Carbon Sources and Dynamics in Afforested and Cultivated US Corn Belt Soils

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Abstract
Afforestation of degraded cropland can sequester atmospheric carbon (C), but soil organic C (SOC) sources in such ecosystems are not well-characterized. This study assessed SOC dynamics and sources in two 35-yr-old, coniferous afforestation sites [i.e., a forest plantation and a shelterbelt situated at northwestern Iowa (Sac) and eastern Nebraska (Mead), respectively] and the adjacent agricultural fields. Composite soil samples were collected at both sites to determine OC and total nitrogen (TN) contents, and stable C isotope ratios (δ^{13}C, natural abundance). In these fine-textured soils, afforestation of cropland carried out through either shelterbelt or forest plantation caused substantial increases in SOC accrual (≥ 57%; $P< 0.05$) in surface soil layers (to 7.5 or 10 cm deep) relative to conventionally-tilled cropping systems. Soils exhibited a marked gradient of δ^{13}C signatures from near constant values in cropped fields (-17 ± 0.1‰) to much depleted in afforested soils (-22 ± 0.4‰) indicating a gradual shift in C sources. Source-partitioning assessments revealed that tree-derived C contributed roughly half of the SOC found directly beneath trees indicating that the additional SOC accrued in these afforested sites can be fully explained by tree-derived inputs.

Key Words
Land-use system, management choice, soil quality, soil resilience, ecosystem services.

Introduction
Soils can act as a net sink of atmospheric C (Follett *et al*. 1997) creating opportunities to mitigate global climate change. Concomitant increases in *in situ* SOC quantities can concurrently enhance soil quality and overall ecosystem resiliency. These various soil processes can be influenced by vegetation type. Within this context, the US Corn Belt landscape is dominated by corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] with these two crops covering 74% of total land surface (NASS 2009). There is abundant knowledge currently available about the comparative effects of these common cropping systems on SOC accrual (Huggins *et al*. 1998). Fewer studies have focused on the practice of tree planting in degraded cropland as a means for SOC accretion and soil quality restoration. After assessing a mature shelterbelt in Nebraska, Sauer *et al*. (2007) reported the advantage of afforestation over cultivation for SOC accrual. Likewise, evaluating two locations in Ohio, Bronick and Lal (2005) found enhanced SOC contents in forest vs. cropland. However, knowledge concerning the relative effects of afforestation vs. cultivation as well as the associated ecophysical factors governing SOC accretion and sources still remains incomplete and fragmented. With the aim of attaining additional insights about SOC dynamics in these ecosystems, conventional SOC inventories need to be supplemented with information about retention of newly-added C into SOC. This critical understanding about SOC dynamics can in part be acquired through assessing C source-partitioning. Using isotope methods, McPherson *et al*. (1993) discriminated the tree-C contribution to SOC in forest-prairie ecotones. Currently, there is no information available about SOC sources for afforested ecosystems in prairie-derived soils. The objective of this study was to assess the relative impacts of cropping vs. afforestation systems on SOC accretion and plant-C sources in two sites within the US Corn Belt.

Materials and Methods
This study was conducted at two sites: Mead and Sac. Mead is located within the University of Nebraska-Lincoln ARDC, NE (41° 9' N, 96° 29' W, 356 m elevation) with soil series Tomek silt loam (fine, smectitic, mesic Pachic Argiudoll) (USDA-NRCS 2002). This site consists of a 35-yr-old, north-south oriented shelterbelt and the two adjacent cultivated fields to the west and east sides of the shelterbelt. Tree species included eastern red cedar (*Juniperus virginiana*) and scotch pine (*Pinus sylvestris*). Trees were arranged in two parallel rows with distances of 3.65 m between rows and 1.8 m between neighbouring trees within rows. The adjacent fields were primarily cultivated to wheat (*Triticum aestivum* L.) –corn–soybean rotation using fall chisel plowing. A rectangular grid for soil sample collection was established across the shelterbelt and the two adjacent cultivated fields with 7 × 17 (north-south × east-west) sampling points distributed in an area of 304.6 m^2. Composite samples (n= 4) were collected near each grid point with 0-7.5 and 7.5-15 cm depth

increments. The Sac site is located at Early, IA (42° 26' N, 95° 9' W, 401 m elevation) with soil series Galva silty clay loam (fine-silty, mixed, superactive, mesic Typic Hapludoll) (USDA-NRCS 2002). This site consists of a 35-yr-old eastern white pine (*Pinus strobus* L.) forest plantation (≈ 5.1 ha) and an adjacent, commercial field under corn-soybean rotation. Distance between pine trees (within rows) and between tree rows averaged 2.73 and 3.50 m, respectively. Tree diameter measured at 1.3 m height was 0.25 m and tree height was 14.0 m, respectively. Prior to soil sample collection, the crop field had a long-term history of tillage (≈ 30 yr under chisel plowing). For soil sample collection, Sac afforested and cropped fields were divided into polygons (5 × 5 m^2), and 5 polygons were randomly selected within each field. Then, 5 composite soil samples (n= 2) were collected within each selected polygon at 0-10, 10-20, and 20-30 cm depth increments. All Mead and Sac soil samples were collected after crop harvest and before fall tillage operation using a 3.2-cm i.d., hammer-driven, split-tube probe after surface plant residue was brushed aside. Leaf and branch samples of dominant tree species at both Mead and Sac sites, and undisturbed soil samples from a native prairie vegetation site near Sac [i.e., Kiowa Area, 42° 28' N, 95° 6' W; soil series Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll] (USDA-NRCS 2002) were also collected as reference materials for SOC sources estimations. Using conventional methods, all samples were dried and ground to powder consistency. We determined OC, TN, and $\delta^{13}C$ isotopic composition via dry combustion method using a Fison NA 15000 Elemental Analyzer interfaced to an isotope-ratio mass spectrometer Delta V Advantage. Because carbonates were presented in Mead soils, a pressure calcimeter method (Sherrod *et al*. 2002) was used to determine and discount soil inorganic C. The SOC mass storage was calculated by multiplying SOC concentration, ρ_b, and soil layer thickness. Gravel was not present in these loess-derived soils. Mass balance for SOC sources was estimated using $\delta^{13}C$ measurements in soil and plant samples as well as reference values by Follett *et al*. (1997). Mean residence time (MRT) of SOC was calculated as Dorodnikov *et al*. (2007). Bulk density (ρ_b) and soil pH (1:1 in water) were also quantified. Analyses of variance (ANOVA) models and Tukey tests at a critical value of 0.05 were run to examine land-use effects.

Results and Discussion

Afforestation Effects on Carbon and Nitrogen Accretion

At the Mead site SOC (19 vs. 38 g/kg; Figure 1A) and TN (1.8 vs. 3.0 g/kg; Figure 1B) contents sharply increase in the surface soil layer ($P< 0.05$) as gradually transitioning from the crop fields to the tree rows. The shallowest soil layer at the Sac site also showed similar results (pine plantation > crop field, $P< 0.001$; Figure 2A; Figure 2B). All three soil layers at the Sac site exhibited consistently wider C/N ratios for the afforested soil ($P< 0.001$; Figure 2C). The divergent C/N ratios between afforested and cropped soils suggest the quality of organic matter differs for these two ecosystems. This result is consistent with data by Martens *et al.* (2003) and Sauer *et al.* (2007) 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 the relatively low quality of C inputs from trees (Melillo *et al.* 1989) could explain these marked patterns of wider C/N ratios in the afforested soils. The SOC expressed on a mass-volume basis for the 0-30 cm profile at Sac indicates greater SOC accrual in the pine-afforested vs. cropped soil (Table 1). A relatively lower SOC amount in the surface depth increment of the annually-plowed, cropped soil suggests that C accrual took place mainly in the surface layer of the pine-afforested soil and/or a tillage-induced C depletion occurred in the surface layer of the cropped soil. Surface soil ρ_b was similar for two Sac fields and roughly 10% higher in the crop field at 10-30 cm depth ($P\leq 0.001$; data not shown). Soil pH was typically lower in afforested vs. cropped soils by 0.6 units (5.6 vs. 6.2) ($P\leq 0.002$; data not shown).

Our finding of enhanced SOC accrual in afforested surface soils is in agreement with previous studies under a broad variety of ecophysical conditions. Bronick and Lal (2005) reported roughly 2-fold increased SOC contents in wooded vs. cultivated land in Ohio. Martens *et al.* (2003) found 46% increases in SOC content in afforested vs. cropped land in Nebraska in association with enhanced soil aggregation. Likewise, examining a grassland-woodland ecotone in Arizona, McPherson *et al*. (1993) observed greater SOC in woodland vs. grassland sites (≈ 21%) to be in close association with increased root biomass in their 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 0-5 cm depth increment. 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 in part attributed to a low soil capacity for SOC stabilization and protection caused by a lack of clay mineral surfaces in their coarse-textured soils (i.e., sandy loam, 69% sand particles). Other previous reports also support the hypotheses that soil texture and mineralogy as well as quantity and quality of tree-C inputs are key controlling factors of

SOC accrual in afforested soils (Melillo *et al.* 1989; Richter *et al.* 1999). Additionally, it can be anticipated that continual, large tree litter production, canopy cover, and water uptake at our conifer-afforested locations could have created consistently cold-dry soil conditions likely causing deceleration in residue-SOC decomposition and enhancing SOC accretion compared to conventionally-tilled cropped fields. These and other inherent aspects of land-use conversion from cropland to forest such as tillage cessation and soil erosion reduction could collectively contribute to enhanced C sequestration in afforested fine-textured soils.

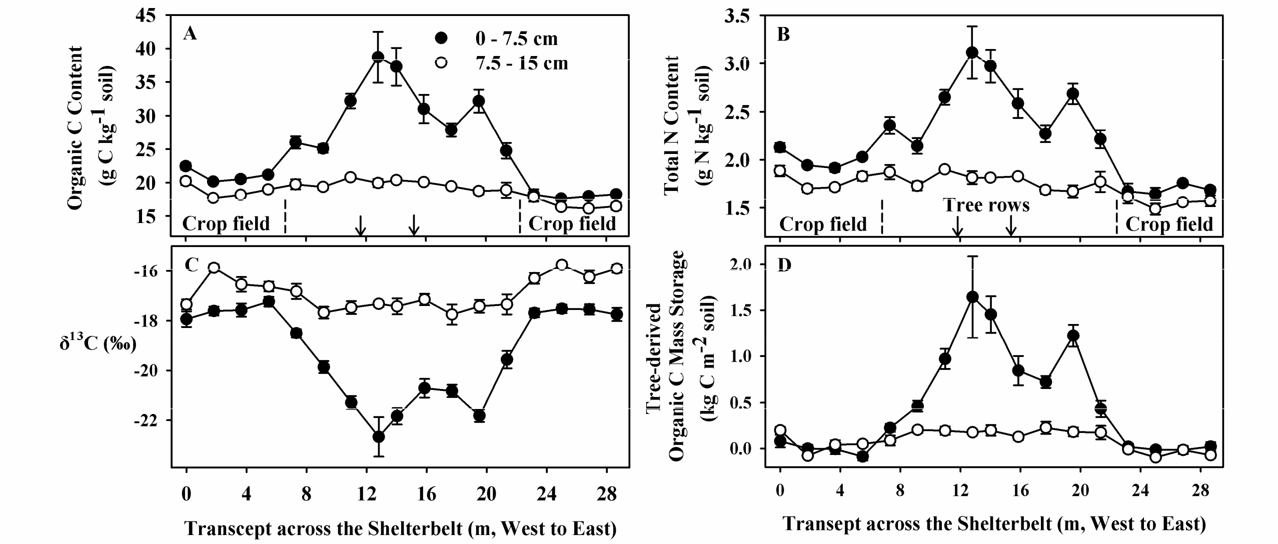

Figure 1. (A) Soil organic carbon and (B) total nitrogen concentrations, (C) stable carbon isotope ratios (δ^{13}C), and (D) estimated organic carbon mass derived from tree input in a transept across the Mead site. Fields boundaries are indicated. Each mean value averaged 7 sampling points. Error bars are ±SE.

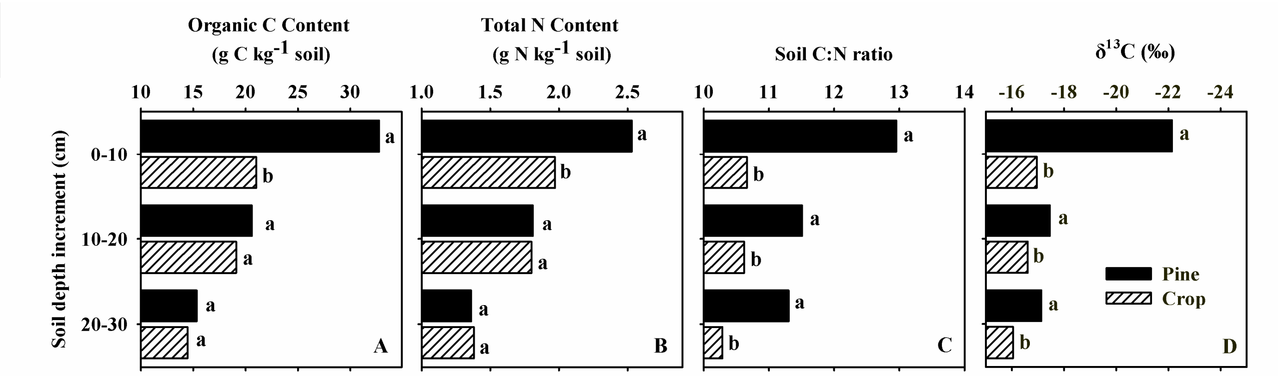

Figure 2. (A) Soil organic carbon and (B) total nitrogen concentrations, (C) organic carbon to total nitrogen (C:N) ratios, and (D) stable carbon isotope ratios (δ^{13}C) at Sac site. Within each depth and variable, land-use systems labelled by the same letter are not different based on Tukey's HSD test (α = 0.05). ***n*** **= 25.**

Table 1. Soil organic carbon (SOC) in a forest plantation and adjacent cultivated field at the Sac site, Iowa.

	SOC Mass Storage (Mg/ha)			
	Soil depth, cm			
Treatment or statistic	0 - 10	10 - 20	20 - 30	0 – 30
Eastern white pine (35-yr-old)	33.6	23.5	19.6	76.7
Corn - soybean rotation	22.3	25.4	20.3	68.0
P > *F* (probability after ANOVA models)	<0.001	NS	NS	<0.001

Stable Carbon Isotope Signatures and Afforestation Impacts on Carbon Sources

Mead soils exhibited a marked gradient of δ^{13}C signatures from near constant values in the cropped fields (-17.6 ± 0.1 ‰) to much more depleted between tree rows (-22.3 ± 0.4 ‰) capturing a gradual shift in SOC sources (Figure 3A). Based on mass balance estimations, SOC source-partitioning revealed that tree-derived SOC contributed 54% (i.e., 1.7 ± 0.2 kg C/m^2) of the existing SOC found directly between trees (Figure 3B). At Sac, soil δ^{13}C values at all three soil layers exhibited depletion in pine-afforested vs. cropped soils ($P \leq$ 0.05; Figure 2D). At Sac pine-afforested soils, δ^{13}C results revealed that tree-derived SOC corresponded to

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47, 12, and 2% of the existent SOC at 0-10, 10-20, and 20-30 cm depth increments, respectively; therefore, masses of tree-derived SOC at these soil layers corresponds to 15.8, 2.8, and 0.4 Mg C/ha, respectively.

Our results collectively suggest that tree-derived C inputs can fully account for all the SOC replenishment following conversion from cropland. Source assessments also indicate that tree-derived C contributed roughly one-half of the current SOC found in surface soil beneath trees at both Mead and Sac (Figure 1A and Figure 2A). Such quantitative information confirming tree inputs (i.e., litter and shallow roots) as major SOC sources in afforestation ecosystems has not been previously reported. Likewise, our results also allowed numerical assessment of SOC turnover based on the premise that these surface soils had reached a new equilibrium after 35-yr of tree establishment (Richter *et al*. 1999). These C-enriched afforested surface soils exhibited MRT for SOC on the order of decades (i.e., 45 and 55 yr for Mead and Sac, respectively) indicating that SOC beneath trees is subject to an intermediate dynamics compared to both fast turnover for soils planted to *Miscanthus* × *giganteus* with MRT of 13 yr (Dorodnikov *et al*. 2007) and relatively slow turnover for corn fields with MRT of 117 yr (Huggins *et al*. 1998).

Conclusions

Land-use change from tilled cropland to conifer-afforestation achieved substantial SOC replenishment in fine-textured surface soils suggesting a positive scenario for soil quality restoration via tree planting in degraded cropland. This on-farm study also supports tree litter on soil surface and shallow tree roots as main sources for enriched SOC. Although afforestation strategies registered a beneficial outcome, underlying mechanisms responsible for SOC sequestration remain unclear. The potential impacts of tree biomass removal (i.e., due to growing interest in biofuel fabrication) on SOC reservoir and dynamics also remains uncertain. Quantitative discrimination of litter- and root-derived tree-C inputs, SOC fractionation, net ecosystem productivity, and soil respiration amounts and sources could aid in elucidating these unknowns.

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