



Effects of switchgrass cultivars and intraspecific differences in root structure on soil carbon inputs and accumulation



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ABSTRACT

Switchgrass (*Panicum virgatum* L.), a cellulosic biofuel feedstock, may promote soil C accumulation compared to annual cropping systems by increasing the amount and retention of root-derived soil C inputs. However, these inputs and stabilization thereof may differ by cultivar, and it is uncertain which root traits favor soil C input and stabilization rates. The aim of this study was to assess how different switchgrass cultivars impact soil C inputs and retention, whether these impacts vary with depth, and whether specific root length (SRL) explains these impacts. We collected soil to a depth of 30 cm (10 cm increments) from six switchgrass cultivars with root systems ranging from high to low SRL. The cultivars (C₄ species) were grown for 27 months on soils previously dominated by C₃ plants, allowing us to quantify both total C and switchgrass-derived C accumulation in the bulk soil and in coarse particulate organic matter (CPOM), fine particulate organic matter (FPOM), silt-sized, and clay-sized fractions. The study led to two main results: (1) bulk soil C concentrations beneath switchgrass cultivars varied by 40% in the 0–10 cm soil depth and by 70% in the 10–20 cm soil depth, and cultivars with high bulk soil C concentrations tended to have relatively high C concentrations in the mineral soil fractions and relatively low C concentrations in the POM fractions; (2) there were significant differences in switchgrass-derived soil C between cultivars at the 0–10 cm depth, where soil C inputs ranged from 1.2 to 3.2 mg C g⁻¹ dry soil. In addition, switchgrass-derived C was positively related to SRL when one outlier data point was removed. These results suggest that switchgrass cultivars differentially impact mechanisms contributing to soil C accumulation.

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1. Introduction

The search for new sources of sustainable energy has cast attention on cellulose-derived ethanol as a potential fuel, and switchgrass (*Panicum virgatum* L.), which is rich in lignocellulosic tissues (Lynd et al., 1991), has shown promise as a cellulosic biofuel feedstock (Schmer et al., 2008). Switchgrass is a fast growing, perennial prairie grass common to the U.S. Great Plains, U.S. Midwest, and eastern U.S. states. It is projected that more than 16.9 Mha of U.S. farmland could eventually be dedicated to switchgrass production, yielding 158 dry Tg y⁻¹ (McLaughlin et al., 2002), with a mean net energy yield of 60 GJ·ha⁻¹ y⁻¹ (Schmer et al., 2008). If biofuel production is carbon (C) negative (i.e., the amount of C sequestered is greater than the amount lost during production, harvest, and transport to a production facility), then, in addition to serving as a renewable energy source,

biofuel crops can contribute to climate change mitigation by removing excess C from the atmosphere (Tilman et al., 2006).

Soil plays an important role in achieving the aim of C negative bioenergy production because soil can stabilize and sequester plant-derived C (Lal, 2004a,b). Carbon sequestration refers to the removal of C from the atmosphere and the storage of this C in long term pools (Lal, 2004a,b). Mechanisms that promote soil C sequestration include increased C inputs, stabilization of soil C (both new inputs and existing C), and placement of C in deeper soil layers (Lal and Kimble, 1997). Thus, plant traits that mediate soil C inputs and soil C stabilization can have important impacts on soil C sequestration. Compared to soils cultivated with annual crops, perennial grassland soils are characterized by high C accumulation rates (Jobbagy and Jackson, 2000; Conant et al., 2001; Jones and Donnelly, 2004; Soussana et al., 2010; Baer et al., 2015). This can be attributed to perennial grasses contributing greater amounts of root-derived C to soil and eliminating the need for annual tillage (Paustian et al., 2000; Jones and Donnelly, 2004; Rees et al., 2005; Jastrow et al., 2007; Baer et al., 2010). Thus, grasslands managed for biofuel production may enhance soil C accumulation by increasing the amount and retention of plant root-mediated soil C inputs

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compared to annual cropping systems (Post and Kwon, 2000; Conant et al., 2001; Jones and Donnelly, 2004; Soussana et al., 2010).

Switchgrass in particular contributes a substantial amount of C inputs to the soil C pool (McLaughlin and Kszos, 2005; Tilman et al., 2006). McLaughlin and Kszos (2005) estimated average soil C accumulation rates under switchgrass plots to be as high as $0.78 \text{ Mg C ha}^{-1} \text{ y}^{-1}$ in regions across the eastern U.S. The positive impact of switchgrass on soil organic C stocks can be attributed to its extensive root system. Switchgrass roots remain alive after harvest of the feedstock and can penetrate as deep as 3.4 m (Weaver and Darland, 1949). Since plant roots are one of the primary conduits for transporting photosynthetically fixed C to the soil (Norby and Jackson, 2000; Rasse et al., 2005; Kong and Six, 2010), these extensive root systems likely strengthen the ability of switchgrass to sequester soil C by affecting the magnitude and depth of soil C inputs. Switchgrass root systems are most prominent in surface soil, with roots in the top 30 cm comprising from 66% to greater than 80% of the total root mass quantified to 90 cm (Garten et al., 2010, 2011; Ma et al., 2000), with the greatest proportion of switchgrass root biomass occurring in the top 10–15 cm of soil (Frank et al., 2004; Ma et al., 2000). This indicates that root-derived C inputs will be most prominent in the uppermost soil layers, especially in early establishment years. Switchgrass cultivars have been shown to differentially affect soil C cycling (de Graaff et al., 2014), but root traits that maximize C inputs and stabilization, and thereby increase the potential for soil C sequestration, have not been well identified.

Intraspecific variations in root morphologies among switchgrass cultivars have the potential to impact soil C inputs and C stabilization. Switchgrass cultivars exhibit a range of root phenotypes; for example, specific root lengths (SRL; m g^{-1} root mass) can vary by a factor of five among cultivars (de Graaff et al., 2013, 2014). Such phenotypic variation may influence the C sequestration potential of different cultivars (Schweitzer et al., 2004; Whitham et al., 2006; Lojewski et al., 2012). Root systems with a low SRL feature a greater abundance of large diameter, longer-lived roots, which are rich in slowly decomposing cellulose and lignins (Guo et al., 2004). Conversely, root systems with a high SRL have a relatively large abundance of small diameter, ephemeral, and easily decomposed roots with high concentrations of nitrogen (N) and labile C compounds (Norby and Jackson, 2000; Guo et al., 2004). Microbes are able to use plant tissues with high concentrations of N and labile C compounds more efficiently than tissues with low N and more recalcitrant C chemistry, and, as a result, labile C may be preferentially stabilized in soil as microbial residues (Gentile et al., 2011a,b; Cotrufo et al., 2013). Fine roots may also exhibit more root exudation on a root weight basis, increasing the concentration of compounds that are easily utilized by soil microbes (Norby et al., 1987; Xu and Juma, 1994; Jaeger et al., 1999; Paterson and Sim, 1999). Due to the greater abundance of N and labile C in fine roots compared to coarse roots, SRL may serve as a useful proxy for identifying switchgrass cultivars that might maximize labile soil C inputs.

Soil organic matter can be characterized by particle size, which provides information about the transformation state and potential long-term fate and stability of the C associated with each particle size fraction. Coarse particulate organic matter (CPOM; $\geq 250 \mu\text{m}$) and fine particulate organic matter (FPOM; $53\text{--}250 \mu\text{m}$) mostly consist of partially decomposed plant residues and microbial debris (Hassink et al., 1997; Six et al., 2002). Carbon associated with silt-sized particles ($2\text{--}53 \mu\text{m}$) is composed mainly of aromatic plant compounds (Christensen, 2001). The C associated with the clay-sized fraction ($\leq 2 \mu\text{m}$) is derived primarily from the metabolic byproducts of microbial decomposition (Christensen, 2001). Carbon associated with the silt- and clay-sized fractions is generally considered to be more stable because it consists of more decomposed and humified material that is physically and chemically protected via association with organomineral complexes (Six et al., 2002). Consequently, the silt- and clay-sized fractions have more long-term C sequestration potential than the coarser POM fractions (Christensen, 2001). Garten and Wullschlegel (2000)

assessed soil C dynamics under switchgrass stocks and found that C associated with the mineral fraction (the combination of the silt- and clay-sized fractions) had turnover times ranging from 26 to 40 years, whereas POM associated C ($>53 \mu\text{m}$) had turnover times ranging from 2.6 to 4.3 years. Hence, if switchgrass cultivars vary in the amount or rate of C inputs to silt- and clay-sized fractions, identifying cultivars and traits that can maximize C inputs to these fractions could have important implications for enhancing the C sequestration potential of switchgrass as a bioenergy crop.

The aim of this study was to assess how different switchgrass cultivars impact soil C inputs, whether these impacts vary with depth, and whether SRL explains these impacts. We hypothesized that root systems with higher SRL would exhibit greater C inputs due to a greater surface area of fine root tips that contribute to exudation and more frequent turnover (Czarnota et al., 2003; Nguyen, 2003; Piñeros et al., 2002). Switchgrass is a C_4 plant, and the cultivars we used for this study had been grown for 27 months on soils previously dominated by C_3 grasses, resulting in different natural abundance $\delta^{13}\text{C}$ values for the plant material and soils. The difference in isotopic values between plants and soils allowed us to quantify plant-derived C inputs to CPOM, FPOM, silt-, and clay-sized fractions.

2. Methods

2.1. Experimental design and sampling protocol

In the fall of 2007, standing vegetation (a mixture of the perennial, cool-season C_3 grasses) in a 5.4-ha field at the U.S. Department of Energy National Environmental Research Park at Fermilab in Batavia, IL, USA ($88^\circ 13' 47'' \text{W}$, $41^\circ 50' 29'' \text{N}$) was treated with herbicide and removed by burning. The following spring, vegetative regrowth was suppressed with another herbicide treatment. In June 2008, *P. virgatum* L. (hereafter: switchgrass) ecotypes originating from different latitudes were planted as a replicated field trial. Monocultures of 17 switchgrass cultivars were sown from seed in $2 \times 3 \text{ m}$ or $2 \times 1 \text{ m}$ replicated field plots ($n = 4$) in a randomized block design on soils that had supported the stand of C_3 cool season grasses for 36 years. The soil at the site is Grays silt loam (Fine-silty, mixed, superactive, mesic Mollic Oxyaquic Hapludalf). In October 2010, we collected soils from six switchgrass cultivars using a 4.8-cm diameter soil corer. Each sample was collected from on top of the crown of one individual from each of four replicate plots to a depth of 30 cm. The selected cultivars included: (1) Alamo, (2) Kanlow, (3) Carthage, (4) Cave-in-Rock, (5) Forestburg, and (6) Blackwell. For the purpose of obtaining a reference measurement for soil C content and natural abundance of stable C isotopic signatures, three soil cores were also collected from an adjacent area of Grays silt loam that remained in C_3 cool season grasses (mainly *Bromus inermis* Leyss., *Elymus repens* (L.) Gould, and *Poa* spp.). Upon collection, all cores were divided into 10 cm increments. The cores were shipped to Boise State University and kept at 6°C until further processing. The soils were sieved (2 mm), rhizomes were removed, and all visible roots were hand-picked from the soil. All roots collected from each depth increment were washed in deionized water and analyzed for root length using WinRhizo (Regents Instruments, Inc.). After root length determinations, the roots were dried at 70°C and weighed, and SRL was calculated as total root length divided by total root dry weight for each depth increment (de Graaff et al., 2014). One Forestburg sample and one Cave-in-Rock sample, both from the 0–10 cm depth increment, were missing and were not included in any analyses.

2.2. Soil fractionation

Subsamples of soil from each plot and from each of the three depth increments were size-fractionated to separate CPOM ($>250 \mu\text{m}$), FPOM ($53\text{--}250 \mu\text{m}$), silt-sized ($2\text{--}53 \mu\text{m}$), and clay-sized ($<2 \mu\text{m}$) fractions using a procedure adapted from Cambardella and Elliott (1992).

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