a fine, smectitic, mesic Pachic Argiudoll). This site consists of a 35-yr-old, north-south-oriented shelterbelt and the two adjacent cultivated fields immediately to the west and east of the shelterbelt. The shelterbelt consists of two parallel rows of trees arranged at distances of 3.6 m between rows and 1.8 m between neighboring trees within the rows. As an agroforestry practice, this type of shelterbelt is typically established across croplands or grasslands to reduce wind speed and associated soil erosion as well as to enhance the local microclimate for crop and animal production. Tree species in the shelterbelt included eastern red cedar (*Juniperus virginiana* L.), Scotch pine (*Pinus sylvestris* L.), and eastern cottonwood (*Populus deltoides* W. Bartram ex Marshall). Other vegetation present in the shelterbelt and the transition zones to the neighboring crop fields includes honeylocust (*Gleditsia triacanthos* L.) and red mulberry (*Morus rubra* L.). The two crop fields adjacent to the shelterbelt were under a crop sequence of corn-soybean-winter wheat (*Triticum aestivum* L.). These two crop fields were cultivated using conventional tillage operations (fall chisel plowing) and received fall-applied beef cattle manure (113 kg N ha⁻¹) only before corn cultivation. In addition, the west crop field also had a history of manure applications with four additional applications of beef cattle manure within the 9 yr before soil sample collection. Further information about the Mead site can be found in Sauer et al. (2007).

A rectangular grid (28.7 by 11.0 m) for soil sample collection was established across the shelterbelt and the two adjacent cultivated fields with seven columns (north-south) and 17 rows (east-west), and sampling points distributed in an area of 314.8 m² (Fig. 1). The shelterbelt included 62 grid points while each cultivated field was represented by 56 grid points. Composite samples ($n = 4$) were collected in the fall of 2003 near each grid point at 0- to 7.5- and 7.5- to 15-cm depth increments using a 3.2-cm-i.d., split-tube probe. Also, leaf and branch samples of the dominant tree species within the shelterbelt were collected in the fall of 2008.

Sac Site

The Sac site is located at Reiff Park, operated by the Sac County Conservation District, Iowa (42°26' N, 95°9' W, 401-m elevation; Fig. 2). The soil series is a Galva silty clay loam (a fine-silty, mixed, superactive, mesic Typic Hapludoll). This site consists of a 35-yr-old eastern white pine (*Pinus strobus* L.) forest plantation (~5.1 ha) and two adjacent, annually cultivated, commercial fields. The distance between pine trees (within rows) averaged 2.7 m while the distance between tree rows was 3.5 m. The tree diameter (at 1.3-m height) averaged 25 cm, and tree height was

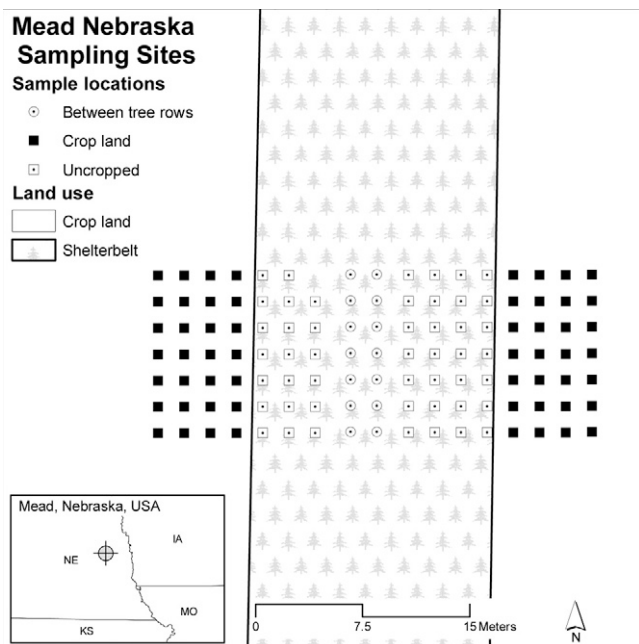


Fig. 1. Geographical location of the Mead site (Nebraska) showing the soil sampling positions arranged in a rectangular grid (seven columns by 17 rows, north–south by east–west) across the shelterbelt and the two adjacent crop fields. Shelterbelt and crop field boundaries are also indicated.

14.0 m. The adjacent cultivated fields were both cropped to a biannual corn–soybean rotation. Before soil sample collection, one of the cropped fields had a long-term history (~30 yr) of continuous conventional tillage management (chisel plow), while the other cropped field had been under conventional tillage for 20 yr and had subsequently been converted to no-till management for the last 10 yr. The no-till management at the Sac site consisted of no mechanical soil disturbance operation during either the spring or the fall. The tilled field was cropped to soybean and the no-till field was cropped to corn during the growing season before soil sample collection in the fall of 2006. Soil sample collection took place after harvest and before any tillage or fertilization operations. The cropped fields received anhydrous NH_4 applications in the fall before corn cultivation.

The soil sampling design at this site was based on dividing each of the two cropped fields and the afforested area covering the Galva soil series into 135 polygons with dimensions of 5 by 5 m^2 . Next, within each cropped and afforested area, five of the original 135 polygons were randomly selected for soil sample collection. Within each selected polygon, five sampling points were established: one initial sampling point centered in a given polygon plus four additional sampling points located at a distance of 2 m from the initial sampling point in all four cardinal directions. Each cropped and afforested area was represented by 25 sampling points.

Bulk soil samples ($n = 2$) were collected at each sampling point at 0- to 10-, 10- to 20-, and 20- to 30-cm depth increments using a 3.2-cm i.d., split-tube probe. The surface plant residue was brushed aside before soil sample collection. Soil samples were placed in plastic bags in the field, transported, and frozen within 8 h of collection. Leaf and branch samples of white pine, as well as undisturbed soil samples (0–21 cm depth) from a native prairie vegetation site near the Sac site (Kiowa Marsh Wildlife Management Area, 42°28' N, 95°6' W), were also collected in the fall of 2008 and subsequently used as reference materials for partitioning organic C sources.

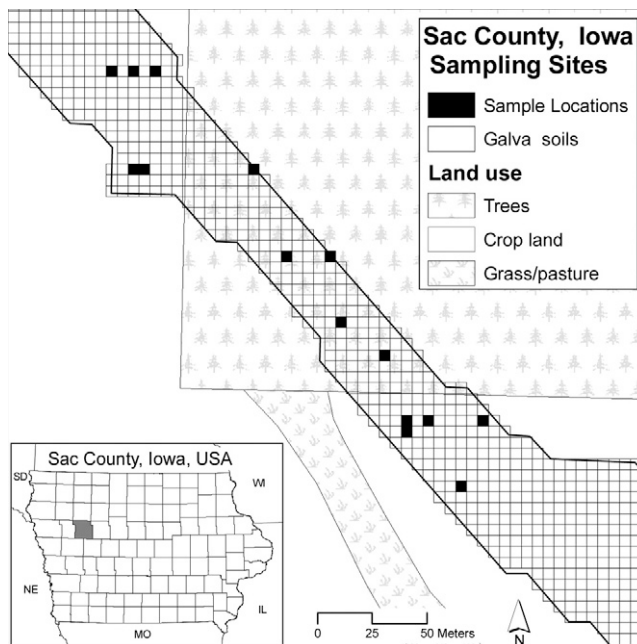


Fig. 2. Geographical location of the Sac site (Iowa) showing the positions of the randomly selected polygons (5 by 5 m) for soil sampling (five sampling points per polygon) within the afforested and adjacent crop fields. Relative to the afforested field, the no-till field is located to the south and the tilled field is to the west.

Laboratory Procedures

Soil samples were sequentially passed through 8- and 2-mm sieves, air dried, and placed on a roller mill (Bailey Manufacturing Inc., Norwalk, IA) for 12 h to create a fine powder consistency. Any identifiable plant material in the soil sample was removed before grinding. Plant samples were washed with deionized water to remove any exogenous material, dried in a forced-air oven at 55°C for 48 h, and ground to pass through a 0.5-mm screen using a Wiley mill (Model 4, Thomas Scientific, Swedesboro, NJ).

We performed soil fractionation on the Mead surface samples (0–7.5 cm) and all Sac samples using physical methods (size-based POM). The POM fraction was determined on 10 g of air-dried, unground soil (<2 mm) dispersed in 30 mL of 5 g L^{-1} sodium hexametaphosphate by shaking in a horizontal, reciprocal shaker at 120 rpm for 18 h (Cambardella and Elliott, 1992). Next, the dispersed material was sequentially passed through a set of two sieves (500- and 53- μm sieves) by washing with deionized water until the water from the bottom of the last sieve ran clear. The POM subfraction of interest was fine POM with particulate diameter sizes between 53 and 500 μm (Moran et al., 2005). We isolated this POM subfraction with the aim of excluding any identifiable tree litter fragments, which were abundant in the range of 500 to 2000 μm . This soil subfraction (fine POM) retained on the 53- μm sieve was transferred into beakers, dried at 50°C in a forced-air oven, weighed, thoroughly mixed, pulverized using an automated, mechanical mortar and pestle for 10 min (Grinder 155, Fisher Scientific, Pittsburgh, PA), and stored at room temperature.

Organic C, total N, and $\delta^{13}\text{C}$ isotopic composition were determined for all plant, soil, and fine POM samples via the dry combustion method using a Fison NA 15000 Elemental Analyzer (ThermoQuest Corp., Austin, TX) interfaced to an isotope-ratio mass spectrometer (Delta V Advantage, Thermo Fisher Scientific, Waltham, MA). Pee Dee

belemnite was used as a standard for natural abundance $\delta^{13}\text{C}$ isotopic ratio determination, which was expressed as

$$\delta^{13}\text{C}(\text{‰}) = \left(\frac{^{13}\text{C}/^{12}\text{C}_{\text{sample}}}{^{13}\text{C}/^{12}\text{C}_{\text{standard}}} - 1 \right) 1000 \quad [1]$$

The analytical precision for $\delta^{13}\text{C}$ measurements was 0.06‰. Sac soil samples did not show evidence of inorganic C after testing with 2 mol L⁻¹ HCl. Mead soils were previously known to contain carbonates; therefore, soil inorganic C concentration analysis was undertaken for all Mead samples using the pressure calcimeter method (Sherrod et al., 2002). These inorganic C measurements were subtracted from the dry combustion values to attain accurate soil organic C concentrations. Following the core method (Soil Survey Laboratory Staff, 1996), bulk density was measured using an undisturbed soil subsample taken on the soil sample collection dates for each sampling point at both sites. Particle size analysis for soil texture was done using the sedimentation method (Gee and Bauder, 1986).

Calculations and Statistical Analyses

Organic C mass storage (M) was calculated for each soil sampling point and separate depth increment (Mead: 0–7.5 and 5–15 cm; Sac: 0–10, 10–20, and 20–30 cm) as

$$M = \text{SOC concentration} \times \text{bulk density} \times \text{soil layer thickness} \quad [2]$$

We estimated the source partitioning of SOC based on an isotope mass balance and $\delta^{13}\text{C}$ values in the soil, plant, and fine POM samples. Similar to Follett et al. (1997) and Huggins et al. (2007), the fractional tree-derived SOC ($F_{\text{Tree-C}}$) was calculated using a two-component mixing equation:

$$F_{\text{Tree-C}} = \frac{\delta^{13}\text{C}_{\text{afforested soil sample}} - \delta^{13}\text{C}_{\text{native soil}}}{\delta^{13}\text{C}_{\text{tree}} - \delta^{13}\text{C}_{\text{native soil}}} \quad [3]$$

where $\delta^{13}\text{C}_{\text{native soil}}$ values are actual measured values from our reference soil under undisturbed, native prairie vegetation located near the Sac site (Kiowa Wildlife Area, $\delta^{13}\text{C} = -16.8 \pm 0.3\text{‰}$). Because there were no suitable native prairie reference locations close to the Mead site, it was assumed that $\delta^{13}\text{C}$ measurements in our soil samples taken from the cropped fields adjacent to the shelterbelt were representative of stable C isotope ratios in these soils before shelterbelt establishment. These $\delta^{13}\text{C}$ values were $-17.6 \pm 0.1\text{‰}$ for the 0- to 7.5-cm soil depth and $-16.3 \pm 0.1\text{‰}$ for the 7.5- to 15 cm depth increments. The reference values for the Mead site were comparable to those reported by Follett et al. (1997) for native prairie sites within Nebraska. The values of $\delta^{13}\text{C}$ used in the $F_{\text{Tree-C}}$ calculations (Eq. [3]) were derived from samples of the dominant tree species at the Mead shelterbelt (eastern red cedar, Scotch pine, and eastern cottonwood), averaging $-26.6 \pm 0.4\text{‰}$, or white pine at the Sac site ($-28.2 \pm 0.6\text{‰}$). Subsequently, the mass of tree-derived SOC was calculated as

$$\text{Mass of tree-derived SOC} = F_{\text{Tree-C}} M \quad [4]$$

Following Balesdent and Mariotti (1996) and Dorodnikov et al. (2007), we estimated the SOC turnover rate and mean residence time (MRT) parameters for the Mead and Sac afforested soils using first-order kinetic modeling and assuming a balance between inputs and outputs as well as steady-state conditions. For convenience, turnover rate

estimation was expressed on the basis of $F_{\text{Tree-C}}$ calculated from Eq. [3] and also logarithmically transformed:

$$\text{Turnover rate} = \frac{-\ln(1 - F_{\text{Tree-C}})}{t} \quad [5]$$

where t is the time period between tree establishment and soil sample collection (35 yr in this study). The MRT value was calculated as the reciprocal of the turnover rate.

Analyses of variance models and Tukey's honestly significant distance tests at a critical value of 0.05 (PROC GLM, SAS 9.1, SAS Institute, Cary, NC) were separately run for each site to examine the effects of afforestation and tillage management on all studied variables. For the Mead site, ANOVAs were run to compare data values from between the two tree rows vs. the two crop fields (Fig. 1). Soil organic C mass storage at the Mead site was not normally distributed; therefore, inferences for this data set were done based on Kruskal–Wallis one-way ANOVA on ranks followed by Dunn's pairwise multiple comparison procedure using SigmaPlot 10 (Systat Software, 2006).

RESULTS

Carbon and Nitrogen Concentrations

At both sampling sites, SOC and total N (TN) concentrations were significantly different between afforested and cropped soils. At the Mead site, both SOC and TN concentrations progressively increased within the surface soil layer ($P < 0.05$), gradually transitioning from the crop fields to the tree rows. The SOC ranged from 19.5 to 38.0 g C kg⁻¹ (Fig. 3A) and TN from 1.85 to 3.04 g N kg⁻¹ (Fig. 3B). The observed large variations in SOC and TN concentrations within the Mead shelterbelt can be attributed to the presence of trees and the associated benefits of increased tree biomass production (C input) (Fig. 3). The shallowest soil layer at the Sac site also showed similar results for SOC, with 33 g C kg⁻¹ for afforested soils and 21 g C kg⁻¹ for tilled fields ($P < 0.001$; Fig. 4A). With respect to TN concentrations, the Sac afforested soil differed from the tilled soil but did not differ from the no-till soil ($P < 0.001$; Fig. 4B). Also at the Sac site, C/N ratios were consistently wider for the afforested soil than for both tilled and no-till soils in all three soil layers ($P < 0.001$; Fig. 4C). Overall, the results for fine POM-C, POM-N, and POM C/N ratios closely showed land-use effects ($P < 0.001$; Fig. 5 and 6) similar to the C, N, and C/N values for the whole soil. Furthermore, the POM results captured much more pronounced patterns as well as broader differences across the assessed land-use systems than the whole soil. Surface fine POM-C, POM-N, and POM C/N ratios were approximately three, two, and 1.2 times greater, respectively, in the afforested soils than in the assessed tilled soils. Moreover, the surface fine POM-C fraction accounted for 23% of the existing SOC beneath the Mead shelterbelt (Fig. 3A and 5A) and 17% of the SOC measured in the Sac forest plantation (Fig. 4A and 6A).

The SOC inventory expressed on a mass per volume basis for the 0- to 30-cm profile at the Sac site indicated greater SOC accrual in the sequence no-till > afforested > tilled soil after ANOVA (Table 1). A relatively lower SOC amount in the 0- to 10-cm depth increment of the annually plowed, cropped soil suggests several pos-

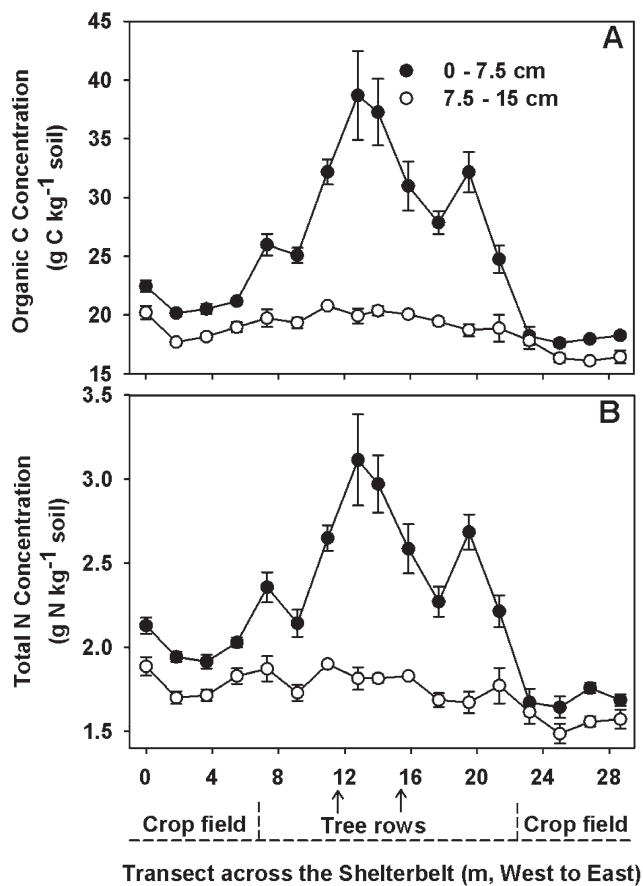


Fig. 3. (A) Soil organic C and (B) total N concentrations in transect across the Mead site, Nebraska, for two depth increments. Organic C and total N densities were presented in Sauer et al. (2007) and are repeated here on a concentration basis for completeness. Shelterbelt zone and crop field boundaries are indicated below the x axis. Within the x axis, the uncultivated tree zone (shelterbelt) was located between 5.5 and 23 m, with the two tree rows at approximately 11 and 14.5 m. Error bars are \pm SE; $n = 7$ (each mean value was calculated using the seven grid sampling points located in the same x axis position [field sampling row]).

sible mechanisms: (i) C accumulated in the surface layers of the no-till and afforested soils; (ii) a tillage-induced C depletion occurred in the surface layer of the tilled soil; (iii) vertical mixing caused dilution of the surface SOC within the tilled soil. The evident SOC stratification in the no-till and afforested soils resulted from plant-C input production and allocation near the soil surface. Concomitantly, the bulk density for the surface soil was typically higher in the no-till fields than in the afforested or tilled soils ($P < 0.001$; Table 1). Soil texture results indicated that the clay content of the Mead soil (0–15-cm depth) was $36.5 \pm 0.4\%$ (w/w), and the sand content was $18.0 \pm 0.6\%$ (w/w). The clay content of the Sac soil (0–30-cm depth) was $37.9 \pm 0.7\%$ (w/w), and the sand content was $2.8 \pm 0.1\%$ (w/w).

Stable Carbon Isotope Signatures

Using the natural abundance of stable C isotopes, distinctive soil $\delta^{13}\text{C}$ shifts were detected across land-use systems. The Mead soils exhibited a marked gradient of $\delta^{13}\text{C}$ signatures, from near-constant values in the cropped fields ($-17.6 \pm 0.1\%$) to much more depleted values between tree rows ($-22.3 \pm 0.4\%$); this captured a gradual shift in SOC sources (Fig. 7A). On the basis

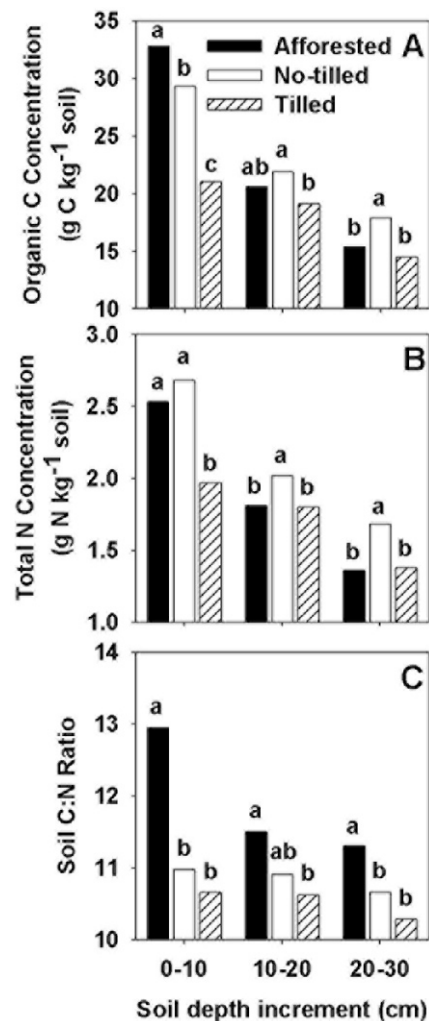


Fig. 4. (A) Organic C concentration, (B) total N concentration, and (C) organic C/total N ratios in the whole soil at the Sac site, Iowa, for three land-use systems and three depth increments. Within each panel and depth increment, land-use systems (bars) with the same letter are not significantly different based on Tukey's honestly significant difference test ($\alpha = 0.05$); $n = 25$.

of mass balance estimations (Eq. [3] and [4]), source partitioning of SOC revealed that tree-derived SOC contributed 54% (i.e., $1.73 \pm 0.16 \text{ kg C m}^{-2}$) of the existing SOC found directly beneath the shelterbelt (Table 2; Fig. 7B). Moreover, the estimated mass of tree-derived SOC allocated into fine POM-C between the tree rows corresponded to $0.52 \pm 0.07 \text{ kg C m}^{-2}$ in the surface layer (Fig. 7B). At the shallowest layer of the Sac site, afforested soils exhibited the most depleted $\delta^{13}\text{C}$ values for both the whole soil and fine POM, followed by no-till and lastly tilled soils ($P < 0.001$; Fig. 8). Focusing on estimated SOC sources of the Sac afforested soils, $\delta^{13}\text{C}$ values revealed that tree-derived SOC corresponded to 47% of the existing SOC in the shallowest soil layer (Table 2). Therefore, the mass of tree-derived SOC in this soil layer corresponded to $1.58 \pm 0.08 \text{ kg C m}^{-2}$ (data not shown but derived from Tables 1 and 2). Furthermore, the estimated quantities of tree-derived fine POM-C were roughly $0.47 \pm 0.03 \text{ kg C m}^{-2}$ in the Sac surface afforested soils (data not shown). Additionally, the $\delta^{13}\text{C}$ values for fine POM in the surface soils from both sites

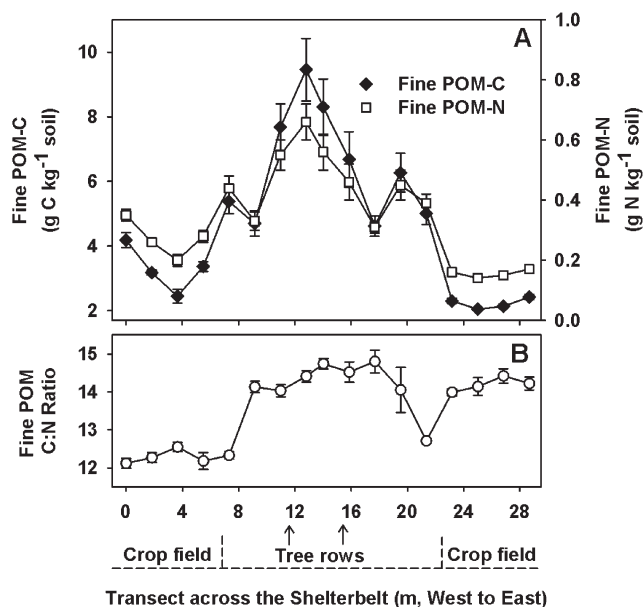


Fig. 5. Fine particulate organic matter (POM) fraction (53–500- μm size) in the transect across the Mead site, Nebraska, for the 0- to 7.5-cm soil depth increment: (A) organic C and total N concentrations, and (B) C/N ratios in the fine POM fraction. Shelterbelt zone and crop field boundaries are indicated below the x axis. Within the x axis, the uncultivated tree zone (shelterbelt) was located between 5.5 and 23 m, with the two tree rows at approximately 11 and 14.5 m. Error bars are \pm SE; $n = 7$ (each mean value was calculated using seven grid sampling points located in the same x axis position [field sampling row]).

were 2 to 4‰ more depleted than the whole soil (Fig. 7A and 8), supporting the distinctive nature of this SOM fraction.

First-order kinetic modeling of SOC increments (Eq. [5]) in the shallowest layers of the afforested soils indicated SOC turnover rates of 0.022 yr^{-1} for the Mead site and 0.018 yr^{-1} for the Sac site (Table 2). The corresponding MRT values were 45 yr for Mead and 55 yr for the Sac site. Similar analyses for fine POM indicate turnover rates of 0.042 yr^{-1} for the Mead site and 0.049 yr^{-1} for the Sac site (Table 3). Concurrently, MRT values for fine POM were 24 yr for Mead and 21 yr for the Sac site. Overall, slower C turnover rates and increased MRT estimates were obtained for deeper soil layers at both sites, reflecting the relatively lower contribution of tree C to C stocks in those soil layers (Tables 2 and 3). Furthermore, the similarities in C turnover parameters between the Mead and Sac afforested soils are also noticeable from these results.

DISCUSSION

Afforestation Impacts on Carbon and Nitrogen Accretion

In these fine-textured soils of the U.S. Corn Belt, afforestation of croplands performed through either shelterbelt or forest plantation caused substantial increases in surface SOC storage ($\geq 57\%$) after 35 yr of tree growing relative to conventionally tilled cropping systems (Table 1; Fig. 3A and 4A). This finding is in general agreement with several previous reports regarding the beneficial effects of afforestation on soil C accretion for a broad variety of ecosystems and ecophysical conditions. Bronick and Lal (2005) reported a roughly twofold increase in SOC concentrations for forested vs. cultivated land in Ohio. Similar to our study, they also linked en-

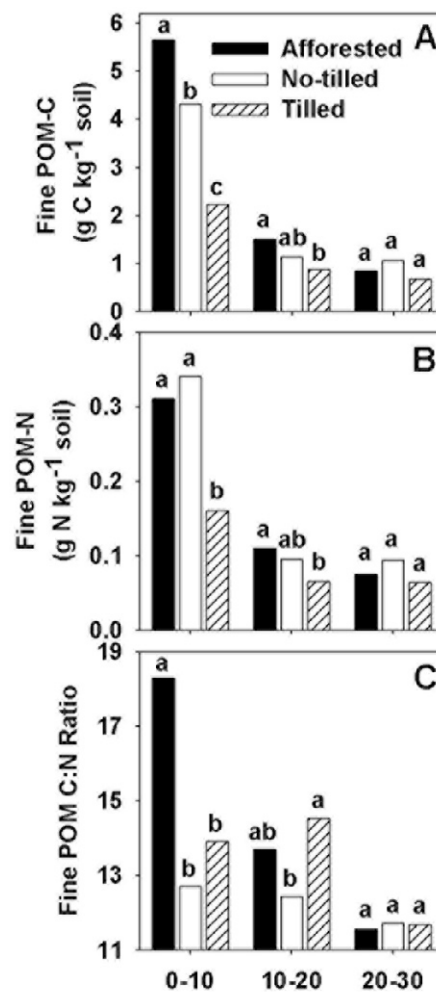


Fig. 6. (A) Organic C concentration, (B) total N concentration, and (C) organic C/total N ratios in the fine particulate organic matter (POM) fraction (53–500- μm size) at the Sac site, Iowa, for three land-use systems and three soil depth increments. Within each panel and depth increment, land-use systems (bars) with the same letter are not significantly different based on Tukey's honestly significant difference test ($\alpha = 0.05$); $n = 25$.

hanced soil C retention with relatively greater POM concentrations (nearly threefold). Our results were similar to Martens et al. (2003), who reported increases (46%) in SOC concentration for afforested vs. cropped land in Nebraska in direct association with enhanced soil aggregation. Likewise, examining a grassland–woodland ecotone in Arizona, McPherson et al. (1993) observed that 21% greater SOC in woodland vs. grassland sites was associated with increased root biomass in tree-covered locations. Similarly, after evaluating a chronosequence (1–29 yr) of afforestation in cropland in Denmark, Vesterdal et al. (2002) quantified SOC increases with time at the 0- to 5-cm depth. Conversely, they also detected gradual SOC depletion with time deeper in the soil profile (5–25 cm). This outcome apparently contradicts the majority of existing reports as well as our findings; however, this could be attributed to minimal tree-C inputs to subsurface soil layers in the early stages of their forest stands in conjunction with a low soil capacity for SOC stabilization and protection caused by a lack of clay mineral surfaces in their coarse-textured soils (sandy loam texture with 69% sand particles).

Table 1. Soil organic C mass storage and bulk density for three adjacent land-use systems in three depth increments and the cumulative profile (0- to 30-cm depth) at the Sac site, Iowa.

Treatment or statistic	0–10 cm	10–20 cm	20–30 cm	0–30 cm
Organic C mass storage, Mg ha ⁻¹				
Afforested†	33.6 b‡	23.5 b	19.6 b	76.7 b
No-till§	36.5 a	29.8 a	24.5 a	90.8 a
Tilled§	22.3 c	25.4 b	20.3 b	68.0 c
Mean	30.8	26.2	21.5	78.5
CV, %	28	15	28	18
P > F¶	<0.001	<0.001	0.027	<0.001
Bulk density, Mg m ⁻³				
Afforested†	1.03 b	1.15 b	1.28 b	1.15 c
No-till§	1.25 a	1.36 a	1.37 a	1.33 a
Tilled§	1.06 b	1.33 a	1.41 a	1.27 b
Mean	1.11	1.28	1.35	1.25
CV, %	12	9	7	12
P > F¶	<0.001	<0.001	<0.001	<0.001

† Eastern white pine 35-yr-old forest plantation.

‡ Within columns and soil parameter, means followed by the same letter are not significantly different according to Tukey's honestly significant difference test ($\alpha = 0.05$).

§ Cultivated fields immediately adjacent to the pine forest plantation cropped to corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation. The no-till field had not received tillage operations for 10 yr before soil sample collection.

¶ Probabilities beyond F values for treatment effects within each soil depth increment and soil parameter after ANOVA models.

Other previous studies also support the hypotheses that the quantity and quality of tree-C inputs (Melillo et al., 1989; Richter et al., 1999; Berg, 2000; Berg et al., 2001; Kiser et al., 2009) as well as soil texture and mineralogy (Melillo et al., 1989; Richter et al., 1999; Leggett and Kelting, 2006) are key controlling factors of SOC accrual in afforested soils. A conceptual model by Melillo et al. (1989) postulated microbial transformation of tree litter into stable soil C forms (e.g., humus) to be governed by both litter characteristics [lignin/(lignin + cellulose) ratio] and soil factors (temperature, water content, preexisting C and N [endogenous or exogenous], and texture). They also suggested that these C transformation processes occur in two sequential steps. The first decomposition stage is hypothetically controlled by both the litter characteristics and soil factors, while a second decay phase is driven only by soil factors. Within this conceptual framework, we can speculate that the conifer trees at our afforested locations potentially create colder and drier soil conditions relative to the cropped fields because of higher water uptake and litter production rates and continuous canopy cover under the conifers. The cool and dry conditions would reduce residue decomposition rates, thereby increasing SOC accretions in the afforested areas. These and other inherent aspects of land-use conversion from cropland to afforestation, such as tillage cessation and soil erosion reduction, could have collectively contributed to enhanced C sequestration in these afforested soils.

Relative to crop fields, increasing SOC concentrations beneath trees were accompanied by wider C/N ratios in both the whole soil (Fig. 4C) and fine POM (Fig. 5B and 6C). This relationship is consistent with data by Martens et al. (2003), Sauer et

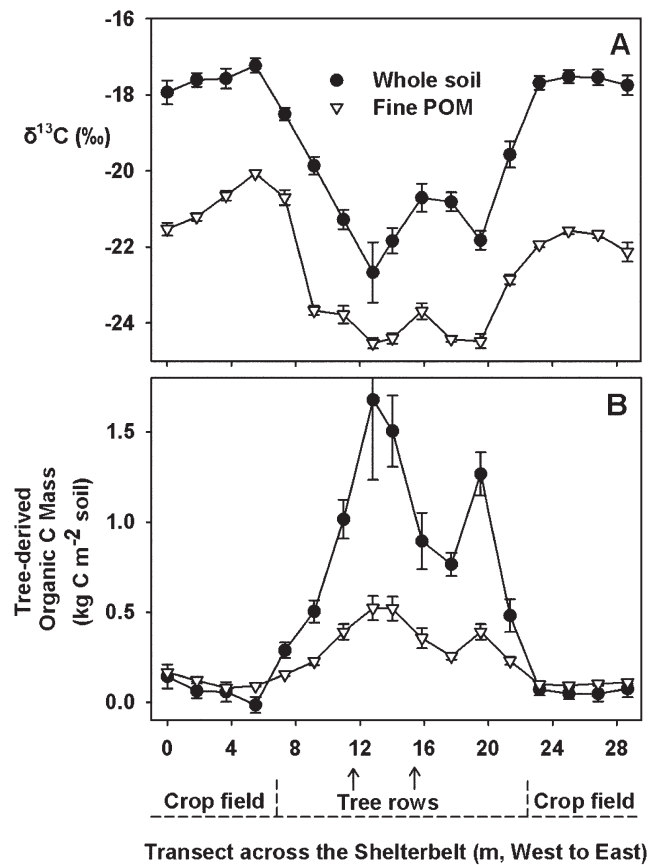


Fig. 7. (A) Stable C isotope ratios ($\delta^{13}\text{C}$) and (B) estimated organic C mass storage derived from tree input in both the whole soil and the fine particulate organic matter (POM) fraction (53–500- μm size) across the Mead site, Nebraska, for the 0- to 7.5-cm soil depth increment. Shelterbelt zone and crop field boundaries are indicated below the x axis. Within the x axis, the uncultivated tree zone (shelterbelt) was located between 5.5 and 23 m, with the two tree rows at approximately 11 and 14.5 m. Error bars are \pm SE; $n = 7$ (each mean value was calculated using seven grid sampling points located in the same x axis position [field sampling row]).

al. (2007), and Kiser et al. (2009) for afforested soils receiving no N fertilizer additions. The absence of exogenous N additions coupled with both a fungal-dominated microbial community beneath trees (Ohtonen et al., 1999) and a naturally low-quality tree input (Melillo et al., 1989) could help to explain these patterns of increasing SOC with wider soil C/N ratios. Above- and belowground conifer inputs are typically characterized by an abundance of C-rich, recalcitrant compounds (lignin) and low N contents (Melillo et al., 1989; Richter et al., 1999; Berg et al., 2001), translating into relatively wide C/N ratios. In our study, C/N ratios were 30 for conifer needles and 54 for conifer branches (data not shown). These various factors may imply SOM resilience to decomposition beneath trees, and hence, an enhanced propensity to long-term SOC sequestration in these N-limited soils where N is intensively subject to microbial and plant competition and demand. Correspondingly, Berg (2000) suggested increased efficiency of litter transformation to stable SOC and associated enhanced SOC accumulation as direct responses to both higher litter N concentrations and narrower litter C/N ratios across multiple forest tree species. These potential roles of N in SOC accretion in ecosystems deserve further examination because existing reports are inconsistent. In afforested systems,

Table 2. Turnover parameters for organic C in the whole soil of afforested locations at the Mead and Sac sites and for various depth increments.

Depth increment cm	Tree-derived C % (w/w)	Turnover rate yr ⁻¹	Mean residence time yr
<i>Mead shelterbelt</i>			
0–7.5	53.9	0.0221	45
7.5–15	10.4	0.00314	319
0–15‡	37.2	0.0133	75
<i>Sac afforested site</i> §			
0–10	47.1	0.0182	55
10–20	12.0	0.00365	274
20–30	2.3	0.00065	1530
0–30‡	24.7	0.0081	123

† Tree species in the shelterbelt included eastern red cedar, Scotch pine, and eastern cottonwood. Turnover estimations for the Mead shelterbelt site used data from the soil samples taken between the two tree rows ($n = 14$).

‡ Cumulative profile.

§ Eastern white pine 35-yr-old forest plantation.

Johnson and Curtis (2001) reported beneficial N fertilization effects on SOC accrual because of increased primary productivity, whereas Leggett and Kelting (2006) found no N effect on SOC parameters 11 yr after a single N addition (45 kg N ha⁻¹ at tree planting), perhaps due to a priming N effect that could stimulate microbial oxidation of preexisting SOC.

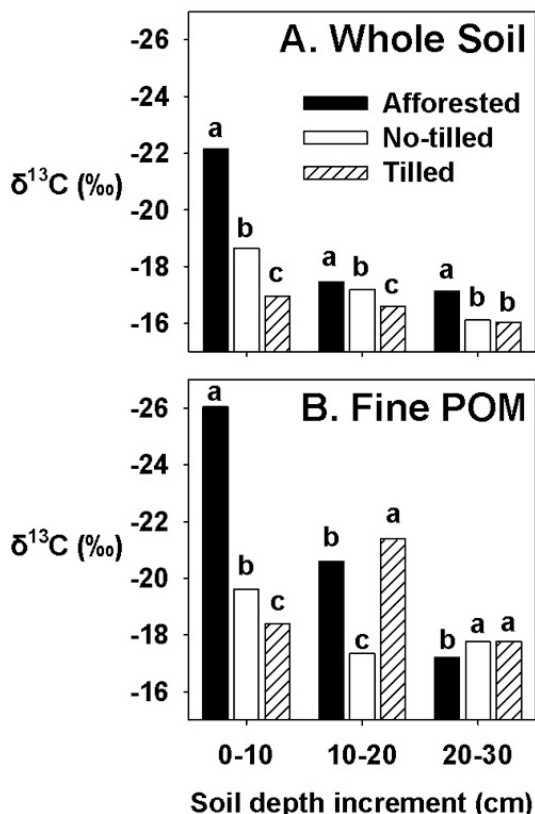


Fig. 8. Stable C isotope ratios ($\delta^{13}\text{C}$) in (A) the whole soil and (B) the fine particulate organic matter (POM) fraction (53–500- μm size) at the Sac site, Iowa, for three land-use systems and three depth increments. Within each panel and depth increment, land-use systems (bars) with the same letter are not significantly different based on Tukey's honestly significant difference test ($\alpha = 0.05$; $n = 25$).

Tree-derived C inputs can fully account for all the additional SOC replenishment following conversion from degraded cropland to afforestation. Using soil $\delta^{13}\text{C}$ signatures (Fig. 7A and 8A), source-partitioning estimations indicate that after 35 yr, tree-derived C contributed roughly half of the current SOC found in the surface soil beneath trees; this is in direct agreement with our finding of twofold higher SOC concentrations in afforested vs. conventionally tilled soils (Fig. 3A and 4A). Moreover, $79 \pm 2\%$ of the measured fine POM-C corresponded to tree-derived C (Table 3), and this tree-derived fine POM-C represented $17 \pm 1\%$ of the SOC pool in these soils. Such quantitative information confirming C inputs from trees (litter and shallow roots) as major SOC sources and their preferential allocation into soil POM in afforested ecosystems has been reported in only a few previous studies (Garten, 2002).

Our results also permitted numerical assessment of SOC turnover on the basis that these surface soils had reached a new equilibrium after 35 yr of tree establishment (Richter et al., 1999; Dorodnikov et al., 2007). These C-enriched afforested surface soils exhibited MRTs for SOC on the order of decades, with values of 45 to 55 yr (Table 2). This result indicates that the SOM beneath trees is subject to moderate turnover dynamics compared with the fast turnover in soils planted to *Miscanthus* \times *giganteus* (J.M. Greef & Deuter ex Hodk. & Renvoize) with a MRT of 13 yr (Dorodnikov et al., 2007), and relatively slow turnover in corn fields with a MRT of 117 yr (Huggins et al., 1998) and 196 yr (Collins et al., 1999). Additionally, our MRT values for fine POM (Table 3) revealed a fast turnover rate in this SOM fraction in the surface soil layer, perhaps suggesting both high addition rates of new tree-C inputs and high microbial activity dedicated to the initial decomposition phases of tree inputs or their reincorporation into POM. Our findings of fast POM turnover rates in these afforested soils also support previous hypotheses of POM as a relatively rapidly decomposable SOM fraction (Cambardella and Elliott, 1992; Gale and Cambardella, 2000). Moreover, because our study indicated that newly added tree-derived C was preferentially allocated into POM, we hypothesize that old SOC from before tree planting would be mostly preserved in mineral-associated forms. This hypothesis merits further examination.

Tillage Management Effects on Carbon and Nitrogen Accrual

Long-term cessation of tillage operations (10 yr) caused enhanced SOC accretion relative to adjacent, repeatedly tilled crop fields (Fig. 4A). The available literature supports this effect (Six et al., 1999, 2006; Huggins et al., 2007; Olchin et al., 2008; Purakayastha et al., 2008; Poirier et al., 2009). Based on a metadata analysis, West and Post (2002) identified rapid SOC sequestration within 5 to 10 yr of conversion from conventional tillage to no-till management, with the most accelerated, pronounced responses occurring in the surface soil layer (West and Post, 2002; Poirier et al., 2009). Poirier et al. (2009) attributed this pattern to greater crop residue accumulation on the soil surface of no-till fields, also typically resulting in reduced soil erosion in no-till fields (Allmaras et al., 2004). Using in situ incubation,

Olchin et al. (2008) found more efficient stabilization of wheat residue into SOC in no-till than in shallow (15-cm-depth) tilled soils. Additionally, similar to our POM results (Fig. 6), Six et al. (1999), Purakayastha et al. (2008), and Yoo and Wander (2008) also observed increased POM accumulation in no-till vs. tilled fields. Enhanced SOC storage for no-till vs. tilled fields has been closely linked to increases in macroaggregate formation and stability, aggregate-associated physical protection of labile SOM, and fungal biomass and activity (Six et al., 2006). In addition, under no-till systems, this overall enhancement in SOC inventory could be in part explained by relatively cold and moist soil conditions in the spring, typically leading to reduced mineralization of both plant residue and preexisting SOC. In no-till fields, these various beneficial factors could particularly favor an efficient retention of C derived from roots, which are known as the primary source of SOC (Balesdent and Balabane, 1996) and POM (Gale and Cambardella, 2000) in relatively undisturbed soils.

In addition to enhanced SOC sequestration, no-till management also retained proportional quantities of TN, translating into a consistently narrow C/N ratio similar to levels in the repeatedly tilled soils (Fig. 4B and 4C). This coherent TN enrichment pattern in the no-till soils could be attributed to the annually repeated N fertilizer inputs shortly following crop residue additions in the late fall in direct synergy with the ongoing long-term no-till management in this field. Beneficial, interacting effects of the simultaneous additions of both N fertilizer and plant residue on the stabilization and accretion of plant-derived SOC has been previously reported after both controlled (Moran et al., 2005) and field (Hernandez-Ramirez et al., 2009) experiments.

As discussed above, this study extends previous knowledge about organic C dynamics and turnover in afforested and cultivated soils; however, several limitations can be recognized. While the side-by-side comparison of tilled vs. afforested soils is duplicated at the two study sites, the no-till management was represented only in one of the two soil sampling sites (Sac, Iowa). These results for no-till management at the Sac site are still valuable because they indicate that both no-till management and afforestation can result in comparable outcomes of increased soil C sequestration when practiced under the same edaphic and climatic conditions (Table 1). In addition, it is noteworthy to point out that the two corn-soybean rotations at the Sac site are unsynchronized. At the time of soil sample collection at the Sac site, a soybean crop had been recently harvested in the west crop field, while the south crop field had been in corn. Therefore, we have no ability to discern transient vs. long-term effects as a function of crop rotation phase or tillage management factors. Additional research with high temporal resolution data (e.g., monthly) could unmask these confounding factors. Furthermore, soil sampling depths at both the Mead and Sac sites could perhaps have not been deep enough to fully account for changes in soil consolidation across assessed land-use systems and to entirely capture a complete SOC inventory.

Table 3. Turnover parameters for organic C allocated in the fine particulate organic matter (POM, 53–500- μm size) fraction of afforested locations at the Mead and Sac sites and for various depth increments.

Depth increment	Tree-derived fine POM-C	Turnover rate	Mean residence time
cm	% (w/w)	yr^{-1}	yr
<i>Mead shelterbelt</i> †			
0–7.5	77.2	0.0422	24
<i>Sac afforested site</i> ‡			
0–10	81.7	0.0486	21
10–20	60.0	0.0262	38
20–30	36.9	0.0132	76
0–30§	72.9	0.0373	27

† Tree species in the shelterbelt included eastern red cedar, Scotch pine, and eastern cottonwood. Turnover estimations for the Mead shelterbelt site used data from the soil samples taken between the two tree rows ($n = 14$).

‡ Eastern white pine 35-yr-old forest plantation.

§ Cumulative profile.

CONCLUSIONS

Land-use change from conventionally tilled cropland to afforestation with conifers achieved substantial SOC replenishment in these fine-textured surface soils, suggesting a positive scenario for soil quality restoration via tree planting in degraded cropland. These C-enriched afforested surface soils exhibited SOC residence times on the order of decades, indicating that increased SOM beneath trees is subject to moderate turnover dynamics. This quantitative description of SOM dynamics can be highly valuable for modeling efforts of C fluxes in terrestrial ecosystems, in particular for temperate afforested ecosystems.

The underlying mechanisms responsible for SOC sequestration seemed to differ between the assessed ecosystems (afforested vs. tilled cropland). This notion is in part supported by the noted differences in C/N ratios between afforested and cropped soils, suggesting their distinct SOM nature. Moreover, contrary to tilled soils, a hypothetical new SOC equilibrium coupled with a significant POM accumulation in the assessed afforested surface soils may indicate an overall slow humification process of newly added, tree-derived C in afforested soils. These various hypotheses need to be further tested. Quantification of litter- and root-derived tree-C inputs, soil respiration amounts and sources, vertical root biomass distribution, macrofauna activity, and net ecosystem productivity could also help to elucidate these unknowns. Regarding land-management effects in afforested soils, the potential impact of tree biomass removal (e.g., due to growing interest in biofuel production) from these ecosystems on SOC dynamics and source-sink relationships remains uncertain.

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