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Relationships among land use, soil texture, species richness, and soil carbon in Midwestern tallgrass prairie, CRP and crop lands

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ABSTRACT

Accumulation of soil carbon (C) in ecosystems could help mitigate climate change, particularly in agricultural landscapes, but accumulation rates are thought to depend on land cover and management practices. To uncover relationships between soil properties and vegetation management strategies in the Midwestern USA, we examined soil C and nitrogen (N) content on lands under five management types that produced different levels of plant species diversity: remnant prairies, high-, medium- and low-diversity grassland restorations, and crop fields. We examined the relationships of soil C, labile C, and N with plant species richness, aboveground biomass production and silt + clay content on land under each of the five management types, in two non-adjacent counties. Field plots were located in sites predicted to have mid-range soil C contents for each county (2.0–2.5% or 2.4–2.9%) based on a SOLIM (Soil Land Inference Model) C model (Libohova, 2010), in an effort to limit variability among sites. However, we found that soil texture data from the Soil Survey Geographic Database (SSURGO; the base data layer for SOLIM) frequently overestimated silt + clay content relative to the hydrometer-measured silt + clay content of our collected soil samples. We found that the low-diversity restorations (which were the most productive sites) had the greatest soil C and N content over the full soil profile (to 90 cm depth). On average soil C was 1.3 and 1.9 times greater, and soil N was 3.7 and 1.5 times greater, in the low diversity restorations compared to remnant prairies in Newton and Lee Counties, respectively. This was likely a consequence of (and a driver of) the high biomass production of the grasses that tended to dominate these fields. We attribute low soil C content in the remnant prairies and high diversity restorations in large part to the patterns of soil texture that led to the historical patterns of land use change, in which less productive areas were left as prairie and the more productive areas tilled. Labile C was highest in the low-diversity restorations at the 0–15 and 15–30 cm depths in both counties. Labile C was greatest from 0–15 cm and decreased with soil depth. Patterns of soil C across the intensely cultivated Midwestern landscape depend on the interaction between the suitability of soil for cultivation, and historical land management in terms of both the soil and vegetation. Our results suggest that the more heavily managed and productive fields in this region often harbor the greatest soil C, and that this soil C cannot be accurately predicted from the SSURGO database, highlighting the challenges and opportunities associated with maintaining and sequestering soil C in the Midwestern agricultural landscape.

1. Introduction

The conversion of lands in the Midwestern USA to agriculture has reduced tallgrass prairie to less than 0.01% of its natural range, once estimated to cover nearly 70 million hectares prior to the conversion to agriculture (Samson and Knopf, 1994). It is estimated that 50–75% of soil organic carbon is lost during cultivation (Lal, 2004; Knops and Tilman, 2000). Cultivation induces soil carbon (C)

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loss through the breakdown of soil aggregates, exposing once-protected organic matter to degradation, erosion by wind and runoff, and leaching of dissolved organic C (Lal, 2002). When soils are removed from cultivation, soil C begins accruing through the growth and decay of fine roots, deposition of root exudates, litter decomposition and microbial residues (Oades, 1984; Jastrow, 1996; Post and Kwon, 2000). Once soils are removed from cultivation, the accrual and storage of soil C in restored prairie becomes an important ecosystem service because soils have the potential to store a large amount of C, which can help mitigate climate change (Lal, 2002). Understanding the mechanisms behind soil C accrual is important for developing more accurate predictions of C storage in restored tallgrass prairie and other grasslands, which can be incorporated into improved climate–carbon models and used to better understand the ecosystem services of agricultural landscapes.

Previous studies have estimated that rates of soil C accrual in various grasslands range from 19.7 $g\,C\,m^{-2}\,yr^{-1}$ to 74.0 $g\,C\,m^{-2}\,yr^{-1}$ (Lal et al., 1999; McLauchlan et al., 2006; Baer et al., 2002; Matamala et al., 2008; Knops and Tilman, 2000; Guzman and Al-Kaisi, 2010). Variations in the estimated rates of carbon accrual can be attributed to a variety of factors including soil texture (Hassink, 1997; Hook and Burke, 2000); the plant community, in terms of biomass production (Baer et al., 2002; Soussana et al., 2004) and species richness (Fargione et al., 2007; Steinbeiss et al., 2008); and land management. Soil texture can influence soil C content by limiting the amount of organic matter than can be protected from decomposition through organo-mineral binding with silt and clay particles (Lal et al., 1999; Hassink, 1997). Soil aggregate size is also influenced by soil texture, as clay particles tend to form smaller aggregates than sand or silt particles, thereby offering greater physical protection of soil organic matter (SOM) (Boix-Fayos et al., 2001). Plant biomass production has been shown to increase soil C and nitrogen (N) content in restored prairies through root growth and decay and production of root exudates (Soussana et al., 2004; Baer et al., 2002). Soil C and N have also been shown to increase with species richness, as species richness has been shown to promote plant biomass production (Fornara and Tilman, 2008; Steinbeiss et al., 2008). However, this pattern has not held true in all cases because species richness has also been shown to vary along nutrient gradients and with water availability as well as with the scale of the study (i.e. quadrat size, sampling area, etc.) (Scheiner et al., 2000; Pausas and Austin, 2001; Loreau et al., 2001).

To examine how different land management regimes, which facilitate different levels of plant diversity (species richness), affect the capacity of agricultural and post-agricultural soils to store carbon and nitrogen, we sampled soil in fields under five management categories in each of two Midwestern counties. These fields were predicted to have similar soil C based on a model incorporating data on soil texture and topography, but not vegetation or management. Based on our assumption that soil texture and topography, and thus historical soil C were relatively similar across sites within each county, we made the following predictions: (1) soil C and N would be positively related to plant biomass production and species richness, but plant biomass would be the strongest predictor for soil C and N content. Species richness has been shown to enhance plant biomass production (Kindscher and Tieszen, 1998; Fornara and Tilman, 2008; Tilman et al., 1997; Waide et al., 1999); thus, we expected remnant prairies to have the greatest soil C and N content, followed by high, medium and low diversity plantings based on the contribution of species richness in supporting biomass production. (2) Soil C and N would increase with silt and clay content. (3) Labile C would be lower in the crop fields compared to the restored grasslands and remnant prairie sites, because aggregate structures are broken apart during tillage leaving labile forms of C unprotected from decomposition (Jastrow, 1987; Follett et al., 2001; Lal, 2002). In addition, restored grasslands and remnant prairie sites would have greater labile C because the reestablishment of a perennial plant community after the cessation of tillage would contribute fresh organic matter to the soil through belowground biomass production and litter fall (Lal, 2002; Gale et al., 2002).

2. Methods

2.1. Field sites

Our study included remnant and restored prairies, lands enrolled in the Conservation Reserve Program (CRP) and crop fields in Newton County, Indiana and Lee County, Illinois. Our sites were selected to provide a gradient of species diversity, with remnant prairies expected to have the greatest diversity, followed by high diversity (HD) prairie restorations, medium and low diversity (MD and LD, respectively) CRP plantings, and crop fields. In Newton County, remnant prairies were located at Beaver Lake Prairie Chicken Refuge administered by the Indiana Department of Natural Resources. The HD restorations in Newton County were located at The Nature Conservancy Efroymson Restoration at Kankakee Sands. In Lee County, the remnant prairies and HD restorations were located at The Nature Conservancy Nachusa Grassland Preserve. Among the various types of conservation practices (CP) that can be implemented under the CRP, two practices were examined in this study, the filter strip (CP21), and the habitat buffer for upland birds (CP33). Filter strips, which serve as our low diversity (LD) treatment in Newton and Lee Counties, consist of narrow bands of grasses and legumes planted parallel to streams, ditches, lakes, ponds and wetlands and may have as few as one legume and one grass species planted (NRCS, 2008). Habitat buffers, which serve as our medium diversity (MD) treatment in Newton and Lee Counties, are strips of vegetation planted adjacent to crop fields to provide habitat for upland birds such as bobwhite quail and ring-neck pheasants. Habitat buffers may be established either through natural succession or through the planting of grasses, forbs and legumes (NRCS, 2007). Crop fields in both Newton and Lee Counties were under soy bean-corn rotation, and were tilled annually. Mean annual temperature in Newton County is 10.6 °C with mean annual precipitation totaling 939 mm. In Lee County, mean annual temperature is 9.5 °C with mean annual precipitation of 881 mm. Measured soil texture, species richness and a list of common species in each treatment can be found in Table 1 for each county, along with the numbers of replicate field sites within each treatment.

2.2. Site selection

Field and transect locations were selected to occur in the mid-range of predicted soil C content for each county based on the SOLIM (Soil Land Inference Model) C model (Libohova, 2010). This model uses digital elevation models and high-resolution aerial photographs of the study counties along with Soil Survey Geographic Database (SSURGO) soil data (but not land use or vegetation data) to map projected soil C. Soils in the study counties were grouped based on drainage class, topographic wetness index (TWI; ratio of the upslope contributing area to the slope) and slope, using fuzzy membership to classify pixels. SSURGO provides estimates of organic matter distributions to soil depths of 150 cm. Soil organic matter (SOM) content was converted to soil organic carbon (SOC) by dividing SOM values by 1.8. The classes of soils derived from the fuzzy membership analysis were multiplied by an associated value for SOC, producing a map of predicted C content for each county (Libohova, 2010). Based on a histogram of the predicted SOC values, the mid-range of SOC was selected as