2014

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Yuri G. Chendev
Belgorod State University

Larisa L. Novykh
Belgorod State University

Thomas J. Sauer
United States Department of Agriculture

Aleksandr N. Petin
Belgorod State University

Evgeny A. Zazdravnykh
Belgorod State University

See next page for additional authors

Authors
Yuri G. Chendev, Larisa L. Novykh, Thomas J. Sauer, Aleksandr N. Petin, Evgeny A. Zazdravnykh, and C. Lee Burras

Chapter 47
Evolution of Soil Carbon Storage and Morphometric Properties of Afforested Soils in the U.S. Great Plains

Yury G. Chendev, Larisa L. Novykh, Thomas J. Sauer, Aleksandr N. Petin, Evgeny A. Zazdravnykh, and C. Lee Burras

Abstract The objective of this project was to use detailed soil profile descriptions and soil carbon analyses to determine the soil C sequestration potential of tree planting across climatic gradients in the U.S. Great Plains. Tree windbreak age ranged from 19 to 70 years and age of cultivation from 22 to ~110 years. At each site, soil pits were prepared within the tree planting, the adjacent crop fields, and nearby undisturbed grassland. Windbreak soils had consistently thicker soil organic carbon (SOC)-enriched A or A+AB horizons when compared to the crop fields. The thickness of A or A+AB horizons in the windbreak soils were comparable to the undisturbed grassland soils. A linear relationship was detected between the difference in A+AB thickness of soils beneath windbreaks and undisturbed grasslands and a climate index (hydrothermal coefficient, HTC). These results indicate that tree windbreaks with more cool and moist climate conditions are more favorable for SOC accumulation in the surface soil. The relationship between SOC accumulation and climate factors enables the estimation of soil carbon stocks in existing windbreaks and the prediction of potential carbon sequestration of future plantings.

Keywords Soil organic carbon • Afforestation • Soil transformation

Y.G. Chendev • L.L. Novykh • A.N. Petin • E.A. Zazdravnykh
Belgorod State University, Belgorod, Russia

T.J. Sauer (✉)
National Laboratory for Agriculture and the Environment, USDA-ARS,
2110 University Boulevard, Ames, IA 50011, USA
e-mail: tom.sauer@ars.usda.gov

C.L. Burras
Iowa State University, Ames, IA, USA

A.E. Hartemink and K. McSweeney (eds.), *Soil Carbon*. Progress in Soil Science,
DOI 10.1007/978-3-319-04084-4_47,

Introduction

The Energy Independence and Security Act of 2007 mandating that 60.5 billion liters of liquid biofuels be produced annually in the U.S. from cellulosic feed stocks by 2022. To meet this production goal it is estimated that 6.5–7.7 million hectares of land will need to be dedicated to feedstock production (Biomass Research and Development Board 2008). In the U.S. Great Plains there is potential for the production of biofuels from grains, crop residues, and dedicated perennial crops, including woody biomass (Rosenberg and Smith 2009). The region has a history of forest plantations as single to multiple rows of trees and/or shrubs as windbreaks or shelterbelts (Brandle et al. 2004). Windbreak plantings have been often employed in sub-humid to semi-arid regions with extensive plantings in both the steppes of Russia (Mirov 1935; Schroeder and Kort 1989) and the U.S. Great Plains (Droze 1977).

Tree windbreaks represent a multiple-benefit land use through their capacity to improve crop growth by modifying the local microclimate, sequester carbon in the soil and roots, and provide a renewable source of feedstock (above-ground biomass) for bioenergy production. Sauer et al. (2007) reported significantly greater soil organic carbon (SOC) in the surface 15 cm of soil beneath a 35 year-old shelterbelt in Nebraska as compared to the adjacent cropped fields. Hernandez-Ramirez et al. (2011), using stable carbon isotope techniques, found that 54 % of the SOC in the 0–7.5 cm soil layer within the Nebraska shelterbelt was tree-derived. Minimizing site disturbance, improved microclimate, and the increased diversity of plant species in tree windbreaks have been credited with reducing C losses and increasing the stability of SOC stocks.

The objective of this research was to determine the soil carbon sequestration potential of tree plantings on marginal agricultural soils across a climatic gradient in the U.S. Great Plains. Here we report on the U.S. phase of a project regarding soil transformations at three U.S. sites. Details of the Russian phase of this project have been reported elsewhere (Chendev et al. 2013).

Study Sites

Three sites representing a gradient in mean annual precipitation (MAP) from 528 to 696 mm and mean annual temperature (MAT) of 4.35–9.56 °C were selected for study (Table 47.1). The hydrothermal coefficient (HTC) of Selyaninov (1928) was used as a climate index, calculated as $HTC = \Sigma Q / 0.1 \Sigma T$ where Q is and T are precipitation (mm) and temperature (°C) during the growing season (defined as $T > 10$ °C).

The Reynolds, North Dakota site is situated on a broad flat landscape having less than 50 cm total relief. The site grades from the poorly drained upland of the glacial Lake Agassiz plain to the well drained stream terrace along Cole Creek. Parent materials are silty and clayey lacustrine sediments over calcareous loamy glacial tills and similarly textured alluvium. Groundwater is at ~2.5 m. The crop field has been cultivated approximately 110 years predominantly to small grains and more recently with some row crops including corn (*Zea mays*, L.), soybean (*Glycine max* (L.) Merr.),

Table 47.1 Sampling sites, elevation, mean annual temperature (MAT), mean annual precipitation (MAP), hydrothermal coefficient (HTC), and tree windbreak details

Site	Lat and long	Elev (m ASL)	MAT (°C)	MAP (mm)	HTC	Age of tree planting (years)	Tree species
Reynolds, ND	47° 42′ 13″ N 97° 10′ 59″ W	282	4.35	528	1.41	54	Green ash, red cedar and caragana
Huron, SD	44° 15′ 43″ N 98° 15′ 12″ W	397	7.71	582	1.31	19	Green ash
Norfolk, NE	42° 03′ 03″ N 97° 22′ 08″ W	492	9.56	696	1.47	70	Siberian elm, red mulberry, and cottonwood

Table 47.2 Soil series and taxonomic classification for sampling sites

Site	Soil series[a]	Soil taxonomy
Reynolds, ND	Antler-Mustinka silt loam	Fine-loamy, mixed superactive, frigid Aeric Calciaquolls
	LaDelle silt loam	Fine, smectitic, frigid Typic Argiaquolls
		Fine-silty, mixed superactive, frigid Cumulic Hapludolls
Huron, SD	Carthage fine sandy loam	Coarse-loamy, mixed, superactive, mesic Pachic Haplustolls
	Hand-Bonilla loams	Fine-loamy, mixed, superactive, mesic Typic Haplustolls &
		Fine-loamy, mixed, superactive, mesic Pachic Haplustolls
Norfolk, NE	Thurman loamy fine sand	Sandy, mixed, mesic Udorthentic Haplustolls
	Hadar loamy find sand	Sandy over loamy, mixed, superactive, mesic Udic Haplustolls

[a]Series identified from Soil Survey Geographic (SSURGO) database (http://soils.usda.gov/survey/geography/ssurgo/description.html)

or sunflower (*Helianthus annuus*). A six-row windbreak was planted in 1958 and now consists primarily of green ash (*Fraxinus pennsylvanica*), box elder (*Acer negundo*), red cedar (*Juniperus virginiana*), and caragana (*Caragana arborescens*). The adjacent grassland was formerly a pasture of primarily smooth brome grass (*Bromus inermis*). Soils at this site are mapped as Antler-Mustinka silt loams in the field and windbreak and LaDelle silt loam in the grassland adjacent to the stream (Table 47.2).

Soils at the Huron site were formed in loamy glacial till and meltwater sandy and loamy sand sediments and are moderately well or well drained. The soils are mapped as Hand-Bonilla loams and Carthage fine sandy loam (Table 47.2). The site had less than 3 % slope with groundwater at ~1.25 m. The entire site was in pasture until 1981 when it was plowed and cropped. In 1983 a 20+ row tree planting was established to evaluate different tree species and the grass area was returned to pasture. The field continued to be cropped to corn, soybean, or grain sorghum (*Sorghum bicolor* (L.) Moench).

The third site was located in Madison County, Nebraska northeast of the city of Norfolk. Soils at this site are very deep and somewhat excessively drained with sandy eolian parent material redeposited from glaciofluvial sands and loamy sands from the Elkhorn River valley. The soils are mapped as Thurman loamy fine sand and Hadar loamy fine sand (Table 47.2). Soils at this site have been cultivated or grazed since European settlement in the 1880s. Irrigation is necessary for optimum crop yield although dryland row crop (corn and soybean), wheat (*Triticum aestivum*, L.), and alfalfa (*Medicago sativa*, L.) are also cultivated. A 5-row tree windbreak was planted in 1942. Dominant species currently include Siberian elm (*Ulmus pumila*, L.), red mulberry (*Morus rubra*, L.), and cottonwood (*Populus deltoides* Marsh).

Methods

Soil profile descriptions were prepared for one crop field, tree, and grass site at each of the three sites in May of 2012. Two additional pits were prepared at the Norfolk site. As both sides of the windbreak at this site were cropped, pits were prepared in both fields. A second pit was also prepared in the windbreak as a 45–60 cm-tall ridge was observed in the middle of the windbreak. All soil pits were prepared by hand to a depth of 1.2–1.5 m. Horizon boundaries and profile descriptions were prepared from observations of three exposed soil faces. Horizon boundaries were measured at five sites on each exposed face. Presence of carbonates was determined by measuring the depth to effervescence following application of dilute acid to the pit sidewalls. Soil samples were taken from 0–15, 15–30, 30–45, 45–60, 60–80, and 80–100 cm depth increments. Visible roots were removed and a subsample passed through a 2 mm sieve, air dried, and roller-milled before total carbon and nitrogen analysis on a Fison NA 15,000 Elemental Analyzer (ThermoQuest Corp., Austin, TX). Soil inorganic carbon (SIC) was determined by modified pressure calcimetry (Sherrod et al. 2002) and SOC calculated by difference. Triplicate horizontal cores (7.8 cm id $\times$ 5.15 cm long) were taken from one exposed soil face to determine soil bulk density. Two cores were collected with a Dutch auger approximately 5 m on each side of the pits. These samples were taken at the same depth increments and analyzed with the same methods as for the pit samples. Results are presented for the means of pit and cores samples.

Results

Topsoil thickness (A+AB horizons) of the uncultivated grass soils decreased from north-to-south; 52, 44, 41 cm thickness for the Reynolds, Huron, and Norfolk sites, respectively (Fig. 47.1). These soils were considered representative of the original, pre-cultivation soil properties. At each site, there were also significantly greater thicknesses of the A+AB horizons in soils beneath tree plantings compared to the adjacent cultivated cropland soils. The difference in A+AB thickness between tree

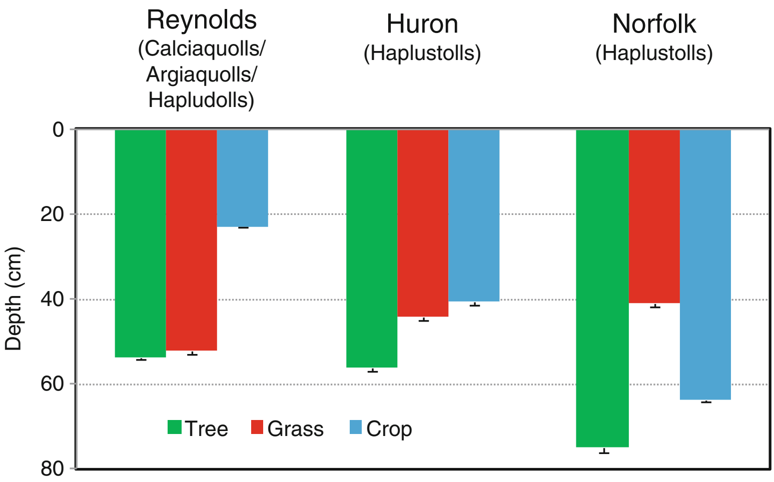

Fig. 47.1 Depth of A or A+AB horizons for U.S. sampling sites. *Error bars* are one standard error (n = 15)

and crop soils was 30.8, 15.5, and 11.2 cm for the Reynolds, Huron, and Norfolk sites, respectively, also following a north–south gradient. It is likely that these differences in thickness of the SOC-enriched surface horizons are due to both continued SOC loss from cropping practices, especially erosion and tillage, and SOC accumulation beneath the trees where there is both greater biomass input and limited soil disturbance.

Depth distributions of SOC and SIC content are consistent with the morphometric properties (topsoil thickness) and illustrate the contrasting effects of land use (Fig. 47.2). The Reynolds site had the greatest SOC and deepest humus-rich surface layers with the soil profile in the grassland having the highest SOC content and stocks at all depths (Fig. 47.2a). Also notable is the depletion of SOC in the cropland soil, especially from 15 to 60 cm. By contrast, the cropland soil had SIC present at all depths and SIC content from 30 to 60 cm represented almost 80 % of the total carbon in the profile at these depths (Fig. 47.2b). Neither grassland nor tree soil had SIC present above 45 cm but all three land uses had similar SIC below 60 cm.

Land use effects on soil thermal and moisture regimes may be the driving forces behind soil carbon transformations when grassland soils are cultivated or planted to trees. When compared with grasslands, cultivated soils have bare soil surfaces for extended periods and increased evaporation from the soil surface may bring pedogenic carbonates upward from underlying parent materials. Lower SIC in the 80–100 cm layer of the Reynolds cropland soil may indicate loss of carbonate due to this upward movement. Under tree cover, soil conditions are cooler with less evaporation from the soil surface than in grasslands and croplands, and carbonates would be more likely to leach (Khokhlova et al. 2013).

The soil beneath trees at the Huron site had greater SOC at all depths than the cropland and grassland soils and, like for the Reynolds site, the cropland soil again

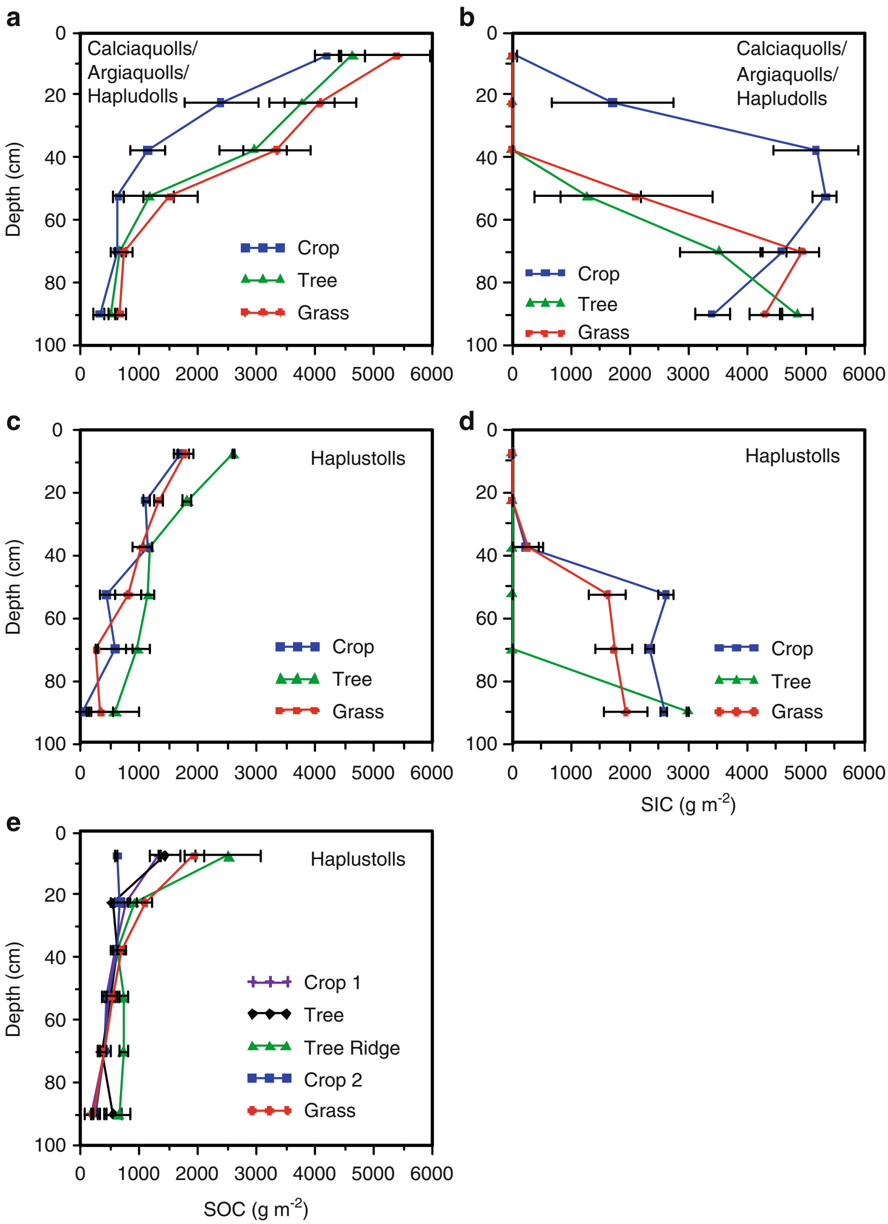

Fig. 47.2 Profiles of SOC and SIC for U.S. sampling sites. Note – no SIC was detected at the Norfolk site. *Error bars* are one standard error (n=3). (**a**) Reynolds SOC. (**b**) Reynolds SIC. (**c**) Huron SOC. (**d**) Huron SIC. (**e**) Norfolk SOC

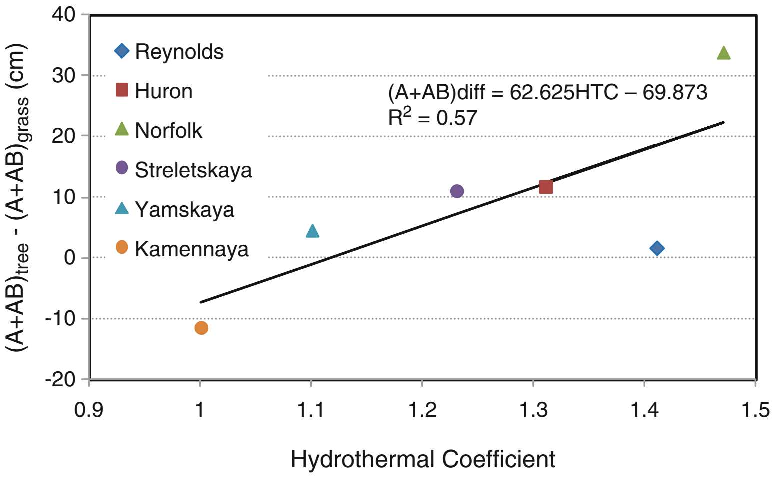

Fig. 47.3 Plot of difference of A+AB horizon thickness of tree and grass soils versus HTC for all U.S. and Russian sites (Chendev et al. 2013)

exhibited carbonate accumulation (Fig. 47.2c, d). The soils of the Huron site exhibited the most distinct changes in SOC and SIC following tree planting yet this location had the youngest trees (19 year-old). The SOC profiles were very similar for the grassland and crop field suggesting that cultivation had not led to significant SOC loss via erosion or decomposition of organic matter accelerated by tillage.

The Norfolk site had the oldest trees (70 year-old) yet exhibited the smallest changes in SOC with land use (Fig. 47.2e). The Tree Ridge profile was collected from a narrow ridge of soil running parallel within the windbreak. This soil exhibited SOC accumulation throughout the profile and is thought to be the result of deposition of topsoil from adjacent fields via wind erosion. The general low SOC and lack of carbonates at this site are likely due to the coarse-textured soils with low water-holding capacity limiting plant growth and warmer temperatures accelerating organic matter decomposition.

Differences of A+AB horizon thickness of tree and grassland soils when plotted versus HTC for the three U.S. sites and three sites in southern Russia using the same methodology (Chendev et al. 2013) exhibit a linear dependence with R^2 of 0.57 (Fig. 47.3). Thus, the effect of tree planting on grassland soils appears to follow the same rate of organic carbon accumulation in the U.S. Great Plains and Central Russian Upland and this rate is strongly linked to climate. The Reynolds site is an outlier to this trend and two factors may explain this finding. First, the soil under the windbreak had a dense layer of glacial origin coarse stone fragments at 38–56 cm. This restrictive layer could slow down the process of SOC accumulation by inhibiting root growth. Second, the grassland soil may have received external organic inputs from intermittent flooding that would increase SOC accumulation.

Conclusions

Mollisols of the Great Plains respond within decades to changes caused by human activity – changing virgin grasslands to arable lands, or arable lands to windbreaks. Tree cover seems to improve soil quality by increasing of A and A+AB horizons thickness, SOC content and stocks. The maximum effect of this soil development was found in more cool and moist conditions and was consistent with findings at three sites in the Russian steppe. Accumulation of carbon in windbreak biomass and soils indicates that afforestation is an effective measure to assimilate carbon from the atmosphere and convert it into ecosystem components. As such, tree planting in the Great Plains can improve or restore soil quality and is as an effective climate change mitigation practice.

Acknowledgements The authors appreciate the assistance of Craig Stange, Martin Rosek, Lance Howe, Dan Mager, and Patrick Cowsert (Natural Resources Conservation Service), Steve Rasmussen (Nebraska Forest Service), Jim Marten (Northeast Community College), John Hinners (South Dakota Department of Agriculture), and Beadle Soil and Water Conservation District. This study was supported by U.S. Civilian Research and Development Foundation Grant RUG1-7024-BL-11.

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