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Prairie yield, moisture and nitrogen content response to harvest time

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Summary

Mixtures of native grassland perennials are characterized by high productivity and large carbon sequestration capacity, and thus have a large potential as biofuel feedstocks. However, the balance among yield, biomass quality, and impacts on environment needs to be carefully considered when selecting a harvest time for prairie mixtures because of the biofuel quantity-quality tradeoff. The effects of harvest time on nitrogen (N) concentration and biomass was evaluated in a restored tall-grass prairie in Urbana, IL. Prairie biomass yield was highest in Oct, and stayed relatively constant during winter. N varied both across and within species throughout the growing season. Most species achieved lowest N in Jan. There was little overall change in N between Jan and Apr. Prairie mixture would potentially remove 84.6 kg N ha^{-1} if harvested in Nov. Our results suggest that the optimal harvest time that balances feedstock quality and yield is between Nov and Jan.

Key words: Biofuel, prairie mixture, nitrogen, harvest time, yield, biomass quality

Introduction

Perennial grasses have several advantages as potential biofuel crops over conventional annual crops such as lower establishment costs, and reduced soil erosion (Roth *et al.*, 2005; McLaughlin *et al.*, 2002). Particularly, perennial grasses can translocate nutrients from aboveground to belowground biomass for overwinter storage, which may reduce the amount of nutrients removed during harvest. In addition translocation of nutrients can substantially reduce the mineral content of feedstock, which allows perennial grasses to generate less pollution during combustion than annual crops that cannot directly cycle nutrients (Heaton *et al.*, 2009). Minimizing feedstock nutrient content and understanding what controls nutrient concentrations is important, as some plant nutrients, such as nitrogen and sulfur, contribute to atmospheric pollutantion upon combustion of the fuel (McKendry, 2002). In addition to impacting feedstock quality, N translocation can reduce the need for external fertilizer, thus saving on both the financial and carbon costs of production. Therefore, allowing biofuel crops to completely senesce and recycle nutrients can reduce fertilizer requirements and improve feedstock quality by reducing biomass moisture and mineral content. A delayed harvest reduces artificial drying cost while providing acceptable biomass material, which it is important in the biofuel production economy. On the other hand, a delayed harvest leads to biomass losses due to losses of leaves and breakdown of stem tips, particularly in temperate climate where snow and ice can reduce or destroy harvestable biomass in the field. In previous studies biomass yield has been shown to drop by up to 35% (Adler *et al.*, 2006). Hence, when choosing an appropriate harvest date, the biomass producer faces a conflict between yield and quality optimization. Therefore, the balance between yield, biomass quality, and impacts on environment needs to be carefully considered when selecting a harvest time for biofuel crops. The trade-off between yield and fuel quality has been studied on *Miscanthus* × *giganteus*, switchgrass (*Panicum virgatum*), reed canary grass (*Phalaris arundiacea*) and other potential energy crop monocultures (Xiong *et al*., 2008, 2009; Heaton *et al*., 2009; Adler *et al*., 2006; Lewandowski *et al*., 2003). However, the effects of harvest time on biomass N concentration, moisture and yield of a prairie production system are not well documented. Mixtures of native grassland perennials are characterized by high productivity, large carbon sequestration capacity and have been considered as potential biofuel feedstock (Tilman *et al*., 2006). It is important to determine the impacts of harvest time on yield, nutrient and moisture content in prairie production system. Considering phenological differences across species in prairie mixture, determining the water and nutrient status on the species level is essential to estimating the overall effects of harvest time. Since different species start senescing at different times, harvest time for prairie mixtures needs to be selected carefully with a consideration of all major species. Given the biofuel quantity-quality trade-off, this papers aims to (1) determine biomass yield, nitrogen and moisture content response to harvest time for prairie mixture; (2) determine the species, nutrient level, and harvest time that will maximize expected net returns.

Materials and Methods

Study site

Twenty eight native species (Table 1) were planted in the tall-grass prairie treatments plots at the Energy Biosciences Institute Energy Farm (40.05°N, 88.18°W), Urbana, IL, USA in 2008. For purposes of simplifying our analyses these species were assigned to four plant functional types (PFT): C_4 grasses, C_3 grasses, legumes and forbs. Seeds for all species were planted at 0.5g m^{-2} evenly. The experiment region had an average elevation of 224 m, a mean annual temperature of 10.7°C, a mean annual precipitation of 1042 mm, and a growing season length that averages 172 days. The experiment plot was in maize-soybean rotation before the planting of the prairie. No water, fertilizers, or herbicides were applied after the prairie was planted. The grasses were mowed in Nov every year though in 2010 small subsets of prairie were left unmowed for sampling throughout the winter. The prairie was 3 years old and was well established when this experiment began. Except *Veronicastrum virginicum*, all the other 27 species originally planted have been found in the prairie during the experiment. Plant density in 2010 was ~40 stems m^{-2}. Stand abundance was recorded as the number of individual stems for forbs and legumes, and was the number of clumps for grasses and sedges.

Biomass sampling

Plant biomass was measured every one to two months across the annual crop production cycle from Jun 2010 to Apr 2011. Species-level aboveground biomass was sampled at four times during the growing season on 7 June, 1 Aug, 1 Oct and 2 Nov, and four after the growing season on the 15th day every month from Jan to Apr. Samples were not taken from within 10 m of the plot border to minimize edge effects. For the sampling during growing season, four 0.25 m^2 quadrats were set up randomly along a 100 m transect to sample biomass. Although the quadrat size is small by agronomic standards, foundational rangeland experiments evaluating the relative efficiencies of quadrat size found 0.25 m^2 quadrats to be suitable to assess biomass production in uniform grass stands (Heaton *et al*., 2009). Eight transects were established across the prairie for a total of 32 plots. Six 2 m × 2 m plots were kept from the annual harvest in Nov for sampling after growing season. Biomass was sampled in each plot using a 0.25 m^2 quadrat from Jan to Apr. During the sampling, each species was cut by hand to a 5 cm stubble height, put in paper bags and weighed fresh. In Jan and Feb 2011, when the bottom part of plant stands was buried by the snow, plants were cut to the surface of snow. Biomass samples were separated into leaf, stem and flower. All samples were then oven-dried to a constant mass at 70°C and species dry matter was calculated by summarizing the dry matter content of each component. Species-level biomass moisture content was determined based on the difference between fresh and oven-dry biomass.

Table 1. *Twenty-eight species planted in Energy Biosciences Institute energy farm*

PFT	Family	Scientific Name	Common Name
C_3 grass	Poaceae	*Elymus canadensis*	Canada wild rye
C_3 sedge	Cyperaceae	*Carex bicknellii*	Copper-shouldered oval sedge
C_4 grass	Poaceae	*Andropogon gerardii*	Big bluestem
C_4 grass	Poaceae	*Schizachyrium scoparium*	Little bluestem
C_4 grass	Poaceae	*Sorghastrum nutans*	Indian grass
Forb	Asteraceae	*Aster novae-angliae*	New England aster
Forb	Asteraceae	*Coreopsis palmata*	Prairie coreopsis
Forb	Asteraceae	*Coreopsis tripteris*	Tall tickseed
Forb	Asteraceae	*Echinacea pallida*	Pale coneflower
Forb	Asteraceae	*Helianthus grosseserratus*	Sawtooth sunflower
Forb	Asteraceae	*Heliopsis helianthoides*	Early sunflower
Forb	Asteraceae	*Parthenium integrifolium*	Wild quinine
Forb	Asteraceae	*Ratibida pinnata*	Yellow coneflower
Forb	Asteraceae	*Rudbeckia subtomentosa*	Sweet black-eyed susan
Forb	Asteraceae	*Silphium integrifolium*	Wholeleaf rosinweed
Forb	Asteraceae	*Silphium laciniatum*	Compassplant
Forb	Asteraceae	*Silphium perfoliatum*	Cup plant
Forb	Asteraceae	*Silphium terebinthinaceum*	Prairie dock
Forb	Asteraceae	*Solidago rigida*	Stiff goldenrod
Forb	Lamiaceae	*Monarda fistulosa*	Wild bergamot
Forb	Lamiaceae	*Pycnanthemum virginianum*	Common mountain mint
Forb	Scrophulariaceae	*Penstemon digitalis*	Foxglove beardtongue
Forb	Scrophulariaceae	*Veronicastrum virginicum*	Culver's root
Legume	Fabaceae	*Astragalus canadensis*	Canadian milkvetch
Legume	Fabaceae	*Baptisia leucantha*	White wild indigo
Legume	Fabaceae	*Desmodium canadense*	Showy tick trefoil
Legume	Fabaceae	*Lespedeza capitata*	Roundhead lespedeza
Legume	Fabaceae	*Dalea purpureum*	Purple prairie clover

Elemental analysis

Species-level biomass carbon (C) and N concentration were measured for all species during each harvest. Following the dry biomass measurements, 0.1–0.2 g material was sampled randomly from leaves of each species. Leaf samples were then ground to a fine powder using a stainless steel pulverizer (Kleco Pulverizer, Kinetic Laboratory Equipment Co., Visalia, CA, USA). A 2–4 mg sample was then weighed on an analytical balance (CPA2P Electronic Microbalance, Sartorius AG, Goettingen, Germany) and encapsulated in tin foil. C and N percentage was determined by combustion and thermal conductivity separation using a combustive elemental analyzer (Costech Analytical Technologies, Valencia, CA, USA), calibrated with an acetanilide standard (C8H9NO, Costech Analytical Technologies). Leaf samples were not available for most plant species after senescence, especially for forbs and legumes. Therefore, both leaf and stem N were measured for all species from Nov to Apr following the same procedure provided above. Standing N mass was calculated using aboveground biomass yield and biomass N concentration.

Data analysis

Data was analyzed using R. Species, PFT and harvesting time were considered as fixed variables. Significance was determined using the F statistic and α=0.05.

Results

Biomass yield and moisture content

Dry biomass yield of prairie mixture achieved peak yield in Oct (17.57 ± 6.98 Mg ha^{-1}) (Fig. 1). From Oct to Nov, dry biomass declined by 32.0% to 12.03 ± 3.22 Mg ha^{-1} and kept decreasing from Nov to Jan (7.74 ± 2.02 Mg ha^{-1}). In general, there was little overall change in dry biomass yield between Jan harvest and Apr harvest. Fresh biomass was not measured in Jun, but changes of fresh yield had the same trend as dry biomass through the rest of the study period. Highest fresh yield (28.82 ± 9.80 Mg ha^{-1}) was observed in Oct 2010. Among PFTs grasses contributed the most to the dry biomass yield through most of the study period (Fig. 1). Both C_3 and C_4 grasses achieved the highest yield in Oct. Yield of C_3 grass was relatively stable between Nov and Feb and started decreasing after Feb. A steady reduction for biomass of C_4 grasses between Oct and Apr was found. Yield of forbs was highest in Aug and slightly fluctuated from Oct to Apr, which might be caused by sampling error. Biomass of legumes was consistently lower than other PFTs. Unidentified biomass, composed of plant litter which was impossible to attribute to species, increased considerably in the Oct harvest, largely because of plant senescence. However, the amount of yield attributing to plant litter dropped from 3.81 ± 1.23 Mg ha^{-1} to 0.21± 0.12 Mg ha^{-1} between Nov and Jan and stayed low in Feb. This is because accumulation of snow in the field largely decreased harvestable biomass in Jan and Feb. Dry weight based biomass moisture content decreased from 140.5% ± 25.2% to 30.5% ± 15.2% from Aug to Jan and maintained relatively constant from Jan to Apr (Fig. 1).

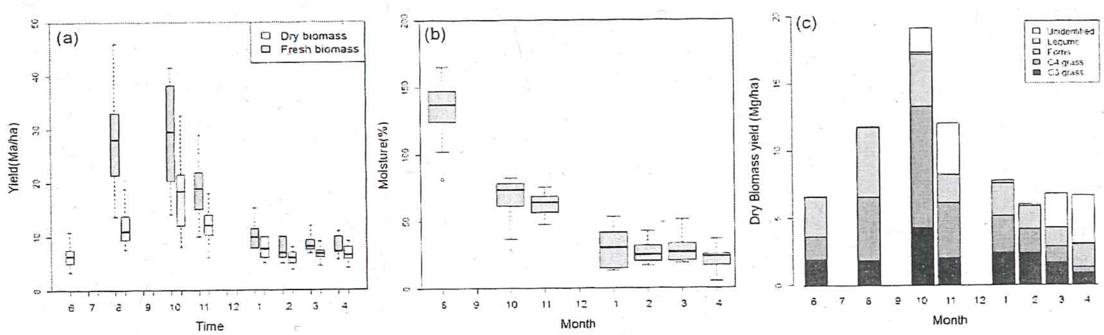

Fig. 1. Seasonal changes in (a) average fresh biomass and dry biomass, (b) average dry standing biomass of each plant functional type, and (c) overall moisture content of mixed prairie standing biomass.

Nitrogen concentration

When averaged across all species, N concentration declined steadily from a high of 1.63% ± 0.41% in young shoot tissue in early summer to 0.60% ± 0.29% in winter for the prairie (Fig. 2). Decrease of N concentration was more dramatic from Jun to Nov. N concentration declined slowly from 0.70% ± 0.39% to 0.60% ± 0.29% from Nov 2010 to Jan 2011 and stayed relative constant (~0.6%) from Jan to April. The seasonal progression of N reduction was generally consistent across all species. Most species achieved lowest N in Jan. Overall, legumes had significantly higher N concentration in standing biomass than other PFTs ($P < 0.001$) through the study period. N concentration of C_4 grasses was lower than other PFTs from Jun to Nov. Although N of C_4 grasses stayed relatively low during winter 2011 compared to other PFTs, the difference was not significant.

Standing N mass

Although average N concentration in prairie standing biomass declined steadily between June and Oct, standing N mass of prairie mixture increased from 107.1 ± 27.1 kg ha^{-1} to 182.4 ± 59.4 kg ha^{-1} (Fig. 3), because of an increase in biomass. Standing N had a dramatic decline by 54% from Oct to Nov, which was caused by a simultaneous significant decline of both biomass and

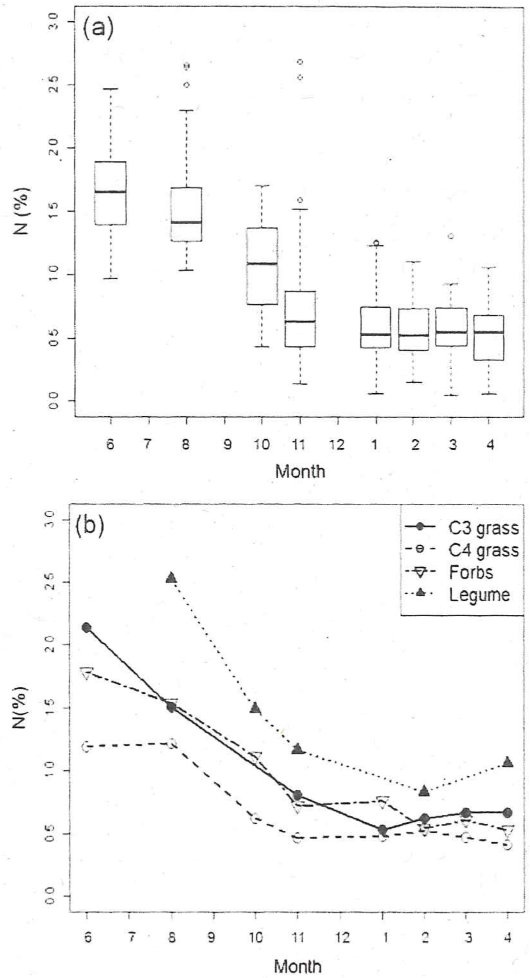

Fig. 2. Changes in average nitrogen concentration (%) of (a) mixed prairie standing biomass and (b) standing biomass of each plant functional type.

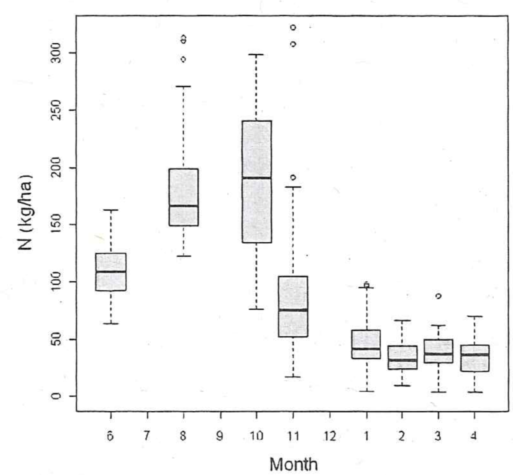

Fig. 3. Seasonal changes in overall standing N mass.

N concentration. Prairie mixture would potentially remove 84.6 ± 46.5 kg N ha^{-1} with a yield of 12.03 ± 3.22 Mg ha^{-1} if harvested in Nov. The amount of N removed through harvesting would decrease to 46.6 ± 22.5 kg ha^{-1} in Jan. However, the decrease of amount of N removed in harvest is mainly due to decrease of biomass. There was little change in stranding N mass from Jan to Apr due to the relatively stable levels of yield and N concentration.

Discussion

Previous studies have shown that yield, biomass quality, and environmental impacts can be strongly affected by harvest time for *Miscanthus* × *giganteus*, switchgrass, reed canary grass and other potential energy crop monocultures (Xiong *et al*., 2008, 2009; Heaton *et al*., 2009; Adler *et al*., 2006; Lewandowski *et al*., 2003). The results of this study demonstrate that the quantity-quality trade-off also exists in this prairie production system, despite the differences among species in senescence phenology. Our findings suggest that harvesting in Nov allows the prairie to senesce and recycle nutrients to a great extent and can potentially reduce fertilizer requirements. Although standing N biomass fell to a lower and stable level in Jan, it was mainly due to biomass reduction instead of changes in C:N ratio. However, biomass moisture continued to decline between Nov and Jan, which suggests that harvest after Nov can potentially improve feedstock quality by reducing biomass moisture and artificial drying costs. In addition, since N concentration had a slight decline from Nov to Jan, harvest after Nov may allow the prairie to senesce more completely. However, considering the dramatic loss of harvestable biomass between Nov and Jan, the prairie mixture might be harvested as soon as possible after moisture achieves a level low enough to optimize the benefits with respect to both yield and environment needs.

The average N concentration in standing biomass of prairie mixture was higher than C_4 monocultures of *Miscanthus* × *giganteus* and switchgrass which generally maintain a N concentration < 0.5% in late fall (Heaton *et al*., 2009; Xiong *et al*., 2008). C_4 grasses generally have lower N concentration than forbs, C_3 grasses and legumes because of high photosynthetic N use efficiency.

Findings of this study suggest that harvest time critically influences N dynamics in mature stands of prairie mixtures in the temperate climate of Illinois. Our results indicate that delaying harvest can reduce the moisture and N concentration in biomass feedstock, but the majority of reductions are realized by late fall and the biofuel crops should be harvested before the risk of weather-related losses overwinter. The harvest time that is optimal with respect to environment, feedstock quality and yield for the prairie studied is between Nov and Jan.

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