Miscanthus and Switchgrass Production in Central Illinois: Impacts on Hydrology and Inorganic Nitrogen Leaching

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Biomass crops are being promoted as environmentally favorable alternatives to fossil fuels or ethanol production from maize (*Zea mays* L.), particularly across the Corn Belt of the United States. However, there are few if any empirical studies on inorganic N leaching losses from perennial grasses that are harvested on an annual basis, nor has there been empirical evaluation of the hydrologic consequences of perennial cropping systems. Here we report on the results of 4 yr of field measurements of soil moisture and inorganic N leaching from a conventional maize–soybean [*Glycine max* (L.) Merr.] system and two unfertilized perennial grasses harvested in winter for biomass: *Miscanthus* × *giganteus* and switchgrass (*Panicum virgatum* cv. Cave-in-Rock). All crops were grown on fertile Mollisols in east-central Illinois. Inorganic N leaching was measured with ion exchange resin lysimeters placed 50 cm below the soil surface. Maize–soybean nitrate leaching averaged 40.4 kg N ha^{-1} yr^{-1}, whereas switchgrass and *Miscanthus* had values of 1.4 and 3.0 kg N ha^{-1} yr^{-1}, respectively. Soil moisture monitoring (to a depth of 90 cm) indicated that both perennial grasses dried the soil out earlier in the growing season compared with maize–soybean. Later in the growing season, soil moisture under switchgrass tended to be greater than maize–soybean or *Miscanthus*, whereas the soil under *Miscanthus* was consistently drier than under maize–soybean. Water budget calculations indicated that evapotranspiration from *Miscanthus* was about 104 mm yr^{-1} greater than under maize–soybean, which could reduce annual drainage water flows by 32% in central Illinois. Drainage water is a primary source of surface water flows in the region, and the impact of extensive *Miscanthus* production on surface water supplies and aquatic ecosystems deserves further investigation.

Maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production on tile drained land in the midwestern United States has altered hydrology and contributes to large transfers of nitrate N from fields to streams and rivers in (David et al., 1997; McIsaac and Hu, 2004; USEPA, 2007; Gentry et al., 2009). Nitrate is a drinking water concern and is the major source of N that leads to hypoxia in the Gulf of Mexico because little is removed as it is transported down the Mississippi River (Royer et al., 2004, 2006; USEPA, 2007). The area planted to maize has expanded in recent years and is projected to increase further to meet an increased demand for fuel ethanol, which could have detrimental consequences for water quality (Donner and Kucharik, 2008; Simpson et al., 2008). In 2008, approximately 30% of the maize grown in the United States was used for fuel ethanol production (USDA–ERS, 2010), which is estimated to produce 1.34 calories of energy for every calorie of fossil fuel invested (Shapouri et al., 2002). Considerably greater energy returns are possible from perennial grasses *Miscanthus* × *giganteus* and switchgrass (*Panicum virgatum*) (Schmer et al., 2008; Heaton et al., 2008; Dohleman and Long, 2009), and these crops are generally thought to have many other environmental benefits as well, such as reduced nitrate losses (Powlson et al., 2005).

A few studies have demonstrated that unfertilized and unharvested perennial grasses in the Conservation Reserve Program produce little inorganic N leaching (Randall et al., 1997; Mitchell et al., 2000; Brye et al., 2001), but no study has examined perennial grasses that have been annually harvested for biomass. Many of the studies on switchgrass in the United States have focused on the Great Plains, where precipitation and leaching are much less than in the tile-drained upper Mississippi River basin (e.g., Schmer et al., 2008) and where the emphasis has been on biomass production (Heaton et al., 2008; Dohleman and Long, 2009). A few studies have examined surface runoff of sediment, nitrate, and P from switchgrass, with most estimating losses by this pathway through modeling (e.g., Nelson et al., 2006; Vadas et al., 2008; Schilling et al., 2008). We know of no studies that assessed inorganic N losses through drainage waters.

Conversion from maize–soybean to perennial crops for biofuel production will likely alter water, carbon, and N dynamics, which may produce benefits (e.g., reduced nitrate leaching, reduced

J. Environ. Qual. 39:1790–1799 (2010)
doi:10.2134/jeq2009.0497
Published online 26 July 2010.
Received 13 Dec. 2009.
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Abbreviations: ET, evapotranspiration; PET, potential evapotranspiration.

flooding, and increased soil carbon storage) as well as costs (e.g., reduced water flows during droughts) (Schilling et al., 2008). Quantifying these benefits and costs requires empirical estimates of the magnitude of these effects. In the Corn Belt of the Midwest, stream flow is greatest during late winter or spring, with lowest flows in late summer into fall (Yeh et al., 1998). Low flows late in the growing season are a result of high evapotranspiration (ET) during the summer, which depletes soil moisture. During the low flow periods, aquatic organisms can be stressed due to high water temperatures and low dissolved oxygen concentrations. In addition, phosphorus concentrations tend to be highest at this time, which can lead to high algal productivity and low dissolved oxygen during early morning hours (Morgan et al., 2006; Royer et al., 2008). If perennial grasses alter soil moisture and concomitantly streamflow, this could have both positive and negative impacts on stream flow and biotic integrity. Powlson et al. (2005) noted that the possible increased use of water by switchgrass and *Miscanthus* needed further study. *Miscanthus* has been shown to produce two to three times as much harvestable biomass as switchgrass and has the potential to produce substantially more biofuel per hectare than maize (Heaton et al., 2008; Dohleman and Long, 2009).

Growing perennial grasses on highly productive Mollisols in the upper Midwest in place of maize–soybean could provide environmental benefits such as adding vegetative diversity to the landscape, reducing nutrient losses, and moderating flood flows. These soils are fertile and have excellent soil moisture holding characteristics (Endres et al*.,* 2001). They also have high nitrate losses from maize–soybean production. Assessing the potential benefits and costs of converting land from maize–soybean to *Miscanthus* or switchgrass requires empirical determination of crop performance in specific regions. Therefore, our objectives were (i) to quantify differences in soil moisture and inorganic N leaching from *Miscanthus* × *giganteus*, switchgrass, and maize–soybean grown in east-central Illinois and (ii) to use these plot-scale differences to estimate larger-scale hydrologic and water quality changes that may occur from widespread conversion from maize–soybean to *Miscanthus* or switchgrass.

Materials and Methods

Study Location

All field plots were located on the University of Illinois Crop Science Research and Education Center, approximately 5 km south of the main campus in Urbana, IL (88.23°W, 40.08°N). East-central Illinois has a warm, humid continental climate. The 1971 to 2000 average or "normal" annual temperature was 10.8°C, and the average annual precipitation was 104 cm, with approximately 6% occurring as snow. During 2005 to 2007, annual temperatures were 0.9 to 1.3°C above normal, and in 2008 the average temperature was 0.3°C below normal. During the study period, precipitation during the growing season was below normal in 2005 and 2007, near normal in 2006, and above normal in 2008.

Experiments were conducted in deep loess Mollisols that are relatively flat (>2% slope) with 4 to 7% organic matter in the top 30 cm. These soils have poor natural drainage largely due to texture and slope but are highly productive when drainage is enhanced by subsurface drains or "tiles." At the study site, and throughout much of the region, tile drains had been installed sometime after 1880, but the precise locations of these drains were not recorded. During the experiment, soil moisture was measured in large (0.2 ha) and small (0.01 ha) plots as described below. The soils in the small plots are classified as Flanagan silt loam (fine, smectitic, mesic Aquic Argiudolls) (Endres et al., 2001). Inorganic N leaching was measured only in the large plots, where the soils are classified as Elburn silt loam (fine-silty, mixed, superactive, mesic Aquic Argiudolls) and Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls) (Endres et al*.,* 2001).

Plot Establishment

Initial comparisons of switchgrass and *Miscanthus* were conducted in four replicate small plots (0.01 ha) of each crop planted in May 2002 as described in Heaton et al. (2008). After tilling and seedbed preparation, switchgrass ('Cave-In-Rock') was seeded at a rate of 13 kg pure live seed ha^{-1}. Although Lemus et al. (2002) reported that there were more productive varieties grown in southern Iowa, Cave-in-Rock was the recommended variety for Illinois at the time the experiment was initiated. *Miscanthus* × *giganteus* is a sterile clone that does not produce seed and must be established by planting live rhizomes. Rhizomes that had been propagated in a greenhouse during the previous winter were planted by hand at a density of one plant per square meter. The plants had 10 to 50 cm of top growth at planting. The plots were irrigated twice during 2002, and weeds were controlled with herbicides in 2003 (Heaton et al., 2008). No fertilizer was applied to these plots in an attempt to evaluate low-input biomass production systems. Both *Miscanthus* and switchgrass are expected to produce maximum yields 3 yr after planting (Heaton et al., 2008; Schmer et al., 2008). Soil moisture was measured in these plots starting in 2005 to obtain observations on mature stands. Heaton et al. (2008) provides data on the biomass production from these plots during 2004 through 2006.

Because small plots are subject to edge effects, larger (0.2 ha) plots were established to compare *Miscanthus*, switchgrass, and maize–soybean managed with conventional agricultural equipment (Dohleman and Long, 2009). In spring 2004, 16 replicate 0.2-ha plots were established. Four plots were randomly assigned to switchgrass, eight to *Miscanthus*, and four to a soybean–maize rotation. Switchgrass seed ('Cave-In-Rock') was drilled at a rate of 11 kg pure live seed per hectare. No fertilizer was applied to the switchgrass plots. Plantings of *Miscanthus* in summer 2004 failed due to insufficient precipitation or irrigation after planting rhizomes. Four 0.2-ha plots were planted in 2005 with *Miscanthus* rhizomes spaced 1.2 m apart (7000 rhizomes ha^{-1}) and were irrigated after planting, which allowed for successful establishment. No fertilizer was applied to the *Miscanthus* plots. Once established, the stands of both crops were considered good but variable (Emily Heaton, Iowa State University, personal communication). Switchgrass and *Miscanthus* were mechanically harvested in the winter when the ground was frozen, and the biomass was removed from the plots.

In spring 2004, soybeans were planted in the plots assigned to the maize–soybean rotation, followed by maize in 2005, soybean in 2006, and maize in 2007. In 2008, the maize–soybean plots were split, with half of each plot planted to maize and the other half to soybeans. In 2005, maize was fertilized with 202 kg N ha^{-1}. In 2007 and 2008, the maize was fertilized with 168 kg N ha^{-1}. Row crops were harvested for grain only, and residues were returned to the soil. After the row crops were harvested, the plots were chisel plowed in the fall (except in 2006 when the soil was too wet to plow) and then disked before planting, leaving little or no crop residues on the soil surface at planting. In this region, the optimal planting dates are approximately 20 April for maize and approximately 7 May for soybean. However, because of unusually rainy weather during normal planting times in 2007 and 2008, maize was planted on 8 May 2007 and 12 June 2008. Soybeans were also planted on 12 June 2008.

Soil Moisture Measurements

Soil moisture was measured in 10-cm-depth increments to 90 cm using a Sentek Diviner 2000 probe (Sentek Technologies, Stepney, Australia). The probe produces a signal that is correlated with the average soil moisture 5 cm above and below the measurement point. Thus, the probe measures soil moisture from 5 cm below the top of its access tube to a depth of 95 cm. The top of the access tube was typically 1 cm above the soil surface, and thus the measurements represent from 4 to 94 cm of the soil profile. Four polyvinylchloride access tubes per plot were installed in each of the *Miscanthus* and switchgrass plots. In the row crops, six access tubes per plot were installed: three within crop rows, and three halfway between rows. Measurements were usually taken every 3 to 7 d during the 2005 to 2008 growing seasons. Periodically, soil samples were taken from opposite sides of an access tube to determine volumetric water content from gravimetric measurements and to create a calibration curve for the Diviner 2000. The plot average volumetric water content was calculated as $0.36 \times SF^{1.53}$, where SF is the scaled frequency recorded by the Diviner 2000 ($R^2 = 0.68$; $N = 45$).

For the row crops, the soil moisture access tubes were removed after harvest and before tillage and reinstalled each spring after planting. For the perennial crops, the tubes remained in place over the winter, although monitoring was discontinued after maize–soybean harvest. Monitoring was resumed in the spring before planting the row crops in all years except 2005, when monitoring began in all treatments after planting the row crop.

Water Budget Estimation

A water budget was developed to estimate ET, drainage, and lateral inflow of water into the plots. Precipitation was measured using calibrated, unshielded tipping bucket rain gages near the plots. Measured values were adjusted for undercatch due to wind speed using the equation of Yang et al. (1998). This had the effect of increasing the value of precipitation by approximately 12%. Potential evapotranspiration (PET) estimates were taken from the Illinois Climate Network station in Champaign (3 km from the study plots), calculated using the approach by Van Bavel as described in Hollinger et al. (1994). The field capacity of the soil was estimated from the observed soil moisture values that occurred 3 or 4 d after precipitation events in the spring and fall when there was little evapotranspiration. The average field capacity for the soil profile was 0.34, which compares favorably with the 0.3-bar tension values for the Drummer and Flanagan soils measured by USDA–NRCS personnel (Don Pitts, USDA–NRCS, personal communication) and is within the range of typical values for silt loams and silty clay loams (USDA–SCS, 1991). When precipitation exceeded the field capacity, the excess water was assumed to leave as subsurface drainage or surface runoff (hereafter referred to as drainage) during the day of the rainfall event. For periods when the soil moisture was below field capacity, depletion of soil moisture was assumed to be actual ET, and a ratio of actual to potential evaporation was calculated. During periods with drainage, the evapotranspiration was estimated by multiplying the PET by recent actual ET:PET ratios. Finally, on three dates, soil moisture increased in excess of 5 mm more than could be accounted for by measured precipitation. The increase that could not be attributed to precipitation was assumed to be lateral or upward flow of water into the top 90 cm of the plots.

Inorganic Nitrogen Leaching

To quantify inorganic nitrogen leaching, ion exchange resin lysimeters were used following the design and methods described in Susfalk and Johnson (2002) and Langlois et al. (2003). The lysimeters consisted of a 5.1-cm-diam. polyvinylchloride pipe and a coupling section that were a total of 7 cm long. A layer of ion exchange resin capable of absorbing nitrate and ammonium was placed between two layers of washed sand and held together in the lysimeter with a permeable nylon membrane. The lysimeters were installed in the soil at 50 cm depth under undisturbed soil. Water draining down through the soil profile passed through the lysimeters, where nitrate and ammonium were adsorbed onto the resin. After a year in the soil, the lysimeters were removed and replaced with new ones containing fresh resin. The mass of nitrate and ammonia absorbed on the year-old resin was determined by KCl extraction. Nitrate and ammonium concentrations in the extract were analyzed colorimetrically by flow injection analysis with a Lachat QuikChem 8000 (Lachat, Loveland, CO). The mass of the nitrate and ammonia absorbed on the resin was determined by multiplying the concentrations by the extract volume.

In spring 2005, six lysimeters were installed in four 0.2-ha plots of switchgrass and maize ($N = 24$ for each crop year). Because of the establishment failure of the *Miscanthus* plots in 2005, lysimeters were first installed in *Miscanthus* plots in spring of 2006. Because the lysimeters had a relatively small surface area, individual lysimeter values could produce highly variable results due to spatial variability in flow paths and N dynamics occurring at a small scale. To reduce the influence of outliers, trimmed mean values and 95% confidence intervals were calculated for each crop and year to make statistical comparisons. To calculate the trimmed means, the maximum and minimum observations were eliminated from the calculation.

Results and Discussion

Soil Moisture

In the small plots, soil moisture in the top 90 cm of soil under *Miscanthus* was significantly less than under switchgrass during the middle and later periods of the 2005 to 2008 growing seasons (Fig. 1). During the dry years of 2005 and 2007, there was little difference in soil moisture before 19 July, but, in the wetter

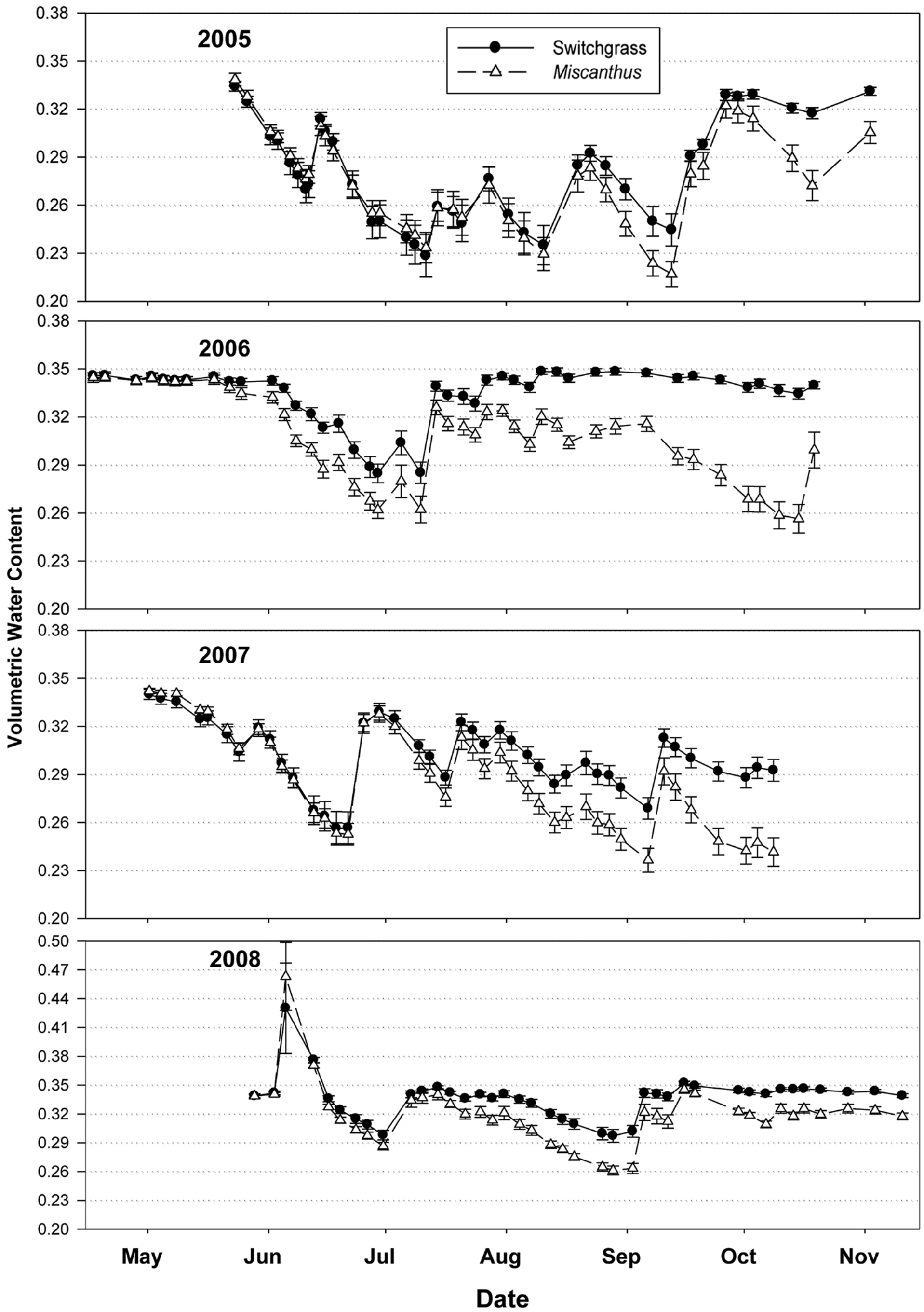

Fig. 1. Mean and 95% confidence interval of volumetric soil moisture content (0–90 cm) in mature switchgrass and *Miscanthus* measured in small plots (0.01 ha) during the 2005 to 2008 growing seasons. Error bars indicate 95% confidence intervals for the mean value.

years of 2006 and 2008, the differences appeared as early as 30 May. The differences in soil moisture represented as much as 70 mm of soil water at the end of the growing season in 2006 (15 October). The 4-yr average difference in soil moisture between the two crops at the end of the growing season was 45 mm.

A similar pattern was observed in the large plots during the 2006–2008 growing season (Fig. 2). The 3-yr average difference between *Miscanthus* and switchgrass soil moisture at the end of the growing season was 52 mm. This difference indicates that end-of-season soil moisture was recharged earlier under switchgrass and thus drainage and runoff would tend to occur sooner from Cave-in-Rock switchgrass than from *Miscanthus*. Late summer and early autumn is the low-flow season for streams throughout much of the Midwest, and the additional water needed to recharge the soil under *Miscanthus* would tend to intensify and prolong the low-flow season.

The maize–soybean system ended the growing seasons with significantly less soil moisture than switchgrass in three ears (2005–2007) out of four, with an average difference of 15 mm, and significantly more soil moisture than *Miscanthus* in two years (2006–2007) out of three, with an average difference of 34 mm at the end of the measurement period. In 2008 the mean values were not statistically different ($p < 0.05$). Early in the 2006 through 2008 growing seasons (before 8 July), soil moisture under the maize–soybean system was significantly greater than under switchgrass (by an average of 31 mm) or *Miscanthus* (by an average of 40 mm). This was likely due to the more rapid growth of the perennial grasses early in the season compared with the annual crops. This was not observed in 2005, which was an unusually dry year and only the second growing season for switchgrass.

During the 2006 growing season, soil moisture changed little under the soybean crop. Evidently, evapotranspiration was essentially balanced by frequent precipitation. In 2007, after 18 July, soil moisture under maize was significantly less than switchgrass and not statistically different from *Miscanthus* until 6 September, when the soil moisture under *Miscanthus* became significantly less than under maize. Finally, in 2008, when both maize and soybeans were grown, the soil moisture under these two crops was not statistically different throughout the growing season, and both are represented in Fig. 2 as a single line. Early in the 2008 growing season, soil moisture was greater under maize–soybean than under switchgrass or *Miscanthus*, but after a series of rainfall events around 9 July, the three systems were statistically indistinguishable. During August, soil moisture under switchgrass was greater than the two other systems. After 1 September, all three systems were statistically indistinguishable when soil moisture on all three systems was essentially recharged to field capacity.

The greatest differences in soil moisture occurred in the uppermost layers of soil (Fig. 3). During the early and middle portions of the growing season, the perennial crops typically reduced soil moisture relative to maize–soybean in the top 60 to 70 cm of soil, whereas soil moisture below 70 cm remained relatively constant. In the latter half of the growing seasons, soil moisture below 70 cm also declined, especially under *Miscanthus* and especially in 2006, when the greatest differences in soil moisture were observed, and the lowest average moisture content at 90 cm depth was observed.

The lower soil moisture under *Miscanthus* is partly due to greater transpiration, as indicated by its greater leaf area index and biomass compared with switchgrass and maize–soybean. Heaton et al. (2008) reported *Miscanthus* biomass production of 42 Mg ha^{-1}, compared with 17 Mg ha^{-1} from switchgrass in the 0.01 ha plots during the 2005–2006 growing season, and that the leaf area index of *Miscanthus* was frequently >8, compared with <7 for switchgrass. Dohleman and Long (2009) reported *Miscanthus* biomass production of 30 Mg ha^{-1} compared with 19 Mg ha^{-1} from maize in the 0.2-ha plots during the 2007–2008 growing season, and green leaf area index of *Miscanthus* was significantly greater than of maize for all of the 2007 the growing season and all but a brief period in the 2008 growing season. In August and September, switchgrass allocates energy to seed production (Vogel, 2004), whereas *Miscanthus* continues to produce vegetative biomass, which requires greater water use and accounts for some the differences in soil moisture later in the season. Differences in canopy structure may also influence differences in evaporation from the soil. Switchgrass has relatively fine leaves and stems that can form a dense mat that may inhibit the rate of gas exchange between the soil and atmosphere compared with *Miscanthus* and maize, which have coarser leaves and stems that allow for greater air movement and evaporation under the canopy.

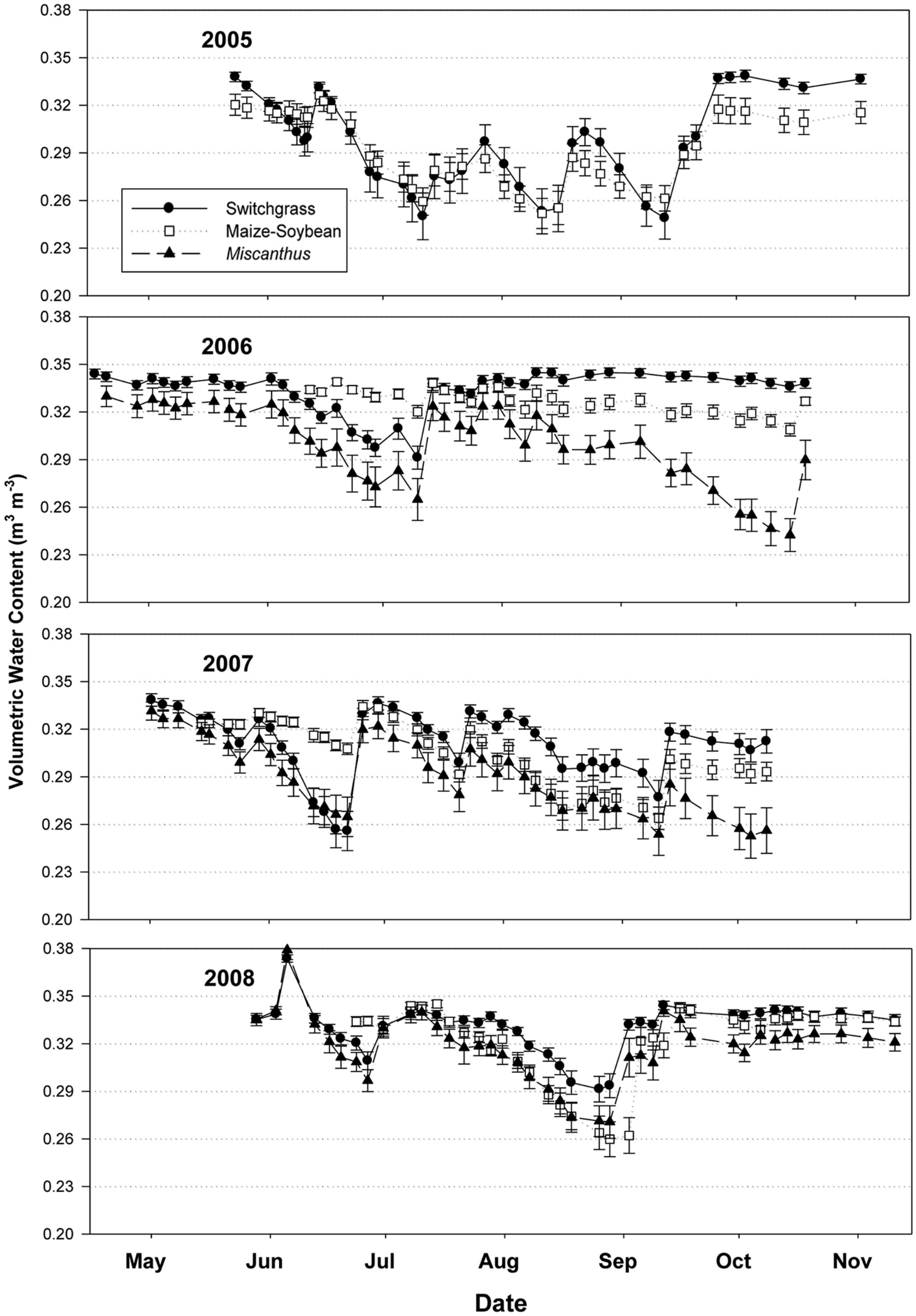

Fig. 2. Average volumetric soil moisture content (0–90 cm) measured in switchgrass, maize–soybean, and *Miscanthus* in large plots (0.2 ha) during the 2005 to 2008 growing seasons. Error bars indicate 95% confidence intervals for the mean value.

Water Balance

Water balance calculations indicate that ET from *Miscanthus* grown in the small plots was, on average, 23 mm greater than the *Miscanthus* in the large plots, whereas estimated ET from switchgrass grown in the small plots was on average 18 mm greater than switchgrass grown in large plots (Table 1). This may have been due to higher planting densities in the small plots, more effective weed control, or edge effects resulting in higher productivity in the small plots (Heaton et al., 2008; Dohleman and Long, 2009). The edge effects contributing to greater productivity may have included lateral seepage of water into the plots as well as greater air turbulence and sun-

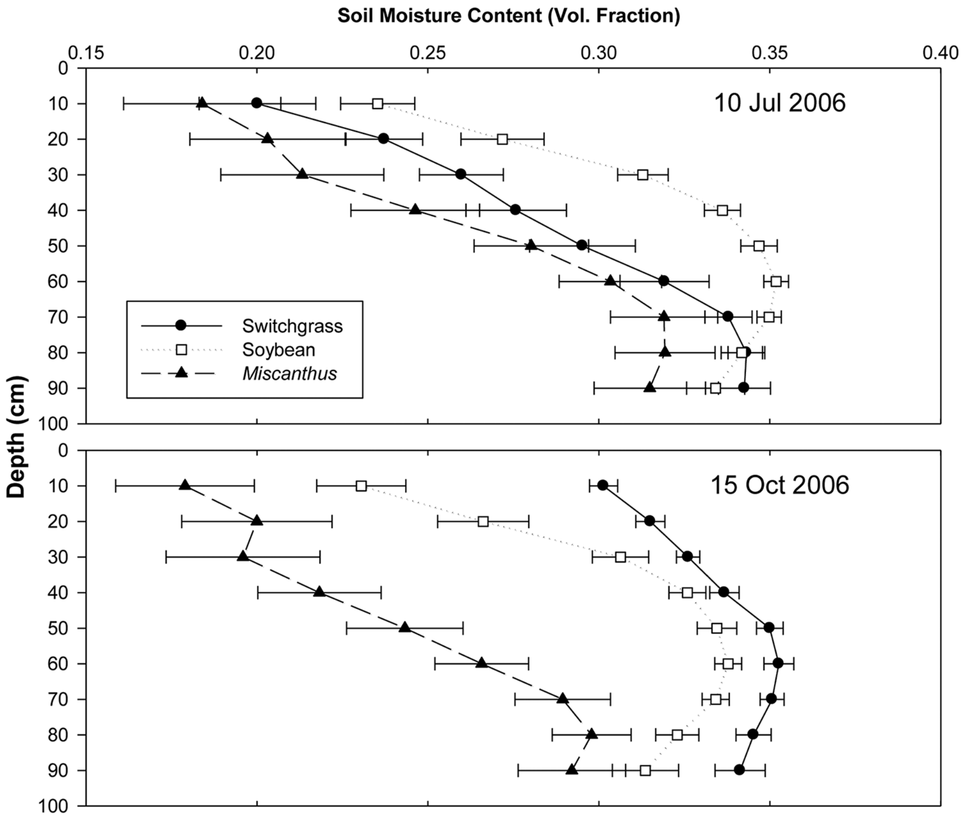

Fig. 3. Variation in soil moisture content with depth in the different cropping systems on 10 July and 15 Oct. 2006. The average soil moistures observed on 15 Oct. 2006 represent the largest observed differences between *Miscanthus* and the other two cropping systems in this study.

light capture. On three occasions, after the soil had become very dry, subsequent precipitation events led to increases in soil moisture that were 5 to 20 mm greater than the measured precipitation input for the small plots. This was observed only once in the large plots in 2005, when an increase in switchgrass soil moisture was 6 mm greater than the measured precipitation. This may have been due to raingage undercatch or lateral seepage from the surrounding sod borders. The small plots were 5 m from a road ditch that could have contributed to lateral seepage. In the small plots, the cumulative soil moisture increase in excess of precipitation was 20 and 21 mm in *Miscanthus* in 2005 and 2007, respectively, and 6 mm in the switchgrass in 2007. These values were treated as external water inputs (in addition to precipitation) in the water balance used to estimate ET values in Tables 1 and 2. It is possible that additional seepage occurred that we were unable to detect because of timing and accuracy of precipitation and soil moisture measurements.

The average difference between estimated ET from *Miscanthus* and switchgrass was similar for small and large plots. For the 0.01-ha plots, the 2006–2008 average difference in ET was 146 mm, compared with 136 mm for the 0.2-ha plots. The greatest differences between the two crops occurred during the wet years of 2006 and 2008, when estimated ET from *Miscanthus* ranged from 131 to 241 mm more than from switchgrass.

In all years except 2005, soil moisture measurements in the perennial crops were initiated before planting of maize or soybeans. The access tubes for measuring soil moisture in the annual crops could only be installed after planting. Consequently, estimated ET values for maize and soybeans were compared with *Miscanthus* and switchgrass values only for the period after planting of the row crops (Table 2). For this period, the average estimated ET from maize–soybean was only about 22 mm greater than from switchgrass, although there was considerable year-to-year variation in the relative differences.

The 2006–2008 average estimated ET from maize–soybean was 104 mm less than from *Miscanthus*. The 30-yr average (1978–2007) annual streamflow from watersheds in central Illinois, as indicated by water yield, is 326 mm (USGS stream flow gauge for the Embarras River at Camargo). Wherever in this region *Miscanthus* replaces maize–soybeans and increases ET by 104 mm, drainage (primarily stream flow) would be reduced by this amount, which would result in a 32% reduction in annual surface

Table 1. Cumulative rainfall, potential evapotranspiration, and estimated evapotranspiration for *Miscanthus* and switchgrass during the 2005 to 2008 growing seasons in small (0.01 ha) and large (0.2 ha) plots.

Observational period	Rainfall	PET†	Estimated evapotranspiration			
			Miscanthus		Switchgrass	
			Small plot	Large plot	Small plot	Large plot
	mm					
23 May to 2 Nov. 2005	377	735	447		337	304
20 Apr. to 19 Oct. 2006	522	775	504	493	263	284
1 May to 8 Oct. 2007	310	815	417	388	359	319
28 May to 10 Nov. 2008	742	721	418	389	278	258
2006–2008 avg.	525	770	446	423	300	287
2005–2008 avg.	541	761	446		308	291

† PET, potential evapotranspiration.

water flow. In a modeling study of the Raccoon River watershed in Iowa, Schilling et al. (2008) estimated that converting corn–soybeans to perennial grasses would increase ET by 47 or 58 mm, depending on whether warm season or cool season grasses were planted, and this would reduce water annual water yields by 46 and 54 mm, respectively. Compared with a baseline water yield of 193 mm, these values represent reductions in water yield of 24 and 28%, respectively.

Our estimates of ET do not account for changes in soil moisture in the top 4 cm or upward flow or root extraction of water from below 94 cm depth. Taking these into account would increase our estimates of ET. Soil moisture content in the lowest depth increment we monitored (84–94 cm) changed little over the course of the growing season (<6 mm of water in any year), which suggests that water extraction deeper in the profile may not be large. To the extent that it occurs, it probably is greater in the perennial crops than in the row crops because of the deeper root systems. On the other hand, there is probably more evaporation from the soil surface in row crops than in the perennial crops. Taking the top 4 cm into account would likely increase estimates of ET for the maize–soybean system to a greater degree than the perennial crops.

Our estimated values of ET for maize–soybean in 2005 and 2006 were about 20% less than values determined using eddy covariance techniques at the Ameriflux site at Bondville, Illinois, approximately 10 km west of our study site (data were not available for 2007 and 2008). Direct comparison between the two sites is confounded by differences in precipitation, soils, and management. The eddy covariance approach also measures evaporation of trace rainfall and dew that is not captured in our water budget (or in most modeling or empirical studies), in addition to extraction of water from below 90 cm. Additionally, our water budget assumes precipitation in excess of field capacity drains in 1 d, which likely underestimates the evaporation and transpiration of this water. These systematic underestimates are probably similar for the three systems we are studying, and thus the differences in estimated ET among the cropping systems are likely more accurate and more useful than the absolute values of our estimates.

Transpiration is also influenced by the productivity of different cultivars (Kiniry et al., 2008). Lemus et al. (2002) reported that the biomass yield of Cave-In-Rock switchgrass was slightly greater than the mean of 20 switchgrass varieties tested in southern Iowa, but two varieties (Alamo and Kanlow) yielded 30% more than Cave-in-Rock. Additionally, switchgrass is more productive with N fertilization (Heaton et al., 2004; Vogel et al., 2002). Thus, under management for maximum biomass production, there would likely be greater ET from switchgrass than estimated from our unfertilized plots. More empirical research is needed to quantify the factors that influence water use by biomass crops.

Inorganic Nitrogen Leaching

Mean values of nitrate leached below 50 cm in the maize–soybean rotation ranged from 34.2 kg N ha^{-1} yr^{-1} in 2006 under unfertilized soybean to 45.9 in 2007 under maize (Table 3) fertilized at 168 kg N ha^{-1}. The mean for 2006–2009 was 40.4 kg N ha^{-1} yr^{-1}. The relatively high value from unfertilized soybean indicates that nitrate is influenced by factors other than fertilization, such as precipitation, drainage, and mineralization of crop residues and soil organic matter. Each year, the mean values of nitrate flux from maize–soybean were statistically greater ($p < 0.05$) than the nitrate flux values measured under switchgrass (range, 0.3–3.9) or *Miscanthus* (range, 1.5–6.6 kg N ha^{-1} yr^{-1}). In 2006–2007, the first full season after establishment of *Miscanthus*, nitrate leached from *Miscanthus* (6.6 kg N ha^{-1} yr^{-1}) was statistically greater ($p < 0.05$) than from switchgrass (0.4 kg N ha^{-1} yr^{-1}), which had been established in 2004 and reached maturity more rapidly. In 2007–2008, the amounts of nitrate leaching from *Miscanthus* and switchgrass were not statistically different.

The 2006 to 2009 mean values of ammonium loss from switchgrass (4.0 kg N ha^{-1} yr^{-1}) were statistically greater ($p <$ 0.05) than ammonium losses from maize–soybean (2.4) or *Miscanthus* (1.8). Ammonium losses from switchgrass were statistically greater than from *Miscanthus* in all years that a comparison could be made, whereas losses from switchgrass were statistically greater than from maize–soybean only in 2007–2008. Additionally, the 2006 to 2009 mean ammonium losses from switchgrass were statistically greater than the nitrate losses from switchgrass, indicating a higher ratio of ammonium to nitrate in the soil under switchgrass. The causes for these differences are unknown but may be due to a combination of factors. There was greater soil moisture and estimated drainage from switchgrass than from *Miscanthus*, and there may be more preferential flow through macropores in switchgrass than in the cultivated plots. If nitrate concentrations in the soil under switchgrass were similar to those under *Miscanthus*, these factors would also contribute to greater leaching of nitrate from switchgrass, but that was not observed. The higher soil moisture in switchgrass may have reduced the rate of nitri-

Table 2. Cumulative rainfall, potential evapotranspiration, and estimated evapotranspiration for *Miscanthus*, switchgrass, maize, and soybean, after planting of the row crops, during the 2005 to 2008 growing seasons in large (0.2 ha) plots.

Observational period	Rain	PET	Estimated ET†		
			Miscanthus	Switchgrass	Maize-soy
	mm				
23 May to 2 Nov. 2005	377	731		304	341
12 June to 19 Oct. 2006	382	546	381	203	273
14 May to 8 Oct. 2007	315	757	375	306	266
23 June to 10 Nov. 2008	509	570	348	235	253
2006–2008 avg.	402	624	368	248	264
2005–2008 avg.	396	651		262	283

† ET, evapotranspiration; PET, potential evapotranspiration.

fication, which would have increased the quantity of ammonia in the soil, and the greater soil moisture may have increased the amount of denitrification, which would have reduced the nitrate available for leaching. Cultivation of the row crops may lead to more rapid nitrification and thus less ammonium available for leaching. The magnitude of the ammonium leaching from switchgrass is relatively small and does not represent a significant agronomic or water quality concern.

Although there were greater ammonium losses from switchgrass, the 2006 to 2009 mean total inorganic N losses from switchgrass and *Miscanthus* were not statistically different, and both were significantly less than total inorganic N losses from maize–soybean. Total inorganic N losses from maize–soybean were dominated by nitrate losses and were on average 7.5 times greater than from switchgrass and 9 times greater than from *Miscanthus*.

The nitrate loss measured in the lysimeters from maize–soybean are somewhat larger than multiyear average values reported by Mitchell et al. (2000) for whole field losses through tile drains (range, 14–38 kg N ha^{-1} yr^{-1} for maize–soybean) or reported by McIsaac and Hu (2004) for losses from tile drained watersheds (range, 13.7–38.1 kg N ha^{-1} yr^{-1}). However, they were within the range of nitrate leaching from two tiles reported by Gentry et al. (2009) for a nearby east-central Illinois watershed (range, 22.7–59.9 kg N ha^{-1} yr^{-1}) or from tiles just south of the biofuel plots in David et al. (1997), where nitrate losses were 20.2 to 48.3 kg N ha^{-1} yr^{-1}. Our lysimeters were at a depth of 50 cm, and additional root uptake or denitrification may have occurred below this depth that would reduce the quantity of nitrate reaching tile drains and streams. This effect would probably be greater for the perennial grasses that tend to develop deeper root systems that are active for a longer portion of the growing season compared with the annual crops.

We are aware of only one study that assessed nitrate leaching in *Miscanthus*. Christian and Riche (1998) estimated nitrate leaching at 90 cm for *Miscanthus* planted on a silty clay loam with no artificial drainage (Rothamsted Farm, England) using porous ceramic cup lysimeters for concentrations and two drain gages for water flux. They found high nitrate losses in unfertilized, first-year Miscanthus (154 kg N ha^{-1} yr^{-1}), which then quickly decreased to 8 and 3 kg N ha^{-1} yr^{-1} in years 2 and 3, respectively. Their year 2 and 3 values were similar to our results, and we also found our highest nitrate flux in year 1, but it was considerably less than their value (that they suggested was due to previous agricultural practices). They also found ammonium losses in all years to be less than 1 kg N ha^{-1} yr^{-1}.

Randall et al. (1997) monitored drainage water from 1.2-m deep tiles in Minnesota during a 6-yr period that included a 2-yr drought and reported nitrate leaching losses from unfertilized perennial grasses (Conservation Reserve Program) that were <1 kg N ha^{-1} yr^{-1}. In an Illinois field study, Mitchell et al. (2000) reported nitrate losses in tile drainage from a field of perennial grass (3.8 kg N ha^{-1} yr^{-1}) that were similar to the values measured in our study, even though the grasses in Mitchell et al. (2000) were not harvested. In our study, grasses were harvested during the dormant season, and this may have the effect of increasing evaporative water loss from soil in the spring and thereby reducing drainage and leaching. Harvesting the unfertilized perennial grasses also removed N from the system, and this may have reduced the N available for leaching. Heaton et al. (2009) reported between 5 and 40 kg N ha^{-1} yr^{-1} is removed in the harvested biomass from switchgrass and *Miscanthus.*

Table 3. Mean ± 95% confidence limits of the annual leaching fluxes of nitrate, ammonium, and total inorganic nitrogen recovered in the ion exchange resin lysimeters at 50 cm depth under maize–soybean, switchgrass, and *Miscanthus*.

Collection period†	Maize–soybean	Switchgrass	*Miscanthus*
		kg N ha^{-1} yr^{-1}	
		NO_3	
2005–2006	41.2 ± 12.6	0.3 ± 0.3	ND‡
2006–2007	34.2 ± 6.5	0.4 ± 0.3	6.6 ± 2.0
2007–2008	45.9 ± 12.9	3.9 ± 3.2	1.6 ± 0.7
2008–2009	43.1 ± 8.9	1.1 ± 0.5	1.5 ± 0.7
2006–2009 avg.	40.4 ± 5.2	1.4 ± 0.7	3.0 ± 1.0
		NH_4–N	
2005–2006	2.8 ± 2.8	0.1 ± 0.05	ND
2006–2007	2.4 ± 0.6	4.2 ± 1.3	1.3 ± 0.2
2007–2008	2.3 ± 0.4	3.9 ± 0.7	2.3 ± 0.7
2008–2009	2.7 ± 0.5	4.0 ± 1.2	1.8 ± 0.4
2006–2009 avg.	2.4 ± 0.3	4.0 ± 0.6	1.8 ± 0.3
		TIN§	
2005–2006	45.4 ± 14.4	0.5 ± 0.3	ND
2006–2007	36.5 ± 6.8	4.6 ± 1.3	7.9 ± 2.0
2007–2008	48.3 ± 13.0	7.8 ± 3.6	3.9 ± 1.2
2008–2009	46.0 ± 9.0	5.1 ± 1.6	3.3 ± 0.9
2006–2009 avg.	43.0 ± 5.4	5.7 ± 1.6	4.8 ± 1.0

† The collection periods began in mid-April to early May and continued to approximately the same date in the following year.

‡ ND, no data collected due to establishment failure.

§ TIN, total inorganic nitrogen.

Vogel et al. (2002) reported that optimum yields from Cave-in-Rock switchgrass were obtained from plots in Iowa and Nebraska when fertilized with 120 kg N ha^{-1} yr^{-1} and when the switchgrass was harvested during the growing season. In this management scheme, the N harvested in the biomass was roughly equal to the N applied in fertilizer, and there was little or no accumulation of nitrate in the soils. Higher N application rates led to accumulation of nitrate in the soil profile. Furthermore, Vogel et al. (2002) indicated that harvesting switchgrass after a killing frost (as occurred in our study) allows for translocation of aboveground N into the roots and would likely reduce the amount of N removed in biomass and would reduce the quantity of fertilizer N required. Thus, we were able to maintain good yields of switchgrass and *Miscanthus* for several years without N fertilizer because of harvesting in the winter and because this experiment occurred on Mollisols with high organic matter.

Fertilizer application is likely to be needed for optimal biomass production for switchgrass; research on the nutrient requirements for *Miscanthus* is ongoing. Although fertilizer application will increase the likelihood of N leaching compared with our measurements, some of the characteristics of perennial grasses suggest that they are capable of retaining N better than corn–soybean: The extensive root systems, longer growing season, and addition of carbon to the soil promote immobilization of nitrate. Thus, well managed perennial grasses have considerable potential for lower N leaching compared with corn–soybean production systems. Our results indicate what is possible in the initial years of conversion from corn–soybean to perennial grasses with no N fertilizer and winter harvest.

In a modeling study of the Raccoon River watershed in Iowa, Schilling et al. (2008) estimated that conversion of corn–soybean to a perennial cool-season grass fertilized with 90 kg N ha^{-1} would reduce the average annual nitrate N flux from 25.5 to 8.9 kg N ha^{-1}. On the other hand, conversion to a warm-season grass fertilized with 157 kg N ha^{-1} was estimated to produce a watershed nitrate loss of 22.7 kg N ha^{-1} (a 10% reduction from the baseline value) even though the water yield was reduced by 28%. Additional empirical research is needed to better quantify the water and N cycle consequences of the range of perennial grass species, cultivars, and management practices that are likely to be implemented in the Corn Belt.

Conclusions

Our data demonstrated that *Miscanthus* × *giganteus* significantly reduced soil moisture throughout much of the growing season compared with maize–soybean and at the end of the growing season compared with unfertilized Cave-in-Rock switchgrass. Switchgrass reduced soil moisture early in the growing season relative to maize–soybean, but later in the growing season soil moisture under switchgrass was frequently greater than maize–soybean. An estimated water budget suggests that growing season ET for maize–soybean was approximately 18 mm greater than for switchgrass for our experimental conditions. Estimated ET from *Miscanthus* was on average 140 mm greater than switchgrass and 104 mm greater than maize–soybean. If planted extensively in central Illinois, a 104-mm increase in ET could cause an annual reduction in surface water flows of approximately 32%.

Ion exchange resin lysimeters indicated that inorganic N leached below 50 cm from unfertilized switchgrass and *Miscanthus* was less than one seventh the magnitude of that leached from maize (fertilized with 168 and 202 kg N ha^{-1} in different years) rotated with unfertilized soybean. Although unfertilized perennial biomass crops are likely to reduce nitrate movement to streams, they will also likely influence the hydrologic cycle, which may produce benefits (e.g., flood reduction) as well as costs (e.g., intensified and prolonged low flows). Further empirical research is needed to quantify the factors that influence water use and inorganic N leaching from biomass crops under a wider range of management practices. Hydrological consequences deserve consideration when designing policies and infrastructure for cellulosic biomass.

Acknowledgments

This research was supported by the State of Illinois through the Illinois Council on Food and Agriculture Research as part of its interdisciplinary Strategic Research Initiative titled "Biomass Energy Crops for Power and Heat Generation in Illinois" led by Drs. Emily Heaton, Frank Dohleman, and Stephen Long. Valuable field and technical support was provided by Mr. Timothy Mies. Dr. Philip Gassman and four anonymous reviewers provided many constructive suggestions during the review process.

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