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Landscape dependent changes in soil properties due to long-term cultivation and subsequent conversion to native grass agriculture

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ABSTRACT

On farmland in undulating landscapes, soil organic carbon (SOC) stocks depend on landscape position. In the North American Prairie Pothole region, we compared a native prairie reference site with a nearby farm undergoing transition to perennial agriculture ("restoration") after a century of producing annual crops. We quantified legacy effects of farming at four upland landscape positions (to 0.9-m soil depth) and three wetland positions (to 1.0-m soil depth). We also quantified short-term (4 years) changes in SOC stocks (to 0.15-m soil depth) during restoration, and how these changes were impacted by historic erosion.

Surface (to 0.05-m soil depth) measurements indicated degradation of the cropland soil relative to the prairie at all landscape positions due to less soil organic matter (SOM) and altered soil properties (e.g., water aggregate stability and microbial activity). All upland and wetland positions of the farm lost SOC stocks (Mg ha^{-1}) relative to the prairie in the top 1.5 Gg ha^{-1} of soil (~14-cm depth). However, when considering a larger mass of soil, 4.5 Gg ha^{-1} (~39-cm depth), loss of SOC stocks was significant ($p < 0.001$) only at the summit (46 Mg ha^{-1}) and shoulder (63 Mg ha^{-1}) landscape positions. Differences in SOC stocks between farm and prairie were smaller and not significant at the backslope, footslope, and in wetlands.

Contrary to expectations, sites of soil deposition did not accumulate soil carbon after restoration. Accretion of soil C during restoration differed according to the severity of historic erosion ($p < 0.001$), with severely eroded soils gaining soil C at the fastest rate. Historic loss of clay at the shoulder and backslope and subsoil compaction in the wetlands may prevent these landscape positions from full restoration of soil C stocks, net primary productivity, and historic vegetation.

1. Introduction

Globally, 70% of naturally occurring grasslands have been cleared or converted for more intensive agricultural use (Ramankutty et al., 2008). In the western corn belt of North America, the situation is especially extreme with 99% of native tallgrass ecosystems converted to cropland or to other land uses (Samson and Knopf, 1994; Wright and Wimberly, 2013). The loss of grasslands is especially significant where the western corn belt overlaps with the Prairie Pothole Region of North America (Fig. 1).

The Prairie Pothole Region is a 750,000 km^2 area in the heart of North America, two-thirds of which is located in Canada and one-third in the north-central United States (Fig. 1). The region contains approximately 5–8 million wetland basins of glacial origin embedded in irregular topography and heterogeneous soils (Van der Valk, 1989). The combination of highly productive grassland and diverse complexes of wetlands produces 50–80% of the wild ducks in all of North America each year (Johnson et al., 2010). The most numerous wetlands are classified as temporary with small shallow basins that hold water for one or two months in spring and early summer (Johnson et al., 2004). The region also includes many larger seasonal and semi-permanent wetlands with longer hydroperiods.

Much of the conversion of the region's native prairie to farmland occurred in the late 19th and early 20th centuries. Prairie Pothole Region wetlands were some of the last parts of the landscape to be converted (DeLuca and Zabinski, 2011) but conversion is still ongoing,

Abbreviations: cPOM, Coarse POM; FDA, Fluorescein diacetate hydrolysis; fPOM, Fine POM; InC, Inorganic C; MAOM, Mineral-associated organic matter; POM, Particulate organic matter; SOC, Soil organic C; SOM, Soil organic matter; TEP, Tillage Erosion Prediction model; TSN, Total soil nitrogen; WAS, Water aggregate stability

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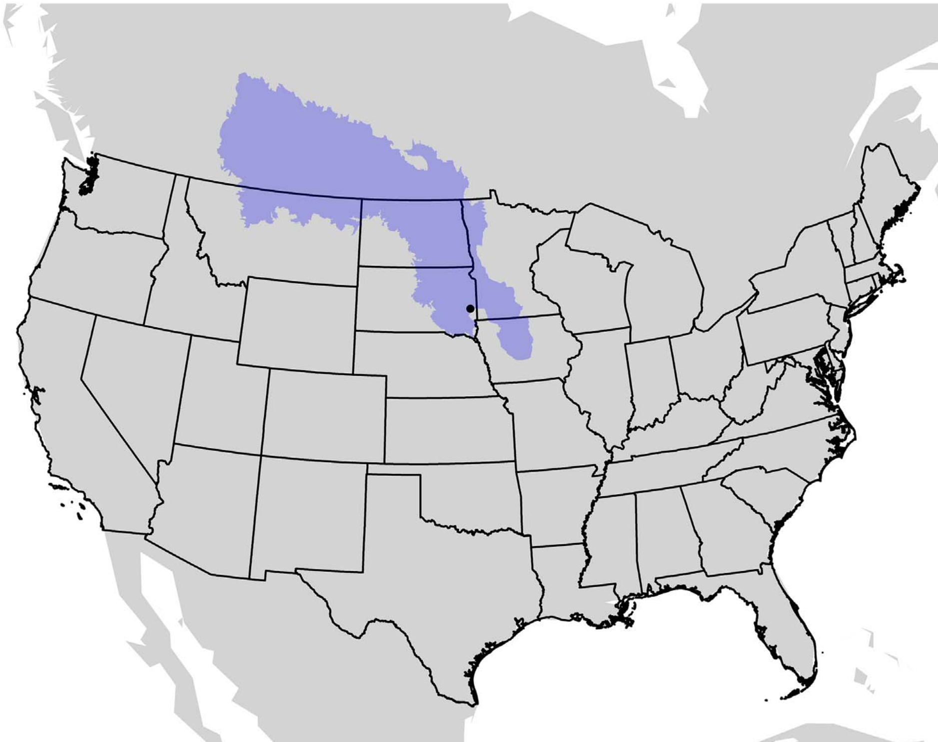

Fig. 1. The study location (44°02′ N, 96° 49′ W) is indicated by a dot in the state of South Dakota, United States of America. The Prairie Pothole Region is the shaded area extending across the border between the United States and Canada. Adapted from Johnson et al. (2010).

partly in response to high commodity crop prices from 2006 to 2011 (Wright and Wimberly, 2013). Converting the region's landscapes to cropland has included farming through intact temporary wetlands during dry years as well as wetland drainage via surface ditches, underground pipes, and underground tile drains. Nearly half of the original wetlands in eastern South Dakota have been drained (Johnson and Higgins, 1997).

Until the latter part of the 20th century, the preferred method of cultivation utilized the moldboard plough and secondary tillage. This resulted in high oxidation rates of soil organic carbon (SOC) within the first 5–30 years after cultivation (DeLuca and Zabinski, 2011). Additionally, intensive tillage combined with the hummocky nature of the landscape has resulted in a high degree of lateral soil transfer within the landscape. The processes of tillage erosion and water erosion interact with one another and occur frequently in this semi-humid region (Schumacher et al., 1999; Lobb, 2011). Depositional sites include footslope positions and wetland depressions within fields. In many cases these are closed basin systems with minimal opportunity for deposition into streams (Richardson et al., 1994) unless artificial surface drainage systems (shallow ditches) were created to connect basins to streams.

Cultivation can cause large changes to physical, chemical, and biological properties within the surface horizon. Significant modifications can also occur in subsoils, affecting hydrology, biogeochemical cycles, greenhouse gas emissions, carbon dynamics, and biological productivity (Chirinda et al., 2014; Smith et al., 2016). Cultivation and changes to soil properties impact ecosystem services associated with the region's wetland complex, including flood abatement, water quality, biodiversity, aquifer recharge, wildlife habitat, waterfowl sustainability, and soil carbon management (Johnson et al., 2010).

Management of SOC has both global and local implications. Increases in SOC provide a positive feedback mechanism for net primary productivity, agricultural yield, and C fixation in soil. Conversely, loss of SOC is a major factor in the degradation of soil (Lal, 2015). Globally, flux of C between soils and the atmosphere has implications for climate change (Amundson et al., 2015). In an actively eroding landscape, soil carbon dynamics are fundamentally changed; controlling processes have been comprehensively described in recent reviews (Kirkels et al., 2014; Doetterl et al., 2016). During dynamic replacement, eroding landscape positions that are depleted of soil organic carbon have increased rates of SOC accumulation while soil transport to areas of deposition during erosion events continues (Stallard, 1998; Harden et al., 1999; Li et al., 2015).

SOC decomposition and stabilization rates during transport and deposition depend on a variety of circumstances, including duration of transport phase, degree of local mixing with C-depleted subsoil, depth and stratification of sediment burial, rate of chemical weathering of parent materials, intensity of the erosion process, moisture content of eroding aggregates, spatial variation in plant growth, differences in field management, the age of eroded aggregates, the degree of aggregation of eroded materials, and soil type (Quinton et al., 2010; Van Hemelryck et al., 2011; Fiener et al., 2015; Doetterl et al., 2015; Hu and Kuhn, 2016). Eroded SOC, though not indefinitely stable, may persist for periods of decades to centuries after burial (Doetterl et al., 2015). Although there have been disagreements about the net global effect of erosion on soil carbon stores (Van Oost et al., 2007, 2008; Lal, 2008), there is broad agreement on the detrimental effect of cultivation-induced erosion on crop productivity and the functioning of global ecosystems (Kirkels et al., 2014).

Despite continued conversion from grassland to cropland in the Prairie Pothole Region, declines in commodity crop prices have recently increased interest in returning some farmed soils to grassland cover (P. Bauman, personal communication, July 2016). A successful conversion of cropland to grassland minimizes erosion and thus may impact both local soil quality and global C stores. Because nearly all land in this region is privately owned, large-scale conversion of cropland to grassland is only viable when the process includes agriculturally based solutions that are profitable to the landowner. These may include the sale of carbon credits (DeLuca and Zabinski, 2011).

A review by Doetterl et al. (2016) recognized the need to link terrestrial and aquatic cycles of C, N, and P but most research has focused on terrestrial C dynamics alone. In the Prairie Pothole Region, few studies have evaluated the C dynamics of cultivated and native landscapes, and fewer yet have included both uplands and wetlands. Several