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Long-term impacts of high-input annual cropping and unfertilized perennial grass production on soil properties and belowground food webs in Kansas, USA

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ABSTRACT

Soil ecosystem properties and processes which simultaneously maintain native fertility and sustain plant yields are of principal interest in sustainable agriculture. Native prairies in Kansas are relevant in this context, as some have been annually harvested for hay for over 75 years with no fertilization or detectable decline in yield or soil fertility. In contrast, annual crop production has resulted in significant reductions in soil fertility and now requires intensive inputs to maintain yields. Soil food webs were compared between hayed native grasslands and adjacent annual croplands in order to determine the long-term effects of these two production systems on soil ecosystem properties. Soil chemical and physical properties, bacterial and nematode community structure and abundance were measured across five paired sites at six depth intervals to 1 m. Soil organic carbon, total nitrogen, and water stable aggregates were all significantly greater in perennial grasslands than in annual croplands to a depth of 60 cm. Microbial biomass carbon was also greater in grasslands than in croplands, and shifts in $\delta^{13}C$ indicated greater input of new carbon at lower depths in grasslands relative to annual croplands. Bacterial and nitrogen fixing communities in croplands and grasslands were significantly different in the surface 40 cm and nematode community differences persisted through 1 m. Nematode community indices suggested enhanced fungal decomposition pathways, fewer plant-feeding nematodes, and greater food web complexity and stability in grassland soils than in annual cropland soils. These data indicate that perennial grasslands in Kansas, even when annually harvested for decades, support higher levels of soil fertility and structure and more complex biological communities than annual cropping systems.

1. Introduction

Nutrient cycling in natural ecosystems is characterized by tightly regulated processes which minimize losses due to leaching, runoff, denitrification, volatilization, and erosion. Plant nutrient acquisition in natural systems depends on (i) net inputs from atmospheric deposition, biological nitrogen fixation and mineral weathering, (ii) internal cycling of nutrients from decomposition of litter and soil organic matter, and (iii) microbial transformations of carbon (C), nitrogen (N), and phosphorus (P) (Grierson and Adams, 1999). In contrast, annual-based agricultural systems typically have much greater nutrient losses – partly due to the removal of agricultural products from the landscape, but also due to inefficiencies in internal nutrient cycling and poor synchronization of nutrient availability with plant demand (Crews, 2005). For example, annual crops commonly to take up less than 50% of the N applied as fertilizer (Cassman and Dobermann, 2002). These losses require that substantial amounts of nutrients are continually applied to sustain agricultural productivity and, in turn, have created or exacerbated a suite of global environmental problems associated with intensive annual agriculture (Tilman et al., 2002).

Soil microbial communities form the foundation of soil food webs, with nearly all biogeochemical transformations directly resulting from microbial activity. Nematodes are not only active players in these food webs, but their community structure can

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serve as an indicator to other soil biota and the soil food web as a whole (Ferris et al., 2001). Collectively, soil food webs exert proximate controls on nutrient mineralization, regulating resources available for plant uptake. However, soil food webs are reciprocally shaped by the aboveground plant community, as they are largely reliant on the timing, location, quantity, and quality of carbon deposition by plant roots (Wardle et al., 2004). As a result, there are often large differences in soil food webs between annual croplands and native plant communities. The pereniality of plants appears to be an important factor in food web structure and function, as soil food webs in managed perennial production systems generally resemble those found in native plant communities more so than those in annual crop fields (Freckman and Ettema, 1993; Neher and Campbell, 1994; Neher, 1999; Ferris et al., 2001).

Herbaceous perennial crops only occupy 6% of harvested cropland worldwide (Monfreda et al., 2008), but have potential in coming decades to provide a range of agricultural products currently produced by annual crops. The development of new herbaceous perennial grasses, legumes, and forbs, and new uses for them, would facilitate their expanded implementation in production systems (Cox et al., 2006; Ragauskas et al., 2006; Tilman et al., 2006; Glover et al., 2007; Jordan et al., 2007; Nash, 2007; Schmer et al., 2008). For example, high-diversity, low-input (HDLI) perennial grasslands yielded more usable biofuel energy, greater C sequestration and caused less pollution than corn grain ethanol or soy-biodiesel (Tilman et al., 2006), and net energy yields reported for high-input, low-diversity perennial systems were even greater than energy yields from the HDLI grasslands (Schmer et al., 2008). While questions persist as to the long-term ability of perennial systems to support high yields and high soil quality (Russelle et al., 2007), more than fifty years of annual harvesting of unfertilized perennial grasslands has not reduced soil organic carbon (SOC) or total soil N levels in the upper 2 m of soil as compared to non-harvested grasslands in the Russian Chernozem (Mikhailova et al., 2000; Mikhailova and Post, 2006). Other studies report that unfertilized grasslands at the Rothamsted Research Park Grass experiment have been hayed twice-annually for 150 years with no declines in yield (Jenkinson et al., 1994; Silvertown et al., 1994) or in total soil N for the past 120 years (Jenkinson et al., 2004).

Glover et al. (2010) reporting on other results of this and related studies, concluded that unfertilized perennial grasslands provide comparable levels of harvested N in biomass as modern yields of adjacent high-input wheat fields provide in harvested grain. Over the approximately 75-year management history of the two systems, roughly 26% more N ha^{-1} has been harvested from the unfertilized perennial grasslands than from the region's annual crop fields. Despite the large annual rates of N removal, the unfertilized perennial fields maintained greater levels of soil C, reduced leaching losses of N, and had substantially lower energy requirements.

Here we build on the work of Glover et al. (2010) by comparing key soil biological, chemical, and physical properties between unfertilized perennial grasslands and adjacent high-input annual cropping systems in Kansas. We hypothesize that soil food webs have played a major role in maintaining native fertility in the hayed grasslands and have directly enabled the sustained export of nutrients from these fields. This study represents the first step in testing this hypothesis by examining the long-term effects of the two annually harvested production systems on soil food webs and soil ecosystem properties through 1-m depth. We anticipated that this comparison would allow us to identify key characteristics of soil ecosystems that are associated with sustained, long-term nutrient removal.

2. Materials and methods

2.1. Site descriptions and soil sampling

The five field sites in this study were located in five counties of North Central Kansas as described by Glover et al. (2010). Specific field site names and respective locations were: **Buckeye**, Dickinson Co. N′ 39.2.344, W′ 97.7.798; **Niles**, Ottawa Co. N′ 38.58.145, W′ 97.28.616; **Goessel**, McPherson Co. N′ 38.15.333, W′ 97.22.307; **New Cambria**, Saline Co. N′ 38.53.54, W′ 97.32.615; **Five Creek**, Clay Co. N′ 38.22.665, W′ 97.18.788. Soil series are as follows: Ottawa Co., Geary silt loam; Dickenson Co., Hobbs fine-silty mesic; Goessel Co., Goessel silty-clay, Saline Co., Detroit silty clay-loam; and Clay Co., Muir silt-loam.

Each field site consisted of a native prairie meadow (perennial grassland) and an adjacent annually cropped field sown primarily or exclusively in wheat (*Triticum aestivum*), located on similar landscape positions and soil types. Prairie sites have never been tilled or fertilized and have been annually harvested for hay production for more than 75 years. Adjacent annually cropped fields have been in production for comparable periods of time and have received fertilizer inputs for the past several decades. In recent years at some sites, farm managers have used short rotations of wheat, sorghum (*Sorghum bicolor*), and/or soybeans (*Glycine max*) and/or have used no-tillage practices for varying periods. Field management followed typical practices for the region (KSUAES, 1996, 1997).

Soils were sampled three times: (i) June 18–22, 2006, (ii) October 5–9, 2006, and (iii) June 17–20, 2007. Four centimeter diameter cores were taken to a depth of 1 m along a 25 m transect across wheat and grassland sites. Five cores were taken from each field and separated into sections by depth: 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm. The five samples from each depth were bulked and mixed until homogeneous. Subsamples of soils were air-dried for soil properties, refrigerated at 4 °C for microbial biomass and nematode analyses, or stored at −20 °C for molecular analyses.

2.2. Soil chemical and physical properties

Soil properties were analyzed at the June 2007 sampling at The Land Institute (TLI) and at the Soil Testing Laboratory at Kansas State University (STL-KSU). Analyses at TLI included: pH (Robertson et al., 1999), bulk density by weighing soil samples of known volume after drying at 105 °C to constant weight (Jareell et al., 1999), soil texture by hydrometer (Elliott et al., 1999), water stable aggregates (WSA) by wet-sieving (Seybold and Herrick, 2001), and readily oxidizable carbon (ROC) (Weil et al., 2003). Analyses at STL-KSU included soil organic matter (SOM) by the Walkley–Black procedure, soil organic carbon (SOC) and total N by dry combustion on a LECO CN 2000 combustion analyzer, total P by a modified Kjeldahl digestion after an ammonium acetate extraction, and total K by flame atomic absorption. Further details on analyses performed at STL-KSU can be found at (Missouri Agricultural Experiment Station, 1998).

2.3. Root biomass

In June 2007, five 12.5-cm diameter soil cores were collected from the Niles perennial grass and annual crop fields to a depth of 2 m and separated into 0.2 m sections. Roots were separated from soil by repeated rinsing on a 425 μm mesh screen. Roots were dried and weighed to determine root mass per area. Because soil cores were collected from only one site, no statistical analyses were performed on the data. Arithmetic means are reported.