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# Soil and Water Quality Rapidly Responds to the Perennial Grain Kernza Wheatgrass

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## ABSTRACT

**Perennial grain cropping systems could address a number of contemporary agroecological problems, including soil degradation, $NO_3$ leaching, and soil C loss. Since it is likely that these systems will be rotated with other agronomic crops, a better understanding of how rapidly perennial grain systems improve local ecosystem services is needed. We quantified soil moisture, lysimeter $NO_3$ leaching, soil labile C accrual, and grain yields in the first 2 yr of a perennial grain crop under development [kernza wheatgrass, *Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey] relative to annual winter wheat (*Triticum aestivum* L.) under three management systems. Overall, differences between annual and perennial plants were much greater than differences observed due to management. In the second year, perennial kernza reduced soil moisture at lower depths and reduced total $NO_3$ leaching (by 86% or more) relative to annual wheat, indicating that perennial roots actively used more available soil water and captured more applied fertilizer than annual roots. Carbon mineralization rates beneath kernza during the second year were increased 13% compared with annual wheat. First-year kernza grain yields were 4.5% of annual wheat, but second year yields increased to 33% of wheat with a harvest index of 0.10. Although current yields are modest, the realized ecosystem services associated with this developing crop are promising and are a compelling reason to continue breeding efforts for higher yields and for use as a multipurpose crop (e.g., grain, forage, and biofuel).**

A major goal of current agronomic research is to make annual grain crop production more sustainable, with management strategies that supply adequate fertility to meet crop demand while conserving soil and water quality. For temperate humid environments, these management strategies typically strive to minimize soil disturbance (e.g., no-till and conservation tillage strategies), maximize plant cover on the soil (e.g., cover crops and no-till), and manipulate fertilizer strategies and sources to reduce nutrient losses to the environment (e.g., organic amendments and precision agriculture) (Robertson, 1997; Raun and Johnson, 1999; Snapp et al., 2005, 2010; Grandy et al., 2006).

The management choices that growers make can have dramatic impacts on local ecosystem services. For example, N fertilizer type, rate, and application in relationship to crop demand are important regulators of N cycling efficiency and loss pathways; this has direct and indirect consequences for water and soil quality (Robertson, 1997; Snapp et al., 2010; Syswerda et al., 2012). Despite the realized environmental benefits of some conservation management strategies, grower adoption of these strategies can be limited for a variety of socioeconomic and biophysical reasons (Snapp et al., 2005; Grandy et al., 2006).

Another approach that has received far less attention than management strategies for improving ecosystem services is to "perennialize" annual grain systems via breeding for new perennial grain crops (Glover et al., 2010b). The perceived benefits of this approach are based on inferences from agronomic research that has consistently shown herbaceous perennial systems, such as forages or restored or native grasslands, outperforming annual cropping systems with regard to soil conservation (Montgomery, 2007), primary production and C cycling efficiencies (Buyanovsky et al., 1987; Jenkinson et al., 1994; Silvertown et al., 1994; Glover et al., 2010a; Zeri et al., 2011), N cycling efficiencies (Jenkinson et al., 2004; Glover et al., 2010a; Syswerda et al., 2012), maintenance of soil nutrient stocks and soil C pools (Buyanovsky et al., 1987; Jenkinson et al., 2004; Mikhailova et al., 2000; Culman et al., 2010; Bremer et al., 2011), and maintenance of soil food webs (Ferris et al., 2001; Culman et al., 2010; DuPont et al., 2010). These benefits have been documented in established herbaceous perennial systems, but future perennial grain systems will likely be rotated with other crops and will have to be reestablished with each rotation. The length of time newly planted perennial crops need to improve ecosystem services is very important because there have been some reports of decreased ecosystem services in establishing herbaceous perennials (McLaughlin et al., 2002; Syswerda et al., 2012).

One promising perennial grain crop is intermediate wheatgrass, a widely adapted, high-yielding, cool-season forage grass that provides excellent feed for livestock in the Great Plains

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**Abbreviations:** POXC, permanganate-oxidizable carbon.

and Intermountain West regions (Ogle et al., 2003; Hendrickson et al., 2005; Karn et al., 2006). This grass was identified as a good candidate for domestication as a perennial grain crop based on agronomic properties (Wagoner, 1990b) and because the seed it produces is a nutritious and highly palatable grain (Becker et al., 1991, 1992). Intermediate wheatgrass has been under selection for grain via bulk breeding and mass selection over the past two decades, with initial efforts at the Rodale Research Center in Kutztown, PA (Wagoner, 1990a; Wagoner, 1995) and more recently at the Land Institute in Salina, KS (DeHaan et al., 2005; Cox et al., 2010). The Land Institute has named this newly developed, experimental grain *kernza*.

The limited number of studies on perennial grain cropping systems have mostly reported on grain yields and plant traits (Piper, 1998; Weik et al., 2002; Murphy et al., 2010; González-Paleo and Ravetta, 2011; Hayes et al., 2012; Jaikumar et al., 2012). To date, there have been no studies that have directly quantified the soil ecosystem services gained in a perennial grain system. Given this lack of empirical field data regarding soil C and N dynamics with perennial grain systems, we examined the perennial grain crop kernza wheatgrass relative to annual winter wheat using three management systems. We were particularly interested in the length of time before improvements in soil ecosystem services were detected. The specific objectives of this study were to: (i) determine the relative impacts of perenniality and management on short-term soil N leaching, C accrual, and soil moisture in a small grain cropping system; and (ii) determine the yield potential of a newly developed population of kernza relative to annual wheat across the three management systems.

## MATERIALS AND METHODS

### Site Description, Experimental Design, and Management

The study was conducted at the W.K. Kellogg Biological Station in Hickory Corners, MI (42°24′ N, 85°24′ W, elevation 288 m). The mean annual precipitation is 890 mm and mean annual temperature is 9.7°C. The soils at this site are Kalamazoo series (fine-loamy, mixed, semiactive, mesic Typic Hapludalfs) with measured soil properties at 0 to 20 cm as follows: pH = 5.5, soil organic C = 8.4 g kg$^{-1}$ soil, total soil N = 0.9 g kg$^{-1}$ soil, Bray P = 27.7 mg kg$^{-1}$ soil, sand = 548 g kg$^{-1}$ soil, silt = 379 g kg$^{-1}$ soil, and clay = 72 g kg$^{-1}$ soil. More detailed soil information was provided by Syswerda et al. (2011) and more general site information can be found at http://lter.kbs.msu.edu/about/site_description/index.php. Previously, the site was in a conventionally managed corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.]–wheat rotation.

In the fall of 2009, a split-plot design with four replications was established, with management as the main treatment and plant species as the nested plots. The management systems were: (i) organic management (Organic), (ii) conventional management, with 90 kg N ha$^{-1}$ (Mid-N), and (iii) conventional management, with 120 kg N ha$^{-1}$ (High-N). The primary differences among the management systems were the fertilizer forms and rates applied and the weed management strategies (herbicides applied only in conventionally managed plots). Organic and Mid-N treatments received the same rate of N (90 kg N ha$^{-1}$) but in different forms (poultry manure vs. urea), while the Mid-N and High-N treatments differed only in the N application rate (90 vs. 135 kg N ha$^{-1}$, respectively). The Mid-N treatment represents the recommended practice in Michigan (Vitosh et al., 1995), and the High-N treatment received 50% more N than the Mid-N treatment. Within each main plot, two plant species were planted: Caledonia annual wheat and perennial intermediate wheatgrass (kernza). The kernza seed used was from a breeding population derived from one cycle of selection primarily for seed size and yield per spike (Cox et al., 2010). The parents used to create the population had previously been through one to two cycles of selection by the Rodale Institute and the USDA Big Flats Plant Materials Center.

Before planting, the site was chisel plowed to 20 cm and limed with 2240 kg ha$^{-1}$ of dolomitic lime. Mid-N and High-N plots received pelleted urea as a starter at 33.6 kg N ha$^{-1}$ and $K_2O$ at 53.8 kg K ha$^{-1}$. Soils at this site are naturally high in available P, and soil tests recommended no P fertilization. Organic plots received 2240 kg ha$^{-1}$ of commercially available pelletized poultry manure (a mix of layer poultry manure and sawdust at 4–3–2 N–P–K from Herbruck's Poultry Ranch, Saranac, MI). This application rate supplied 90 kg ha$^{-1}$ total N equivalent. All fertilizer was surface applied and then incorporated with a soil finisher.

In the first year, population densities were kept consistent between the annual and perennial plots. This required a compromise of higher than recommended seeding rates for the intermediate wheatgrass and lower than recommended seeding rates for the annual wheat. A very rainy and cool fall delayed the initial planting. On 12 Nov. 2009, the plots were planted with a grain drill at a rate of 310 seeds m$^{-2}$ (1.25 million seeds acre$^{-1}$) at 15-cm row spacing. Annual wheat stands were relatively thin and poor yields resulted (see below). In the following year, the annual wheat seeding rate was increased to 432 seeds m$^{-2}$ (1.75 million seeds acre$^{-1}$). Plots measured 3.66 by 5.5 m.

Conventional plots were topdressed with urea at 28 and 50.4 kg N ha$^{-1}$ for the Mid-N and High-N treatments, respectively, on 23 Apr. and 26 May 2010. Conventionally managed plots were sprayed for broadleaf weeds with a mixture of thifensulfuron-methyl (methyl 3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylic acid) and tribenuron-methyl (methyl 2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)methylamino]carbonyl]amino]sulfonyl]benzoate) at 5.4 mL ha$^{-1}$, and Organic plots were hand weeded in 2010. Annual wheat was harvested on 9 July 2010 and kernza was harvested on 8 Sept. 2010. Yields were assessed by randomly placing two 0.25-m$^2$ quadrats in the plot and clipping whole plants 10 cm above the soil surface. Threshed grain weight (free of hulls) was determined and the average grain weight and aboveground plant biomass between the two quadrats sampled per plot were reported. Subsamples were taken for moisture determination by oven drying at 70°C for 72 h. Oven-dry weights of grain and biomass are reported.

In the fall of 2010, fields were fertilized at the same rates as the previous year, with the exception that no lime was applied. Fertilizers were incorporated into the annual wheat plots with tillage but were not incorporated in the perennial kernza plots. In the annual wheat plots, the soil was tilled with a small tractor-pulled rototiller rather than the chisel plow used the previous year to preserve the instrumentation installed in the plots (see below), and the seed bed was firmed with a cultipacker. Second-year annual wheat was planted on 8 Oct. 2010 at a rate of 432 seeds $m^{-2}$. Conventional plots were topdressed with urea at the same rates as outlined above on 5 April and 10 May 2011. No weed control was necessary in 2011. Annual wheat and kernza were harvested on 21 July and 1 Aug. 2011, respectively, using the methods described above.

## Soil Moisture and Lysimeter Sampling

Soil moisture and lysimeter $NO_3$ concentrations were determined every 2 wk throughout the growing season. Soil moisture was determined at four separate depths for each plot (0–20, 20–40, 40–70, and 70–100 cm) using a Trime T3 time domain reflectometer probe (IMKO). Before planting, 5.1-cm polyvinyl chloride tubes were installed vertically in every plot. The tubes extended 1 m into the soil profile and were capped when not in use to prevent moisture from entering the tube.

Prenart super quartz (polytetrafluoroethylene/quartz) soil water samplers (Prenart Equipment) were installed in every plot on 18 to 19 Mar. 2010. At the edge of each plot, a 3.2-cm-diameter tunnel was made with a steel drive point rod mounted on a Geoprobe 540MT hydraulic probe assembly (Geoprobe Systems). The tunnel was made at a 45° angle and extended under the plot to a depth of 135 cm. Soil water samplers were installed with a silica flour slurry to ensure a good soil–sampler interface, and the tunnels were backfilled with soil and sand. Irrigation boxes were installed at the edge of the plot to house lysimeter collection bottles. On the same weeks that soil moisture was determined, each lysimeter was sampled by applying 50 kPa of vacuum for 24 h. Soil water was collected in 500-mL media bottles and the volumes of water collected were determined by weight. Samples were filtered through a 2.5-μm cellulose filter (Whatman no. 42) and frozen until analysis. Nitrate concentrations of each sample were determined colorimetrically with a continuous-flow analyzer (OI Analytical) with a detection limit of 0.02 mg N $L^{-1}$ for $NO_3$.

## Modeling Nitrate Loss

Total $NO_3$ leaching in each system was modeled by combining the lysimeter $NO_3$ concentrations with modeled soil water drainage rates calculated using the Systems Approach for Land Use Sustainability (SALUS) model (Basso et al., 2006, 2010). The SALUS model simulates crop growth and soil processes under various management practices over multiple years. The soil water balance component of SALUS is based on the "cascading bucket" approach to soil water movement through the soil used in the CERES models but includes a revised method for calculating runoff, infiltration, and evaporation (Basso et al., 2010). Four separate buckets were modeled, reflecting the four depth profiles at which soil moisture was measured (see above). Management in each system was simulated based on actual field operations. The methods followed those described more fully by Syswerda et al. (2012) for experiments conducted at a nearby site in southwestern Michigan.

Measured lysimeter $NO_3$ concentrations were averaged for each plant × management combination on each date, and daily values were interpolated using the package *zoo* in R (Zeileis and Grothendieck, 2005). These concentrations were multiplied by the daily drainage rates to evaluate the total N mass flux from the soil. To avoid overextrapolation, daily values were interpolated only from the first date of measurement (15 Apr. 2010) to the last of measurement (24 Oct. 2011), representing the vast majority of two growing seasons. Root mean square errors (RMSEs) indicated close agreement of modeled soil water results with measured values. The RMSEs over both years by the respective depths, 0 to 20, 20 to 40, 40 to 70, and 70 to 100 cm, were as follows: High N, wheat (0.054, 0.048, 0.028, 0.023); Mid N, wheat (0.053, 0.043, 0.033, 0.029); Organic, wheat (0.050, 0.038, 0.025, 0.029); High N, kernza (0.057, 0.049, 0.051, 0.035); Mid N, kernza (0.059, 0.047, 0.034, 0.030); and Organic, kernza (0.055, 0.051, 0.044, 0.037).

## Soil Sampling and Analyses

Soils were sampled on 16 to 17 June 2011 to three depths, 0 to 10, 10 to 20, and 20 to 40 cm. Six-centimeter-diameter cores were taken with a Geoprobe 540MT hydraulic probe at three randomly selected locations in the plot. The three samples from each depth were composited, sieved to 6 mm, and mixed until homogeneous.

### Carbon Mineralization

One-day C mineralization was determined on rewetted soils following Franzluebbers et al. (2000) and Haney et al. (2001). The amount of water need to bring soils to 50% water-filled pore space was determined gravimetrically for each depth before the incubations. Ten grams of air-dried soil was weighed in duplicate into 100-mL beakers and placed inside a 237-mL canning jar. Deionized water was added to the soil, the jars were capped tightly, and a zero-time $CO_2$ concentration was determined immediately by sampling 0.5 mL of air from the headspace and injecting into a Li-Cor LI-820 infrared gas analyzer. The jars were incubated at 25°C for 24 h and a 1-d $CO_2$ concentration was determined. Carbon mineralization was determined as the difference between the zero-time and 1-d $CO_2$ concentrations.

### Permanganate-Oxidizable Carbon

All permanganate-oxidizable C (POXC) analyses and calculations were based on Weil et al. (2003) and are described fully at http://lter.kbs.msu.edu/protocols/133. Briefly, 20 mL of 0.02 mol $L^{-1}$ $KMnO_4$ was added to a 50-mL centrifuge tube containing 2.5 g of air-dried soil. The tubes were shaken for exactly 2 min at 240 oscillations $min^{-1}$, allowed to settle for exactly 10 min, and 0.5 mL of the supernatant was transferred into a second 50-mL centrifuge tube and mixed with 49.5 mL of deionized water. Sample absorbance was read with a SpectraMax M5 using Softmax Pro software (Molecular Devices) at 550 nm.

## Statistical Analyses

Analysis of variance (ANOVA) was performed on soil and plant data with the PROC MIXED procedure in SAS version 9. Sampling time, soil depth, management system, and plant species were treated as fixed effects and block as a random effect, with significant differences determined at $\alpha = 0.05$. For soil moisture analysis, due to computing constraints, we modeled each depth separately, with sampling date as a repeated measure. Lysimeter concentration data were also modeled, with date as a repeated

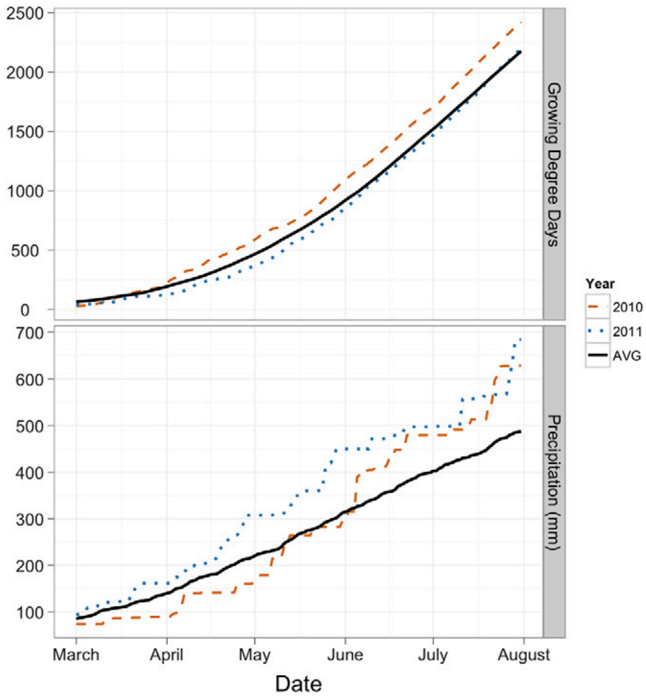


**Fig. 1. Cumulative growing degree days and precipitation from March through July for the 2010 and 2011 growing seasons and 24-yr average at the Kellogg Biological Station, Hickory Corners, MI. Growing degree days were calculated by the method of Baskerville and Emin (1969) with base = 0°C.**

measure and both years modeled independently. Modeled results of daily $NO_3$ fluxes were determined as a single mean value for each plant × management combination, so no statistical analyses were performed on these data. Carbon mineralization and POXC were modeled, with depth as a repeated measure. Means were compared with an adjusted Tukey's pairwise means comparison procedure using PROC MIXED in SAS. All graphing was performed with the package *ggplot*2 (Wickham, 2009) in R (R Core Team, 2011).

## RESULTS AND DISCUSSION

### Weather and Plant Development

Precipitation and temperatures during the spring (March–May) differed dramatically in 2010 and 2011 (Fig. 1). Cumulative precipitation in the spring was average in 2010 but was 55% greater than average in 2011. Conversely, the spring of 2010 was the warmest spring in the past 24 yr at the Kellogg Biological Station, with 253 more growing degree days (GDD) than in 2011 (Fig. 1). These weather factors, coupled with management, impacted plant growth and development. The rainy, cool conditions in the fall of 2009 resulted in a very late planting date and minimal vegetative growth before vernalization, as only 138 GDD accumulated between planting and 1 January (Table 1). In contrast, a relatively early fall planting date and warm fall in 2010 resulted in 487 GDD for wheat accumulated before 1 January. (Kernza was well established by the fall of 2010.) Because temperature is a good predictor of leaf appearance and development of winter wheat (Baker et al., 1986) and because increased temperatures can lead to large yield reductions in winter wheat due to faster phenological development (Rosenzweig and Tubiello, 1996), differences in yields between the years were expected (see below). Differences in development

**Table 1. Anthesis of annual wheat and perennial kernza wheatgrass as affected by time and growing degree days at the Kellogg Biological Station, Hickory Corners, MI.**

| Plant | Planting date | Anthesis date (d after planting) | Growing degree days: 1 Jan. to anthesis | Growing degree days: Planting to anthesis |
|---|---|---|---|---|
| | | | °C d | |
| 2010 | | | | |
| Annual | 11 Nov. 2009 | 1 June 2010 (201) | 1095 | 1233 |
| Perennial | 11 Nov. 2009 | 11 July 2010 (241) | 1946 | 2084 |
| 2011 | | | | |
| Annual | 8 Oct. 2010 | 4 June 2011 (238) | 921 | 1408 |
| Perennial | NA† | 23 June 2011 (NA) | 1317 | NA |

† NA, not applicable; kernza wheatgrass was not planted in 2011 because it was a perennial second-year plant.

**Table 2. Soil moisture *F* statistics and significance by depth generated from ANOVA with repeated measures analysis by sampling date at the Kellogg Biological Station, Hickory Corners, MI.†**

| Year | Source of variation | *F*-statistic: 0–20 cm | 20–40 cm | 40–70 cm | 70–100 cm |
|---|---|---|---|---|---|
| 2010 | Sand content (covariate) | 39.1*** | 130.8*** | 60.4*** | 201.1*** |
| | Plant species (P) | 127.3*** | 39.4*** | 30.4*** | 97.1*** |
| | Sampling date (D) | 36.1*** | 8.4*** | 4.3*** | 4.5*** |
| | D × P | 4.5*** | 1.8* | 1.1 | 0.3 |
| 2011 | Sand content (covariate) | 52.3*** | 106.4*** | 44.1*** | 215.4*** |
| | Plant species (P) | 19.7*** | 9.0*** | 0.2 | 61.5*** |
| | Sampling date (D) | 203.3*** | 17.6*** | 4.4*** | 2.9*** |
| | D × P | 6.8*** | 1.3 | 1.0 | 0.3 |

* Significant at $P < 0.05$.

*** Significant at $P < 0.001$.

† Management main effects and interactions were included in the model, but yielded no significant results (data not shown).

due to plant species were also apparent; kernza anthesis in 2010 was 41 d later than the annual wheat, while kernza anthesis in 2011 was only 20 d after annual wheat (Table 1).

### Soil Moisture

Total soil moisture varied greatly over the 2 yr and was primarily affected by soil depth, sampling date, plant type, and soil texture (Table 2; Fig. 2). Soil moisture was most strongly influenced by soil texture at the 0-to-20-cm and 70-to-100-cm depths (larger *F* statistics for sand, Table 2) and by the sampling date for the surface depths (larger *F* statistics at the 0–20-cm depth, Table 2). The influence of plant type on soil moisture was greatest at the 0-to-20-cm and 70-to-100-cm depths. In contrast, management had no significant effect on soil moisture (data not shown).

Kernza had consistently lower soil moisture values at the lowest depth (70–100 cm) compared with annual wheat (Fig. 2). This suggests greater rooting activity at this depth or less drainage from surface depths to this lower depth (or both; see below). Within the 0-to-20-cm layer in 2010, kernza had drier soils than beneath annual wheat, but this trend was often reversed in 2011. The reason for this is not certain, but drier surface soil beneath annual wheat could have resulted from greater evaporative losses due to a less developed canopy or from increased rooting activity

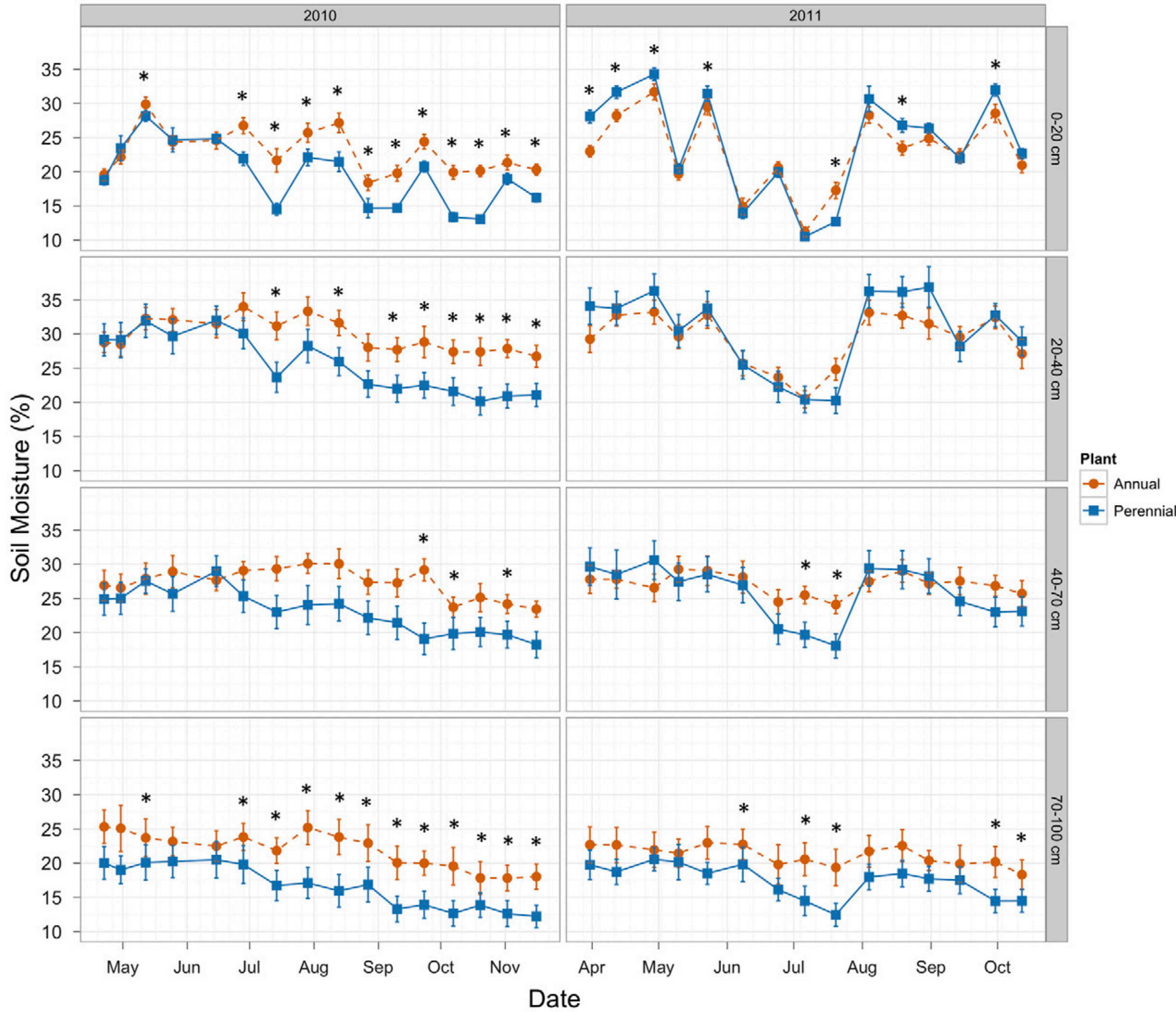


**Fig. 2. Total volumetric soil moisture values for annual wheat (circles, dashed line) and perennial kernza wheatgrass (squares, solid line) throughout four soil depths over the 2010 and 2011 growing seasons at the Kellogg Biological Station, Hickory Corners, MI. Error bars represent one standard error of the mean. *Sampling time with significantly different ($\alpha$ = 0.05) soil moisture between annual and perennial plants.**

and turnover in kernza that increased the soil pore space and thus led to greater infiltration during 2011.

Overall, there were differences in soil moisture between years, with the effects of plant type being stronger in 2010 than 2011 ($F$ statistics in Table 2; pairwise comparisons in Fig. 2). McIsaac et al. (2010) found similar trends regarding overall lower soil moisture values during the establishment year of annual row crops and perennial bioenergy crops relative to subsequent years in Illinois. At our southwest Michigan site, the 2011 growing season received ~150 mm more rain than in 2010 (March–October), which likely alleviated some soil moisture constraints and contributed to the limited differences observed with plant type in 2011 (Fig. 2).

## Soil Nitrate Leaching

The concentration of lysimeter $NO_3$ collected below the rooting zone was not affected by plant species or management in the establishment year (2010) but was strongly affected by both factors in the second year (Table 3; Fig. 3). In 2010, lysimeter $NO_3$ concentrations varied significantly by date of sampling but were not significantly different due to management or plant type. Lysimeter $NO_3$ concentrations typically ranged between 5 and 30 mg $L^{-1}$ before harvest but started to show trends regarding management and plant type in the second half of the year (Fig. 3). Most notably, $NO_3$ concentrations in the High-N plots started to differentiate by plant species, with

**Table 3. Lysimeter concentration *F* statistics and significance generated from ANOVA with repeated measures analysis by sampling date at the Kellogg Biological Station, Hickory Corners, MI.**

| | *F*-statistic | |
|---|---|---|
| Source of variation | 2010 | 2011 |
| Management (M) | 0.9 | 7.3** |
| Plant species (P) | 0.1 | 32.9*** |
| M × P | 1.2 | 3.7† |
| Sampling date (D) | 3.9*** | 4.7*** |
| D × M | 1.5 | 0.9 |
| D × P | 1.6† | 2.8*** |
| D × M × P | 1.4 | 0.6 |

** Significant at $P < 0.01$.
*** Significant at $P < 0.001$.
† Significant at $P < 0.10$.

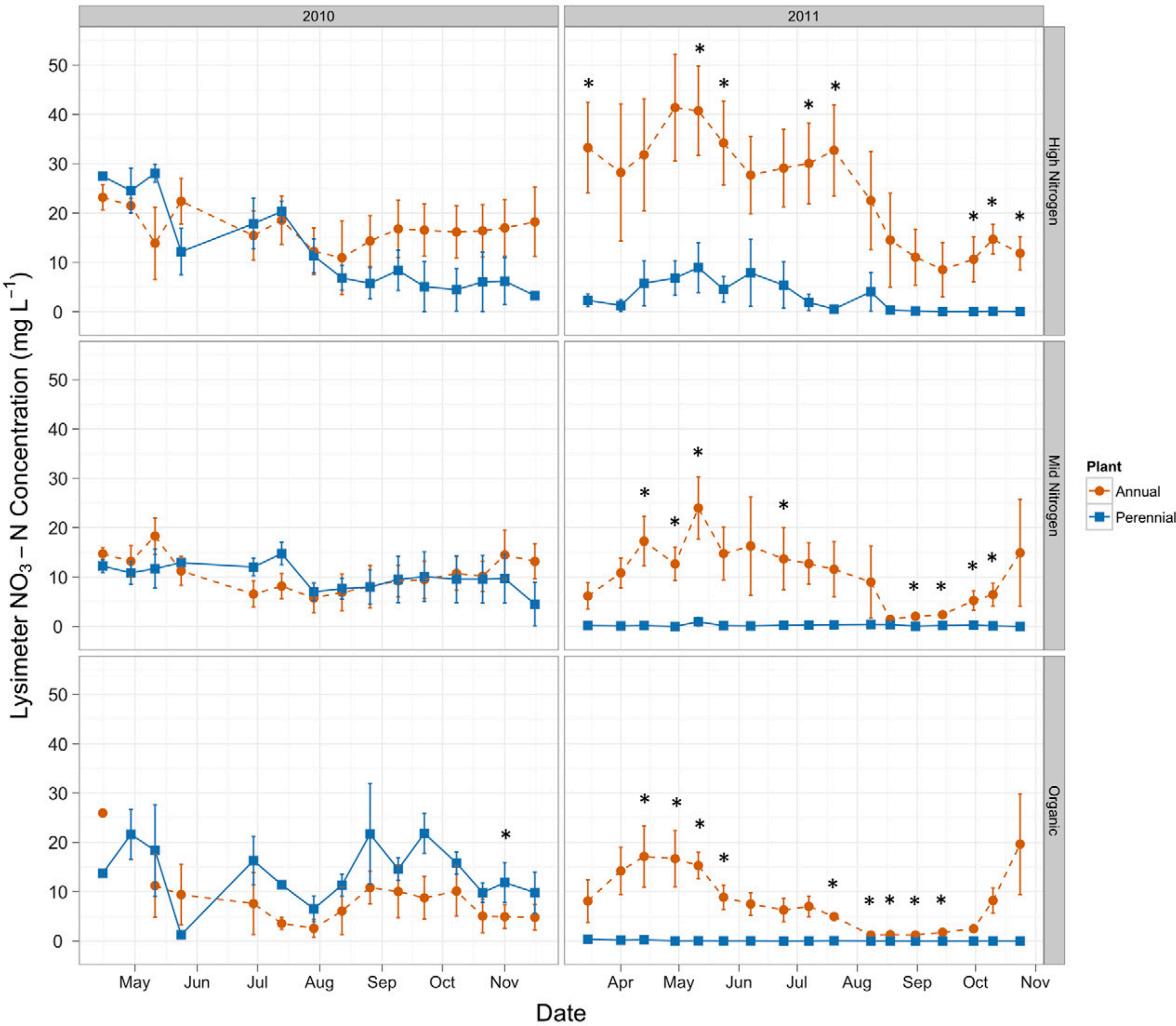


**Fig. 3. Nitrate concentrations of soil water collected from lysimeters under annual wheat (circles, dashed line) and perennial kernza wheatgrass (squares, solid line) plots for three management systems over the 2010 and 2011 growing seasons at the Kellogg Biological Station, Hickory Corners, MI. Error bars represent one standard error of the mean. *Sampling time with significantly different (α = 0.05) lysimeter concentrations between annual and perennial plants.**

annual wheat plots showing upward trends in $NO_3$ concentrations. Management differences also began to show in the latter half of the season in annual wheat plots, where $NO_3$ concentrations under organic management trended downward relative to the High-N plots (Fig. 3).

The 2011 season showed significant differences in lysimeter $NO_3$ concentrations due to plant type and management, with the magnitude of the effect of plant type 4.5 times larger than that of management ($F$ statistic = 32.9 and 7.3, respectively; Table 3; Fig. 3). The marginally significant management × plant type interaction indicated that management had a larger effect on $NO_3$ levels in annual wheat than in kernza. The High-N annual wheat plots showed greater lysimeter $NO_3$ values (30–40 mg $L^{-1}$) than the Mid-N and Organic plots (10–20 mg $L^{-1}$) during the growing season. Kernza plots did not show the same pattern ($P = 0.15$). The Mid-N and Organic kernza plots had virtually undetectable levels of lysimeter $NO_3$ throughout the entire 2011 growing season, with only two sampling points measuring >1 mg $L^{-1}$.

Total $NO_3$ leaching in each system was modeled by combining the lysimeter $NO_3$ concentrations with modeled soil water drainage rates in SALUS. Model results largely reflect trends in $NO_3$ concentrations, showing minimal differences in total $NO_3$ leached between annual wheat and perennial wheatgrass in the first year, while revealing large differences in the second year (Fig. 4; Table 4). Differences in management in the first year appear to be more pronounced in the modeled $NO_3$ leaching data (Table 4) than in the $NO_3$ concentration data (Table 3), indicating that drainage rates among the management treatments had a substantial effect on the total $NO_3$ lost.

Total $NO_3$ lost in the second year of production (2011) was driven primarily by plant type, although management also had a large effect. Modeled results indicate that in the second year, perennial kernza reduced total $NO_3$ leaching by 85.8% in High-N plots, 98.2% in Mid-N plots, and 99.4% in Organic plots relative to annual wheat during the growing season (Table 4). Management also had large effects on the total $NO_3$ lost, as nearly four times as much $NO_3$ was lost from the High-N annual wheat plots than the Organic annual wheat plots. The $NO_3$ leaching that we observed in annual wheat was within range of rates from two long-term studies of a corn–soybean–wheat rotation: 62.3 to 70 kg $NO_3$–N $ha^{-1}$ $yr^{-1}$ for a conventionally managed system

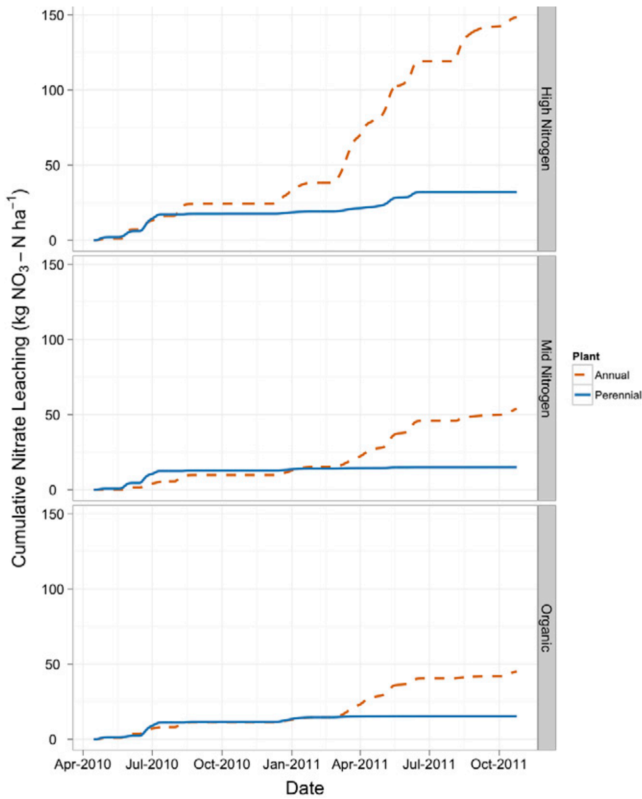


**Fig. 4. Cumulative total NO3–N leached under annual wheat (dashed line) and perennial kernza wheatgrass (solid line) plots for three management systems over the 2010 and 2011 growing seasons at the Kellogg Biological Station, Hickory Corners, MI. Values based on daily leaching fluxes from the SALUS model.**

**Table 4. Cumulative $NO_3$ losses for annual wheat and perennial kernza wheatgrass under three management systems during the growing seasons of 2010 and 2011 and over both growing seasons at the Kellogg Biological Station, Hickory Corners, MI.†**

| | | Cumulative $NO_3$ leached | | |
|---|---|---|---|---|
| Plant type | Management | 15 Apr.–24 Oct. 2010 | 15 Apr.–24 Oct. 2011 | 15 Apr. 2010–24 Oct. 2011 |
| | | kg $NO_3$–N $ha^{-1}$ | | |
| Annual | High-N | 24.3 | 69.8 | 148.3 |
| | Mid-N | 9.8 | 27.5 | 53.8 |
| | Organic | 11.3 | 17.7 | 45.1 |
| Perennial | High-N | 17.7 | 9.9 | 32.0 |
| | Mid-N | 12.7 | 0.5 | 15.0 |
| | Organic | 11.6 | 0.1 | 15.3 |

† To avoid overextrapolation, daily flux values were interpolated only from the first date of measurement (15 Apr. 2010) to the last date of measurement (24 Oct. 2011).

and 19 to 40 kg $NO_3$–N $ha^{-1}$ $yr^{-1}$ for reduced-input and organic systems (Snapp et al., 2010; Syswerda et al., 2012).

Herbaceous perennial systems typically reduce subsurface $NO_3$ leaching compared with annual crops (Randall et al., 1997; Mitchell et al., 2000; Huggins et al., 2001; Oquist et al., 2007; McIsaac et al., 2010; Syswerda et al., 2012). Previous studies have often compared $NO_3$ leaching rates of herbaceous perennial systems that are not fertilized or not harvested (e.g., Conservation Reserve Program [CRP]) with annual cropping systems. Our results add to the limited research on $NO_3$ leaching in intensive annual and perennial cropping systems that are both fertilized and harvested. In this study, we were not able to differentiate the relative effects of tillage vs. plant species on N leaching rates in the second year, because the annual wheat plots were tilled and perennial kernza plots were not tilled in the fall of 2010. Regardless of this, no-till or reduced-tillage management is an inherent feature of perennial grain cropping systems, and so these effects will, by necessity, co-occur and complement each other to reduce soil $NO_3$–N leaching.

**Table 5. Soil permanganate-oxidizable C (POXC) and C mineralization by depth for annual wheat and perennial kernza wheatgrass for the June 2011 sampling at the Kellogg Biological Station, Hickory Corners, Michigan. *F*-statistics and significance from ANOVA are reported below the treatment means.**

| Depth | Plant type | POXC | C mineralization |
|---|---|---|---|
| | | µg C g $soil^{-1}$ | µg $CO_2$ g $soil^{-1}$ $d^{-1}$ |
| 0–10 cm | annual | 294 ± 13† | 61 ± 3 |
| | perennial | 308 ± 19 | 70 ± 2 |
| 10–20 cm | annual | 258 ± 16 | 48 ± 2 |
| | perennial | 259 ± 12 | 49 ± 2 |
| 20–40 cm | annual | 114 ± 16 | 27 ± 2 |
| | perennial | 118 ± 11 | 25 ± 2 |
| | ***F*-statistic** | | |
| Source of variation | | | |
| Management regime (M) | | 2.0 | 1.7 |
| Plant species (P) | | 1.0 | 7.1* |
| M × P | | 1.2 | 1.7 |
| Depth (D) | | 281.5*** | 386.0*** |
| D × M | | 0.2 | 1.7 |
| D × P | | 0.4 | 7.2** |
| D × M × P | | 1.5 | 0.4 |

* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
*** Significant at $P < 0.001$.
† Means ± standard errors of the means.

## Labile Soil Carbon

In this study, we did not measure soil organic C (SOC) levels directly because these changes often take years to detect (Wander, 2004). Instead, we used two measures of labile organic C as early indicators of SOC accrual or loss. One and a half years after the start of the experiment, C mineralization in the kernza plots was significantly greater than in annual wheat ($P = 0.026$), but no differences were detected for POXC (Table 5). In both measures of labile C, depth was significant, while management had no detectable effect.

Carbon mineralization rates reflect the size of the biologically active organic matter pool because they typically correspond well to long-term C mineralization rates, soil microbial biomass, particulate organic matter, and N mineralization potential (Franzluebbers et al., 2000; Haney et al., 2001). Carbon mineralization has been shown to be a sensitive and early predictor of total soil C sequestration in soils in both perennial grasslands (Baer et al., 2002) and annual cropping systems (Franzluebbers et al., 1994; Staben et al., 1997; Grandy and Robertson, 2007). After 4 to 7 yr in CRP dominated by wheatgrass species, Staben et al. (1997) found that C mineralization rates were significantly greater under CRP than

**Table 6. Annual wheat and perennial kernza wheatgrass grain and vegetative biomass yields and harvest index under three management systems in 2010 and 2011 at the Kellogg Biological Station, Hickory Corners, MI.**

| Year | Plant type | Management | Grain yield | Vegetative biomass | Harvest index |
|---|---|---|---|---|---|
| | | | kg ha$^{-1}$ | | |
| 2010 | annual | High-N | 2807 ± 273 b† | 3470 ± 367 | 0.45 |
| | | Mid-N | 2946 ± 266 ab | 4021 ± 489 | 0.42 |
| | | Organic | 3761 ± 164 a | 4416 ± 203 | 0.46 |
| | perennial | High-N | 157 ± 32 | 4984 ± 521 a | 0.03 |
| | | Mid-N | 112 ± 15 | 3881 ± 376 b | 0.03 |
| | | Organic | 156 ± 12 | 3982 ± 359 b | 0.04 |
| 2011 | annual | High-N | 5017 ± 340 | 4634 ± 210 | 0.52 |
| | | Mid-N | 4248 ± 425 | 4036 ± 338 | 0.51 |
| | | Organic | 4460 ± 628 | 3714 ± 607 | 0.55 |
| | perennial | High-N | 1428 ± 185 | 13083 ± 799 b | 0.10 |
| | | Mid-N | 1662 ± 183 | 17131 ± 653 a | 0.09 |
| | | Organic | 1390 ± 80 | 12202 ± 1004 b | 0.10 |
| | | | ***F*-statistic** | | |
| Source of variation | | | | | |
| 2010 | | | | | |
| Management regime (M) | | | 4.4* | 1.2 | 3.3‡ |
| Plant species (P) | | | 518.4*** | 138.9*** | 3271.6*** |
| M × P | | | 4.8* | 13.5** | 1.1 |
| 2011 | | | | | |
| M | | | 0.5 | 4.4 | 2.8‡ |
| P | | | 159.6*** | 166.7*** | 2098.8*** |
| M × P | | | 1.4 | 11.2** | 0.8 |

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

*** Significant at $P < 0.001$.

† Means ± standard errors. Means followed by different letters in the same column represent significantly different treatment means within a plant species and year.

‡ Significant at $P < 0.10$.

paired annual wheat sites. Permanganate-oxidizable C reflects a relatively processed pool of labile organic C and is a sensitive indicator of ecosystem change (Weil et al., 2003; Culman et al., 2012), but no differences were apparent after the first 1.5 yr. Although these systems are undoubtedly still in flux, the C mineralization results suggest that over a relatively short time, more biologically active C is being stored in soils under kernza than annual wheat.

## Agronomic Yields

Annual wheat and perennial kernza differed substantially in grain yield and vegetative biomass (Table 6). In 2010, annual wheat yielded more grain and total aboveground biomass than kernza. The following season showed higher grain yields for both annual wheat and kernza, while aboveground vegetative biomass remained similar for annual wheat but increased dramatically for kernza.

Annual wheat grain yields varied from 2.8 to 3.8 Mg ha$^{-1}$ in 2010 and 4.2 to 5.0 Mg ha$^{-1}$ in 2011 (Table 6) and were similar to yields reported previously for wheat at this southwest Michigan site (Smith et al., 2007; Snapp et al., 2010). The higher yields in 2011 were likely due to multiple factors, including an increase in seeding rate (see methods above), an earlier planting date that allowed quicker stand establishment, and a decrease in weed pressure in 2011. The weather in 2011 was also much more amenable to small grain production, with a cooler and wetter spring allowing ample vegetative growth before the beginning of reproductive development. In 2010, increased weed pressure due to higher available soil N was a likely reason for the decreased annual wheat yields in the High-N and Mid-N plots relative to the Organic plots; the trend was reversed in 2011 and aligned more with what would typically be expected along a N fertility gradient. In 2011, a high proportion of High-N kernza plants lodged in a storm, leading to reduced aboveground biomass relative to the Mid-N kernza plots.

Intermediate wheatgrass seed yields (including the seed hulls) for established commercial forage cultivars are typically 168 to 280 kg ha$^{-1}$ under dryland conditions and 504 to 616 kg ha$^{-1}$ under irrigated conditions (Ogle et al., 2003; Weik et al., 2002). Loeppky et al. (1999) reported a range of 269 to 442 kg ha$^{-1}$ over a N fertilization gradient in northeastern Saskatchewan; Lee et al. (2009) reported a range of 150 to 250 kg ha$^{-1}$ over topographical positions in South Dakota. Seed yields of forage cultivars as high as 800 to 950 kg ha$^{-1}$ have been reported in the Great Plains (Wagoner, 1995). Our second-year yields were higher than those previously reported, ranging from 1390 to 1662 kg ha$^{-1}$. This is likely due to a number of factors. First, this is a new breeding population, selected over the past 15 yr for seed size and yields, not for forage attributes. Second, seed yields in perennial grasses vary over growing seasons, with yields typically peaking the second or third year and then declining (Wagoner, 1990a). Most reports of intermediate wheatgrass seed yields are from stands 3 yr or older. Additional data will need to be collected to determine if yields for this breeding population of kernza wheatgrass decline over time. Third, most intermediate wheatgrass seed yields have been reported from the Great Plains or Intermountain West, under lower rainfall and fertility conditions than our site in Michigan. Greater yields could be expected at our site, given that both seed and vegetative productivity of intermediate wheatgrass are responsive to inputs (Loeppky et al., 1999; Ogle et al., 2003; Xue et al., 2011). Fourth, planting and tiller densities can vary considerably, as most intermediate wheatgrass cultivars managed for forage seed are planted in rows at wide spacing and these rows are maintained over the years. Our plots were planted at 15-cm row spacing, but by the second year, kernza rhizomes had created thick sod, greatly increasing the tiller density relative to the first year. Finally, most reports of seed yields were from mechanically harvested plots. Our plots were hand harvested and therefore likely overestimate realized yields because a substantial amount of intermediate wheatgrass seed can be lost during mechanical harvesting (Wagoner 1990b).

The differences in seed yield between annual wheat and kernza were great (Table 6). Averaged across management practices, first-year kernza yielded 4.5% compared with annual wheat in 2010, and second-year kernza yielded 33% compared with wheat in 2011. The vegetative biomass of annual wheat was 93% of the kernza biomass in 2010, whereas annual wheat was only 29% of the kernza vegetative biomass in 2011. Seed yield of kernza wheatgrass appears to be more sensitive to late planting than winter wheat, perhaps due to the relatively slower vegetative development of wheatgrass. Early planting of kernza wheatgrass will often result in earlier flowering dates and greater first-year yields (DeHaan, unpublished data, 2012). The late fall planting in 2009 and unusually warm spring likely contributed to the lower seed yields and total aboveground biomass production in 2010.

Intermediate wheatgrass is a very productive plant and in recent biofuel evaluations, has performed comparably to big bluestem (*Andropogon gerardii* Vitman) and switchgrass (*Panicum virgatum* L.) in South Dakota (Lee et al., 2009) and to switchgrass in North Dakota (Xue et al., 2011). In light of the total aboveground productivity of kernza in the second year, little of this fixed C was allocated to seed (harvest index = 0.10). Total productivity is an important characteristic of perennial grain crops because the greater allocation of photosynthate into reproductive effort has historically been a primary mechanism for increasing yields (Gifford et al., 1984). If the total aboveground productivity in the second year is maintained for several subsequent years and if continued breeding efforts are able to increase the harvest index to $\sim$0.30, kernza would yield grain comparable to annual wheat. Past breeding efforts with this grass have shown a large degree of genetic diversity that can be manipulated, with 10 to 20% increases in seed yield per selection cycle (Knowles, 1977; Wagoner, 1995; Cox et al., 2002). It should be noted that any yield gains should be balanced with ecosystem services.

Additional possibilities attainable in the near term would be management of these systems as a multipurpose crop for forage, grain, and biofuel. Previous work has explored the economic possibility of an intermediate wheatgrass dual-use system (forage and grain; Watt, 1989), as well as a perennial wheat dual-use system (Bell et al., 2008) because income from forage could offset the reduced income from lower yields in perennial systems.

## CONCLUSIONS

This study examined soil moisture, soil C accrual, $NO_3$ leaching, and agronomic performance of a new perennial grain wheatgrass cultivar relative to annual wheat across three management regimes. Overall, differences between perennial kernza and annual wheat impacted the measured soil properties much more than N management. In the first 2 yr, kernza demonstrated reduced $NO_3$ leaching, lower soil moisture at depth, increased labile soil C, but reduced yields of grain. Continued evaluations are needed to determine how these systems perform over time, and continued breeding efforts are necessary to increase grain yields. Kernza shows promise, however, for rapidly improving local soil ecosystem services and for addressing some of the most chronic environmental challenges associated with current food production systems.


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