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Root biomass, root/shoot ratio, and soil water content under perennial grasses with different nitrogen rates

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ABSTRACT

Roots help in soil water and nutrient uptake and provide carbon (C) input for soil C sequestration, but information on root biomass of bioenergy perennial grasses is lacking. Root/shoot ratios are used to estimate crop root biomass and C inputs, but the values for perennial grasses are also scanty. We examined root biomass, root/shoot ratios, and soil water contents to a depth of 120 cm after grass harvest in the fall for three bioenergy perennial grasses applied with four nitrogen (N) fertilization rates from 2011 to 2013 in the northern Great Plains, USA. Perennial grasses were intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth and Dewey), smooth bromegrass (*Bromus inermis* L.), and switchgrass (*Panicum virgatum* L.), and N fertilization rates were 0, 28, 56, and 84 kg N ha^{-1}. Root biomass declined with depth and about 60% of the total biomass was located at 0–15 cm where intermediate wheatgrass and switchgrass had higher biomass than smooth bromegrass in 2011. Shoot biomass was greater in intermediate wheatgrass in 2011 and in switchgrass in 2013 than other grasses and increased with increased N rates. Root/shoot ratio was greater in switchgrass than other grasses at 0–120 cm in 2011, but was greater in smooth bromegrass than switchgrass at 0–60, 0–90, and 0–120 cm in 2012 and 2013. Mean root/shoot ratios across N rates and years were not different among grasses and varied from 1.54 at 0–15 cm to 2.54 at 0–120 cm, which were substantially greater than 0.15 and 0.33, respectively, observed for spring wheat (*Triticum aestivum* L.). Soil water content increased with depth and was greater under switchgrass than other grasses at 0–120 cm in 2011 and 2013. Water content varied with N rate at various soil depths and years. Root biomass was negatively correlated with soil water content ($r = -0.56$, $P = 0.03$, $n = 15$). Because of greater root and shoot biomass, intermediate wheatgrass reduced soil water content due to increased water uptake and will likely provide more C inputs for soil C sequestration from belowground biomass compared to smooth bromegrass and spring wheat.

1. Introduction

Perennial grasses, such as ligno-cellulosic feedstock materials, have been shown to be promising crops for bioenergy production (Pacala and Solocolow, 2004; USDOE, 2007). These grasses have additional advantages compared with food crops, such as corn (*Zea mays* L.), for producing bioenergy: (1) they reduce pressure for using food crops for bioenergy, (2) they use water, N, and solar radiation more efficiently and require reduced amounts of chemicals, such as fertilizers, herbicides, and pesticides, (3) they can be easily grown on marginal lands, (4) they are more productive per unit land area, and (5) they recycle nutrients seasonally between roots and shoots (Pacala and Solocolow, 2004; USDOE, 2007).

Although production of shoot biomass has been known for various perennial grasses, relatively little information is available about root biomass. Roots absorb water and nutrients from the soil and support aboveground shoot growth whose yield depends on the growth of belowground root biomass (Merrill et al., 2002; Stone et al., 2001). As the aboveground biomass of crops is usually harvested for grain, hay, litter, or fuel, roots form the main component of C input for soil C sequestration (Paustian et al., 1997). Besides root biomass, rhizodeposit in the form of exudates, secretions, cap cells, lysates, and mucilages can also form important sources of C for enriching soil organic C (Hawes et al., 2003; Nguyen, 2003). Roots may play a dominant role in the soil C cycle (Gale et al., 2000; Puget and Drinkwater, 2001) and may have relatively greater influence on soil organic matter than the

Abbreviation: IW, intermediate wheatgrass; SB, smooth bromegrass (SB); SG, switchgrass; SW, spring wheat

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aboveground plant biomass (Norby and Cotrufo, 1998).

One of the management practices to sequester atmospheric CO_2 in agricultural and range soils and enrich soil organic matter is to plant perennial grasses either alone or in rotation with cereal crops (Paustian et al., 1997). The reason is that perennial grasses have higher root biomass that contributes more C to the soil than cereal crops (Paustian et al., 1997; Bollinder et al., 1997, 2002). Furthermore, the relatively undisturbed soil condition under perennial grasses reduces mineralization of soil organic matter and therefore favors soil C accumulation. Because of the difficulty of accurately measuring root biomass in the field due to high variability and tedious work of separating roots from the soil, measurement of root biomass, especially for perennial grasses, is often neglected (Bollinder et al., 2002). Other sources of variation in the measurement of root biomass include the soil sampling strategy employed, different sieve size used to separate roots from the soil affecting the quantification of root biomass, variation in root growth during the crop growing season making the sampling time critical, and age of the grass establishment (van Nordwijk et al., 1987; Amato and Pardo, 1994).

The root/shoot ratio at crop harvest is used to estimate root biomass and C input from belowground residue (Bollinder et al., 1997, 2002). Because of variations in root and shoot growth due to various soil and climatic conditions among regions and during different periods of crop growth, root/shoot ratios can vary for perennial grasses. Root/shoot ratios for perennial grasses have been mostly reported for pasture and natural grassland, which ranged from 0.57 to 6.25 in USA (Mo et al., 1992; Mortimer, 1992) and from 0.18 to 2.44 in other countries (Bray, 1963; Bollinder et al., 2002). The values also vary with the depth of soil sample collected for determining root biomass and age of grasses (Campbell and de Jong, 2001; Bollinder et al., 2002). For example, the root/shoot ratio of various perennial grasses can vary from 0.28 at 0–15 cm in the year of establishment to 2.33 at 0–45 cm in successive years (Bollinder et al., 2002).

Variations in root growth and distribution in the soil profile among crops can lead to differences in water and nutrient uptake by roots. Roots that grow near water and nutrient availability are usually dense, have large diameter, and are active in growth and resource uptake (Pierret et al., 2007). Only 10–30% of the total root length of a given root system, however, is actively involved in water and nutrient uptake (Robinson, 1991). Water stress can extend roots to a greater soil depth for water uptake more in grasses than legumes or forbs, resulting in greater root biomass and therefore greater root/shoot ratio in grasses (Skinner and Comas, 2010). Culman et al. (2013) reported that soil water content to a depth of 1 m was lower with intermediate wheatgrass than winter wheat, suggesting that perennial grasses are more effective in water uptake from the soil profile than cereal crops.

Nitrogen fertilization can have a variable effect on shoot and root biomass of perennial grasses among various regions and years due to variations in soil and climatic conditions. Heggenstaller et al. (2009) found that N fertilization at 140 kg N ha^{-1} maximized shoot and root biomass (0–30 cm) of switchgrass in the same proportion, after which both declined with increased N rate. As a result, the root/shoot ratio of switchgrass was unaffected by N fertilization rates. Ibrahim et al. (2016) reported that increased N rate increased switchgrass shoot biomass in the first year, but not in the second year. Increased N rate from 0 to 90 kg N ha^{-1} enhanced root and shoot biomass, after which root biomass remained constant, but shoot biomass continued to increase with further increases in N rate in smooth bromegrass (Power, 1988).

Little is known about the effect of perennial grasses and N fertilization rates on root biomass and root/shoot ratio of grasses and their relationships with soil water content compared with cereal crops. Differences in root biomass growth due to variations in grass species and N rates may result in different C inputs for C sequestration and soil water acquisition. We evaluated root and shoot biomass, root/shoot ratio, and soil water content to a depth of 120 cm for various perennial grasses with different N fertilization rates and compared them with annual spring wheat applied with recommended N rate from 2011 to 2013 in eastern Montana, USA. Our objectives were to: (1) quantify root and shoot biomass and root/shoot ratios of bioenergy perennial grasses applied with 0–84 kg N ha^{-1}, (2) compare root biomass and root/shoot ratio of perennial grasses and a cereal crop, and (3) relate these parameters with soil water content. We hypothesized that root and shoot biomass, root/shoot ratio, and soil water content vary with perennial grass species and N fertilization rates, and root biomass and root/shoot ratio will be greater, but soil water content will be lower for perennial grasses than for spring wheat.

2. Materials and methods

2.1. Treatments and grass management

Perennial grasses were established on 5% sloping land on April 2009 and the study was conducted from 2011 to 2013 at the USDA Conservation District Farm, 11 km north of Culbertson, MT, USA. The soil in the experimental site was a Williams loam (fine-loamy, mixed, superactive, frigid, Typic Argiustoll), with 660 g kg^{-1} sand, 180 g kg^{-1} silt, 160 g kg^{-1} clay, 10.1 g kg^{-1} SOC, 7.2 pH, and 1.27 Mg m^{-3} bulk density at the 0–15 cm depth during the initiation of the experiment in April 2009. Mean (115-yr average) monthly air temperature ranges from −8 °C in January to 23 °C in July and August and a mean annual precipitation of 341 mm, 80% of which occurs during the growing season (April to October). Previous cropping history (10 yr) at the site was continuous spring wheat under conventional tillage.

Perennial grasses included three grasses (intermediate wheatgrass, smooth bromegrass, and switchgrass) as the main plot (plot size, 12.2 × 30.5 m) treatment where N fertilizer was applied at four rates (0, 28, 56, and 84 kg N ha^{-1}) as the split-plot (plot size, 3.1 × 30.5 m) treatment. Intermediate wheatgrass and smooth bromegrass are cool-season grasses, whereas switchgrass is a warm-season grass. Treatments were arranged in a randomized complete block design with four replications. For this study, because of physical constraints, only three replications based on uniform slope with reduced spatial variability were considered. At the time of grass establishment in late April 2009, monoammonium phosphate (11% N, 23% P) at 280 kg ha^{1} was broadcast, which supplied N at 31 kg N ha^{-1} and P at 64 kg P ha^{-1}. Immediately after fertilization, plots were cultivated using conventional tillage with a field cultivator to a depth of 7–8 cm for seedbed preparation and weed control. Using a no-till drill, intermediate wheatgrass, smooth bromegrass, and switchgrass were planted at 17, 24, and 17 kg ha^{-1}, respectively, at 20 cm spacing following tillage. In April, 2011–2013, N fertilizer at 0–84 kg N ha^{-1} as urea (46% N) was broadcast at the soil surface in split plots. No K fertilizer and irrigation were applied. Depending on the shoot growth, aboveground biomass was harvested at 5 cm above the ground one to two times a year (July and October) from two 0.5 m^2 areas by hand, randomly within the plots and composited. A subsample was oven-dried at 60 °C for 3 d to determine dry matter yield, from which shoot yield was determined. Total shoot yield in a year was determined by adding yields from individual cuttings.

For comparing above- and belowground biomass of grasses with cereal crop, spring wheat was planted in a nearby area outside grass plots in April 2013. Wheat was planted at 71 kg ha^{-1} under no-tillage using a no-till drill as above in three plots (plot size, 3.1 × 30.5 m) as three replications. Nitrogen fertilizer as urea and monoammonium phosphate at 100 kg N ha^{-1}, P fertilizer as monoammonium phosphate at 29 kg P ha^{-1}, and K fertilizer as muriate of potash (52% K) at 47 kg K ha^{-1} were banded 5 cm to the side and 5 cm below the seed at planting. Herbicides and pesticides were applied as needed before and during crop growth. In August 2013, wheat was harvested from two 0.5 m^2 areas by hand, randomly within the plot as above, separated into grain and vegetative biomass, oven dried at 60 °C for 3 d, and yields