



## Soil particulate organic matter increases under perennial bioenergy crop agriculture



I.B. Kantola<sup>a, c</sup>, M.D. Masters<sup>a, c</sup>, E.H. DeLucia<sup>a, b, c, d, \*</sup>

<sup>a</sup> Energy Biosciences Institute, University of Illinois at Urbana-Champaign, Urbana, IL 61803, United States

<sup>b</sup> Department of Plant Biology, University of Illinois at Urbana-Champaign, Urbana, IL 61803, United States

<sup>c</sup> Institute for Sustainability, Energy, and Environment, University of Illinois at Urbana-Champaign, Urbana, IL 61803, United States

<sup>d</sup> Department of Plant Biology, University of Illinois at Urbana-Champaign, Urbana, IL 61801, United States

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### ABSTRACT

Annual row crop agriculture contributes to carbon (C) losses from Midwest soils, while the establishment of perennial crops for food and fuel has the potential to increase soil C stocks. Perennial grasses eliminate the need for tillage and increase belowground biomass, both critical to the accumulation and conservation of soil organic matter and to soil C sequestration. The effect of C<sub>4</sub> perennial grasses on particulate organic matter carbon (POM-C), consisting primarily of partially decomposed plant material, was evaluated in Illinois, where native switchgrass (*Panicum virgatum* L.) and a sterile hybrid of the Asian grass *Miscanthus* (*Miscanthus* × *giganteus*) were planted as bioenergy feedstocks at the University of Illinois Energy Farm in 2008. Six years after establishment of perennial crops, POM-C was compared with a maize-maize-soybean (*Zea mays* L., *Glycine max* L.) rotation typical of the area and a 28-species restored prairie. POM-C concentrations increased for all crops between 31 and 71% over 6 years, with the greatest increases in prairie and *M. x giganteus* soils. POM-C concentrations were highest at the 0–10 cm depth. Isotopic analyses showed 23–44% of POM-C was new C<sub>4</sub> material under perennial bioenergy crops after 6 years. As soil organic matter is primarily plant-derived, increases in POM-C reflect increased organic matter inputs or decreases in the rate of decomposition from the cessation of tillage. Increases in POM-C under annual row crops may result from the incorporation of aboveground organic matter by tillage, while POM-C increases in untilled perennial crops mirror increases in belowground biomass. As soil aggregation protects POM-C from microbial degradation, untilled soils under long-term perennial crop production increase the residence time for soil C.

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### 1. Introduction

Approximately 70 million hectares of maize (*Zea mays* L.) and soybean (*Glycine max* L.) are grown in the Midwestern United States for human consumption, animal feed, and bioenergy production (USDA, 2012). In recent years, interest has arisen in replacing maize-based grain ethanol with cellulosic ethanol production, particularly the use of perennial grasses for cellulose feedstocks. Perennial crops, for food and fuel, have the potential to improve soil quality through belowground carbon (C) inputs and the cessation of tillage (Jastrow, 1996; Paustian et al., 1997; Allison and Jastrow, 2006; Dou et al., 2013; Chimento et al., 2014; Ontl et al., 2015), to

provide yield security through drought resistance and resiliency (Glover et al., 2010, 2012), and to extend these benefits to marginal lands where conventional agriculture is inadvisable or unprofitable (Davis et al., 2012; Dou et al., 2013; Guzman et al., 2014).

Two C<sub>4</sub> perennial grasses under consideration for bioenergy production in the Midwest, *Miscanthus x giganteus* Greef & Deuter ex Hodkinson & Renvoize (*M. x giganteus*) and *Panicum virgatum* L. (switchgrass, var. 'Cave in Rock'), can produce higher biomass yields at maturity (3 + years after establishment) compared to maize grain for ethanol production (Heaton et al., 2008; Dohleman and Long, 2009; Anderson-Teixeira et al., 2013), though yields vary by species and location (Heaton et al., 2008; Arundale et al., 2014; Sanford et al., 2016). The perennial life cycles of *M. x giganteus* and switchgrass eliminate tillage practices that disturb soil and lead to C losses through erosion and accelerated decomposition (Six et al., 2000; Conant et al., 2001; Glover et al., 2010; Chimento et al.,

\* Corresponding author. Energy Biosciences Institute, University of Illinois at Urbana-Champaign, Urbana, IL 61803, United States.

E-mail address: [delucia@life.illinois.edu](mailto:delucia@life.illinois.edu) (E.H. DeLucia).

2014). Additionally, these crops require less fertilizer, herbicide, and pesticide than conventional maize, and perennial crops allocate a larger portion of their biomass to roots and rhizomes, resulting in higher belowground C inputs (Anderson-Teixeira et al., 2009, 2013; Chimento et al., 2014; Ontl et al., 2015; Masters et al., 2016). Modeled projections indicate that replacing annual row agriculture with perennial grasses that resemble native prairie will restore a portion of the soil organic carbon (SOC) lost over the last two centuries of agriculture in this region (Davis et al., 2012; Hudiburg et al., 2014; Duval et al., 2015).

The transition from annual to perennial crops may increase soil C stocks in agricultural soils, depending on the mechanism of C stabilization in the soil. Increased organic matter input alone is not enough to ensure increased SOC, as the microbial turnover of soil organic matter (SOM) drives both C loss and the long-term storage of C in the soil (Grandy and Neff, 2008; Kallenbach et al., 2015; Lehmann and Kleber, 2015). Carbon may be retained in soil because organic matter is chemically resistant to microbial consumption or because microbial consumption of plant material and root exudates results in increased soil microbial biomass or partially degraded material that is more stable than fresh litter. Organic matter may be physically protected by aggregation, which shields organic matter from microbial decomposition or creates an anoxic environment in which microbial activity is reduced (Oades and Waters, 1991; Allison and Jastrow, 2006; Cotrufo et al., 2013). Unincorporated organic matter, such as annually produced aboveground litter, is particularly susceptible to depletion through mechanical destruction or removal under land use change (Wander and Traina, 1996; Marriott and Wander, 2006).

Particulate organic matter (POM), defined as fresh or decomposing organic material between 53 and 250  $\mu\text{m}$  in diameter, is a useful index of microbially-important SOM because it consists of recognizable organic matter that can be isolated from mineral soils, and is sensitive to changes in soil management (Franzluebbers, 2000; Wander and Traina, 1996; Willson et al., 2001; Wander, 2004). POM preserved in aggregate structures decomposes on a decadal scale, with unincorporated POM decomposing at approximately twice that rate (Liao et al., 2006.) When soil aggregates are mechanically destroyed during tillage and cultivation, organic matter previously protected within soil aggregate structure is released into the microbially-accessible organic pools (Besnard et al., 1996; Six et al., 2000; Allison and Jastrow, 2006; Grandy and Neff, 2008). The rate of POM turnover also is driven by environmental factors, including moisture, temperature, and pH, affecting microbial activity. Modeled predictions of soil C in the Midwest under maize/soy agriculture show a gradual loss of soil C over time that is reversed under perennial grasses (Davis et al., 2012; Hudiburg et al., 2014; Duval et al., 2015). As POM has been shown to be sensitive to land use change and faster to respond than SOC, measuring POM may allow us to visualize soil C changes and predict patterns of SOC ahead of measurable SOC change.

In this study, SOC and POM-C in soils under potential perennial bioenergy grasses were compared with conventional row crops in a 6-year study to identify the SOC sequestration potential of each crop. A side-by-side replicated field trial of a maize-maize-soybean rotation, *M. x giganteus*, switchgrass, and a 28-species restored prairie simulating the historic vegetation of the area prior to settlement and cultivation were compared. All plots in this study were managed according to the best-known Midwestern U.S. agricultural practice for each species to accurately represent soils found under future bioenergy production.

The primary objectives of this research were to assess: i) the change in SOC under each crop over a 6-year period; and ii) to determine the relationship between SOC and POM accumulation for these crops. We hypothesize that perennial crops will increase

POM-C (representative of litter inputs) and SOC (representing organic matter retained) to a greater extent than annual crops over this 6-year period, and that rates of perennial POM-C accumulation will exceed rates of accrual of whole soil-SOC due to delays between litter inputs and litter consumption by heterotrophs. We also hypothesize that, in contrast with the perennial crops, the rate of change of the isotopic signature of POM under annual crops will exceed the rate of SOC accumulation, due to incorporation of aboveground organic matter by tillage.

## 2. Materials and methods

### 2.1. Site description and design

This study was conducted at the University of Illinois Energy Farm (40°3'46"N, 88°11'46"W) in Urbana, IL, USA, established in 2008. Prior to establishment, the Energy Farm produced row crop agriculture, primarily maize and soybean, for more than 100 years. The experiment was a randomized block design, with five blocks each containing one plot of each of the four vegetation types. Four 3.8-ha plots (sized to provide the minimum fetch for eddy covariance towers as described in Zeri et al., 2011) and sixteen 0.7-ha plots were planted in *M. x giganteus*; switchgrass; a 28-species restored native prairie mixture including grasses, forbs, and several N-fixing species (see Zeri et al., 2011 for complete species list); and a maize-maize-soybean rotation.

Soils on the site are predominately Argiudolls: Dana silt loam (fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls) with some Flanagan silt loam (fine smectitic, mesic, Aquic Argiudolls), Blackberry silt loam (fine-silty, mixed superactive, mesic Oxyaquic Argiudolls), and Drummer silty clay loam (fine-silty, mixed superactive, mesic Typic Endoaquolls) inclusions. Mean annual temperature is 10.9 °C, and mean annual precipitation is 1051 mm (Angel, 2010, 1981–2015 average).

*M. x giganteus* was propagated by rhizomes, while switchgrass and prairie were broadcast seeded, and maize was planted by drill seeding. Delayed rhizome planting in 2008 and a harsh winter in 2008–2009 resulted in high mortality of juvenile *M. x giganteus* rhizomes, requiring replanting in 2009 and partial replanting in 2010 (see Smith et al., 2013). Soybean was alternated with maize every third year (2010, 2013) to mimic conventional row crop production in this area. Nitrogen fertilizer was applied prior to maize planting as 28% urea ammonium nitrate at 168 kg N ha<sup>-1</sup> (2008, 2011, 2014) and 202 kg N ha<sup>-1</sup> (2009, 2012), and to switchgrass as granular urea, at 56 kg N ha<sup>-1</sup> from 2010 to 2014. *M. x giganteus*, soybean, and prairie were not fertilized. Row crop plots were chisel plowed each fall following maize harvest according to the convention of the region, and worked with a field cultivator (Sunflower Mfg., AGCO Corp., USA) in spring prior to planting both maize and soybean. Perennial crops were untilled after planting.

### 2.2. Biomass measurement

Aboveground and belowground biomass were measured annually at peak biomass (determined by LAI measurements, Zeri et al., 2011), typically in late August or September. Aboveground biomass was sampled at four random locations in each 0.7-ha plot and 8 locations in each 3.8-ha plot from within a 0.20 m<sup>2</sup> quadrat for prairie and switchgrass and a 0.56 m<sup>2</sup> quadrat for maize, soybean, and *M. x giganteus*. The larger quadrat was sized to encompass only a single row of maize or soybean, to eliminate variation in biomass due to sampling multiple rows. Belowground biomass was collected from within each quadrat by three randomly placed 5.1-cm diameter cores taken to 30 cm. Cores were divided into two depths (0–10 and 10–30 cm), and pooled within a quadrat. Roots

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