ENVIRONMENTAL AND ECONOMIC RESEARCH AND DEVELOPMENT PROGRAM

Sustainability of Switchgrass for Biofuel in Southwestern Wisconsin

Final Report
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List of Acronyms

°C - degrees Celsius
ac - acre
ANOVA - analysis of variance
btu - British thermal unit
C - carbon
CH_4 – methane
Cl^- - chloride ion
cm - centimeters
cm s^{-1} - centimeters/second
CO_2 - carbon dioxide
CRP - conservation reserve program
D-IMAZ+GLY - Diverse species planting with pre-emergent applications of glyphosate and imazapic
DM - dry matter
g - grams
g ae ha^{-1} - grams acid equivalent/hectare
GHG - greenhouse gas
Gj - gigajoule
GLY - Pre-emergent applications of glyphosate
GLY+OATS - Oats (*Avena sativa*) planted as a companion crop + pre-emergent applications of glyphosate
GLY+2,4-D - Pre-emergent applications of glyphosate + post-emergent applications of 2,4-D
ha - hectare
ISO - International Organization for Standardization
kg ha^{-1} - kilogram/hectare
km h^{-1} - kilometer/hour
L. - Linnaeus
lb - pounds
m - meters
m^2 - meters squared
$m^{-2}h^{-1}$ or $m^{-2}hr^{-1}$ - per meter squared per hour
Mg - megagram
Mj - megajoule
mm - millimeters
Michx. - André Michaux
N - nitrogen
npp - net primary production
N_2O - nitrous oxide
p - p-value
PLS - pure live seed
S-IMAZ+GLY - Switchgrass only planting with pre-emergent applications of glyphosate and imazapic
SPAL - Soil and Plant Analysis Lab
Spp. - species

Executive Summary

The purpose of this project was to provide information that contributes to the development of economically and environmentally sound energy production in Wisconsin. The production of energy from perennial biomass crops holds potential to supplement fossil fuel use and thereby reduce fossil fuel emissions. Perennial biomass crops also have the potential to decrease soil erosion, improve soil quality, increase carbon (C) sequestration, and also provide other benefits such as wildlife habitat. Switchgrass and mixtures of native prairie plants (warm season grasses and forbs) have been identified as potential herbaceous bioenergy crop candidates. We evaluated the sustainability of these energy crops when planted on marginal agricultural land in Wisconsin. Specifically we estimated productivity of select agronomic practices (weed management and fertility) and estimated how potential carbon sequestration, soil erosion, greenhouse gas fluxes, and global warming potential were affected by these practices. Below is a summary of the results from this project within each of these categories.

The specific project objectives were to:

1. Assess soil C sequestration and global warming potential of establishing switchgrass stands.
2. Evaluate the potential for soil loss among various establishment methods.
3. Measure optimum N fertilizer application rates for productivity and how they impact biomass quality and thermal energy.

METHODOLOGY

- This study was located on six working farms in Grant County, Wisconsin.
- Five experimental treatments at each farm were established in May 2008.
    - Treatments included
        - 3 switchgrass monocultures.
        - switchgrass planted with a companion crop of oats (*Avena sativa*).
        - a diverse mixture that included 5 native grasses and 4 native forbs.
    - Weed management treatments for switchgrass included
        - pre-emergent applications of glyphosate.
        - pre-emergent applications of glyphosate + post-emergent applications of 2,4-D.
        - pre-emergent applications of glyphosate and imazapic.
        - oats (*Avena sativa*) planted as a companion crop + pre-emergent applications of glyphosate.
    - Additionally the effect of nitrogen fertilizer rate and harvest timing (early fall, late fall, spring) on switchgrass was productivity and fuel quality were evaluated at each site across establishment treatments.
- In May 2009, each experimental field was further divided into four plots to evaluate effects of second-year weed management strategies. These second-year treatments included
    - low-intensity prescribed burn.
    - glyphosate.
    - imazapic + glyphosate.
    - untreated control.

ESTABLISHMENT AND PRODUCTIVITY:

- A range of weed management methods were effective at establishing a productive switchgrass stand on marginal lands in Wisconsin.
- Additional management after the establishment year did not improve productivity of either switchgrass or diverse stands.

- While fields produced minimal amounts of biomass in the establishment year (< 1 ton/acre(ac)), treatments yielded between 2 and 4 tons/ac annually, two and three years after establishment.
- The diverse prairie treatment yielded between 2 and 3 tons/ac annually, two and three years after establishment. Yield was less than the most productive switchgrass treatment in 2009, but similar to all switchgrass treatments in 2010.
- Annually adding up to 100 lb/ac of nitrogen (N) fertilizer after the establishment year increased productivity of switchgrass stands by 0.5-1.5 tons/ac each year.
- Fuel quality was improved by delaying harvest until spring, but this delayed harvest decreased yield by between 1 and 2 tons/ac.

CARBON SEQUESTRATION:

- Below-ground carbon sequestered in plant material and microbes respiring carbon dioxide (CO_2) were similar between switchgrass monocultures and diverse stands.
- Burning monocultures of switchgrass increased sequestered carbon in above ground tissue compared to diverse stands, but unburned switchgrass monoculture had similar amounts of carbon sequestered.

GREENHOUSE GAS FLUXES:

- No differences in CO_2 or methane (CH_4) fluxes were found in 2009 or 2010 with respect to establishment treatments or fertilizer application.
- Nitrous oxide (N_2O) fluxes were increased with fertilizer applications in 2009 and 2010.

GLOBAL WARMING POTENTIAL:

- Burning switchgrass monocultures during establishment may support greater soil C accumulation, but simply planting and harvesting this perennial grass should achieve desired goals of minimizing global warming potential for a harvested perennial grass system.
- Even lower global warming potential would likely be realized from switchgrass stands that left more residual material present or were even left unharvested as grass cover would keep soils cool thereby reducing soil respiration.

SOIL EROSION:

- Estimated soil loss calculations did not differ between establishment practices in 2008 or 2009.
- Values of soil loss ranged between 11.0 and 18.6 tons/ac in 2008 and 2.2 and 7.6 tons/ac in 2009, and were closely related to slope of the field.
- A noticeable decline in soil loss occurred from 2008 to 2009, demonstrating the benefit of planting a perennial crop.
- Field or plot level measures of switchgrass planted as a primary crop are required to validate model outputs on soil erosion.

Results suggest that switchgrass and diverse prairies can be established on marginal soils in Wisconsin and become productive in the second or third production year. Fuel quality will increase as fields are harvested late in fall to early spring. While this increased quality will be desired by industry, producers will require increased premium prices for this product as delaying harvest can result in a substantial loss in productivity. Although differences among management and plant community treatments in carbon sequestration and greenhouse gas fluxes were measured, these differences were relatively small. For example, spring burning switchgrass monocultures during establishment may support greater soil C accumulation, but simply planting and harvesting this perennial grass should achieve desired goals of minimizing global warming potential for a harvested perennial grass system.

Object of Research

The purpose of this project was to provide information that contributes to the development of economically and environmentally sound energy production in Wisconsin. We established switchgrass on marginal agricultural land to compare the effectiveness of various agronomic practices for achieving successful crop establishment and maximizing harvestable biomass for bioenergy use. Because the effects of bioenergy crops on the environment also influence their potential for long-term use, we evaluated the effects of establishment and management methods on key ecosystem services including carbon sequestration, soil stability, and nutrient availability. We compared the results obtained from switchgrass monocultures to those obtained from a mixture of native warm-season grasses planted in conjunction with native legume species. These demonstrations provide valuable information on environmental impact of native perennial grassland species used for bioenergy production in Wisconsin.

The specific project objectives were to:

1. Assess soil C sequestration and global warming potential of establishing switchgrass stands.
2. Evaluate the potential for soil loss among various establishment methods.
3. Measure optimum N fertilizer application rates for productivity and how they impact biomass quality and thermal energy.

Methods

Study site

This study was located on six working farms in Grant County, Wisconsin. Grant County is in the unglaciated Driftless Area of Southwestern Wisconsin, which is characterized by relatively steep and rugged topography. Fields selected for inclusion in this study had a history of glyphosate-resistant annual crops grown with minimum to no tillage, and were selected for their lower productivity and/or greater potential for erosion relative to other fields within each farm. Weed populations, while variable across sites, consisted of annual grasses (primarily *Setaria* species (spp.)) and annual and biennial broadleaf weeds, with few perennial weeds. Soils at these sites are moderately eroded, well-drained silt loams in the Dubuque, Fayette, and Hixton series (mixed, superactive, mesic Typic Hapludalfs) (SSS 2010). Thirty-year mean annual precipitation is 88.7 centimeters (cm) and mean growing-season temperature (April (Apr) - October (Oct)) is 16.1 degrees Celsius (°C) (USDA 2010).

Field establishment

To evaluate the effects of various weed suppression strategies on biomass crop production and ecosystem services, we established five experimental treatments at each farm in May 2008 (Table 1). These treatments were selected because they targeted common weed species in the region, are common weed management strategies, and include low and high intensity management options. Treatments included 3 switchgrass monocultures, switchgrass planted with a companion crop of oats (*Avena sativa*), and a diverse mixture that included 5 native grasses and 4 native forbs (Table 1). Weed management treatments for switchgrass included pre-emergent applications of glyphosate (hereafter GLY), pre-emergent applications of glyphosate + post-emergent applications of 2,4-D (hereafter GLY+2,4-D), pre-emergent applications of glyphosate and imazapic (hereafter S-IMAZ+GLY), and oats (*Avena sativa*) planted as a companion crop + pre-emergent applications of glyphosate (hereafter GLY+OATS) (Table 1). The companion crop treatment was selected to reduce soil erosion during switchgrass establishment and to suppress weeds.

The Cave-in-Rock variety was used in all switchgrass treatments. Species planted in the diverse treatment (hereafter D-IMAZ+GLY) included: switchgrass (Forestburg variety; *Panicum virgatum* L.; 1.12 kilograms/hectare (kg ha^{-1})), side-oats grama (*Bouteloua curtipendula* [Michx.] Torr.; 1.68 kg ha^{-1}), indian grass (*Sorghastrum nutans* [L.] Nash; 2.24 kg ha^{-1}), big blue-stem (*Andropogon gerardii* Vitman; 2.24 kg ha^{-1}), little blue-stem (*Schizachyrium scoparium* [Michx.] Nash; 2.80 kg ha^{-1}), Illinois bundle flower (*Desmanthus illinoensis* [Michx.] MacMill ex. B.L. Rob & Fernald; 0.28 kg ha^{-1}), partridge pea (*Chamaecrista fasiculata* [Michx.] Greene; 0.56 kg ha^{-1}), Canada milk vetch (*Astragalus canadensis* L.; 0.56 kg ha^{-1}), and yellow coneflower (*Ratibida pinnata* [Vent.] Barnhart; 0.14 kg ha^{-1}). All rates are pure live seed (PLS). The prairie mixture was established with either a Truax conventional drill or a Truax FLEXII no-till drill (Truax Company; New Hope, Minnesota); row spacing was 19 cm with 0.6 - 1.3 cm seeding depth. We utilized pre-emergent herbicides (imazapic 70 grams acid equivalent/hectare (g ae ha^{-1}) + glyphosate 140 g ae ha^{-1}) at all farms in 2008 to promote robust early establishment, rather than the alternative application of glyphosate post-emergence, which likely would have contributed to poor forb establishment. This herbicide mixture was selected for residual control of broadleaf weeds and control of annual grasses, as foxtails (*Setaria* spp.) are among the most common agricultural weeds in this region (Fickett et al. 2008). Forbs were selected for tolerance to the pre-emergent herbicide imazapic used in this study. Weed height exceeded the height of sown plants at two farms 3 months after planting, and these plots were mowed to 15 cm height in August 2008 to remove the weed canopy.

Table 1 Pre-establishment field crops and tillage for switchgrass and diverse species mixture bioengery crops at each farm; Grant County, Wisconsin.

Farm	Slope (%)	Previous Crop	Field Preparation	Field History (2006-2007)
CR	9-18%	Corn	Fall chisel, spring disked	Corn planted into corn residue using fall chisel/spring disk system[a,b]
DS	1-2%	Winter rye	No-till	Corn planted into corn residue using fall chisel/spring disk system[a,b]
FR	4-7%	Corn	No-till	Corn planted into soybean residue; spring disked[a]. Soybeans planted into corn residue using fall chisel/spring disk system[b]
TS	9-11%	Soybeans	No-till	Soybeans planted into corn residue using no-till system[a]. Corn planted into corn residue using no-till system[b]
SC	15-25%	Soybeans	Spring disked	Soybeans planted into corn residue using fall chisel/spring disk system[a] . Corn planted into soybean residue; spring disked[b].
WO	10-16%	Corn	No-till	Corn planted into corn residue using no-till system[a,b]

[a] Crop year 2007
[b] Crop year 2006

Second year management

In May 2009, each experimental field was further divided into four plots to evaluate effects of second-year weed management strategies. These second-year treatments included a low-intensity prescribed burn (hereafter burn), herbicide management as glyphosate (1.12 kg ae ha^{-1}), a mixture of imazapic + glyphosate (imazapic 70 g ae ha^{-1} + glyphosate 140 g ae ha^{-1}), and an untreated control (hereafter control). Prescribed fire is a common tool for natural areas management. Glyphosate is a standard herbicide treatment for establishing native perennial species, and the mixture of imazapic and glyphosate provides additional control for annual grasses 1-2 months after application at the rate applied. Herbicide treatments were applied between 12 – 15 May 2009. Many introduced forbs and native grasses had emerged at this time; native grasses ranged from 1-5 cm in height with 1-2 fully exposed leaves. Visual herbicide injury was noticed on planted grasses after application, but was not evident by the time species composition surveys were conducted.

Prescribed burn treatments were conducted on 06 May 2009 at five farms and on 11 May 2009 at one farm. The fuel type at 5 of the 6 farms was 15 cm stubble that remained standing after plots were harvested in autumn 2008. One farm burned on 06 May was not harvested in autumn 2008 because of steep slopes and the fuel type was 1 meter (m) tall dead grasses and forbs; because the vegetation had remained standing over winter, the standing grasses and forbs were compressed and prostrate over approximately 60% of the plot area. Across both dates, ambient temperature ranged from 13-17° C and wind speeds ranged from 0-16 kilometers/hour (km h^{-1}) (gusting to 24 km h^{-1} at one of the mowed farms). Average relative humidity was 79% on 06 May and 58% on 11 May. Cool temperatures and high relative humidity contributed to low-intensity fires (flame lengths ranging from 0.07 – 0.60 m; average rate of spread 6.1 cm/second (cm s^{-1})). Average ground surface area burned (determined by tallying observations of charred vs. uncharred vegetation at 100 sample points along a transect placed across each burned plot) was 32 ± 14 % across all farms.

Fertility experiments

The experimental design at each site was a randomized complete block, split-plot with four replications. The whole plot factor was N fertilization rate in the form of granular ammonium nitrate and was applied by hand on 18 June 2009 and 21 June in 2010. The whole plot N rates were 0, 56, 112, 168 and 224 kg $ha^{-1}$of N. Across sites, each treatment was replicated 16 times. The split-plot factor within the whole plot N rate treatments was harvest timing. The split-plot treatments were three harvest times: one in mid-fall, another in late-fall and the final harvest in early spring. Harvest times for the 2009 growing season were 19 October 2009 (mid-fall harvest), 11 November 2009 (late-fall harvest) and 9 May 2010 (spring harvest). For the 2010 growing season, harvest times were 25 October 2010 (mid-fall harvest), 23 November 2010 (late-fall harvest) and 31 March 2011 (spring harvest).

Each site measured 33.5 × 21.3 m (0.07 ha). Plot dimension for the N fertilizer treatments measured 3.0 x 9.1 m. To make the split-plots for harvest timing treatments, the whole plot N rate treatments were divided evenly into 3 × 3 m sub-plots and assigned a harvest timing. Placement of N rate and harvest timing treatments were randomized across blocks. Alleys were mowed with a DR field and brush mower on 28 July 2009, 29 July 2010 and 18 August 2010 (DR Power Equipment, Vergennes, VT).

Measurements

Biomass estimates (objective 1)

In 2008, plots were harvested to 15 cm stubble height using a small plot harvester and biomass from four 4.5 meter squared (m^2) area quadrats was collected and weighed in the field; wet mass was recorded to 0.05 kg accuracy, and grab samples were collected and returned to the laboratory. Moisture of grab samples was determined by recording wet mass for each sample, drying samples at 60 °C for 48 hours, and recording dry mass. Moisture values for these grab samples were used to calculate dry mass yield from wet biomass weighed in the field for each plot. We note that in practice, these perennial bioenergy crops would not be harvested in the first year of establishment because of low yield; our 2008 harvests were conducted for the purposes of our study only. In 2009 and 2010, we estimated yield by harvesting three 1.0 m^2 quadrats to 15 cm stubble height in each plot using hand-operated landscaping shears. Biomass was weighed in the field and grab samples were collected to determine moisture content for calculating dry biomass yield, as described above.

Carbon sequestration in soil and biomass (objective 1)

We sampled soil at the end of the growing season in 2009 and 2010. In each experimental plot, we took 10 soil samples to 15 cm depth using a 2.5 cm diameter stainless steel soil probe, and composited these 10 samples into a single sample for analysis. Composited samples were sieved through a 2 millimeter (mm) screen to remove stones and root fragments. A subsample was removed, dried for 48 hours at 60° C, and ground to a fine powder before analysis via dry oxidation/fluorescence on a Carlo-Erba C N analyzer.

We estimated C content in below-ground biomass using ingrowth root cores. We installed four, 5 cm diameter x 15 cm height ingrowth root cores before the growing season in each experimental plot. Each core was filled with a standard mixture of 75% field soil and 25% sand. Ingrowth root cores were removed at the end of the growing season in each year, following a killing frost and the biomass harvest. Each core was returned to the lab and soil was washed from the roots using deionized water. Roots were placed in a drying oven for 48 hours at 60° C and weighed. Dried roots were ground to pass a 1 mm screen, and analyzed for percent C and N content as above. We calculated estimates of below-ground C content from percent C content in roots and the total root biomass obtained from each ingrowth core.

We removed 3 subsamples of above ground biomass from the end-of-season biomass harvested from each plot, ground each subsample to pass a 1mm screen, and analyzed percent C as above. We calculated above ground C content from the mean percent C content in biomass subsamples and the total biomass yield from each plot.

Greenhouse gas fluxes (objective 1)

We sampled greenhouse gas (GHG) fluxes at 2 week intervals from each of the four focus treatments in the main project, and from each of the fertility treatments in 2009. In 2010, we sampled GHG fluxes from fertility treatments at approximately daily intervals for one week prior and one week post fertilizer application. We also sampled GHG fluxes for one date near the end of the growing season to evaluate persistent effects of fertilization on GHG fluxes. We used a closed static chamber and removed two 30 milliliter (mL) samples of chamber air, one at 0 and the other at 30 minutes. Each sample was injected into a glass vacuum vial, returned to the lab, and analyzed for CO_2, CH_4, and N_2O concentrations. Flux rates were calculated from the difference in concentration between samples taken at 0 and 30 minutes.

Soil erosion estimates (objective 2)

The soil loss model RUSLE2 (version 1.26.6.4) was used to estimate soil loss for 2008 and 2009. Model input for each plot included soil type, slope percent and slop length, location (county), crop management factors (tillage, previous crop, when and how previous crop was harvested, current crop, seeding practice, etc.).

Biomass estimates (objective 3)

Harvests were conducted by randomly placing a 1 m^2 quadrate within each harvest timing plot. Switchgrass was cut 15 cm above the soil surface. Fresh weights were recorded on-site. Weeds and switchgrass were separated and subsamples were collected, weighed, and dried at 60°C to determine dry matter (DM) yield, moisture content and the concentration of weeds in the switchgrass.

Biomass quality analysis (objective 3)

Tissue samples from the 0, 56 and 112 kg ha^{-1} N rate treatments in all three harvest treatments at sites 1 and 4 were analyzed for chloride ion (Cl^-) concentration. The Cl^- can clog up boilers during burning and low mineral concentrations are preferred. Cl^- was selected as an indicator of switchgrass quality. Sites 1 and 4 were chosen because they had minimal weed pressure and produced greater switchgrass yields than sites 3 and 4. Fertilizer treatments of 168 and 224 kg ha^{-1} N rate treatments were excluded from nutrient analysis because there was little evidence of a yield response above the 112 kg ha^{-1} N rate. The University of Wisconsin’s Soil and Plant Analysis Lab (SPAL) carried out the Cl^- analysis of switchgrass. A digital chloridometer (LabConCo model # 442-5000, Labconco Corporation, Kansas City, Missouri) was used to determine chloride concentrations in the switchgrass samples (Chloride Determination, 1980).

Biomass British thermal unit (Btu) analysis

The thermal energy content of switchgrass was determined on a bomb colorimeter (Parr 1266 Isoperibol Bomb Calorimeter, Parr Instrument Company, Moline, Illinois). The analysis followed the standard International Organization for Standardization (ISO) 1928:2009 for thermal content of a material. Switchgrass samples from N rate treatments of 0 and 112 kg ha^{-1} of the fall and spring harvests of the 2009 and 2010 growing seasons were analyzed. Samples from the 2009 growing season were weighed on a scale that went to the 0.001 g and the 0.0001 g was extrapolated. Samples from the 2010 growing season were weighed on a digital scale that went to the 0.0001 g.

Summary of Results/Accomplishments:

Objective 1: Assess soil C sequestration and global warming potential of establishing switchgrass and prairie stands

A significant component of potential C sequestration is C fixed by plants via net primary production (npp). The other main part of the C sequestration equation is microbial respiration of CO_2 to the atmosphere. Hence, here we report on treatment effects on both npp and microbial respiration of CO_2.

How does field establishment and management affect biomass yield?
There were no significant differences in biomass yield among treatments in the establishing year (2008) (p=0.10). In 2009, we observed the greatest yield in the switchgrass imazapic + glyphosate treatment and the lowest yield in the switchgrass glyphosate + oats treatment (p=0.006). In 2010, the switchgrass imazapic + glyphosate and glyphosate + 2,4-D treatments produced greater yield than the switchgrass glyphosate + oats treatment (p=0.004) (Figure 1). The diverse prairie treatment yielded less than the most productive switchgrass treatment in 2009 (imazapic + glyphosate) (p=0.006), but did not differ from any switchgrass treatments in 2010.

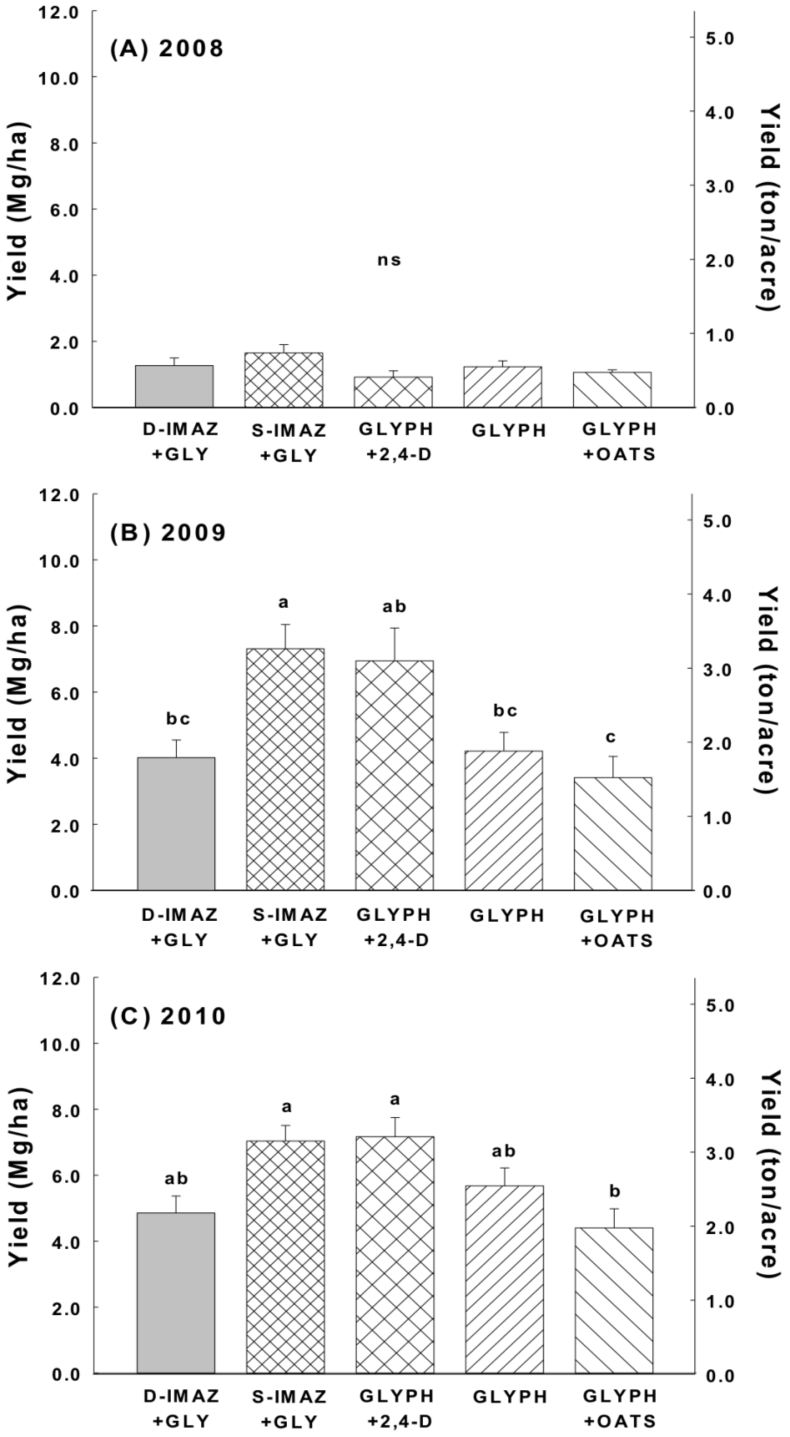

Figure 1. Dry mass of biomass yield from each experimental treatment established in 2008, for 2008 (A), 2009 (B), and 2010 (C). Lowercase letters indicate statistically significant differences among means for each year. Diverse imazapic + glyphosate (D-IMAZ+GLY); switchgrass imazapic + glyphosate (S-IMAZ+GLY); switchgrass glyphosate + 2,4-D (GLYPH+2,4-D), switchgrass + glyphosate (GLYPH); switchgrass glyphosate + oats (GLYPH+OATS).

How does establishment success in the first year influence yields in later years?
We found that the percent cover by switchgrass in 2008 was positively correlated with yield in 2009 and 2010, indicating that more successfully established switchgrass stands would produce greater biomass in subsequent years, although the trend appears to be declining over time (Figure 2).

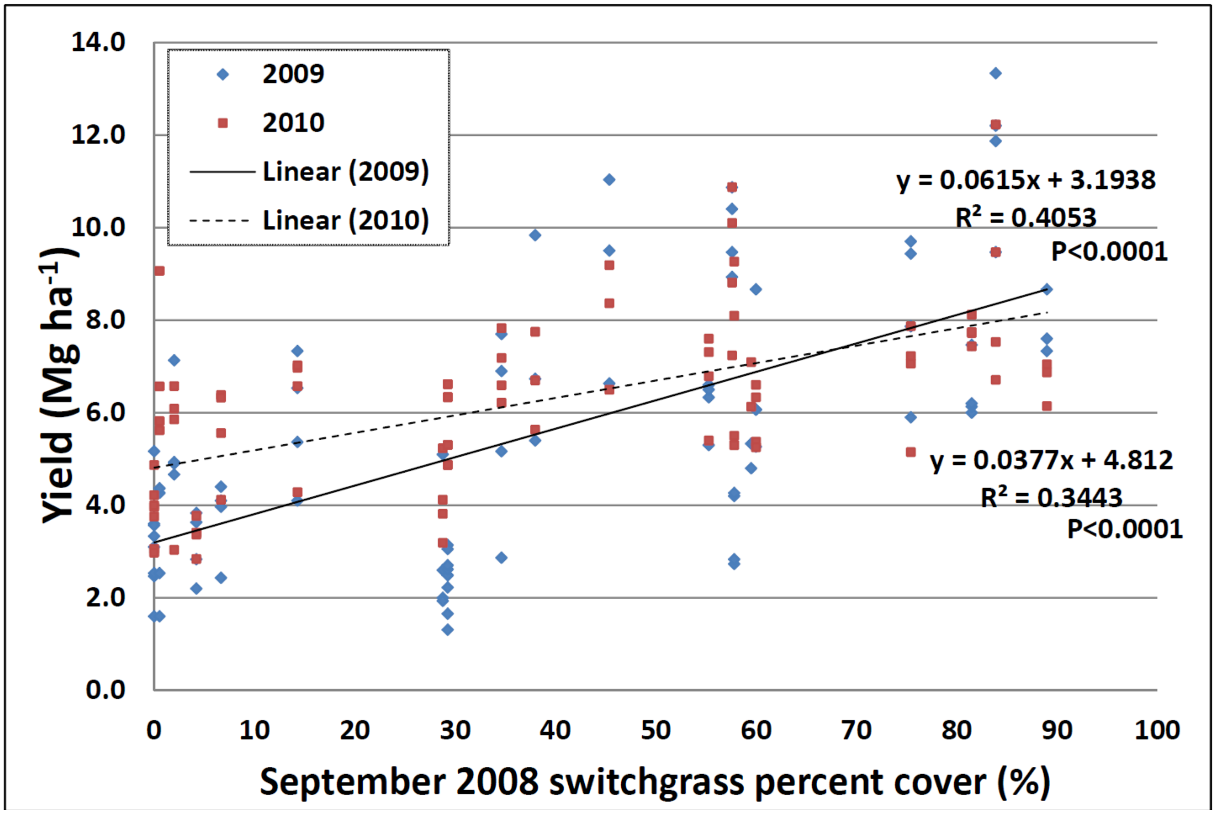

Figure 2. Scatter plot of switchgrass percent cover in 2008 by biomass yield obtained in 2009 (blue circles) and 2010 (red squares). Equations, R^2, and significance values are given for line of best fit for 2009 (solid) and 2010 (dashed).

How does additional weed management treatments, applied in the year following stand establishment, influence yield in the second and third growing seasons post-establishment?
There were no statistically significant effects of post-establishment weed management treatments on yield in the second or third growing seasons, within any of the establishment treatments (p>0.05 for all) (Figure 3). This suggests that management of weed species should be focused in the establishment year to ensure adequate establishment, and management after establishment does not influence productivity.

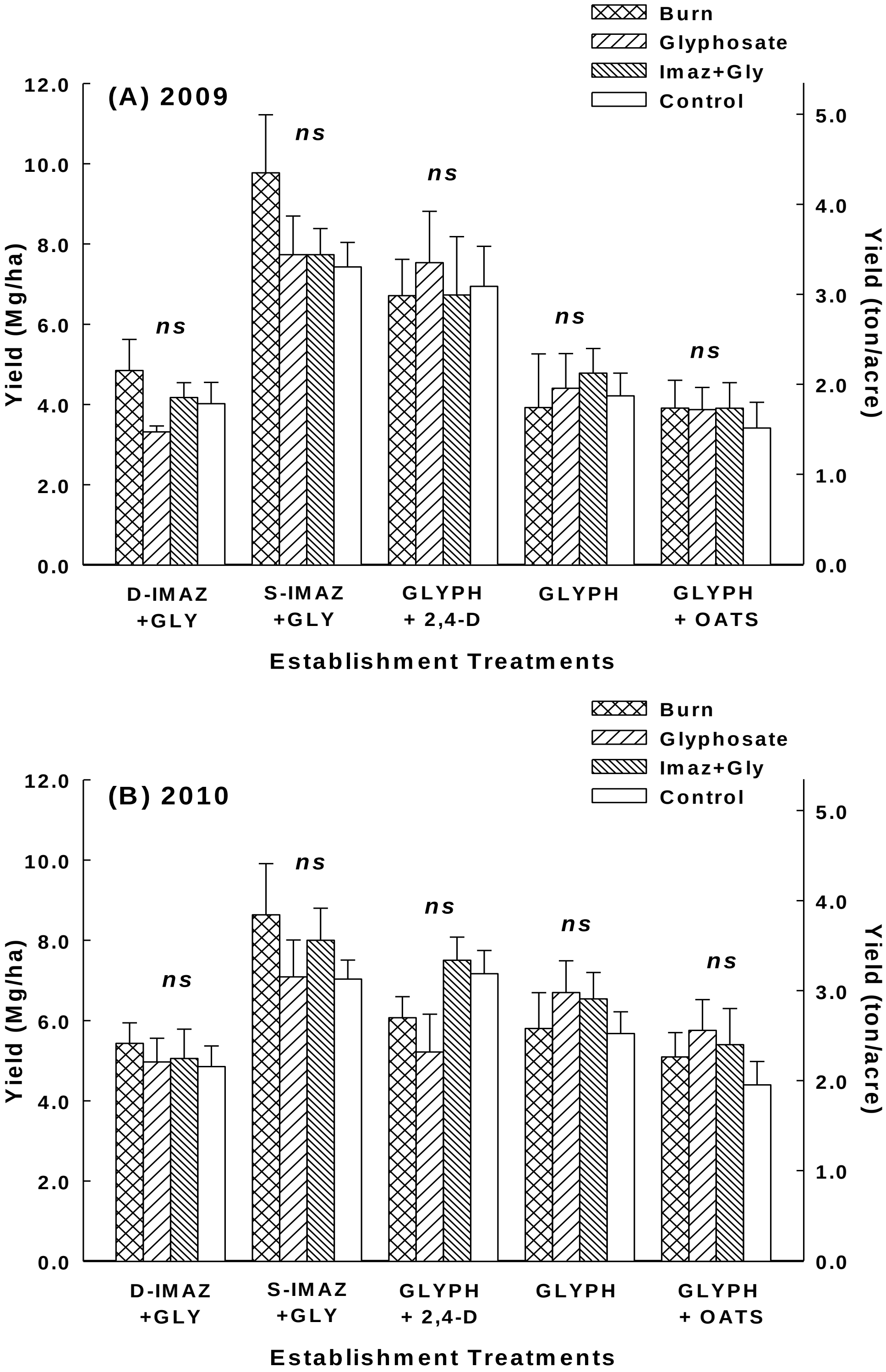

Figure 3. Yield from second-year weed management treatments overlaid on each 2008 establishment treatment, measured in 2009 (A) and 2010 (B). Lowercase letters indicate statistically significant differences among means for each year. Treatment abbreviations follow Figure 1.

Was total soil C affected by management treatments?

No significant differences in total soil C were observed across treatments for either 2009 or 2010 (Figure 4). Results suggest that soil C is similar between pure switchgrass stands and diverse prairie plantings. It also appears that weed management within these stands does not affect soil C.

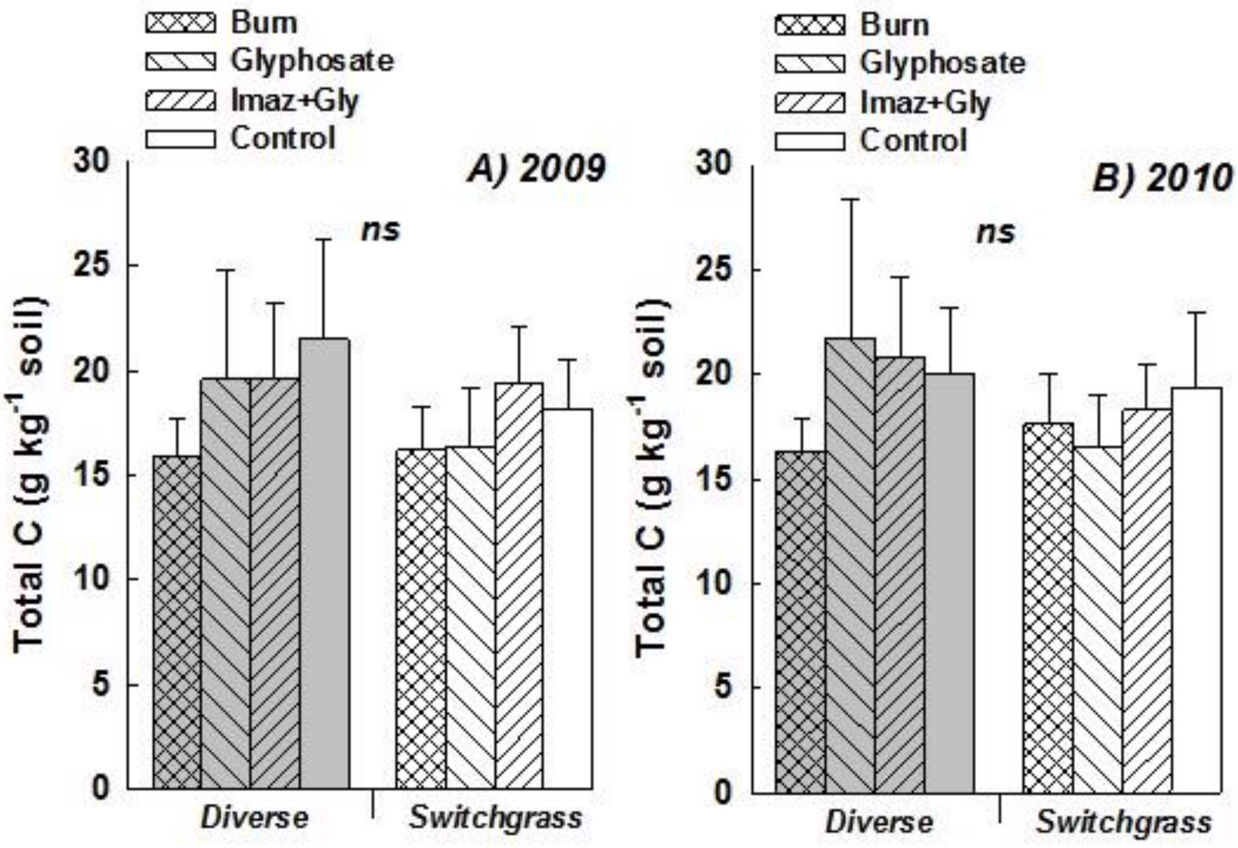

Figure 4. Soil total carbon (C) concentration in 2009 (A) and 2010 (B) in diverse mixture (shaded bars) and switchgrass monoculture bioenergy crops in Grant County, Wisconsin. Bar pattern indicates second-year weed management strategy applied to each crop.

How did treatments affect total C content of above and below-ground biomass?

The switchgrass monoculture treated with prescribed fire supported a greater biomass C concentration than did the unburned and burned diverse mixture. There was no statistically significant difference in biomass C concentration between the unburned switchgrass monoculture and any other treatment. These patterns were identical between 2009 (above ground p=0.0001; below-ground p= 0.189) and 2010 (above ground p<0.0001; below-ground p=0.295) (Figure 5).

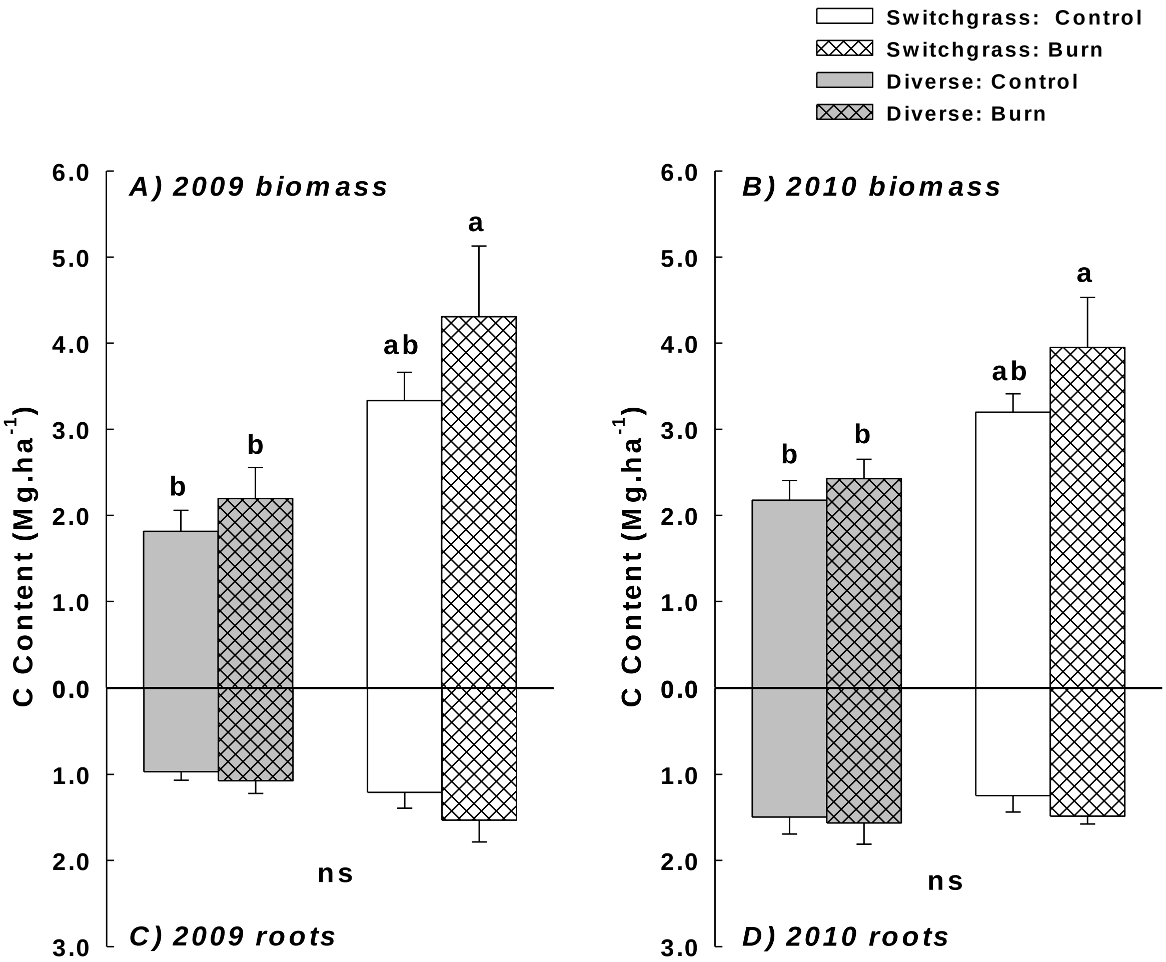

Figure 5. Carbon (C) content sequestered in above ground biomass (A, B) and roots (C, D) in 2009 and 2010 in Grant County, Wisconsin. Shaded bars indicate diverse mixture. Bar pattern indicates second-year weed management strategy applied to each crop.

How did treatments affect emissions of GGH from soils to the atmosphere?

No significant effects of treatments were observed on microbial respiration (CO_2 flux in Fig 6A), CH_4 consumption from the atmosphere into soils (Figure 6B), or N_2O fluxes the year after establishment (2009) (Figure 6C). There were also no differences in CO_2 and CH_4 flux rates among fertility treatments at any sampling date in 2009. In contrast there were differences in N_2O flux among fertility treatments only at the July 30 sampling date. At this date, N_2O flux was greater in the 150 lb/ac (168 kg ha^{-1}) treatment than in the 50 lb/ac (56 kg ha^{-1}) treatment, but neither of these treatments differed significantly from the 0, 100, and 200 lb/ac (0, 112, and 224 kg ha^{-1}) treatments (p=0.035) (Figure 7). There were no differences in CO_2 and CH_4 flux rates among fertility treatments at any sampling date before or after the application of fertilizer in 2010 (Figure 8), but we did observed statistically significant differences in N2O fluxes among fertility treatments at the 27 May (pre-treatment, p=0.024), 04 June (post treatment, p=0.020), and 07 June (post-treatment, p= 0.028) sampling dates (Table 2). Differences in N_2O fluxes on these dates were observed with various rates of N applied when compared to the untreated control.

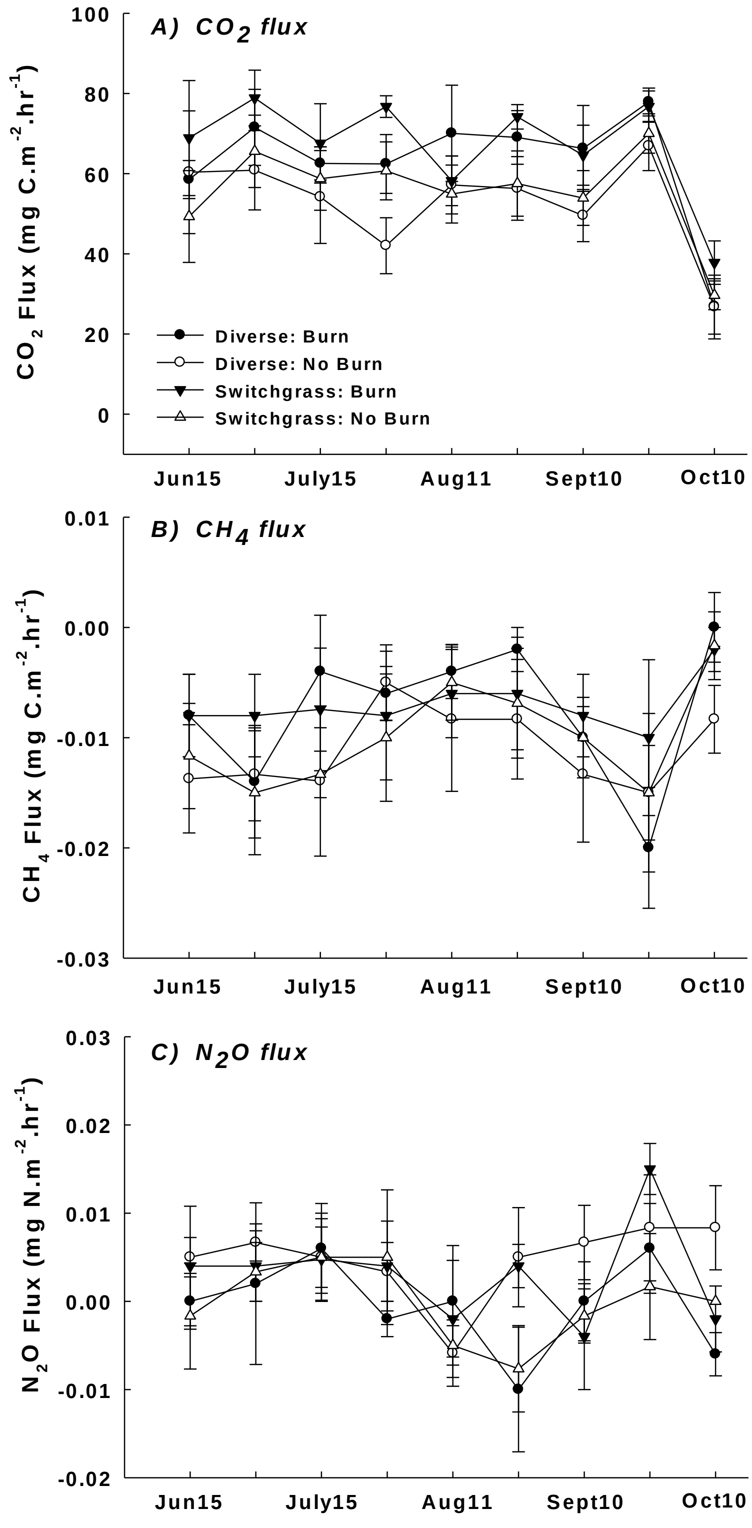

Figure 6. Greenhouse gas fluxes in burned and unburned switchgrass monoculture and diverse mixture treatments, monitored biweekly in 2009. Note differences in Y-axis scales among (A) CO_2 (carbon dioxide) flux, (B) CH_4 (methane) flux, and (C) N_2O (nitrous oxide) flux. Legend for (B) and (C) follows (A).

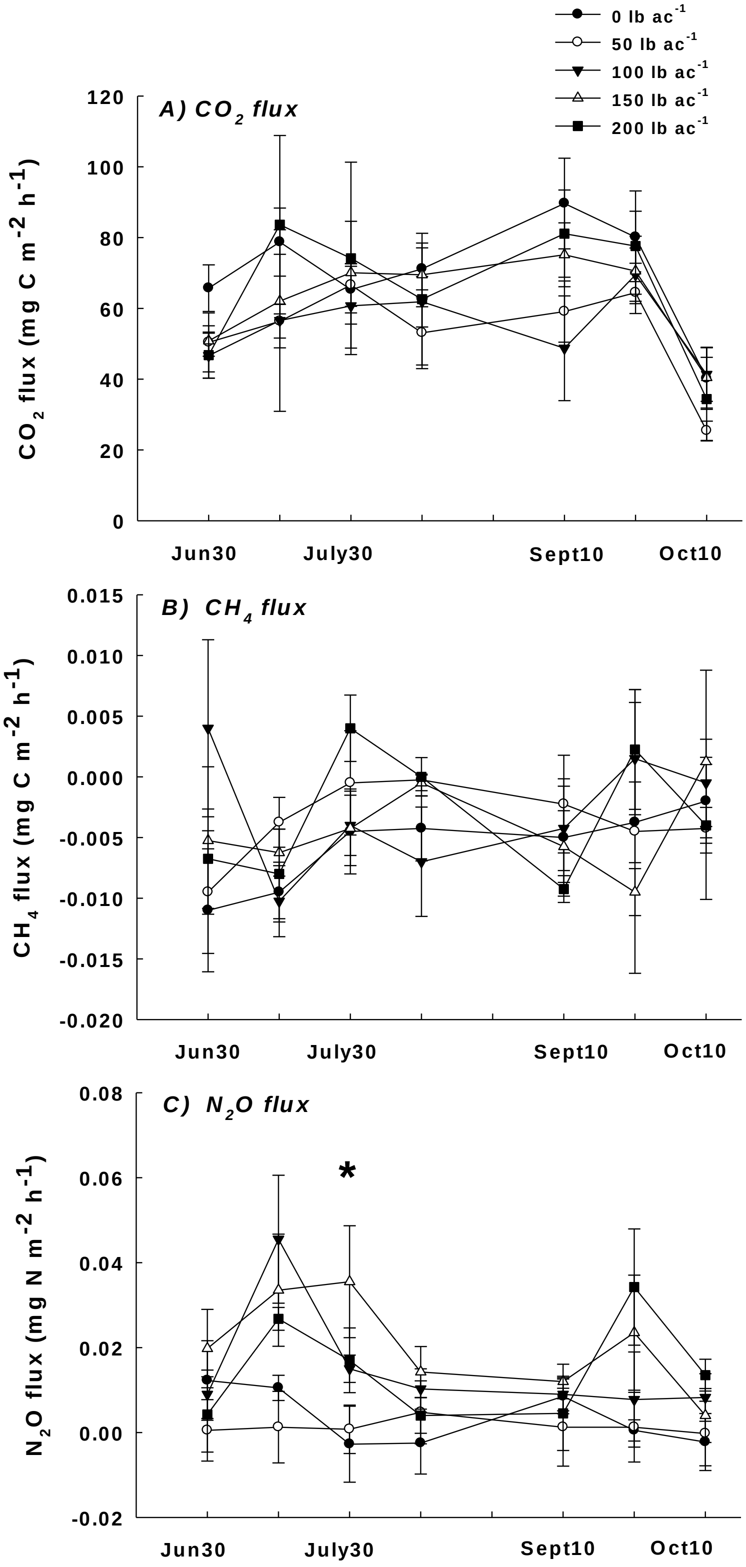

Figure 7. Greenhouse gas fluxes in fertilized switchgrass monoculture, monitored biweekly in 2009. Note differences in Y-axis scales among (A) CO_2 (carbon dioxide) flux, (B) CH_4 (methane) flux, and (C) N_2O (nitrous oxide) flux. Legend for (B) and (C) follows (A). Asterisks (*) indicate significant differences among treatments within a measurement period.

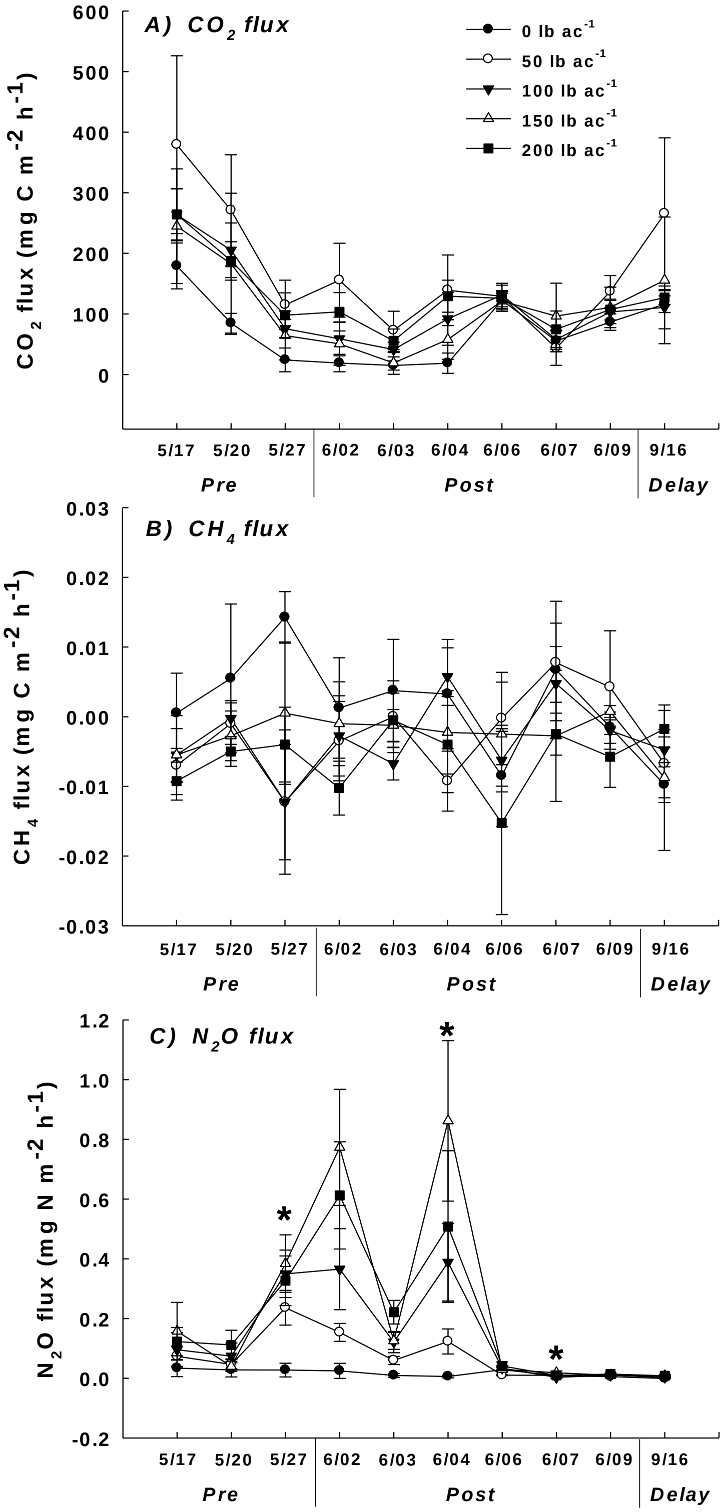

Figure 8. Greenhouse gas fluxes in fertilized switchgrass monoculture, measured before (*Pre*) and after (*Post* and *Delay*) fertilizer application in 2010. Note differences in Y-axis scales among (A) CO_2 (carbon dioxide) flux, (B) CH_4 (methane) flux, and (C) N_2O (nitrous oxide) flux. Legend for (B) and (C) follows (A). Asterisks (*) indicate significant differences among treatments within a measurement period.

Table 2. Means separations for N_2O fluxes for sampling dates at which significant differences among treatments existed. Letters indicate significant differences among treatment means, within sampling date.

Date		**Treatment (lb/ac)**			
	0	50	100	150	200
27 May	*b*	*ab*	*ab*	*a*	*ab*
04 June	*b*	*ab*	*a*	*ab*	*ab*
07 June	*b*	*b*	*ab*	*ab*	*a*

Summary of Objective 1 Work

Effects of treatments on components of ecosystem C balance were only observed on above ground plant production, where burned switchgrass monocultures were more productive than diverse treatments whether burned or not. The switchgrass monoculture was not significantly more productive than unburned switchgrass. Burning had no significant effects on C fluxes as CO_2 or CH_4 or N_2O. Hence, spring burning switchgrass monocultures during establishment may support greater soil C accumulation, but simply planting and harvesting this perennial grass should achieve desired goals of minimizing global warming potential for a harvested perennial grass system. Even lower global warming potential would likely be realized from switchgrass stands that go unharvested because grass cover would keep soils cool thereby reducing soil respiration.

Objective 2: Evaluate the potential for soil loss among various establishment methods

Estimated soil loss ranged between 11.0 and 18.6 tons/ac in 2008 and 2.2 and 7.6 tons/ac in 2009 (table 3). This estimate did not differ with respect to establishment treatments tested in 2008 (p=0.77) or 2009 (p=0.28). A noticeable decline in soil loss occurred from 2008 to 2009. This can be attributed to greater plant growth and greater exposed, bare soil during the establishment year. Direct measures of soil loss from switchgrass plots or fields are noticeably absent from the scientific literature. Most studies have evaluated switchgrass as a grass used in buffer strips, and the result has generally been positive. Switchgrass, when planted at the field edge, can reduce edge-of-field losses of sediment up to 91% (Blanco-Canqui, 2010). **Field or plot level measures of switchgrass planted as a primary crop are required to validate our assumptions or model outputs.** Differences in estimated soil loss are likely a result of soil slope. The slope of the field is the main factor responsible for demarking fields as "marginal". In this study, field slopes ranged from less than 1 to 25% and greater slopes were associated with greater soil loss. Regression analysis between slope percentage and estimated soil loss resulted in an R^2 value of 0.70 for 2008 and 0.64 in 2009 (data not shown).

RUSLE2 is typically used to evaluate soil loss over an entire rotation, so continued estimation or measurement of soil loss for the length of the switchgrass "rotation" is of interest. If soil loss continues to decline over the length of rotation, then the large soil loss in the first year has less impact. It should also be noted that RUSLE2 programmers are attempting to improve the prediction of soil loss for over-wintering crops (such as switchgrass and alfalfa). The new RUSLE2 (version 2) is not yet publically available but is using a new vegetation database. One major "fix" is the current RUSLE2 underestimates for residue cover for perennial vegetation, which can result in an overestimation of erosion from hay fields.

Table 3. RUSLE2 model estimates of soil loss for each 2008 establishment treatment, modeled for 2008 and 2009.

Establishment treatment	2008 Soil loss estimate (tons/ac)	2009 Soil loss estimate (tons/ac)
Diverse mixture		
Imazapic +Glyphosate	10.2 ± 2.0	6.3 ± 0.9
Switchgrass treatments		
Imazapic + Glyphosate	11.0 ± 2.9	2.2 ± 0.5
Glyphosate	11.5 ± 2.5	6.3 ± 1.2
Glyphosate + 2,4-D	18.6 ± 4.2	3.6 ± 0.4
Glyphosate + Oats	11.8 ± 1.9	7.6 ± 0.6

Objective 3: Measure optimum N fertilizer application rates for productivity and how they impact biomass quality and thermal energy.

How did N rates and harvest timing affect biomass production?

DM yield of switchgrass ranged from 0.6 to 17.0 megagram (Mg) ha^{-1} across treatments, sites and both growing seasons (table 4). There was one plot at spring harvest in the 2010 growing season where no switchgrass was collected because of a dominance of weeds. When averaged across sites and treatments by year, DM switchgrass yield improved from 5.5 Mg ha^{-1} in 2009 to 8.2 Mg ha^{-1} in 2010, an increase of 46%. The increase in switchgrass yield from the 2009 to 2010 growing season was expressed across all sites but was variable per site, with increases of DM Mg ha^{-1} ranging between 8% and 96%.

N fertilizer positively increased switchgrass yield up to a rate of 112 kg ha^{-1} of N in both the 2009 and 2010 growing seasons when analyzed over all sites and harvest timings (Figure 9). Averaged across harvest timing treatments in the 2009 growing season, the 112 kg ha^{-1} of N treatment produced a greater switchgrass yield than the 0 kg ha^{-1} of N treatment. The 112 kg ha^{-1} of N treatment produced a similar yield to the 56 kg ha^{-1}, 168 kg ha^{-1} and 224 kg ha^{-1} of N treatments. However, the 56 kg ha^{-1} of N treatment yielded less than the 168 and 224 kg ha^{-1} of N treatments. During the 2010 growing season, the 56 kg ha^{-1} of N treatment produced more switchgrass than the N rate of 0 kg ha^{-1}. The 112 kg ha^{-1} of N treatment yielded significantly more switchgrass than both the 0 and 56 kg ha^{-1} of N treatments and was not statistically different than yield the 168 or 224 kg ha^{-1} of N treatments.

Averaged across N rates, switchgrass yields were highest at mid-fall harvests in both the 2009 and 2010 growing seasons at 7.3 and 9.1 Mg DM ha^{-1}, respectively (Table 4). In the 2009 growing season, yields significantly decreased with later harvest timings, relative to mid-fall harvest, to 5.4 Mg DM ha^{-1} at late-fall and 3.9 Mg DM ha^{-1} at spring harvest. Yield reductions across N rates were a reduction of 26% from mid-fall to late-fall harvest and a further reduction of 29% from late-fall to spring harvest (Table 4). During the 2010 growing season, switchgrass yield was not significantly different between the mid-fall and late-fall harvests. The switchgrass yield at spring harvest was 28% less than mid and late-fall harvest at 6.3 Mg DM ha^{-1}.

Table 4. Average switch grass dry matter (DM) yield and analysis of variance (ANOVA) results for site and across site as affected by nitrogen (N) rate and harvest timing (H).

	2009					2010				
Treatments	Site 1	Site 2	Site 3	Site 4	Ave.	Site 1	Site 2	Site 3	Site 4	Ave.
	---------- Mg ha^{-1} ----------									
N Rate (kg ha^{-1})										
0	6.2	2.7	3.4	6.0	4.6	6.4	4.1	5.3	6.3	5.5
56	7.6	3.4	2.7	5.5	4.8	8.6	7.8	5.7	8.9	7.8
112	8.7	4.5	3.3	6.2	5.7	9.7	8.2	7.8	10.1	9.1
168	9.2	5.1	4.0	7.0	6.3	9.4	8.9	7.3	10.0	8.9
224	8.7	5.0	3.8	7.6	6.3	9.3	9.2	7.6	10.2	9.1
Harvest timing										
Mid fall	10.2	5.8	5.2	8.2	7.3	9.9	8.7	8.4	9.5	9.1
Late fall	8.1	3.6	3.1	6.8	5.4	9.5	8.5	7.2	10.1	8.8
Spring	6.0	3.1	2.1	4.3	3.9	6.8	5.8	4.7	8.0	6.3
	---------- $p < F$ ----------									
Variation										
Block	0.139	0.128	0.402	0.515	-	0.002	0.240	0.149	0.915	-
N rate	<0.001	0.003	0.186	0.192	<0.001	<0.001	<0.001	0.012	<0.001	<0.001
H	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
N × H	0.541	0.896	0.302	0.560	0.697	0.017	0.690	0.462	0.517	0.065

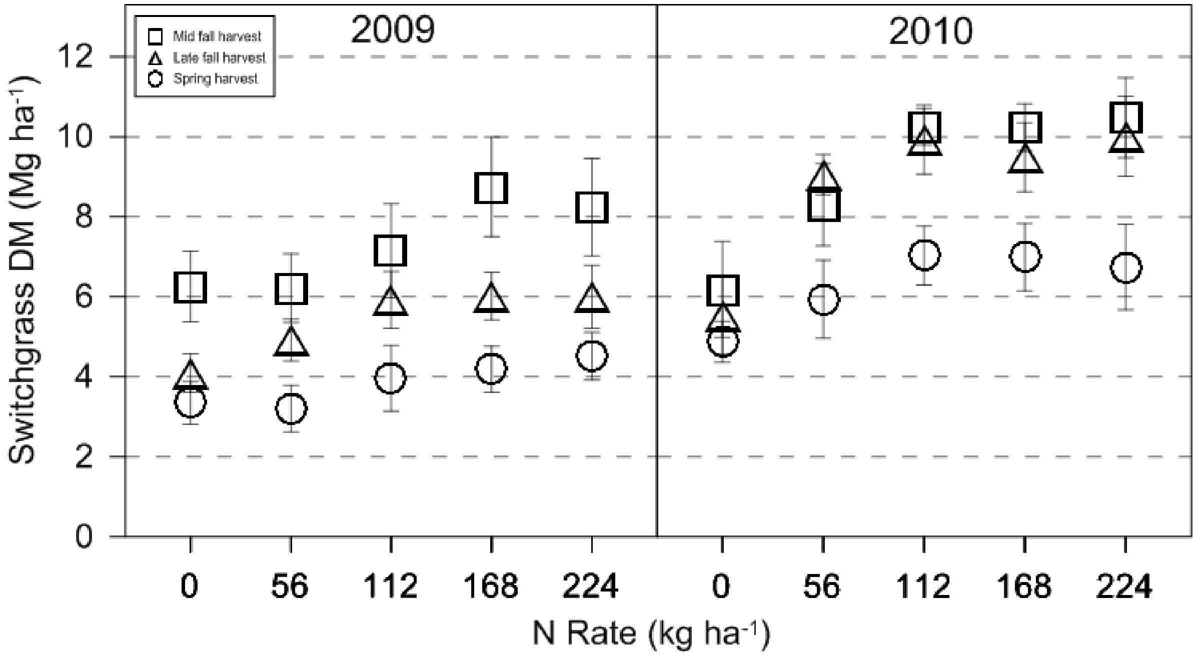

Figure 9. Switchgrass dry matter (DM) yield averaged across sites as affected by nitrogen (N) rate and harvest timing for the 2009 and 2010 growing seasons.

How did N rates and harvest timing affect biomass quality?

Cl^- was used as an indicator of switchgrass quality for burning. Averaged across harvest timings, concentrations of Cl^- in switchgrass were influenced by N rate treatments in both the 2009 and 2010 growing seasons (Figure 10). Concentrations of Cl^- in switchgrass increased with higher N rates. Harvest timing treatment, when averaged across N rate, influenced concentrations of Cl^- in switchgrass grown during both growing seasons. The concentrations of Cl^- had the greatest rate of decreased with each harvest in both the 2009 and 2010 growing seasons, falling by more than70% from mid-fall to spring harvest.

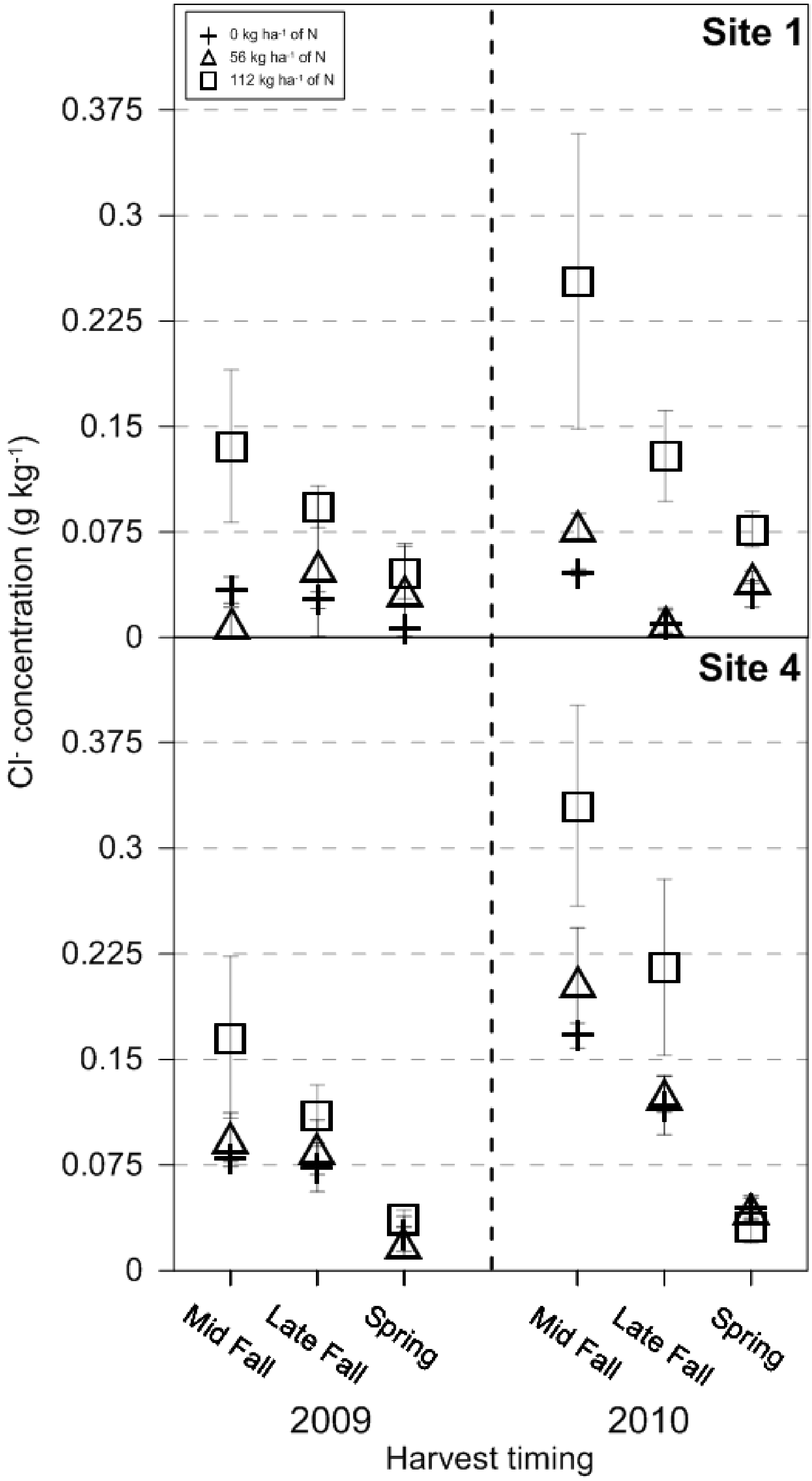

Figure 10. Chloride (Cl^-) concentration in switchgrass as affected by site, nitrogen (N) rate and harvest timing for the 2009 and 2010 growing seasons.

How did N rates affect thermal energy content and yield?

The thermal energy content of switchgrass on a weight basis had little variability across treatments and years (CV=3). The thermal energy content of switchgrass was not affected by N fertilizer rate or harvest timing with a mean thermal content of 18.3 megajoule (Mj) kg^{-1} (Figure 11). The thermal energy yield from a hectare of switchgrass ranged from 60.0 to 230.1 gigajoul (Gj) ha^{-1} across growing season, sites and treatments. When energy yield is averaged across harvest timing treatments, the thermal energy yield per hectare increased by 41% in 2009 and 38% in 2010 with the application of 112 kg ha^{-1} of N. Averaged across N rate, a harvest timing in the spring decreased the thermal energy yield by 35% and 27% in the 2009 and 2010 growing seasons, respectively (Figure 12). There was an interaction between N rate and harvest timing in 2010. While the mid-fall harvest's 0 and 112 kg ha^{-1} N treatments were significantly different, spring's 0 and 112 kg ha^{-1} N treatments were not significantly different from one another.

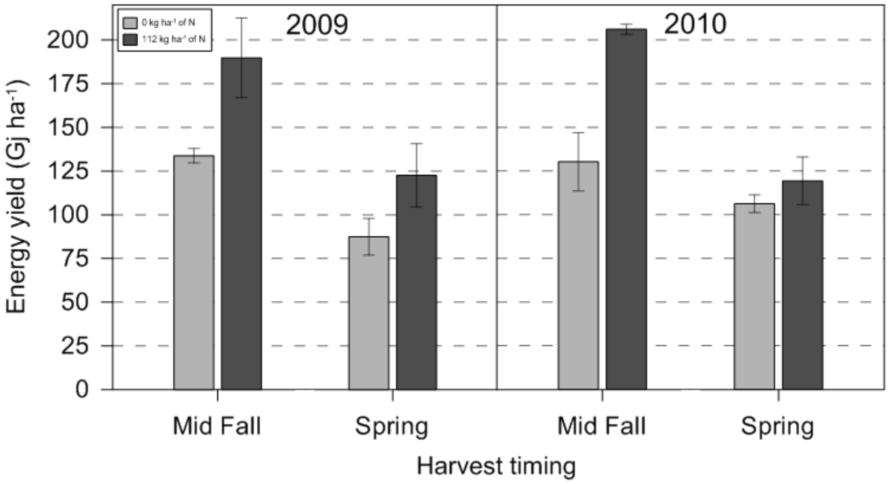

Figure 11. Thermal energy content reported as higher heating value of switchgrass from 0 and 112 kg ha^{-1} nitrogen (N) rate and mid fall and spring harvest treatments.

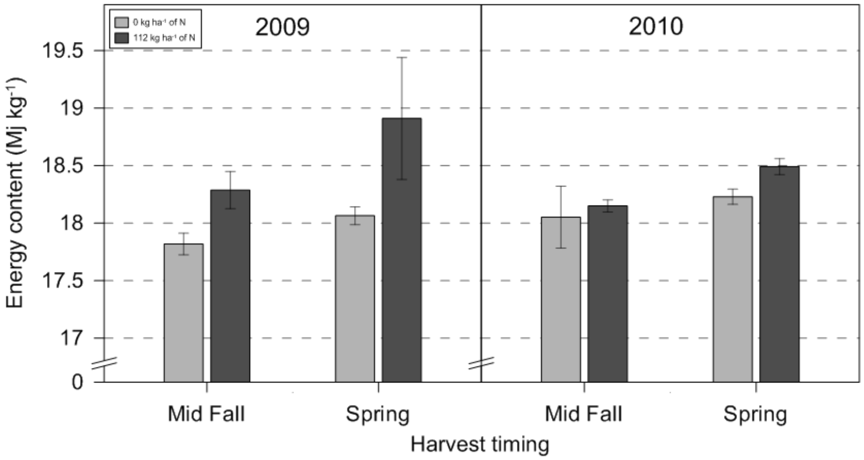

Figure 12. Thermal energy yield reported as higher heating value of switchgrass from 0 and 112 kg ha^{-1} nitrogen (N) rate and mid fall and spring harvest treatments.

Summary of Objective 3 Work

As a nascent industry, the bioenergy sector has a considerable opportunity for optimization of how it produces biogenic fuel sources and how they are utilized. By understanding how crop management strategies affect the quantity and quality of switchgrass grown as solid fuel for use in industrial boilers, growers and energy producers will be able to expect certain quantities of acceptable quality for energy production. Quantity on an area basis is improved by applying N fertilizer to switchgrass, and fuel quality is improved by delaying harvest. While N fertilizer does not strongly affect fuel quality, delaying harvest decreases yield and the potential of slagging, fouling and corrosion of boilers. On-farm management strategies for switchgrass to meet the goals of the grower and the energy producer will necessitate collaboration between the two parties. Growers will need to work with energy producers to balance the trade-offs between yield and improved fuel quality in establishing crop management strategies. Fuel quality parameters will be based on the type and tolerances of the energy conversion technology that the energy producer employs. Because yield is lost through fuel quality improvements with delayed harvests, premiums will need to be paid on higher quality fuel.

Future Directions/Activities

Of the 6 farm fields utilized in this study, 2 have been enrolled in the conservation reserve program (CRP) and are no longer available for research that involves harvesting biomass. Two other farmers have expressed interest in continuing to make their fields available for research, which provides valuable opportunity to investigate longer-term trends in bioenergy crop establishment on erodible soils in Southwestern Wisconsin.

The quantity and extent that switchgrass bioenergy cropping is able to perform ecosystem services for a region lacks understanding and academic research. Further research is not only needed in harvest equipment technology for bioenergy crops but also breeding programs to improve quantity and fuel quality. Small-plot research is less likely to encompass an understanding of the geo-spacial effects switchgrass cropping will have on a region’s aquatic ecosystem. To perform this research, significantly larger areas will need to be put into switchgrass production.

Presentations and Research Papers

Presentations of data from this study include:

Miesel, J.R., M.D. Raudenbush, M.J. Renz, and R.D. Jackson. 2011. Nitrogen dynamics, soil respiration, and microbial exoenzyme activity in contrasting perennial bioenergy systems in southwestern Wisconsin. Ecological Society of America 96th Annual Meeting, Austin, TX. 7-12 August 2011. *Poster.*

Miesel, J.R., J.E. Doll, M.J. Renz, S. Bertjens, and R.D. Jackson. 2010. Net ecosystem carbon budgets for contrasting perennial biomass crops in southwestern Wisconsin. Ecological Society of America 95th Annual Meeting, Pittsburgh, PA. 1-6 August 2010. *Poster.*

Miesel, J.R., M.J. Renz, M.D. Raudenbush, R.D. Jackson, J.E. Doll, and S. Bertjens. 2010. Using native species mixtures for energy crops: effects of management practices on crop yield and other ecosystem services. The Stewardship Network's Science, Practice, & Art of Restoring Ecosystems Conference, Lansing, MI. 22-23 January 2010. *Poster.*

Research papers generated through this project include:

Miesel, J.R., M.J. Renz, J.E. Doll, and R.D. Jackson. Effectiveness of weed management in establishment of switchgrass and a native species mixture for biofuels. Biomass and Bioenergy. *Accepted.*

Miesel, J.R., and M.J. Renz. Reconstructed prairie for bioenergy feedstocks and ecological restoration: effects of weed management on plant community characteristics. *In Preparation for Restoration Ecology.*

Miesel, J.R., M.J. Renz, and R.D. Jackson. Carbon stocks and fluxes in contrasting perennial biomass crops in southwestern Wisconsin. *In Preparation for Agriculture, Ecosystems & Environment.*

Miesel, J.R., M.J. Renz, and R.D. Jackson. Nitrogen dynamics and microbial activity in soils amended with biochar, sawdust and manure. *In Preparation for Biology & Fertility of Soils.*

Miesel, J.R., M.R. Raudenbush, and M.J. Renz. Species composition influences N availability and microbial activity in reconstructed grasslands. *In Preparation for Soil Biology & Biochemistry.*

Miesel, J.R., M.J. Renz, M.D. Ruark, and R.D. Jackson. Global warming potential of switchgrass monocultures under increasing fertilization rates. *In Preparation for Agriculture, Ecosystems & Environment.*