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Nitrogen conservation decreases with fertilizer addition in two perennial grass cropping systems for bioenergy

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A B S T R A C T

Warm-season prairie grasses are promising bioenergy crops that exhibit conservative nitrogen use and cycling, which promise to reduce expensive N amendments and contributions to environmental N pollution associated with annual cropping systems. However, efforts to maximize crop yields with fertilizer may reduce N conservation in these systems. We used two perennial grass systems of differing diversity levels – a restored tallgrass prairie and a *Panicum virgatum* (switchgrass) monoculture—to determine the effects of N fertilizer level and harvest timing on biomass yields, N concentrations and N removal at harvest. To address plant N conservation, we measured N resorption efficiency (proportion of N resorbed), resorption proficiency (minimum N level attained after senescence), and timing of resorption under different N fertilizer rates. Yield responses to N fertilizer were not consistent between cropping system, year, or harvest timing, and were generally weak, resulting in an average of only 1.27 times more biomass compared to unfertilized plots. In contrast, fertilized plots removed 1.67 times more N relative to unfertilized plots, as N removal was largely driven by increases in biomass N concentrations rather than increases in yield. N resorption was affected by fertilizer in switchgrass, but not in selected prairie species. Fertilized switchgrass plants took longer to reach their maximum resorption levels and had reduced resorption proficiency, despite higher resorption efficiencies. Our results suggest that striving to increase biomass yields with N fertilizer may be an imprudent approach to sustainable bioenergy production, because yield responses are highly variable and N conservation mechanisms are compromised.

1. Introduction

Perennial grasses have the potential to be an important source of cellulosic biofuel feedstocks for renewable energy and depending on management practices, may reduce agriculturally-related nitrogen (N) pollution (Dale et al., 2014). In an effort to meet renewable energy goals, some productive croplands may undergo transition to dedicated bioenergy crops. To avoid competing with food, farmers may expand bioenergy crops to nonagricultural lands, thereby causing a net increase of managed lands (Tilman et al., 2009; Walsh et al., 2003) or intensify production on so-called marginal lands (Gelfand et al., 2013). Agricultural intensification often leads to negative environmental consequences, including increases in N pollution (Drinkwater and Snapp, 2007). N pollution associated with production practices and fertilizer inputs has caused significant environmental decline, altering plant communities, soil tilth, water quality and air quality (Galloway et al., 2003; Schlesinger, 2009) and comes with significant costs to society (Galloway et al., 2008; Johnson et al., 2010). Therefore, producing bioenergy crops that mitigate, rather than contribute to N pollution is an important part of producing bioenergy crops sustainably (Bhardwaj et al., 2011; Robertson et al., 2011). Improving production practices that reduce our reliance on N fertilizer and limit N losses to the environment remains a major challenge (Robertson and Vitousek, 2009; Syswerda and Robertson, 2014). One way to increase agricultural production and simultaneously reduce N losses is to use cropping systems that are conservative and efficient with N resources, which reduces the need for N fertilizer (Robertson and Vitousek, 2009; McSwiney et al., 2010).

Perennial grasses have remarkable attributes that make them highly productive, yet conservative with N use (Dell et al., 2005).

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One important trait is high N-use efficiency. Perennial grasses that use the C_4 photosynthetic pathway make biomass production per unit of N acquired more productive compared to grasses that use the C_3 photosynthetic pathway (Brown, 1999). A keystone nutrient-conserving strategy used by many perennial plants is recycling internal N stores (Chapin, 1980; Killingbeck, 1996). Prairie grasses have been found to be exceptionally efficient in retranslocating, or resorbing nutrients and carbohydrates to roots and crowns during senescence for storage over winter to be recycled for subsequent growth (Clark, 1977; Heckathorn and Delucia, 1996). In bioenergy cropping systems, N resorption limits N losses through litterfall, and more importantly, N removal via harvest. Reducing N losses should allow plants to become less dependent on exogenous N sources.

Despite the high N-conserving strategies of perennial grasses, general management recommendations call for the use of N fertilizer to optimize biomass production (U.S. Department of Energy, 2011). However, numerous studies have evaluated perennial grass yields, and fertilizer responses have been mixed. While there are many studies that show positive yield responses to fertilization (Heaton et al., 2004; Heggenstaller et al., 2009; Lemus et al., 2008a), others found instances of limited or no yield responses (Jarchow and Liebman, 2012; Jung and Lal, 2011; Mulkey et al., 2008; Thomason et al., 2004). Yield responses to fertilizer are often highly variable and site-dependent (Haque et al., 2009; Parrish and Fike, 2005; Wullschleger et al., 2010) and fertilizer responses for many perennial feedstocks remain uncertain (Bonin and Lal, 2012). The lack of N response often reported may be explained by the conservative N-use inherent to these crops, as well as uncharacterized microbial associations, such as mycorrhizal fungi or N_2-fixers in the rhizosphere (Parrish and Fike, 2005).

Plant biomass N concentrations also have variable responses to N fertilizer inputs. Plant tissue N concentrations often increase with N fertilization (Garten et al., 2011; Guretzky et al., 2010; Heggenstaller et al., 2009; Jarchow and Liebman, 2012; Jung and Lal, 2011; Madakadze et al., 1999), but not always (Lemus et al., 2008b; Waramit et al., 2011). Biomass N concentration is an important consideration, because along with yield, it drives how much N is removed from the field at the time of harvest. Current management recommendations suggest harvesting after plants have completely senesced, which ensures plants have completed resorption. This reduces the N removed from the field and decreases the amount of fertilizer needed for the following season. Additionally, biomass with low N concentrations improves feedstock quality for most bioenergy uses (Adler et al., 2006; Anex et al., 2007); therefore, a threshold concentration of 0.6% N has been recommended for biomass feedstocks (Kauter et al., 2003). While delaying harvest has advantages for nutrient conservation and biomass quality, harvest delay also significantly reduces yields (Adler et al., 2006; Heaton et al., 2009; Vogel et al., 2002). Minimizing the trade-off between yield and N removal at harvest remains a challenge for sustainable biomass production.

Understanding drivers of N resorption in bioenergy crops may be a key to minimizing the trade-off between yield and N removal. N resorption efficiencies vary considerably among perennial plants, ranging from 0 to 90%, with a global mean of 62% for unfertilized perennial plants and graminoids averaging even higher rates at 75% (Vergutz et al., 2012). An understanding of what underpins this variability is beginning to emerge. Plant genetics are one factor, as switchgrass accessions have resorption efficiencies that range from 20 to 60% (Yang et al., 2009). Other sources of variability are environmental factors, such as climate, water stress, and soil nutrient levels. Some studies have found N resorption rates decrease with increasing soil-N availability (Huang et al., 2008; Kobe et al., 2005; Norris and Reich, 2009), while others have found no effect of N availability on resorption (Aerts and Chapin, 2000; Aerts, 1996); therefore, fertility effects on resorption rates remain equivocal. N resorption has been documented specifically in perennial grasses managed for bioenergy production (Heaton et al., 2009; Garten et al., 2010), although no research has explored how the resorption strategies of these bioenergy species will be affected by different fertilizer rates. The timing of N resorption also has significant agronomic implications, since delaying harvest reduces biomass yields. More research is needed to understand the rate, timing and extent of N resorption in managed bioenergy crops (Sanderson and Adler, 2008; Sanderson et al., 2006), and more specifically, how N fertilizer affects the resorption capabilities of bioenergy crops.

We measured how two perennial grass cropping systems – a restored prairie and a switchgrass monoculture – responded to varying N fertilizer rates at different harvest timings, as well as how N fertilizer affected N resorption. We hypothesized that N removal with harvest would increase with N fertilizer rate at all harvest timings, driven by increased biomass N concentrations, yields, or both and N resorption would decrease with increasing N fertilizer rates.

2. Materials and method

2.1. Site characteristics and experimental design

The experiment was conducted from 2009 through the spring of 2012 at the Arlington Agricultural Research Station in Arlington, Wisconsin (43°8′N, 89°21′W). Average temperature and precipitation totals for the years of study were 6.5 °C and 856 mm, 7.8 °C and 889 mm, and 7.4 °C and 757 mm for 2009, 2010, and 2011, respectively. Precipitation in the first two years of our study was above the 12-yr average of 849 mm, while 2011 precipitation totals were significantly below normal for south central Wisconsin (UW-Extension, 2012). Soils at the site are classified as Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudolls), which are highly-productive mollisols.

Experimental units were positioned on a larger framework of plots established for the Wisconsin Integrated Cropping Systems Trial—a long-term research project examining crop rotations and on-farm biodiversity of cropping systems in southern Wisconsin (Posner et al., 2008). Switchgrass plots were seeded in August 2007 with the cultivar Forestburg at a rate of 11.2 kg PLS ha^{-1} (plots were previously in corn since 1999). The prairie plots were seeded in 1999 with 25 species native to the tallgrass prairie, including C_4 grasses, legumes and forbs. At the time of study, many plots had significant encroachment of C_3 European forage grasses. Broadleaf weeds were managed with herbicide as needed. Prescribed burns were conducted on the prairie plots from 1999 to 2008 approximately every 2–3 years, but no burns were conducted for the duration of this experiment. Both prairie and switchgrass plots were not historically harvested for biomass.

Management treatments applied to the prairie and switchgrass plots included three N fertilizer rates of 0, 50, and 150 kg N ha^{-1} (hereafter, none, medium, and high N levels), and three harvest timings (summer, fall and the following spring). Fertilizer was hand-applied in June of 2009, 2010, and 2011 as ammonium-nitrate. These rates were chosen to reflect general recommendations for N replacement of the previous year's removed N (medium N level), as well as an excessive N treatment (high N level), which should have eliminated any N limitation to plant growth. The summer harvest occurred at anthesis of the dominant species within each cropping system (*Panicum virgatum* for the monoculture and *Andropogon gerardii* and *Sorghastrum nutans* for the prairie), the fall harvest two weeks after a killing frost (temperature reached ≤ -2.2 °C for a minimum of 4 h), and the spring harvest as soon as possible after snow-melt when field conditions permitted, thereby harvesting