FINAL REPORT – EXECUTIVE SUMMARY

Project Number: R006-013
Recipient: North Dakota Natural Resources Trust
Award Amount: $280,000
Total Project Costs: $420,000

Goal of Project: Evaluate perennial herbaceous energy crops in North Dakota to assess establishment potential and management requirements; biomass yield and chemical composition; optimum harvest frequency; and soil quality and carbon storage.

Significant Findings: Cool-season grasses such as intermediate and tall wheatgrass were successfully established in central and western North Dakota. Establishment of warm season grasses such as big bluestem and switchgrass was not as successful in western North Dakota due to lower moisture conditions. During the establishment year, mowing weeds can be used for weed control. In warm season grasses, glyphosate can be used to control cool season weedy grasses. Adding legumes for nitrogen appears to lessen the need for fertilizer, but herbicides used to control weeds would be detrimental to legumes. After full establishment, management is minimal compared to annual cash crops. Biomass yield varied by species and their mixes, by site, and by year due to climatic and soil conditions. From 2007-2011, highest average yields (tons/ac) were: Sunburst switchgrass at Williston irrigation site (5.96) and Carrington (4.73); Williston dry site, haymaker intermediate wheatgrass (1.34). At Minot, Alkar tall wheatgrass and its mixtures had the highest yields from 2007 to 2008; from 2010 to 2011, Sunburst switchgrass had the highest yield; from 2007-2011 Sunburst switchgrass and Alkar tall wheatgrass combination had the highest yield (3.61 tons/acre). At Streeter, the five-year average yield was highest for Alkar tall wheatgrass and Sunburst switchgrass combination (2.99 tons/acre). Biennial harvest only accounted for 63% total biomass compared to annual harvest over all sites and years. However, biennial harvest yields varied by location, with Williston dry lands the highest (76%), following by Minot (71%), Williston irrigated lands and Streeter (66%), and the least at Carrington (56%). With colder and drier locations, biennial harvest could be an option especially the wildlife habitat and lower management costs take into the consideration. Harvest method (swather-like machine) may have impacted yields. If a mower and rake had been used, more of the litter likely would have been collected, thus increasing biennial harvest yield. Tall wheatgrass and its mixtures had superior quality to other species for ethanol production and also seemed to be better than other species for direct combustion. Potential exists for fireside ash deposition and potential corrosion problems for some of the biomass materials characterized in this study. Perennial herbaceous crops had subtle short-term effects on soil properties in central and western North Dakota. Changes in soil properties were most prevalent at the Williston site, where less fertile sandy soil and high biomass production contributed to increases in soil organic carbon, total nitrogen, and available phosphorus. Coarse-textured soils have the greatest potential to respond positively from perennial biofeedstocks in the short-term. Combined, this data indicates that perennial growth may improve soil quality. Larger aggregates increase pore space which improves air and water movement and reduces compaction. Larger aggregates act as microbial habitats for increased nutrient cycling.

Next Steps: Distribute the Final Report and continue the study through 2016.

FINAL
EVALUATION OF PERENNIAL HERBACEOUS BIOMASS CROPS IN NORTH DAKOTA

Summary Report
April 2012

Switchgrass plot following the 2011 harvest at NDSU Central Grasslands Research Extension Center, Streeter, ND. Photograph by Rick Bohn

Sponsored by the ND Natural Resources Trust, ND State University, U.S. Department of Agriculture-Agriculture Research Service, Northern Great Plains Research Lab and Natural Resources Conservation Service, Great River Energy, ND Farmers Union, ND Association of Rural Electric Cooperatives, ND Game and Fish Department, and ND Commerce Department

Report Authors:

Paul E. Nyren, Guojie Wang, Bob Patton, Quigwe Xue, Gordon Bradbury, Mark Halvorson, and Ezra Aberle, NDSU; Mark Liebig and Kristine Nichols, USDA-Agriculture Research Service, Northern Great Plains Research Laboratory, Mandan, ND

Compiled By: Karen Kreil, North Dakota Natural Resources Trust
Submitted in Cooperation with Project Partners:

- **Great River Energy**
- **North Dakota State University**
  - **Research Extension Centers – Streeter, Carrington, Dickinson, Minot, and Hettinger**
- **USDA, Natural Resources Conservation Service**
- **North Dakota Farmers Union**
- **USDA, Agriculture Research Station, Northern Great Plains Research Lab, Mandan, ND**
- **North Dakota Commerce Department**
- **North Dakota Game and Fish Department**
- **Great Plains Institute**
- **North Dakota Association of Rural Electric Cooperatives**

This report was prepared by the North Dakota Natural Resources Trust pursuant to an agreement with the Industrial Commission of ND, which partially funded the report. None of the North Dakota Natural Resources Trust or its partners or any of its subcontractors, the Industrial Commission of North Dakota, or any person acting on behalf of any of them:

(A) Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights; or

(B) Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Industrial Commission of North Dakota. The views and opinions of authors expressed herein do not necessarily state or reflect those of the Industrial Commission of North Dakota.

Table of Contents

Cover Page……..1

Authors and Disclosure……..2

Table of Contents……3

Executive Summary……..4

Project Background……..5

Results and Discussion……6

Communication Plan

Deliverables……..12

Summary of Completed Tasks……15

List of Tables and Figures

Figure 1 – Location of study sites in North Dakota……5

FINAL REPORT – EXECUTIVE SUMMARY

Project Number: R006-013
Recipient: North Dakota Natural Resources Trust
Award Amount: $280,000
Total Project Costs: $420,000

Goal of Project: Evaluate perennial herbaceous energy crops in North Dakota to assess establishment potential and management requirements; biomass yield and chemical composition; optimum harvest frequency; and soil quality and carbon storage.

Significant Findings: Cool-season grasses such as intermediate and tall wheatgrass were successfully established in central and western North Dakota. Establishment of warm season grasses such as big bluestem and switchgrass was not as successful in western North Dakota due to lower moisture conditions. During the establishment year, mowing weeds can be used for weed control. In warm season grasses, glyphosate can be used to control cool season weedy grasses. Adding legumes for nitrogen appears to lessen the need for fertilizer, but herbicides used to control weeds would be detrimental to legumes. After full establishment, management is minimal compared to annual cash crops. Biomass yield varied by species and their mixes, by site, and by year due to climatic and soil conditions. From 2007-2011, highest average yield (tons/ac) were: Sunburst switchgrass at Williston irrigation site (5.96) and Carrington (4.73); Williston dry site, haymaker intermediate wheatgrass (1.34). At Minot, Alkar tall wheatgrass and its mixtures had the highest yields from 2007 to 2008; from 2010 to 2011, Sunburst switchgrass had the highest yield; from 2007-2011 Sunburst switchgrass and Alkar tall wheatgrass combination had the highest yield (3.61 tons/acre). At Streeter, the five-year average yield was highest for Alkar tall wheatgrass and Sunburst switchgrass combination (2.99 tons/acre). Biennial harvest only accounted for 63% total biomass compared to annual harvest over all sites and years. However, biennial harvest yields varied by location, with Williston dry lands the highest (76%), following by Minot (71%), Williston irrigated lands and Streeter (66%), and the least at Carrington (56%). With colder and drier locations, biennial harvest could be an option especially the wildlife habitat and lower management costs take into the consideration. Harvest method (swather-like machine) may have impacted yields. If a mower and rake had been used, more of the litter likely would have been collected, thus increasing biennial harvest yield. Tall wheatgrass and its mixtures had superior quality to other species for ethanol production and also seemed to be better than other species for direct combustion. Potential exists for fireside ash deposition and potential corrosion problems for some of the biomass materials characterized in this study. Perennial herbaceous crops had subtle short-term effects on soil properties in central and western North Dakota. Changes in soil properties were most prevalent at the Williston site, where less fertile sandy soil and high biomass production contributed to increases in soil organic carbon, total nitrogen, and available phosphorus. Coarse-textured soils have the greatest potential to respond positively from perennial biofeedstocks in the short-term. Combined, this data indicates that perennial growth may improve soil quality. Larger aggregates increase pore space which improves air and water movement and reduces compaction and act as microbial habitats for increased nutrient cycling.

Next Steps: Distribute the Final Report and continue the study through 2016.

Project Background

Using biomass as feedstock in bioenergy production has the potential to replace fossil fuels as well as corn grain that may be better used as human and livestock feed. The northern Great Plains provides a vast number of acres for perennial biomass production, particularly in highly erodible and non-productive areas, which would have a low impact on food production. To achieve the most success in biomass conversion, feedstocks most suited to the region in terms of biomass quantity and quality need to be identified. **This study evaluated perennial herbaceous biomass energy crops in North Dakota to assess establishment potential and management requirements; biomass yield and chemical composition; optimum harvest frequency; and soil quality and carbon storage.**

Six sets of plots were located at five sites across central and western North Dakota (Figure 1). Each set of plots contains ten species/varieties of perennial grasses planted alone and in combination in two harvest treatments (annual and biennial).

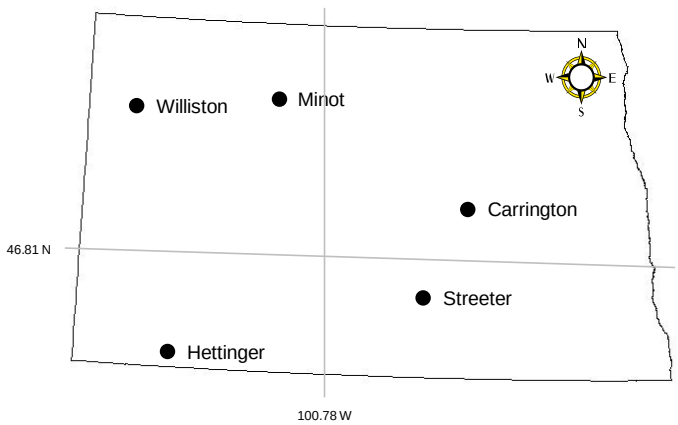


Figure 1. Location of study sites in North Dakota, in relation to 100th meridian.

Results and Discussion

Biomass Stand Establishment and Maintenance

The establishment of cool-season grasses such as intermediate wheatgrass and tall wheatgrass was appreciable for all study sites; however, the establishment of warm-season grasses such as switchgrass and big bluestem was problematic at Hettinger and Williston without irrigation. In comparison, at Williston with irrigation the warm-season grasses were soundly established under same cultural management as Williston dry land. Therefore, the establishment of the warm-season grasses in these dry areas was mainly driven and constrained by the available soil water in the growing season. Furthermore, intermediate wheatgrass and tall wheatgrass are the alternatives for the biomass production in these dry areas from the establishment perspective. At Streeter and Minot, weed control was crucial to establish warm-season grasses, otherwise more years needed to let the warm-season build themselves and outcompete with common weeds. Roundup could be used to control early growing weed species in spring before the warm-season grasses start to grow, however, the application rate and time window need to be further tested. At Carrington, the establishment of warm-season grasses was promising, with mechanical mowing in the establishment year being helpful as well as with the appropriate ecological and climatically conditions. The seeding methods (timing, rate, depth, seedbed preparation et al.) at all study sites were the exactly same, site-specific seeding strategy should be investigated if establishment of warm-season grasses is the goal.

Due to poor stand establishment of warm season grasses (switchgrass and big bluestem) in 2007, the Hettinger plots were reseeded in 2008. Although they were harvested the following two years, the decision was made to abandon these plots as the stands were still not productive enough to obtain meaningful data. Establishment and maintenance of switchgrass in central and western North Dakota can be difficult, depending on moisture, soil quality, and weed invasion. For example, switchgrass plots were established at Streeter, but some of these plots became invaded by brome and quack grass. Mowing weeds can be used in place of herbicides.

If the biomass produced is to be burned for energy, total yield is the important metric. However, if the product is to be used for ethanol then a more pure stand may be needed and the amount of species that invade the biofuel crop may decrease its value. The need for a pure crop for ethanol production could pose a problem for producers trying to raise cool season forages such as wheatgrasses. In switchgrass or other warm season grass stands, glyphosate can be used to control cool season weedy grasses. There is no chemical on the market that can control cool season weedy grasses in wheatgrass stands. Maintaining a pure crop will be an added expense to the producer.

Biomass Yields

For annual harvest, study site accounted for 63% of the total data set variance and was a main factor for biomass production. With irrigation at Williston, the production (4.29 tons/acre) was the highest, following by wettest study site Carrington (4.12 tons/acre), then Minot (2.99 tons/acre) and Streeter (2.40 tons/acre), the lowest at Williston without irrigation (1.04

tons/acre). The study site biomass production and its long-term mean annual precipitation were in the same order. However, the highest productive species or their combinations varied at each study site. Sunburst switchgrass produced the highest consistently from 2007 to 2011 at Williston irrigated land and Carrington with average production of 5.96 tons/acre and 4.73 tons/acre, respectively. At Williston non-irrigated land, haymaker intermediate wheatgrass was consistently the highest from 2007 to 2011 with an average production of 1.34 tons/acre. The results at Minot and Streeter were mixed and complex. At Minot, Alkar tall wheatgrass and its mixtures were the highest from 2007 to 2008 while in 2009, they were still the highest but all the entries were statistically same. From 2010 to 2011, Dakota switchgrass, Sunburst switchgrass, and Sunnyview big bluestem were the highest. As a result, five years average was not significantly different for all the entries, however, Sunburst switchgrass + Alkar tall wheatgrass combination (3.61 tons/acre) was the highest numerically. At Streeter, the similar trend as at Minot was found, namely, from 2007 to 2009, cool-season grasses produced higher than warm-season grasses, they were similar in 2010, while in 2011, Sunburst switchgrass produced the highest (4.34 tons/acre). Five years average of Alkar tall wheatgrass + Sunburst switchgrass combination (2.99 tons/acre) was the highest.

Higher yields at Carrington are likely due to higher precipitation levels and better soil quality compared to the other sites. Based on long-term average annual harvest yields, wheatgrasses yielded best on drier sites and switchgrass and its mixtures yielded best on wetter sites. At Streeter, the pure warm season plots were sprayed with glyphosate the third week of May 2011. This application gave good control of cool season grasses including smooth brome and quackgrass and subsequently improved yields of Sunburst switchgrass and its mixtures, but did not improve yields of Trailblazer switchgrass.

For biennial harvest, similar results were found as annual harvest, i.e. study site with higher annual harvest production was also had higher biennial harvest production; species with higher annual harvest production at each study site normally had higher biennial harvest production in that corresponding study site. However, at Williston non-irrigated land biennial harvest of Sunburst switchgrass or its combination with Mustang altai wildrye was the highest (1.00 tons/acre) while annual harvest of Haymaker intermediate wheatgrass was the highest.

Annual Versus Biennial Harvest Yields

Overall, biennial harvest biomass production could only account for 63% total biomass from two-year annual harvest. However, it accountability varied with study sites, with Williston dry land (76%) the highest, following by Minot (71%), Williston irrigated land and Streeter (66%), and the least at Carrington (56%).

The hypothesis of this study was that by harvesting biomass plots every other year the loss in total yield would be offset by the reduction in harvesting costs. For most of the plots the reduction in yearly yield due to biennial harvesting ranged between 20 to 50 percent. The dryland plots at Williston varied the most with switchgrass + wildrye plots having higher yield on the biennial harvest. Lower yields of biennial harvest varied considerably by location and harvest method may have impacted yields. A swather-like machine was used to harvest the standing crop. If a mower and rake had been used, more of the litter likely would have been collected, thus increasing yield.

Biomass and Ethanol Production

Tall wheatgrass and its mixtures had superior quality to other species for ethanol production and also seemed to be better than other species for direct combustion. Potential exists for fireside ash deposition and potential corrosion problems for some of the biomass materials characterized in this study.

In a nutshell

- **In central North Dakota, Sunburst switchgrass established and produced well, however, in western North Dakota switchgrass establishment was problematic and intermediate wheatgrass could be an alternative. Irrigation improved western North Dakota warm-season grass establishment and had a profound effect on biomass production.**
- **Weed control was crucial, especially at Streeter and Minot. Switchgrass can take up to three years to establish because the initial energy and growth occurs below ground in the root system. Tall wheatgrass establishes more quickly than switchgrass, therefore the combination of switchgrass and tall wheatgrass at Streeter and Minot could stabilize the first three years' production.**
- **The highest productive species or their combinations varied at each study site. Sunburst switchgrass produced the highest consistently from 2007 to 2011 at Williston irrigated land and Carrington with average production of 5.96 tons/acre and 4.73 tons/acre, respectively. At Williston non-irrigated land, haymaker intermediate wheatgrass was consistently the highest from 2007 to 2011 with an average production of 1.34 tons/acre. At Minot, Alkar tall wheatgrass and its mixtures were the highest from 2007 to 2008. From 2010 to 2011, Dakota switchgrass, Sunburst switchgrass, and Sunnyview big bluestem were the highest. As a result, Sunburst switchgrass + Alkar tall wheatgrass combination (3.61 tons/acre) was the highest numerically for 5-year average. At Streeter, the similar trend as at Minot was found, namely, from 2007 to 2009, cool-season grasses produced higher than warm-season grasses,**

they were similar in 2010, while in 2011, Sunburst switchgrass produced the highest (4.34 tons/acre). Five years average of Alkar tall wheatgrass + Sunburst switchgrass combination (2.99 tons/acre) was the highest.

Soil Profile Attributes

Perennial herbaceous crops were found to have subtle short-term effects on soil properties at the sites included in the study. Effects of harvest schedule and plant species on soil properties were infrequent and inconsistent across sites, and were unlikely to induce change in soil function. Inherently fertile soil conditions, high within-site variation in soil properties, and trends in biomass production among research sites likely contributed to observed results.
Changes in soil properties due to growth of perennial herbaceous crops were most prevalent at the Williston site, where the less fertile sandy soil and high biomass production contributed to increases in SOC, TN, and available P. Soil organic C increased at the Williston dryland site by 6 Mg C ha^{-1} yr^{-1}, supporting previous findings where perennial grasses managed for bioenergy production sequestered C within fragile, sandy soils.

In surface soil samples, differences in dry aggregate size distribution (DASD) and water-stable aggregation (WSA) could not be detected between treatments at any site. However, differences in three aggregate size classes (ASC; 1-2, 0.25-1, 0.053-0.25 mm) were observed within and across sites. Differences in ASC were detected during the baseline (2006) and 5-yr (2011) samplings, as well as between the two sampling periods. Results indicated growth of perennial biomass crops shifted more soil into the largest ACS (1-2 mm). Larger aggregates increase pore space and improve microbial habitat, thereby enhancing air/water movement and nutrient cycling in soil. Accordingly, perennial crops included in the study served to improve near-surface soil quality.

Broad outcomes from this short-term study indicate perennial herbaceous crops can maintain or improve soil properties, depending on inherent soil conditions and site productivity. In that regard, coarse-textured soils have the greatest potential to respond positively in the short-term from the growth of perennial herbaceous crops. Such focused production – based on soil type – would not only improve the condition of fragile soils, but would also serve to improve wildlife habitat, decrease water pollution, and reduce wind and water erosion compared to annual row crop production.

In a nutshell

- **Production of perennial herbaceous crops as biofeedstocks had subtle short-term effects on soil properties in central and western North Dakota.**
- **Changes in soil properties were most prevalent at the Williston site, where the less fertile sandy soil and high biomass**

production contributed to increases in soil organic carbon, total nitrogen, and available phosphorus.

- **Coarse-textured soils have the greatest potential to respond positively from perennial biofeedstocks in the short-term.**

Soil Surface Properties

The energy source for all animals, whether it has been food or fuel, comes from plants converting sunlight into carbon-based fuels. Because fossil fuels are a finite energy source and economic and social concerns exist in obtaining these fuels, alternative energy sources are being sought such as biofuels from perennial biomass. This project was designed to identify regionally appropriate and consistent high biomass perennials for the cold, semi-arid northern Great Plains. The environmental impacts, particularly soil parameters, of this production will be assessed. In this report, soil aggregation and glomalin production are reported. Soil aggregation is a major component of soil functions, such as water infiltration, water holding capacity, gas exchange, and nutrient cycling. The pore space provided between aggregates impacts water and gas movement whereas the aggregates themselves act as microbial habitats for nutrient cycling. Arbuscular mycorrhizal (AM) fungi provide nutrients to plants in exchange for carbon compounds by directly connecting plant roots and soil aggregates. Soil aggregates are formed and stabilized by AM fungi through the production of hyphae (i.e. fine threads) and glomalin, a sticky glycoprotein. Analysis showed that across all sites, treatments, and aggregate size classes only site and aggregate site class had significant differences between samples. For water-stable aggregation (WSA) and glomalin (measured as Bradford-reactive soil protein, BRSP) values, the Williston Dryland and Minot sites had the highest values in 2006 while in 2011 Carrington and Minot had the highest values. Within each site, only aggregate size class was significantly different. The differences between the aggregate size classes showed a shift from smaller aggregates to larger aggregates over the five years of production in this study.

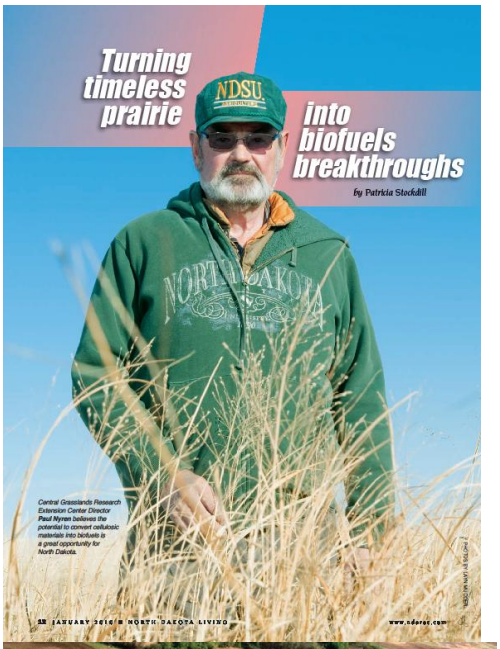
In a Nutshell:

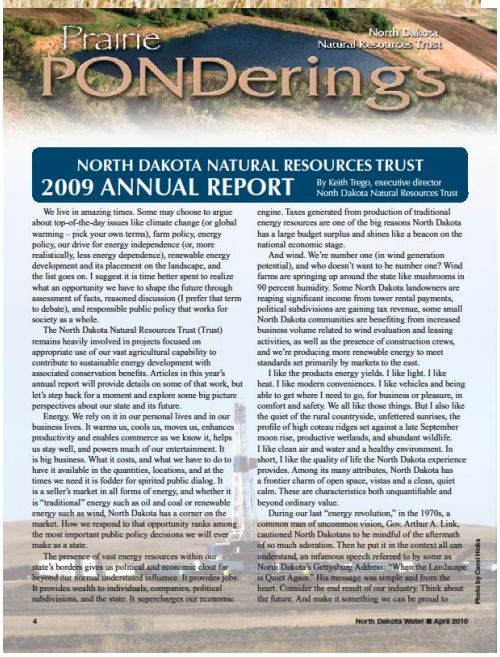
- A significant difference could not be detected between treatments across all six sites for the dry aggregate size distribution and water-stable aggregation values. A site difference was detected for the water-stable aggregation and glomalin values.
- A difference was found between the three aggregate size classes (1-2, 0.25-1, and 0.053-0.25 mm) across all the sites and within each site. This difference was detected in both baseline samples collected in 2006 and in samples collected 2011 after 5 years of growth as well as the difference between these two sampling periods.

- The data showed that over the five years of growth more soil was distributed into the largest aggregate size class while it declined in the two smaller sizes.
- In 2006, the BRSP amounts of glomalin also differed by aggregate size class rather than treatment. However, in 2011, because the main difference in aggregation was the shift to the largest aggregate size class and no treatment difference was detected between treatments, glomalin was only extracted from the largest aggregate size class. A site difference was detected but a treatment difference was not.
- Combined this data indicates that perennial growth may improve soil quality. Larger aggregates increase pore space which improves air and water movement and reduces compaction. Larger aggregates act as microbial habitats for increased nutrient cycling.

Deliverables – Communication Plan

Communication and coordination on the study and the results generated were important aspects of the study. A communication plan was developed that outlined tasks, the responsible entity, and a timetable for completion. Communication tasks included publication of articles in partner magazines and newsletters; posting information on partner websites; distribution of information to agriculture producers through direct mailings; field tours and research reviews; presentations at agriculture and energy related workshops and conferences; and bi-annual conference call/meeting of project partners.





Participants view the perennial energy crop plots at the July 2010 “Annual Field Tour” held at the NDSU Central Grasslands Research Extension Center at Streeter, ND.

North Dakota State University
Central Grasslands Research Extension Center (CGREC)
Grass-N-Beef Research Review
at Central Grasslands Conference Room
4824 48th Ave SE, Streeter
10:00 a.m. Wednesday, January 26, 2011

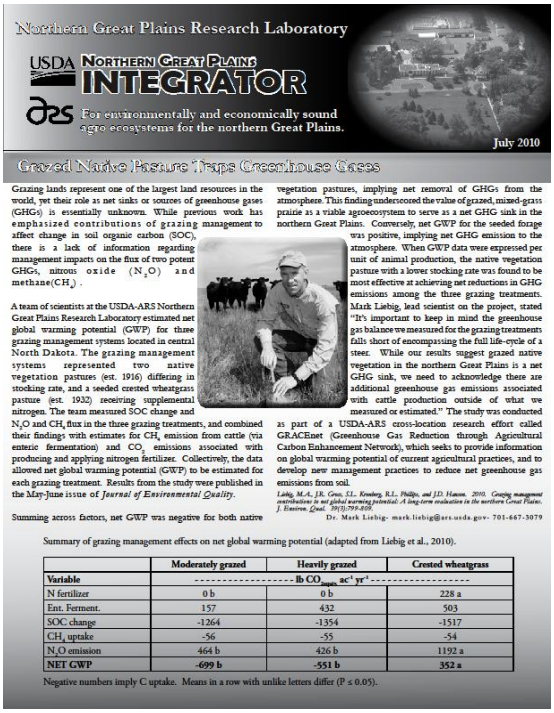
Master of Ceremonies: Amanda Gearhart, Research Specialist, NDSU School of Natural Resource Sciences

10:00 a.m	**Introduction and Welcome** Paul Nyren, Director, CGREC
10:15 a.m.	**Opening Remarks** Ken Grafton, Director, ND Ag Experiment Station
10:30 a.m.	**Utilizing Annual Cover Crops to Extend Grazing** Kevin Sedivec, Professor/Rangeland Mgt Specialist, NDSU Natural Resources MGT
11:00 a.m.	**Effects of Grazing Pressure on Efficiency of Grazing on Northern Great Plains Rangeland** A.J. Smart, Professor, Department of Animal & Range Sciences, South Dakota State University Bob D. Patton, Range Scientist, CGREC
11:30 a.m.	**Culture and Agriculture: Living and Working on the Coteau** Tom Isern, Distinguished Professor, NDSU History Dept.
Noon-1:00	**Catered Lunch**
1:00 p.m.	**China, Hay Bales and Economics** Chip Poland, Dept Chair, Agriculture and Technical Studies, Dickinson State University
1:30 p.m.	**New Animal Research Program at CGREC** Bryan Neville, Animal Scientist, CGREC
1:45 p.m.	**Grazed Native Pasture Traps Greenhouse Gases** Mark Liebig, USDA-ARS Mandan
2:00 p.m.	**Screening and Evaluation of Legume Species/Varieties for Forage Production, Soil Health and Cover Crops** Guojie Wang, Forage Agronomist, CGREC
2:15 p.m.	**Production and Sustainability of Perennial Biofuels Crops** Paul Nyren, Director, CGREC
2:30 p.m.	**Use of Patch Burning for Revitalization of Native Prairies** Amy Ganguli, Professor, NDSU School of Natural Resources
2:45 p.m.	**A Naturalist’s Guide to the Coteau** Chuck Lura, Professor of Biology, Dakota College Bottineau
3:00 p.m.	**Producer Discussion and Interaction** Jerry Doan, Chair, CGREC Advisory Board
3:30 p.m.	**Door Prizes and Adjourn**

DIRECTIONS TO CENTRAL GRASSLANDS
Four miles north of Streeter, or 11 miles south of I-94 on Highway 30, take 48th Street and drive 5 miles west to 48th Ave and ¼ mile south.

Examples of articles published in partner magazines are shown below, including North Dakota Living (ND Association of Rural Electric Cooperatives); North Dakota Water (ND Natural Resources Trust “Prairie Ponderings” space in magazine, ND Water Education Foundation); and Union Farmer (ND Farmers Union).

Powerpoint presentation given by Sandra Broekema, Great River Energy, at two conferences held in 2009.



Northern Great Plains Research Laboratory

USDA NORTHERN GREAT PLAINS INTEGRATOR

ARS For environmentally and economically sound agro ecosystems for the northern Great Plains.

July 2010

Grazed Native Pasture Traps Greenhouse Gases

Grazing lands represent one of the largest land resources in the world, yet their role as net sinks or sources of greenhouse gases (GHGs) is essentially unknown. While previous work has emphasized contributions of grazing management to affect change in soil organic carbon (SOC), there is a lack of information regarding management impacts on the flux of two potent GHGs, nitrous oxide (N_2O) and methane(CH_4).

A team of scientists at the USDA-ARS Northern Great Plains Research Laboratory estimated net global warming potential (GWP) for three grazing management systems located in central North Dakota. The grazing management systems represented two native vegetation pastures (est. 1916) differing in stocking rate, and a seeded crested wheatgrass pasture (est. 1932) receiving supplemental nitrogen. The team measured SOC change and N_2O and CH_4 flux in the three grazing treatments, and combined their findings with estimates for CH_4 emission from cattle (via enteric fermentation) and CO_2 emissions associated with producing and applying nitrogen fertilizer. Collectively, the data allowed net global warming potential (GWP) to be estimated for each grazing treatment. Results from the study were published in the May-June issue of *Journal of Environmental Quality*.

Summing across factors, net GWP was negative for both native vegetation pastures, implying net removal of GHGs from the atmosphere. This finding underscored the value of grazed, mixed-grass prairie as a viable agroecosystem to serve as a net GHG sink in the northern Great Plains. Conversely, net GWP for the seeded forage was positive, implying net GHG emission to the atmosphere. When GWP data were expressed per unit of animal production, the native vegetation pasture with a lower stocking rate was found to be most effective at achieving net reductions in GHG emissions among the three grazing treatments. Mark Liebig, lead scientist on the project, stated "It's important to keep in mind the greenhouse gas balance we measured for the grazing treatments falls short of encompassing the full life-cycle of a steer. While our results suggest grazed native vegetation in the northern Great Plains is a net GHG sink, we need to acknowledge there are additional greenhouse gas emissions associated with cattle production outside of what we measured or estimated." The study was conducted as part of a USDA-ARS cross-location research effort called GRACEnet (Greenhouse Gas Reduction through Agricultural Carbon Enhancement Network), which seeks to provide information on global warming potential of current agricultural practices, and to develop new management practices to reduce net greenhouse gas emissions from soil.

Liebig, M.A., J.R. Gross, S.L. Kronberg, R.L. Phillips, and J.D. Hanson. 2010. Grazing management contribution to net global warming potential: A long-term evaluation in the northern Great Plains. J. Environ. Qual. 39(5):799-809.

Dr. Mark Liebig- mark.liebig@ars.usda.gov- 701-667-3079

Summary of grazing management effects on net global warming potential (adapted from Liebig et al., 2010).

	Moderately grazed	Heavily grazed	Crested wheatgrass
Variable	lb CO_{2equiv} ac^{-1} yr^{-1}		
N fertilizer	0 b	0 b	228 a
Ent. Ferment.	157	432	503
SOC change	-1264	-1354	-1517
CH_4 uptake	-56	-55	-54
N_2O emission	464 b	426 b	1192 a
NET GWP	**-699 b**	**-551 b**	**352 a**

Negative numbers imply C uptake. Means in a row with unlike letters differ ($P \leq 0.05$).

The USDA-Agriculture Research Service, Northern Great Plains Research Lab newsletter, "Northern Great Plains Integrator".

COMMUNICATION PLAN – SUMMARY OF COMPLETED TASKS

TASK	ENTITY*	TIMETABLE
Presentation "Biomass Fuel: Which Comes First, the Market or the Supply". 2009 Northern Plains Bioeconomy: What Makes Sense. Fargo, ND	GRE	Sept. 22, 2009
Case Study Presentation at Forum on The Future of Coal and Biomass in a Carbon Constrained World, sponsored by Great Plains Institute. Fargo, ND	GRE, TNC	Nov. 2, 2009
Formal Report Out on Feasibility Study of a Biomass Supply for the Spiritwood Industrial Park. ND Industrial Commission/Renewable Energy Council meeting, Fargo, ND.	GRE	Dec. 7, 2009
"Biomass Co-firing" Presentation at Energy Generation Conference, Bismarck, ND	GRE	Jan. 26, 2010
Summary of Biomass Plots Study results and related Spiritwood Project activities in NDSU Extension Service bi-weekly newsletter.	NDSU	Dec. 2009, 2010, 2011
Annual Report on Biomass Plots Study. Prepared, posted on Website, and distributed to 25,000 agriculture producers/constituents throughout central ND.	NDSU	Dec. 2009, 2010, 2011
Grass and Beef Research Review for agriculture producers/constituents	NDSU	Jan. 20, 2010 Jan. 26, 2011 Jan. 25, 2012
Annual Field Tour for area agriculture producers/constituents on Biomass Plots Study results	NDSU	June 23, 2010 June 29, 2011
Friends and Neighbors Day – Presentation on study results for area agricultural producers	ARS	July 22, 2010 July 21, 2011
ND Water Magazine article	NDNRT, NDWEF	April 2010 issue

ND Living Magazine article	NDNRT, NDARE, GRE	Jan 2010 issue
Union Farmer Publication article	NDNRT, NDFU, GRE	Feb 2010 issue
Presentations by project partners at local, regional, or national biomass energy related meetings, workshops, or conferences		Throughout study
Bi-Annual conference call/meeting of project partners	NDNRT lead	January 22, 2010 July 19, 2010 January 24, 2011
Rural Developers' Round Table Talk – Featuring Spiritwood Biomass project	NDAREC, GRE, NDSU	February 9, 2010
Bioenergy Research Summary – "Integrator Newsletter"	ARS	July 2010
Presentation "Evaluation of perennial herbaceous forages for bioenergy in central and western North Dakota" at 2011 North American's Grasslands Conference, Sioux Falls, SD.	NDSU	August 15-17, 2011
Grant wrap-up session	NDNRT, NDSU, ARS	April 10, 2012

* ARS = U.S. Department of Agriculture, Agriculture Research Service, Northern Great Plains Research Laboratory, Mandan, ND
GPI=Great Plains Institute
GRE=Great River Energy
NDAREC = North Dakota Association of Rural Electric Cooperatives
NDFU = North Dakota Farmers Union
NDGFD = North Dakota Game and Fish Department
NDNRT = North Dakota Natural Resources Trust
NDSU = North Dakota State University Research Extension Center, Streeter
NDWEF = North Dakota Water Education Foundation
TNC = The Nature Conservancy

FINAL

EVALUATION OF PERENNIAL HERBACEOUS BIOMASS CROPS IN NORTH DAKOTA

Technical Report

April 2012

Paul E. Nyren, Guojie Wang, Bob Patton, Quigwe Xue, Gordon Bradbury, Mark Halvorson, and Ezra Aberle, NDSU; Mark Liebig and Kristine Nichols, USDA-Agriculture Research Service, Northern Great Plains Research Laboratory, Mandan, ND

Compiled By: Karen Kreil, North Dakota Natural Resources Trust
Submitted to NDIC in Cooperation with Project Partners:

- **Great River Energy**
- **North Dakota State University**
  - **Research Extension Centers – Streeter, Carrington, Dickinson, Minot, and Hettinger**
- **USDA, Natural Resources Conservation Service**
- **North Dakota Farmers Union**
- **USDA, Agriculture Research Station, Northern Great Plains Research Lab, Mandan, ND**
- **North Dakota Commerce Department**
- **North Dakota Game and Fish Department**
- **Great Plains Institute**
- **North Dakota Association of Rural Electric Cooperatives**

This report was prepared by the North Dakota Natural Resources Trust pursuant to an agreement with the Industrial Commission of ND, which partially funded the report. None of the North Dakota Natural Resources Trust or its partners or any of its subcontractors, the Industrial Commission of North Dakota, or any person acting on behalf of any of them:

(A) Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights; or

(B) Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Industrial Commission of North Dakota. The views and opinions of authors expressed herein do not necessarily state or reflect those of the Industrial Commission of North Dakota.

Table of Contents

Executive Summary……...…….…… 4

Biomass Production of Selected Perennial Herbaceous Warm-season and Cool-season Grasses and Legumes in Central and Western North Dakota for Bioenergy……5

Evaluation of Perennial Herbaceous Biomass Crops in North Dakota: Soil Profile Attributes, 2006-2011……..……24

Evaluation of Perennial Herbaceous Biomass Crops in North Dakota – Impacts on Surface Soils 2006 -2011…….70

Analysis Report: Chemical and Heat Value Characterization of Perennial Herbaceous Biomass Mixtures……126

FINAL REPORT – EXECUTIVE SUMMARY

Project Number: R006-013
Recipient: North Dakota Natural Resources Trust
Award Amount: $280,000
Total Project Costs: $420,000

Goal of Project: Evaluate perennial herbaceous energy crops in North Dakota to assess establishment potential and management requirements; biomass yield and chemical composition; optimum harvest frequency; and soil quality and carbon storage.

Significant Findings: Cool-season grasses such as intermediate and tall wheatgrass were successfully established in central and western North Dakota. Establishment of warm season grasses such as big bluestem and switchgrass was not as successful in western North Dakota due to lower moisture conditions. During the establishment year, mowing weeds can be used for weed control. In warm season grasses, glyphosate can be used to control cool season weedy grasses. Adding legumes for nitrogen appears to lessen the need for fertilizer, but herbicides used to control weeds would be detrimental to legumes. After full establishment, management is minimal compared to annual cash crops. Biomass yield varied by species and their mixes, by site, and by year due to climatic and edaphic conditions. From 2007-2011, highest average yield (tons/ac) were: Sunburst switchgrass at Williston irrigation site (5.96) and Carrington (4.73); Williston dry site, haymaker intermediate wheatgrass (1.34). At Minot, Alkar tall wheatgrass and its mixtures had the highest yields from 2007 to 2008; from 2010 to 2011, Sunburst switchgrass had the highest yield; from 2007-2011 Sunburst switchgrass and Alkar tall wheatgrass combination had the highest yield (3.61 tons/acre). At Streeter, the five-year average yield was highest for Alkar tall wheatgrass and Sunburst switchgrass combination (2.99 tons/acre). Biennial harvest yields only accounted for 63% of the total biomass compared to annual harvest yields over all sites and years. However, biennial harvest yields varied by location, with Williston dry lands the highest (76%), following by Minot (71%), Williston irrigated lands and Streeter (66%), and the least at Carrington (56%). With colder and drier locations, biennial harvest could be an option especially when wildlife habitat and lower management costs are taken into consideration. Harvest method (swather-like machine) may have impacted yields. If a mower and rake had been used, more of the litter likely would have been collected, thus increasing biennial harvest yield. Tall wheatgrass and its mixtures had superior quality to other species for ethanol production and also seemed to be better than other species for direct combustion. Potential exists for fireside ash deposition and potential corrosion problems for some of the biomass materials characterized in this study. Perennial herbaceous crops had subtle short-term effects on soil properties in central and western North Dakota. Changes in soil properties were most prevalent at the Williston site, where less fertile sandy soil and high biomass production contributed to increases in soil organic carbon, total nitrogen, and available phosphorus. Coarse-textured soils have the greatest potential to respond positively from perennial biofeedstocks in the short-term.

Next Steps: Distribute the Final Report and continue the study through 2016.

Biomass Production of Selected Perennial Herbaceous Warm-season and Cool-season Grasses, and Legumes in Central and Western North Dakota for Bioenergy

Paul E. Nyren[1], Guojie Wang[1], Bob D. Patton[1], Anne Nyren[1], Qingwu Xue[2], Eric Eriksmoen[3], Gordon Bradbury[4], Mark Halverson[5], Ezra Aberle[6], Kris Nichols[7], and Mark Liebig[7]

[1]Central Grasslands Research Extension Center, North Dakota State University, Streeter, ND 58483
[2]Texas AgriLife Research and Extension Center, Texas A & M University, Amarillo, TX 79106
[3]Hettinger Research Extension Center, North Dakota State University, Hettinger, ND 58639
[4]Williston Research Extension Center, North Dakota State University, Williston, ND 58801
[5]North Central Research Extension Center, North Dakota State University, Minot, ND 58701
[6]Carrington Research Extension Center, North Dakota State University, Carrington, ND 58421
[7]Northern Great Plains Research Laboratory, USDA-ARS, Mandan, ND 58554

ABSTRACT

The state of North Dakota has a great potential to produce perennial herbaceous biomass for bioenergy purposes due to its large area of Conservation Reserve Program (CRP) and erodible, saline, and marginal croplands. Switchgrass (*Panicum virgatum* L.) has been identified as a "model" bioenergy crop by the Department of Energy (DOE) of the USA. Biomass production of switchgrass as well as other promising species such as intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth & D.R. Dewey), tall wheatgrass (*Thinopyrum ponticum* [Podp.] Z.-W. Liu & R.-C. Wang), big bluestem (*Andropogon gerardii* Vitman) were investigated at Carrington, Hettinger, Minot, Streeter, and Williston across central and western North Dakota from 2006 to 2011. At Williston, a paired irrigation site was used to compare the effect of irrigation on species biomass production. The field study plots harvested annually or biennially to investigate the harvest frequency effects on species biomass production.

The establishment of cool-season grasses such as intermediate wheatgrass and tall wheatgrass was appreciable for all study sites; however, the establishment of warm-season grasses such as switchgrass and big bluestem was problematic at Hettinger, as well as Williston without irrigation. In comparison, at Williston with irrigation the warm-season grasses were soundly established under the same cultural management as Williston dry land. Therefore, the establishment of the warm-season grasses in these dry areas was mainly driven and constrained by available soil water in the growing season. Furthermore, intermediate wheatgrass and tall wheatgrass are the alternatives for the biomass production in these dry areas only from the establishment perspective. At Streeter and Minot, weed control was crucial to establish warm-season grasses, otherwise more years are needed to allow the warm-season grasses to build root systems and outcompete common weeds. Glyphosate could be used to control early growing weed species in spring before the warm-season grasses start to grow, however, the application rate and time window need to be further tested. At Carrington, the establishment of warm-season

grasses was promising, with mechanical mowing in the establishment year being helpful as well as the appropriate ecological and climatic conditions. The seeding methods (timing, rate, depth, seedbed preparation et al.) at all study sites were the exactly same, site-specific seeding strategy should be investigated if establishment of warm-season grasses is the goal.

For annual harvest, study site accounted for 63% of the total data set variance and was a main factor for biomass production. While with irrigation at Williston, the production (9.61 Mg/ha) was the highest, following by wettest study site Carrington (9.23 Mg/ha), then Minot (6.70 Mg/ha) and Streeter (5.38 Mg/ha), the lowest at Williston without irrigation (2.34 Mg/ha). The study site biomass production and its long-term mean annual precipitation were in the same order. However, the highest productive species or their combinations varied at each study site. Sunburst switchgrass produced the highest consistently from 2007 to 2011 at Williston irrigated land and Carrington with average production of 13.35 Mg/ha and 10.60 Mg/ha, respectively. At Williston non-irrigated land, haymaker intermediate wheatgrass was consistently the highest from 2007 to 2011 with an average production of 3 Mg/ha. The results at Minot and Streeter were mixed and complex. At Minot, alkar tall wheatgrass and its mixtures (9-10 Mg/ha) were the highest from 2007 to 2008 while in 2009, they were still the highest but all the entries were statistically same. From 2010 to 2011, Dakota switchgrass, Sunburst switchgrass, and Sunnyview big bluestem were the highest. As a result, five years average was not significantly different for all the entries, however, Sunburst switchgrass + Alkar tall wheatgrass combination (8.09 Mg/ha) was the highest numerically. At Streeter, the similar trend as at Minot was found, namely, from 2007 to 2009, cool-season grasses produced higher than warm-season grasses, they were similar in 2010, while in 2011, Sunburst switchgrass produced the highest (9.73 Mg/ha). Five years average of Alkar tall wheatgrass + Sunburst switchgrass combination (6.70 Mg/ha) was the highest.

For biennial harvest, similar results were found as annual harvest, i.e. study site with higher annual harvest production was also had higher biennial harvest production; species with higher annual harvest production at each study site normally had higher biennial harvest production in that corresponding study site. However, at Williston non-irrigated land biennial harvest of Sunburst switchgrass or its combination with Mustang altai wildrye was the highest (2.24 Mg per ha per year) while annual harvest of Haymaker intermediate wheatgrass was the highest. Overall, biennial harvest only accounted for 63% total biomass compared to annual harvest over all sites and years. However, biennial harvest yields varied with study sites, with Williston dry land (76%) the highest, following by Minot (71%), Williston irrigated land and Streeter (66%), and the least at Carrington (56%).

In central North Dakota, Sunburst switchgrass established and produced soundly, however, in western North Dakota the switchgrass establishment was problematic and intermediate wheatgrass could be an alternative. Weed control was crucial at Streeter and Minot, the combination of switchgrass and tall wheatgrass in these areas could stabilize first three years production. In the dry area, biennial harvest could be an option since their high accountability.

Irrigation improved stand establishment and had profound effect on biomass production while its economical and environmental feasibility needs further study.

INTRODUCTION

The 1970s energy crisis consisted of the 1973 oil crisis, caused by the Arab Oil Embargo of OAPEC, and the 1979 energy crisis, caused by the Iranian Revolution. Following that, the fuel price panic after Hurricane Katrina in 2005 renewed our memory about energy safety (Ragauskas, Williams et al. 2006). Currently in 2011 and hereafter, the projected gasoline price will reach the historical record of $5/Gal, probably caused by Arab Spring and Iranian Nuclear Program Crisis as well as others. However, we are apt to forget and ignore all the issues related to energy safety, and devaluate the effort to diversify energy sources either domestically or internationally, and from fossil energy to renewable energy. Oil dependency, especially on Middle East, has already increased economic costs up to $233 billion/year over last 30 years because of above mentioned periodic oil price shocks (McLaughlin, Ugarte et al. 2002). Furthermore, the true social costs of oil energy include both market exchange and other direct and/or indirect nonmarket aspects, such as global warming, acidic rain, water contamination, and human health.

The investigation and development of bioenergy is one of the important measures to meet the USA and worldwide energy challenges in the future. Currently, bioenergy is produced from cash crops, primarily ethanol from corn and biodiesel from soybeans. This results in cash crop resources moving away from feed and food production and into the energy sector, increasing food prices and food scarcity worldwide as a result. Meanwhile, crop residues were considered as an alternative bioenergy feedstock, however, neither corn cobs and stalks nor wheat straw meet the production level economically, environmentally, and mechanically, and further research is needed to clarify the appropriate proportion of crop residue collected in the field and their effects on soil quality and agricultural sustainability (Boehmel, Lewandowski et al. 2008). In the US and EU, biomass research has investigated both woody and herbaceous crops grown for bioenergy (Lewandowski, Scurlock et al. 2003), which included tree species (*Salix* spp, *Populus* spp.), traditional row crops (*Zea Mays*, *Triticum* spp. *Sorghum* spp.) and perennial herbaceous grasses (*Arundo*, *Panicum*, *Phalaris*, *Miscanthus*). Of these, the last group has the most characteristics promising to bioenergy production.

As late as 1920 in the US, draft animals such as horses and mules, estimated at 27 million heads, fed by 35-40 million hectares of herbaceous biomass such as grasses and legumes powered the transportation and agricultural industry (Lewandowski, Scurlock et al. 2003). In the 21st century, perennial grasses may be set for a comeback through a number of different energy conversion pathways. Since the mid-1980s, the US Department of Energy (DOE) initiated several programs to evaluate the candidates of perennial grasses for bioenergy feedstock. After evaluating 18 herbaceous perennial grasses between 1985 and 1989, it was concluded that switchgrass was the candidate grass which showed the greatest potential. Consequently, in 1991, switchgrass was

decided to be a “model” crop for bioenergy use and more researches were done to develop a cropping system in order to rapidly attain its maximal output.

Switchgrass is a native perennial warm-season (C_4) grass belongs to the subfamily *Panicoideae* of the *Gramineae* family where it occurs naturally from 55°N latitude to central Mexico, with exception for the areas west of the Rocky Mountains. Switchgrass is deep rooted, and has the capacity for high yields on relatively poor quality sites, where water and nutrient availability would prevent the successful production of conventional crops. It has high water, nutrient, and solar radiation use efficiency because of its C_4 photosynthesis pathway, and positive environmental attributes—including effects on soil quality and stability (Frank, Berdahl et al. 2004), cover value for wildlife, and relatively low inputs. Furthermore, Switchgrass can easily be integrated into conventional farming operations because conventional equipment for seeding, crop management and harvesting can be used. However, establishment of good stand of switchgrass is a key and bottleneck in reality, especially in drier areas because soil water availability is crucial for establishment, and weed competition is also a major reason for switchgrass stand failure (Mitchell, Vogel et al. 2010). Fertilization application and its level depend on the specific site soil quality and normally optimal level is 50-100 kg N $ha^{-1}year^{-1}$. Optimal harvest date and frequency were studied over the US and the postanthesis harvest in the south and after a killing frost in the north were recommended with one cut per year (Adler, Sanderson et al. 2006; Lee, Owens et al. 2007).

Successful biomass production from perennial herbaceous plants requires the choice of the suitable plant species and varieties for the given location conditions. Therefore, other perennial C_4 grasses as well as some promising C_3 grasses were also evaluated in the US, Canada, and EU, especially for northern and western areas with short growing season and low precipitation, for example, prairie cordgrass (*Spartina pectinata* Link.) in South Dakota (Boe and Lee 2007) and Canada (Madakadze, Coulman et al. 1998); reed canary grass (*Phalaris arundinacea* L.) in EU (Lewandowski, Scurlock et al. 2003) and US (Jasinskas, Zaltauskas et al. 2008), as well as smooth bromegrass (*Bromus inermis* Leyser.), western wheatgrass (*Pascopyrum smithii* [Rydb.] A. Love.), and northern wheatgrass (*Elymus lanceolatus* Scribn. & J.G. Sm.) in the west of the Rocky Mountains and Canada (Jefferson, McCaughey et al. 2004; Robins 2010). In some cases, C_3 perennial grasses production were higher than switchgrass and other C_4 grasses due to the short growing season and low precipitation even though C_4 grasses have superior characteristics than C_3 grasses, whether selection of C_3 or C_4 grasses as a bioenergy feedstock is site-specific.

The Northern Great Plains (NGP) is the transition zone between native tallgrass prairie on the east and midgrass even shortgrass prairie on the west, and the split occurs at approximately 98°W longitude (). Switchgrass occurs naturally on mesic sites such as river valleys, low-lying areas, and road ditches west of 98°W longitude, however, the natural prairie was dominated by C_3 grasses rather than C_4 grasses except for blue grama with low stature and productivity. Furthermore, Vogel et al. (1985) suggested that moving switchgrass populations north of their origin would result in greater biomass yield, however, warm-season grasses should not be moved

more than 500 km north of their origin because of potential winter injury, and this was already tested by studies in western of North Dakota (Berdahl, Frank et al. 2005).

The NGP has been identified as an important area for biomass production. In particular, North Dakota is ranked first in terms of its potential for producing perennial grasses and other dedicated bioenergy crops among the 50 states. With over 2.8 million ha of highly erodible and saline crop land as well as 1.2 million ha of Conservation Reserve Program (CRP), some counties in the west part of the state have as much as 90% of the cropland being classified for bioenergy crop production. However, historical studies on switchgrass biomass production were mainly in the east of 98°W longitude with the exception of studies in Mandan and Dickinson, North Dakota (Frank, Berdahl et al. 2004; Berdahl, Frank et al. 2005). The establishment, cultural management, and harvest regime of switchgrass in western North Dakota still remains mostly unknown. Furthermore, switchgrass cultivars of southern origin such as Alamo, Kanlow, Cave-in-Rock, and Blackwell had doubtable winter hardy 500 km north of their origin, test and selection of the right populations of switchgrass is important even if the switchgrass can establish and produce sound west of 98°W of North Dakota.

With monoculture of biomass crops in the landscape it will increase the risk of pest and disease spread, the risk of acceptance of landowners, and it can also degrade landscape visual diversity and decrease the capacity to provide habitat to different animals (Lewandowski, Scurlock et al. 2003). So a mixture of different plant species is not only an alternative to switchgrass establishment failure or poor production, but also a social as well as environmental concern. Legume species might sustain soil nitrogen level to meet the biomass production needs and lower the inputs from fertilizer because of its nitrogen fixation capacity. However, the mixtures of legumes with grasses have not yet been tested for biomass production intensively.

Most of the studies related to biomass harvest regimes took place east or south of North Dakota and did not take into account of snowfall early in the fall and wet soil conditions in the spring in North Dakota. Furthermore, North Dakota, especially the Prairie Potholes Region, is one of the most important areas for wildlife such as waterfowls. For the sake of site specificity, new harvest regime fitting both timing limits and wildlife habitat needs should be investigated in North Dakota. As best of our knowledge, no irrigation study for biomass production has been done in North Dakota yet, and knowledge about irrigation effects on biomass energy crop establishment and yield is critical before the landowners implement irrigation practices on biomass energy crops.

Therefore, the objectives of this study were to: 1) ascertain different switchgrass varieties as well as other promising perennial herbaceous plant species or their mixtures (10 entries) establishment and biomass yield harvested annually or biennially across central and western North Dakota; and 2) evaluate irrigation effects on biomass crop production at Williston, North Dakota.

MATERIALS AND METHODS

The biomass field study was located across central and western North Dakota (Figure 1). The study site location characteristics were shown in Table 1. In summary, all the sites were located west of 98°W longitude and north of 46°N latitude with Carrington the furthest east and Williston the furthest west, and with Hettinger the furthest south and Minot/Williston the furthest north. The soils are loams with exception of Williston loamy fine sand.

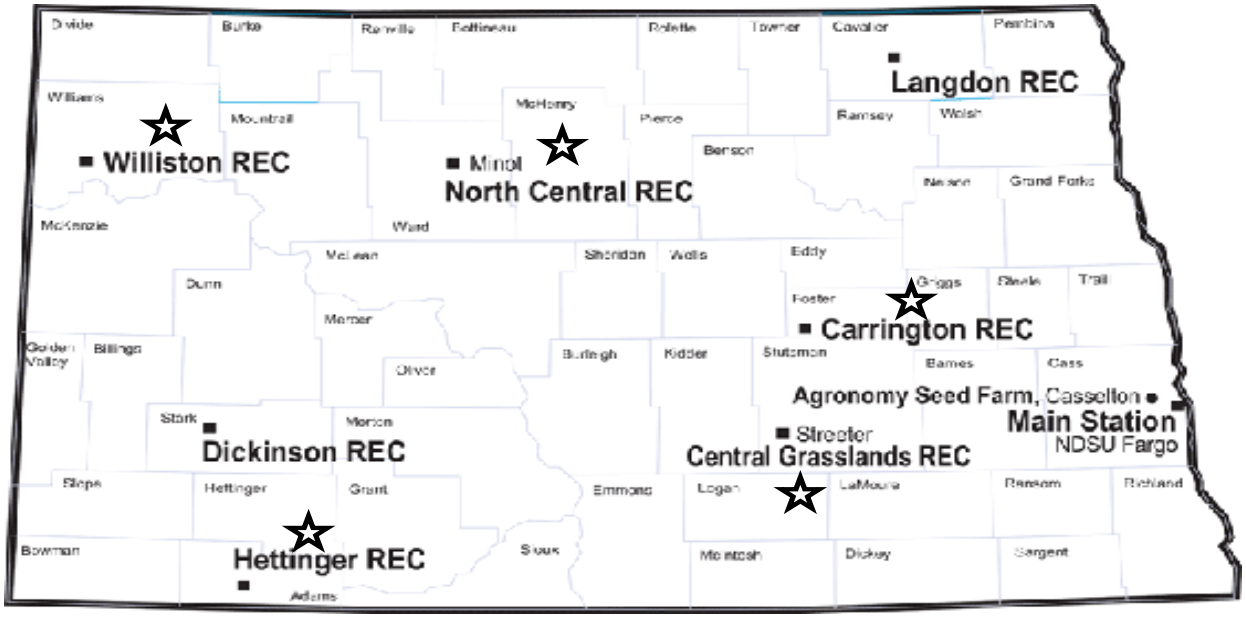


Figure 1. Field locations of biomass study plots across central and western North Dakota. North Dakota State University Agricultural Experimental Station system includes seven Research Extension Centers (REC): Carrington REC, Central Grasslands REC at Streeter, Dickinson REC, Hettinger REC, Langdon REC, North Central REC at Minot, and Williston REC as well as one Agronomy Seed Farm at Casselton. The stars shows the locations that the biomass study took place, which was leaded by Central Grasslands REC.

Table 1. Field locations characteristics for biomass study across central and western North Dakota.

Location	Longitude	Latitude	Prevalent soil type	Soil classification
Carrington	W99.12°	N47.49°	Heimdal-Emrick loams, 0 to 3% slope	Coarse-loamy, Mixed, Superactive, Frigid Calcic and Pachic Hapludolls
Hettinger	W102.64°	N46.02°	Belfield-Savage-Daglum silt loams, 3 to 6% slope	Fine, Smectitic, Frigid, Glossic and Vertic Natrustolls and Fine, Smectitic, Frigid, Vertic Argiustolls
Minot	W101.30°	N48.18°	Bowbells-Tonka complex, 0 to 3% slope	Fine-Loamy, Mixed, Superactive, Frigid Pachic Argiustolls and Fine, Smectitic, Frigid Argiaquic Argialbolls
Streeter	W99.50°	N46.75°	Barnes-Svea loams, 0 to 3% slope	Fine-Loamy, Mixed, Superactive, Frigid Calcic and Pachic Hapludolls
Williston	W103.11°	N48.16°	Lihen loamy fine sand, 0 to 3% slope	Sandy, Mixed, Frigid, Entic Haplustolls

The monthly temperature (^{o}C) for both the study years and the long-term (1971-2000) average was shown in Table 2. Hettinger has a warmer winter and Williston has a warmer spring compared with other sites. 2006 was the hottest year in the 6 years study period. Table 3 showed the growing season (April-September) monthly and total precipitation (mm) for the study years and the long-term (1971-2000) monthly and total precipitation (mm). Carrington has highest (505 mm), Minot (474 mm) and Streeter (434 mm) in the middle, and Hettinger (394 mm) and Williston (366 mm) the least long-term average annual precipitation. 2006 and 2009 growing season precipitation was well below long-term growing season average at all the locations except for 2006 in Streeter and Williston and 2009 in Williston. 2011 growing season precipitation was well above average at all locations except for Hettinger, at which 2007 was the wettest year.

Table 2. Mean temperature (^{o}C) data for biomass study cross central and western North Dakota.

Site	Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Mean1[a]
Carrington	2006	-3	-12	-3	9	14	18	22	20	13	4	-3	-6	6
	2007	-11	-15	-1	5	14	19	22	18	14	8	-2	-12	5
	2008	-14	-14	-4	4	10	16	20	20	13	7	-2	-16	3
	2009	-17	-13	-7	4	11	16	18	18	17	3	2	-14	3
	2010	-13	-14	0	9	12	17	20	20	13	8	-3	-13	5
	2011	-15	-13	-8	3	11	17	21	20	14	9	-1	-5	4
	Mean2[b]	-14	-9	-3	6	14	18	21	20	14	7	-3	-11	5
Hettinger	2006	-1	-6	-2	9	13	19	25	22	13	5	0	-5	8
	2007	-6	-9	3	5	13	18	24	20	15	8	0	-6	7
	2008	-9	-8	0	5	11	16	22	21	14	7	-1	-12	5
	2009	-9	-8	-5	4	12	15	18	18	17	3	3	-12	5
	2010	-10	-11	0	8	10	17	20	21	13	9	-2	-11	5
	2011	-11	-11	-5	4	10	16	22	21	14	10	0	-4	5
	Mean2[b]	-10	-6	-1	6	12	17	21	20	13	7	-2	-8	6
Minot	2006	-2	-9	-2	10	13	19	23	21	14	4	-2	-6	7
	2007	-10	-13	1	6	13	19	24	19	15	8	-2	-10	6
	2008	-11	-12	-2	5	11	16	20	21	14	7	-2	-15	4
	2009	-15	-12	-7	4	11	16	18	18	18	3	3	-15	4
	2010	-12	-13	-1	8	11	17	20	20	13	9	-3	-13	5
	2011	-14	-12	-8	4	11	17	22	21	15	9	-1	-4	5
	Mean2[b]	-13	-9	-3	5	13	18	20	19	13	6	-3	-10	5
Streeter	2006	-4	-9	-2	9	13	18	23	20	13	4	-2	-5	6
	2007	-11	-15	0	4	13	18	22	18	14	8	-2	-10	5
	2008	-13	-12	-3	4	10	16	20	20	14	7	-1	-15	4
	2009	-15	-12	-7	3	11	16	18	18	17	3	3	-13	4
	2010	-13	-13	0	9	12	18	20	21	13	8	-2	-12	5
	2011	-15	-12	-7	4	11	17	22	20	14	9	0	-5	5
	Mean2[b]	-13	-9	-3	5	12	17	20	19	13	6	-3	-10	4
Williston	2006	-2	-7	-2	10	14	18	24	22	14	4	-2	-6	7
	2007	-8	-12	2	6	13	19	25	20	15	8	-1	-9	7
	2008	-11	-10	-1	6	12	17	22	21	14	7	0	-14	5
	2009	-12	-10	-5	6	12	17	19	19	19	3	3	-14	5
	2010	-11	-11	0	8	11	18	21	20	13	9	-3	-12	5
	2011	-12	-12	-6	4	11	17	22	22	16	10	-1	-4	6
	Mean2[b]	-13	-8	-1	7	13	18	21	21	14	7	-3	-10	6

[a] Mean1 is the mean annual temperature for the corresponding study years (2006-11).
[b] Mean2 is the long-term (1971-2000) mean monthly temperature.

Table 3. Mean precipitation (mm) data for biomass study cross central and western North Dakota.

Site	Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Total[a]
Carrington	2006				31	29	88	27	54	25				255
	2007				12	136	66	85	85	36				419
	2008				12	30	127	47	39	99				354
	2009				43	34	41	38	51	55				262
	2010				36	66	82	50	42	107				383
	2011				25	50	87	157	133	60				511
	Mean[b]	13	10	19	37	63	96	79	63	47	46	21	10	505[c]
Hettinger	2006				53	24	57	11	43	72				260
	2007				23	156	77	56	83	12				407
	2008				22	99	102	35	41	14				313
	2009				21	35	98	53	84	14				305
	2010				52	93	74	93	50	82				443
	2011				58	113	81	43	53	9				357
	Mean[b]	8	8	15	40	65	75	55	37	36	34	13	8	394[c]
Minot	2006				41	23	48	63	41	38				254
	2007				19	205	116	28	14	15				396
	2008				12	68	136	60	80	46				402
	2009				32	38	48	42	37	100				298
	2010				40	93	123	58	69	89				472
	2011				37	175	71	95	46	45				468
	Mean[b]	20	15	26	40	58	76	64	51	45	36	27	16	474[c]
Streeter	2006				28	55	31	57	169	71				411
	2007				13	172	104	76	100	51				516
	2008				12	3	129	74	62	73				354
	2009				33	20	54	52	62	47				267
	2010				29	99	56	164	47	123				518

	2011				42	47	175	104	95	22				485
	Mean[b]	8	9	17	32	50	77	78	60	50	28	18	7	434[c]
Williston	2006				95	35	40	11	30	43				254
	2007				5	127	65	25	12	15				248
	2008				5	35	54	20	33	47				194
	2009				39	15	38	65	70	7				235
	2010				23	112	50	54	78	22				339
	2011				46	178	56	31	25	30				366
	Mean[b]	12	9	16	29	53	69	62	41	40	24	15	11	381[c]

[a] total = the sum of growing season (April-September) precipitation for each study year 2006-11.
[b] mean is the long-term (1971-2000) average monthly precipitation.
[c] long-term (1970-2000) mean annual precipitation.

The studied ten entries are shown in Table 4. Switchgrass and big bluestem are C_4 grasses, tall wheatgrass, intermediate wheatgrass, basin wildrye, and altai wildrye are C_3 grasses, alfalfa is a perennial legume, and yellow sweetclover is a biennial legume. There were three varieties of switchgrass in this study. The Sunburst was seeded at all locations, and Trailblazer was seeded at Hettinger, Streeter, and Carrington, while Dakota was seeded at Williston and Minot. The reason for using Dakota instead of Trailblazer at Williston and Minot was that Trailblazer had a higher risk to loss stand by winter kill than Sunburst and Dakota at these locations.

Table 4. Species/Varieties or their combinations and the corresponding seeding rate (pure live seed kg/ha) for biomass study across central and western North Dakota in May 2006.

Species/Varieties or their combinations	Latin name	Seeding rate
Switchgrass/Sunburst	*Panicum virgatum* L.	11.2
Switchgrass/Trailblazer or Dakota *	*Panicum virgatum* L.	11.2
Tall Wheatgrass/Alkar	*Thinopyrum ponticum* (Podp.) Z.-W. Liu & R.-C. Wang	12.3
Intermediate Wheatgrass/Haymaker	*Thinopyrum intermedium* (Host) Barkworth &D.R. Dewey	11.2
CRP mix 1		12.3
Intermediate Wheatgrass/Haymaker	*Thinopyrum intermedium* (Host) Barkworth &D.R. Dewey	5.6
Tall Wheatgrass/Alkar	*Thinopyrum ponticum* (Podp.) Z.-W. Liu & R.-C. Wang	6.7
CRP mix 2		11.2
Intermediate Wheatgrass/Haymaker	*Thinopyrum intermedium* (Host) Barkworth &D.R. Dewey	4.5
Tall Wheatgrass/Alkar	*Thinopyrum ponticum* (Podp.) Z.-W. Liu & R.-C. Wang	5.0
Alfalfa/Vernal	*Medicago sativa* L.	1.1
Yellow Sweetclover/Blossom	*Melilotus officinalis* (L.) Lam.	0.6
$C_4 + C_3$ 1		11.2
Switchgrass/Sunburst	*Panicum virgatum* L.	5.6
Tall Wheatgrass/Alkar	*Thinopyrum ponticum* (Podp.) Z.-W. Liu & R.-C. Wang	5.6
C4 combination		10.6
Switchgrass/Sunburst	*Panicum virgatum* L.	7.8
Big Bluestem/Sunnyview	*Andropogon gerardii* Vitman	2.8
$C_4 + C_3$ 2		20.1
Switchgrass/Sunburst	*Panicum virgatum* L.	7.8
Altai Wildrye/Mustang	*Leymus angustus* (Trin.) Pilg.	12.3
C_3 combination		17.9
Basin Wildrye/Magnar	*Leymus cinereus* (Scribn. & Merr.) A. Love	5.6
Altai Wildrye/Mustang	*Leymus angustus* (Trin.) Pilg.	12.3

*Trailblazer was seeded at Hettinger, Central Grasslands, and Carrington, while Dakota at Williston and Minot.

The irrigation amount and distribution at Williston was: Jul. 5, 15 mm; Jul. 11, 15 mm; Jul. 13, 15 mm; Jul. 15, 20 mm; Jul. 22, 18 mm; Jul. 27, 18 mm; Aug. 10, 20 mm; Aug 25, 20 mm; Sep. 7, 18 mm and totally, 178 mm. Adding total irrigation amount to the natural precipitation, the growing total acceptable water amount at Williston irrigated sites is comparable with Carrington without irrigation and slightly higher.

The experimental design at all sites was a three-replicate randomized complete block design with ten entries (Table 4) and two harvest regimes (annually and biennially, two sets of ten entries plots), totally 10 (entries) × 2 (harvest regimes) × 3 (blocks) = 60 plots for each site. Each plot

consisted of 30 rows 9.2 m long with a 15-cm spacing between rows (4.6 m wide). The seeding rate for each entry was shown in Table 4. In 2006, all the plots across all the locations were seeded the week of May 15 starting in Hettinger and ending with Carrington (Table 5) and a plot dill designed and built at the USDA-ARS, Mandan to seed small-seeded grasses and legumes by Mr. Louie Zachmeier was used. The field plots after seeding at each location were maintained by different mowing and spraying herbicides for weed control if necessary (Table 5). 2006 is an establishment year and no harvest was done. The plots of annual harvest regime was harvested every year and the plots of biennial harvest regime was harvest in 2007, 2009, and 2011in the second or third week of September depending on the weather by a self-propelled plot harvester provided by the USDA-ARS, Mandan. A 123 cm wide strip in the center of each plot was cut to a 8-cm stubble height and weighted in kg by the machine. Dry matter percentage of biomass from each plot was measured from a 0.4- to 0.8-kg grab sample that was dried at 60 ^{o}C and used to adjust plot yields to a dry matter basis. Plot species composition (weeds and designated species) were visually monitored during the harvest process.

Table 5. Cultural management for biomass study across central and western North Dakota.

Location	Year	Seeding	Establishment	
			Herbicide application	Mowing
Carrington	2006	May 19	Oct. 6 with 16 oz Banvel	Jul. 7; Aug. 23; Sep. 22
Hettinger	2006	May15	May 15 with 16 oz Glyphosate; May 25 with 16 oz Glyphosate; Jun. 15 with 16 oz Bromoxynil; Jun. 27 with 0.3 oz Prosulfuron and 16 oz Bromoxynil; Aug. 3 with 6 oz Fluroxypyr; Sep. 19 with 16 oz 2,4-D	
	2008	Spring		
Minot	2006	May 17	Jul. 14 with 0.33 oz Harmony GT	Jul. 21; Aug. 18
Streeter	2006	May 19	Jun. 26 with 24 oz Bromoxynil; Sep. 13 with 64 oz 2,4-D and 8 oz Banvel	Jul. 5; Aug. 15; Sep. 5
	2010		May 17 with 64 oz Glyphosate	
	2008	Spring		
Williston	2006	May 16	Jun. 23 with 32 oz Buctril and 16 oz Starane	Jul. 26; Sep. 6 irrigated only

Production data from 2007 biennial harvest was dropped since all the plots except Hettinger were mowed in 2006 (Table 5), “Biennial harvest” data in 2007 was an actual annual instead of biennial harvest. Hettinger study site was dropped due to stand establishment failure. Annual and biennial harvest production data were analyzed using the ANOVA procedure separately for a randomized completely block design in SAS. Location, harvest year, and entry were considered to be fixed effects while replications were treated as random. There were significant location × harvest year × entry interactions. Therefore, additional analysis was conducted by location and by year. Mean separations were based on LSD procedure. Biennial harvest data in 2009 was divided by the sum of annual harvest data in 2008 and 2009, and again biennial harvest data in 2011was divided by the sum of annual harvest data in 2010 and 2011. The new constructed data set was analyzed by ANOVA procedure as mentioned above.

RESULTS

Establishment

The seedbed was dry at Hettinger site in 2006 due to lower precipitation and higher temperature than long-term average (Table 2, Table3). Germination and emergence commenced with late spring rainfall, while weeds, especially kochia, were abundant and competed with developing biomass study plot stands. Weed control was implemented intensively by different herbicides application in different dates (Table 5). With all the effort to establish sound stands at Hettinger, it turned out a stand failure in 2007. The plots were reseeded in 2008 with higher precipitation than 2006; however, warm-season grasses were still failed to establish in both 2009 and 2010.

Even though Williston dry land site data were collected as other plots from other study sites, the plots stand composition was dominated by crested wheatgrass in all C_4 grasses entries. It is 2011 that the only year C_4 grasses were shown in the plots that it could be visually monitoring.

The switchgrass at Streeter study site did not establish soundly from 2006 in 2007. A year later in 2008 the switchgrass plots were reseeded in an attempt to improve the poor stands. On May 17, 2010 the Sunburst switchgrass plots were sprayed with 64 oz/acre of glyphosate to control weeds. The treatment worked well and the switchgrass responded positively. The key to a successful glyphosate treatment is to apply it to the plots just before the warm-season grasses emerge from their winter dormancy and the cool-season unwanted grasses are already at the 3 to 4 leaf stage.

From 2007, Carrington and Williston irrigated land sites were sound established with the dominant stands being designated species. By 2009, Minot and Streeter had solid switchgrass stand and no further effort made hereafter.

Annual Harvest Production

Overall, all the factors considered in the annual biomass production as well as their interactions were significant at <0.0001 (Table 6). However, study site alone accounted for 63% of the total variance. Averaged over five years and ten entries, Williston irrigated land (9.61 Mg/ha) had the highest annual biomass production, following by Carrington (9.23 Mg/ha), Minot (6.70 Mg/ha), Streeter (5.38 Mg/ha), and the lowest at Williston dry land (2.34 Mg/ha). Study year alone only accounted for 1.6% of the total variance. Averaged over five study sites and ten entries, 2007 (7.20 MG/ha) and 2011 (7.14 Mg/ha) annual biomass production was higher than 2010 (6.36 Mg/ha), 2008 (6.32 Mg/ha), and 2009 (6.23 Mg/ha). Similarly, study entry alone only accounted for 3.2% of the total variance. Average over five study sites and five study years, Sunburst switchgrass (7.40 Mg/ha) was the highest entry, following by Sunburst switchgrass + Mustang Altai wildrye combination (7.38 Mg/ha), Sunburst switchgrass + Alkar tall wheatgrass combination (7.32 Mg/ha), Sunburst switchgrass + Sunyview big bluestem combination (6.98 Mg/ha), Alkar tall wheatgrass (6.83 Mg/ha), Haymaker intermediate wheatgrass (6.38 Mg/ha),

CRP mix 1 (6.35 Mg/ha), Dakota or Trailblazer switchgrass (6.31 Mg/ha), CRP mix 2 (6.06 Mg/ha), and the lowest for Magnar basin wildrye + Mustang Altai wildrye combination (5.49 Mg/ha) for annual biomass production.

Table 6. Analysis of variance (ANOVA) for biomass production (Mg/ha) for 5 sites (Carrington, Minot, Streeter, Williston dry land, Williston irrigation land) over 5 years (2007-2011) with annual harvest regime across central and western North Dakota.

Source of variation	df[a]	Sum of squares	Mean square	F value	p value
Site	4	5351.64	1337.91	812.72	<0.0001
Year	4	137.32	34.33	20.85	<0.0001
Entry[b]	9	274.33	30.48	18.52	<0.0001
Site × year	16	349.57	21.84	13.27	<0.0001
Site × entry	36	842.70	23.41	14.22	<0.0001
Year × entry	36	224.38	6.23	3.79	<0.0001
Site × year × entry	144	531.43	3.69	2.24	<0.0001
Error	500	823.11	1.65		
Total	749	8534.48			

[a] df means degree of freedom.

[b] entry lists shown in table 4.

Since site × year × entry interaction had significant effect on annual biomass production (Table 6), the production data was shown in Table 7 by site and by year for entry. At Carrington, Sunburst switchgrass had the highest annual biomass production two years out of five years, and also the highest over five years average (10.60 Mg/ha). At Minot, annual biomass production in 2007 and 2008 of C_3 grasses were higher than C_4 grasses, in 2009 they were similar, while in 2010 and 2011 C_4 grasses were higher than C_3 grasses. As a result, over five years average there was no significant difference between entries. Numerically, Sunburst switchgrass + Alkar tall wheatgrass combination produced highest annual biomass production (8.09 Mg/ha). At Streeter, the similar trend as at Minot was found, in 2007, 2008, and 2009, C3 grasses produced more than C4 grasses, in 2010, they were similar, while in 2011, Sunburst switchgrass produced most biomass (9.73 Mg/ha). Sunburst switchgrass + Alkar tall wheatgrass combination produced the highest annual biomass production (6.70 Mg/ha) over five years. At Williston dry land, haymaker intermediate wheatgrass annual biomass production was the highest all five years and the production reached 3.00 Mg/ha over five years. At Williston irrigation land, Sunburst switchgrass annual biomass production was the highest almost every year over five years, and reached 13.35 MG/ha over five years.

Table 7. Annual biomass production (Mg/ha) at each study site for each study year. Means in the same column for each study site followed by different letters differ significantly at P < 0.05. Entry lists see Table 4.

Site	Entry	2007	2008	2009	2010	2011	Average
Carrington	Tall Wheatgrass	10.44bcde	9.80abc	8.84bcd	9.25a	10.17ab	9.70abcd
	CRP mix 1	9.32de	8.39bcd	7.67de	7.24de	10.54a	8.62de
	CRP mix 2	11.04bcd	8.48bcd	7.24e	7.34de	9.71abc	8.76cde
	Intermediate wheatgrass	9.97cde	7.49cd	7.20e	6.64de	7.91c	7.84ef
	C_3 combination	8.65e	6.98d	6.97e	6.17e	8.10bc	7.40f
	Sunburst switchgrass	12.01abc	11.50a	11.00a	9.05ab	9.39abc	10.60a
	$C_4 + C_3$ 2	11.60bc	11.11ab	9.92ab	7.65bcd	9.40abc	9.95ab
	C_4 combination	12.28ab	10.88ab	9.43bc	8.86abc	9.55abc	10.20ab
	$C_4 + C_3$ 1	11.85abc	8.96abcd	8.94bcd	7.78bcd	9.47abc	9.41bcd
	Trailblazer switchgrass	13.91a	10.23abc	8.27cde	7.50cde	9.60abc	9.90abc
Minot	Tall Wheatgrass	9.39a	9.17a	7.02a	7.43ab	5.75ab	7.75a
	CRP mix 1	10.01a	8.03ab	4.57a	4.69b	5.57b	6.59a
	CRP mix 2	9.23a	7.23ab	6.28a	6.46ab	6.84ab	7.21a
	Intermediate wheatgrass	8.22a	9.26a	5.49a	6.12ab	6.62ab	7.15a
	C_3 combination	5.26b	5.53bc	6.09a	6.21ab	6.69ab	5.96a
	Sunburst switchgrass	5.35b	3.65c	5.00a	7.79ab	6.97ab	5.76a
	$C_4 + C_3$ 2	5.12b	8.01ab	6.92a	7.20ab	7.31ab	6.92a
	C_4 combination	4.80b	3.75c	4.56a	8.56a	8.03a	5.94a
	$C_4 + C_3$ 1	10.26a	9.16a	7.28a	7.72ab	5.99ab	8.09a
	Dakota switchgrass	3.45b	2.95c	5.28a	9.00a	7.75ab	5.69a
Streeter	Tall Wheatgrass	7.65a	5.90ab	5.19b	6.53a	5.32bc	6.12abc
	CRP mix 1	7.57a	5.97ab	6.03ab	5.78a	6.27bc	6.32ab
	CRP mix 2	5.74b	3.70cd	4.62b	5.28a	5.75bc	5.02bcd
	Intermediate wheatgrass	6.04b	6.13ab	7.42a	6.31a	5.92bc	6.36ab
	C_3 combination	3.73c	3.38cd	4.11b	4.83a	5.02c	4.21d
	Sunburst switchgrass	4.21c	1.66de	4.42b	6.09a	9.73a	5.22bcd
	$C_4 + C_3$ 2	4.00c	4.71bc	5.32ab	4.88a	7.59ab	5.31abcd
	C_4 combination	3.55c	4.43bc	4.17b	4.91a	6.34bc	4.68cd
	$C_4 + C_3$ 1	8.83a	6.93a	5.67ab	6.16a	5.84bc	6.70a
	Trailblazer switchgrass	3.83c	0.00e	4.11b	6.06a	5.22bc	3.85d
WillistonD	Tall Wheatgrass	2.16ab	1.58ab	2.35ab	2.41a	3.86ab	2.42bc
	CRP mix 1	2.34a	1.61ab	2.36ab	2.57a	3.63ab	2.55b
	CRP mix 2	1.95abc	1.38ab	1.74c	2.54a	4.41ab	2.40bc
	Intermediate wheatgrass	2.75a	1.77a	2.84a	2.95a	4.65a	3.00a
	C_3 combination	0.61bc	1.31ab	2.01bc	2.25a	3.79ab	2.02c
	Sunburst switchgrass	0.61bc	1.11b	2.07bc	2.30a	4.37ab	2.08c
	$C_4 + C_3$ 2	0.69bc	1.68ab	1.91bc	2.22a	3.92ab	2.08c
	C_4 combination	0.77bc	1.55ab	2.25bc	2.40a	4.32ab	2.26bc
	$C_4 + C_3$ 1	2.38a	1.52ab	2.09bc	2.35a	3.55b	2.37bc
	Dakota switchgrass	0.78bc	1.34ab	1.89bc	2.52a	4.31ab	2.17bc
WillistonI	Tall Wheatgrass	11.16ab	7.08e	8.60bcd	7.24def	6.90de	8.20d
	CRP mix 1	10.07bc	7.27e	6.28d	7.65cde	7.20de	7.68de
	CRP mix 2	8.33c	6.27e	7.80cd	6.15ef	6.01e	6.92e
	Intermediate wheatgrass	9.41bc	7.50e	8.34bcd	5.61f	6.90de	7.55de
	C_3 combination	9.38bc	6.86e	7.42cd	7.67cde	8.27d	7.93de
	Sunburst switchgrass	13.06a	16.31a	12.91a	11.93a	12.60a	13.35a
	$C_4 + C_3$ 2	13.11a	12.75b	12.81a	12.17a	12.53a	12.68ab
	C_4 combination	11.03ab	13.16b	11.26a	11.45ab	12.27ab	11.83b
	$C_4 + C_3$ 1	12.57a	9.55d	8.77bc	8.86cd	10.46bc	10.04c
	Dakota switchgrass	9.66bc	11.01c	10.65ab	9.51bc	8.81cd	9.92c

Biennial Harvest Production

Overall, all the factors considered except study year in the biennial biomass production as well as their interactions were significant (Table 8). Similar results of biennial harvest were found as annual harvest. Study site alone accounted for 58% of the total variance. Averaged over two years and ten entries, Williston irrigated land (12.12 Mg/ha) had the highest biennial biomass production, following by Carrington (9.76 Mg/ha), Minot (8.80 Mg/ha), Streeter (6.72 Mg/ha), and the lowest at Williston dry land (3.78 Mg/ha). Similarly, study entry alone only accounted for 9% of the total variance. Average over five study sites and two study years, Sunburst switchgrass + Mustang Altai wildrye combination (9.69 Mg/ha) was the highest entry, following by Sunburst switchgrass + Sunyview big bluestem combination (9.51 Mg/ha), Sunburst switchgrass (9.32 Mg/ha), Sunburst switchgrass + Alkar tall wheatgrass combination (9.25 Mg/ha), Alkar tall wheatgrass (8.54 Mg/ha), Magnar basin wildrye + Mustang Altai wildrye combination (7.75 Mg/ha) Dakota or Trailblazer switchgrass (7.63 Mg/ha), CRP mix 1 (7.25 Mg/ha), CRP mix 2 (6.83 Mg/ha), and the lowest for Haymaker intermediate wheatgrass (6.58 Mg/ha) for biennial biomass production.

Table 8. Analysis of variance (ANOVA) for biomass production (Mg/ha) for 5 sites (Carrington, Minot, Streeter, Williston dry land, Williston irrigation land) over 2 years (2009 and 2011) with biennial harvest regime across central and western North Dakota.

Source of variation	df[a]	Sum of squares	Mean square	F value	p value
Site	4	598.88	149.72	232.29	<0.0001
Year	1	0.05	0.05	0.07	0.7860
Entry[b]	9	92.10	10.23	15.88	<0.0001
Site × year	4	38.05	9.51	14.76	<0.0001
Site × entry	36	133.04	3.70	5.73	<0.0001
Year × entry	9	11.92	1.32	2.05	0.0353
Site × year × entry	36	38.09	1.06	1.64	0.0179
Error	200	128.91	0.64		
Total	299	1041.02			

[a] df means degree of freedom.
[b] entry lists shown in table 4.

Since site × year × entry interaction had significant effect on biennial biomass production (Table 8), the production data was shown in Table 9 by site and by year for entry. At Carrington, Sunburst switchgrass or its combination with others had the highest biennial biomass production. At Minot, biennial harvest biomass production in 2009 of C_3 grasses were higher than C_4 grasses, while in 2011 C_4 grasses were higher than C_3 grasses. As a result, over two years average there was no significant difference between entries. At Streeter, Sunburst switchgrass + Alkar tall wheatgrass combination produced the highest biennial harvest biomass production (5.02 Mg/ha) over two harvest years. At Williston dry land, the Sunburst switchgrass + Mustang Altai wildrye combination had highest biennial harvest production (2.24 Mg/ha), while the combination of Sunburst switchgrass + Sunyview big bluestem had highest biennial harvest production (8.42 Mg/ha).

Table 9. Biennial biomass production (Mg/ha, averaged over two years) at each study site for each study year. Means in the same column for each study site followed by different letters differ significantly at $P < 0.05$. Entry lists see Table 4.

Site	Entry	2009	2011	Average
Carrington	Tall Wheatgrass	4.52bc	5.40ab	4.97ab
	CRP mix 1	3.88c	4.29b	4.08b
	CRP mix 2	3.56c	4.34b	3.94b
	Intermediate wheatgrass	3.83c	4.91ab	4.37b
	C_3 combination	3.45c	4.30b	3.88b
	Sunburst switchgrass	6.00ab	5.22ab	5.62a
	$C_4 + C_3$ 2	6.45a	5.74a	6.09a
	C_4 combination	5.87ab	5.87a	5.87a
	$C_4 + C_3$ 1	4.60bc	5.43ab	5.02ab
	Trailblazer switchgrass	4.50bc	5.43ab	4.97ab
Minot	Tall Wheatgrass	6.07a	4.09abc	5.08a
	CRP mix 1	4.57ab	3.01bc	3.79a
	CRP mix 2	4.69ab	3.61abc	4.14a
	Intermediate wheatgrass	4.21b	2.76c	3.49a
	C_3 combination	4.71ab	4.32abc	4.50a
	Sunburst switchgrass	4.85ab	5.02a	4.93a
	$C_4 + C_3$ 2	4.91ab	4.65abc	4.77a
	C_4 combination	4.02b	3.75abc	3.88a
	$C_4 + C_3$ 1	5.97a	4.30abc	5.13a
	Dakota switchgrass	3.59b	4.91ab	4.26a
Streeter	Tall Wheatgrass	4.50ab	4.33abc	4.41ab
	CRP mix 1	3.98bc	3.17bcde	3.58bc
	CRP mix 2	3.35bcd	3.00bcde	3.18cd
	Intermediate wheatgrass	3.21cd	1.93e	2.58de
	C_3 combination	2.81de	2.93cde	2.87cde
	Sunburst switchgrass	1.83ef	4.44ab	3.14cd
	$C_4 + C_3$ 2	3.11cd	3.09bcde	3.09cd
	C_4 combination	3.10cd	4.18abcd	3.65bc
	$C_4 + C_3$ 1	5.32a	4.70a	5.02a
	Trailblazer switchgrass	1.38f	2.80de	2.08e
WillistonD	Tall Wheatgrass	1.29ab	2.17b	1.72bc
	CRP mix 1	1.56a	2.51ab	2.04ab
	CRP mix 2	1.06b	2.06b	1.57c
	Intermediate wheatgrass	1.37ab	2.48ab	1.93ab
	C_3 combination	1.37ab	2.39b	1.88bc
	Sunburst switchgrass	1.52a	2.45ab	1.97ab
	$C_4 + C_3$ 2	1.46a	3.01a	2.24a
	C_4 combination	1.30ab	2.62ab	1.95ab
	$C_4 + C_3$ 1	1.40ab	2.16b	1.77bc
	Dakota switchgrass	1.30ab	2.30b	1.79bc
WillistonI	Tall Wheatgrass	6.14c	4.16d	5.15cd
	CRP mix 1	4.68d	4.58bcd	4.64de
	CRP mix 2	4.28d	4.22cd	4.26e
	Intermediate wheatgrass	4.41d	3.80d	4.10e
	C_3 combination	7.36bc	5.13bcd	6.25b
	Sunburst switchgrass	7.80b	7.47a	7.64a
	$C_4 + C_3$ 2	7.94ab	8.06a	8.00a
	C_4 combination	9.22a	7.61a	8.42a
	$C_4 + C_3$ 1	6.86bc	5.53bc	6.18b
	Dakota switchgrass	6.08c	5.85b	5.96bc

Annual vs. Biennial Harvest Production

Biennial harvest biomass production could only account for 63% total biomass from two-year annual harvest total over all the locations, years, and entries. However, different locations had significant effect on biomass recovery for biennially harvest (Table 10), with Williston dry land the highest (76%), following by Minot (71%), Williston irrigated land (66%), Streeter (66%), and the least in Carrington (56%). Furthermore, entry had significant effects too (Table 10), with Magnar basin wildrye + Mustang altai wildrye combination (73%) and Sunburst switchgrass (72%) the highest, haymaker intermediate wheatgrass (54%) and its mixtures (63%) the lowest.

Table 10. Analysis of variance (ANOVA) for biennial/annual for 5 sites (Carrington, Minot, Streeter, Williston dry land, Williston irrigation land) over 2 years (2009 and 2011) across central and western North Dakota.

Source of variation	df[a]	Sum of squares	Mean square	F value	p value
Site	4	1.26	0.32	13.79	<0.0001
Year	1	0.33	0.33	14.38	0.0002
Entry[b]	9	0.94	0.10	4.56	<0.0001
Site × year	4	0.72	0.18	7.88	<0.0001
Site × entry	36	1.57	0.04	1.90	0.0029
Year × entry	9	0.17	0.02	0.84	0.5786
Site × year × entry	36	0.83	0.02	1.01	0.4610
Error	200	4.58	0.02		
Total	299	10.40			

[a] df means degree of freedom.

[b] entry lists shown in table 4.

Detailed results were shown in Table 11. At Carrington, all the entries were similar concerning biennial or annual harvest, biennial harvest only could recovery 46-67% of production of annual harvest. Interestingly, Sunburst switchgrass and its mixture with Sunyview big bluestem biennial harvest in 2009 were higher than annual harvest two year totals, but this trend was ended in 2011 at Minot. Similarly, the warm-season grasses plots could recovery higher in biennial harvest than cool-season grasses at Streeter and Williston.

Table 11. Biennial/annual harvest production (%) at each study site for each study year. Means in the same column for each study site followed by different letters differ significantly at $P < 0.05$. Entry lists see Table 4.

Site	Entry	2009	2011
Carrington	Tall Wheatgrass	48	56
	CRP mix 1	50	48
	CRP mix 2	47	52
	Intermediate wheatgrass	53	68
	C_3 combination	50	61
	Sunburst switchgrass	53	57
	$C_4 + C_3$ 2	61	68
	C_4 combination	58	64
	$C_4 + C_3$ 1	51	64
	Trailblazer switchgrass	48	63
Minot	Tall Wheatgrass	78bcd	63
	CRP mix 1	73bcd	59
	CRP mix 2	69cd	54
	Intermediate wheatgrass	56d	43
	C_3 combination	82bcd	66
	Sunburst switchgrass	117a	73
	$C_4 + C_3$ 2	69cd	65
	C_4 combination	100ab	46
	$C_4 + C_3$ 1	79bcd	73
	Dakota switchgrass	89bc	59
Streeter	Tall Wheatgrass	84a	75ab
	CRP mix 1	66ab	51bc
	CRP mix 2	81a	54abc
	Intermediate wheatgrass	47b	32c
	C_3 combination	75ab	60abc
	Sunburst switchgrass	80a	59abc
	$C_4 + C_3$ 2	61ab	52abc
	C_4 combination	71ab	76ab
	$C_4 + C_3$ 1	87a	83a
	Trailblazer switchgrass	68ab	49bc
WillistonD	Tall Wheatgrass	67b	72b
	CRP mix 1	79ab	78ab
	CRP mix 2	69b	62b
	Intermediate wheatgrass	60b	66b
	C_3 combination	80ab	79ab
	Sunburst switchgrass	97a	73b
	$C_4 + C_3$ 2	84ab	97a
	C_4 combination	69b	78ab
	$C_4 + C_3$ 1	78ab	74b
	Dakota switchgrass	83ab	68b
WillistonI	Tall Wheatgrass	79b	60
	CRP mix 1	69bcd	63
	CRP mix 2	61cd	70
	Intermediate wheatgrass	56d	61
	C_3 combination	104a	67
	Sunburst switchgrass	54d	61
	$C_4 + C_3$ 2	62bcd	65
	C_4 combination	76bc	64
	$C_4 + C_3$ 1	75bc	58
	Dakota switchgrass	57d	64

ACKNOWLEDGEMENTS

This research was funded in part by the North Dakota State University Agric. Exp. Stn., USDA-ARS Northern Great Plains Research Laboratory, North Dakota Natural Resources Trust, North Dakota Game and Fish Department, North Dakota Department of Commerce, North Dakota Farmers Union, Jamestown/Stutsman Development Corporation, Dakota West RC&D, Dakota Prairie RC&D, and USDA- NRCS. Special appreciation is extended to the following for help with this research: Matt Denzl for climatic data gathering and Dwight Schmidt, Rick Bohn, and Rodney Schmidt for technical assistance.

REFERENCES

Adler, P. R., M. A. Sanderson, et al. (2006). "Biomass yield and biofuel quality of switchgrass harvested in fall or spring." Agronomy Journal **98**(6): 1518-1525.

Berdahl, J. D., A. B. Frank, et al. (2005). "Biomass yield, phenology, and survival of diverse switchgrass cultivars and experimental strains in western North Dakota." Agronomy Journal **97**(2): 549-555.

Boe, A. and D. K. Lee (2007). "Genetic variation for biomass production in prairie cordgrass and switchgrass." Crop Science **47**(3): 929-934.

Boehmel, C., I. Lewandowski, et al. (2008). "Comparing annual and perennial energy cropping systems with different management intensities." Agricultural Systems **96**(1-3): 224-236.

Frank, A. B., J. D. Berdahl, et al. (2004). "Biomass and carbon partitioning in switchgrass." Crop Science **44**(4): 1391-1396.

Jasinskas, A., A. Zaltauskas, et al. (2008). "The investigation of growing and using of tall perennial grasses as energy crops." Biomass & Bioenergy **32**(11): 981-987.

Jefferson, P. G., W. P. McCaughey, et al. (2004). "Potential utilization of native prairie grasses from western Canada as ethanol feedstock." Canadian Journal of Plant Science **84**(4): 1067-1075.

Lee, D. K., V. N. Owens, et al. (2007). "Switchgrass and soil carbon sequestration response to ammonium nitrate, manure, and harvest frequency on conservation reserve program land." Agronomy Journal **99**(2): 462-468.

Lewandowski, I., J. M. O. Scurlock, et al. (2003). "The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe." Biomass & Bioenergy **25**(4): 335-361.

Madakadze, I. C., B. E. Coulman, et al. (1998). "Evaluation of selected warm-season grasses for biomass production in areas with a short growing season." Bioresource Technology **65**(1-2): 1-12.

McLaughlin, S. B., D. Ugarte, et al. (2002). "High-value renewable energy from prairie grasses." Environmental Science & Technology **36**(10): 2122-2129.

Mitchell, R. B., K. P. Vogel, et al. (2010). "Herbicides for Establishing Switchgrass in the Central and Northern Great Plains." Bioenergy Research **3**(4): 321-327.

Ragauskas, A. J., C. K. Williams, et al. (2006). "The path forward for biofuels and biomaterials." Science **311**(5760): 484-489.

Robins, J. G. (2010). "Cool-season grasses produce more total biomass across the growing season than do warm-season grasses when managed with an applied irrigation gradient." Biomass & Bioenergy **34**(4): 500-505.

Evaluation of Perennial Herbaceous Biomass Crops in North Dakota:

Soil Profile Attributes, 2006-2011

Mark A. Liebig and Kristine A. Nichols

USDA Agricultural Research Service

Northern Great Plains Research Laboratory

Mandan, ND

Summary

Utilization of perennial herbaceous crops as biofuel sources has been suggested to reduce negative consequences associated with current large scale biofuel production in the U.S.. Most assessments of perennial herbaceous biofeedstocks in the northern Great Plains have focused on switchgrass (*Panicum virgatum* L.), where previous modeling efforts have shown its production for bioenergy to be economically feasible. Information associated with the production of other grasses in the region for potential use as biofeedstocks, such as wheatgrasses, alfalfa (*Medicago* spp.), big bluestem (Andropogon gerardii *Vitman*), and species mixtures, is lacking. Information related to the harvest management (e.g., annual vs. biennial harvest) of perennial herbaceous biofeedstocks is also lacking.

The objective of this study was to quantify changes in soil bulk density, electrical conductivity, soil pH, and equivalent mass soil organic carbon (SOC), total nitrogen (TN), and available phosphorus (P) under perennial herbaceous biofeedstocks at five sites in central and western North Dakota. These soil properties were selected for evaluation due to their direct or indirect contributions to soil structural attributes, such as porosity and aggregation (soil bulk density), soil buffering capacity (soil pH), fertility (available P), and biological soil quality, water-holding capacity, and aggregate stability (SOC and TN). This investigation was done in conjunction with a broader study objective which sought to determine appropriate grass and legume species, harvest methods, and management practices to maintain productive perennial biomass stands in North Dakota.

Sites included in this study were located in central and western North Dakota at NDSU Research Extension Centers near Carrington, Hettinger, Minot, Streeter, and Williston. Mean annual temperature and precipitation at the sites ranged from 4.5 to 5.6°C and 381 to 505 mm, respectively. Soils at the sites possessed moderate to high inherent fertility, and were characterized by Albolls, Ustolls, and Udolls as taxonomic suborders. Ten perennial plant species and species combinations, each split by two harvest schedules (annual and biennial), were seeded at all sites in spring 2006. Soil samples were taken prior to seeding of treatments and again in 2011 to a depth of 1.2 m. Collected samples were processed and analyzed following standard laboratory protocols.

Perennial herbaceous crops were found to have subtle short-term effects on soil properties at the sites included in the study. Effects of harvest schedule and plant species on soil properties were infrequent and inconsistent across sites, and were unlikely to induce change in soil function. Inherently fertile soil conditions, high within-site variation in soil properties, and trends in biomass production among research sites likely contributed to observed results.

Changes in soil properties due to growth of perennial herbaceous crops were most prevalent at the Williston site, where the less fertile sandy soil and high biomass production contributed to increases in SOC, TN, and available P. Soil organic C increased at the Williston dryland site by 6 Mg C ha^{-1} yr^{-1}, supporting previous findings where perennial grasses managed for bioenergy production sequestered C within fragile, sandy soils.

Broad outcomes from this short-term study indicate perennial herbaceous crops can maintain or improve soil properties, depending on inherent soil conditions and site productivity. In that regard, coarse-textured soils have the greatest potential to respond positively in the short-term from the growth of perennial herbaceous crops. Such focused production – based on soil type – would not only improve the condition of fragile soils, but would also serve to improve wildlife habitat, decrease water pollution, and reduce wind and water erosion compared to annual row crop production.

In a nutshell

- Production of perennial herbaceous crops as biofeedstocks had subtle short-term effects on soil properties in central and western North Dakota.
- Changes in soil properties were most prevalent at the Williston site, where the less fertile sandy soil and high biomass production contributed to increases in soil organic carbon, total nitrogen, and available phosphorus.
- Coarse-textured soils have the greatest potential to respond positively from perennial biofeedstocks in the short-term.

Acknowledgments

We gratefully acknowledge the North Dakota Natural Resources Trust and the North Dakota Industrial Commission for financial support to conduct soil evaluations at the five perennial biofeedstock production sites. We thank Karen Kreil and Keith Trego for project management and administrative guidance, and Arnold Kruse for providing the project 'vision' in 2004.

Many people contributed in a technical role during sample collection, processing, and laboratory analyses. We are especially grateful to Jason Gross, Holly Johnson, Johannah Miller, Steven Petrik, Angela Renner, Gail Sage, Andrew Schmid, and Becky Wald. Furthermore, Paul Nyren, Ezra Aberle, Gordon Bradbury, Eric Eriksmoen, Mark Halvorson, Brian Jenks, Bob Patton, Jim Staricka, Guojie Wang, and Quingwe Xue provided critical site support through the establishment and maintenance of the perennial biofeedstock treatments, as well as helpful pre-sampling logistics in 2006 and 2011.

This report was prepared in collaboration with the North Dakota Natural Resources Trust pursuant to an agreement with the Industrial Commission of North Dakota, which partially funded the report. None of the North Dakota Natural Resources Trust or its partners or any of its subcontractors, the Industrial Commission of North Dakota or any person acting on behalf of any of them:

(A) Make any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights; or

(B) Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in the report.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Industrial Commission of North Dakota. The views and opinions of authors expressed herein do not necessarily state or reflect those of the Industrial Commission of North Dakota.

The U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS), is an equal opportunity/affirmative action employer and all agency services are available without discrimination. Mention of commercial products and organizations in this report is solely to provide specific information. It does not constitute endorsement by USDA-ARS over other products and organizations not mentioned.

List of Tables

Table 1. Location, mean annual precipitation and temperature, prevalent soil type, and soil classification for sites included in study.

Table 2. Species, seeding rates, and harvest schedule for biomass plots included in study.

Table 3. Initial soil conditions for sites included in study. Mean values and corresponding standard error are presented by site and depth.

Table 4. Soil bulk density for annual and biennial harvests under switchgrass, tall wheatgrass, and CRP mix treatments in 2011.

Table 5. Electrical conductivity for annual and biennial harvests under switchgrass, tall wheatgrass, and CRP mix treatments in 2011.

Table 6. Soil pH for annual and biennial harvests under switchgrass, tall wheatgrass, and CRP mix treatments in 2011.

Table 7. Soil organic C, total N, and available P for annual and biennial harvests under switchgrass, tall wheatgrass, and CRP mix treatments in 2011. Results provided for three soil masses approximately equivalent to 0-0.3, 0-0.6, and 0-0.9 m depths.

Table 8. Soil bulk density for seven perennial grass treatments in 2011.

Table 9. Electrical conductivity for seven perennial grass treatments in 2011.

Table 10. Soil pH for seven perennial grass treatments in 2011.

Table 11. Soil organic C, total N, and available P for seven perennial grass treatments in 2011. Results provided for three soil masses approximately equivalent to 0-0.3, 0-0.6, and 0-0.9 m depths.

Table 12. Soil bulk density, electrical conductivity, and soil pH during the initial and 5-year samplings under annually harvested plant species treatments.

Table 13. Soil organic C, total N, and available P during the initial and 5-year samplings under annually harvested plant species treatments.

List of Figures

Figure 1. Approximate location of sites included in study.

Figure 2. Soil organic C (A) and total N (B) for Williston dryland and irrigated plant species treatments at two soil masses (3600 and 7300 Mg ha^{-1}) in 2006 and 2011.

Abbreviations

CRP, Conservation Reserve Program; GHG, Greenhouse gas; LCA, Life-cycle assessments; SOC, Soil organic carbon; TN, Total nitrogen

Introduction

Current large-scale biofuel production in the U.S. has significant negative environmental and social consequences, including increased net greenhouse gas (GHG) emissions and rising food costs (Scharlemann and Laurance, 2008). Utilization of perennial herbaceous crops as biofuel sources has been suggested to reduce these negative consequences (McLaughlin et al., 2002), due mainly to their lower requirements of agricultural inputs and their ability to be grown on marginal land (Hill et al., 2006). Moreover, recent net energy and life-cycle assessments (LCAs) of biofuel crops indicate significant energetic and GHG benefits from perennial grasses [e.g., switchgrass (*Panicum virgatum* L.)] as compared to grain-derived sources (Adler et al., 2007; Schmer et al., 2008), underscoring the viability of the former as a potentially important component of a renewable biofuel economy in the U.S.

Despite the increased emphasis on perennial biofeedstocks as renewable biofuel crops, information is lacking regarding their impact the soil resource. Most evaluations have investigated switchgrass effects on soil carbon dynamics, with particular emphasis on accrual rates of soil organic carbon (SOC). Increases in SOC under switchgrass across a broad range of growing conditions throughout North America has been observed to range from 1.7 to 10.1 Mg C ha^{-1} yr^{-1} (Garten and Wullschleger, 2000; Zan et al., 2001; Frank et al., 2004; Lee et al., 2007; Liebig et al., 2008; Schmer et al., 2011). Biological indicators of soil quality, such as carbon mineralization and microbial biomass C, have also been observed to increase over time under switchgrass (Ma et al., 2000). Switchgrass-induced changes in soil properties have been linked to root biomass input, which has been found to be substantially greater than annual crops, such as corn (*Zea mays* L.) (Zan et al., 1997; Liebig et al., 2005).

Most assessments of perennial herbaceous biofeedstocks in the northern Great Plains have focused on switchgrass, where previous modeling efforts have shown its production for bioenergy to be economically feasible (Walsh, 1998). Information associated with the production of other grasses in the region for potential use as biofeedstocks, such as wheatgrasses, alfalfa (*Medicago* spp.), big bluestem (Andropogon gerardii *Vitman*), and species mixtures, is lacking. Information related to the harvest management (e.g., annual vs. biennial harvest) of perennial herbaceous biofeedstocks is also lacking, and has significant implications concerning the role of agricultural land to serve as wildlife habitat (Roth et al., 2005).

The objective of this study was to quantify changes in soil bulk density, electrical conductivity, soil pH, and equivalent mass SOC, total nitrogen (TN), and available P under perennial herbaceous biofeedstocks at five sites in central and western North Dakota. These soil properties were selected for evaluation due to their direct or indirect contributions to soil structural attributes, such as porosity and aggregation (soil bulk density), soil buffering capacity (soil pH), fertility (available P), and biological soil quality, water-holding capacity, and aggregate stability (SOC and TN) (Schmer et al., 2011). This investigation was done in conjunction with a broader study objective which sought to determine appropriate grass and legume species, harvest methods, and management practices to maintain productive perennial biomass stands in North Dakota (NDSU-CGREC, 2012).

Methodology

Sites included in this study were located in central and western North Dakota at NDSU Research Extension Centers near Carrington, Hettinger, Minot, Streeter, and Williston (Fig. 1). Major land resource areas represented in the study included 53B (Central dark brown glaciated plains; Minot), 54 (Rolling soft shale plain; Hettinger and Williston), and 55B (Central black glaciated plains; Carrington and Streeter), which encompass approximately 17 Mha (USDA-NRCS, 2006). Climate within the study region is characterized as semiarid to subhumid continental, with cold and dry winters, warm to hot summers, and erratic precipitation (Bailey, 1995). Mean annual temperature and precipitation at the sites ranged from 4.5 to 5.6°C and 381 to 505 mm, respectively (Table 1). Soils at the sites possessed moderate to high inherent fertility, and were characterized by Albolls, Ustolls, and Udolls as taxonomic suborders (USDA-NRCS, 1999).

Ten perennial plant species and species combinations, each split by two harvest schedules (annual and biennial), were seeded at all sites the week of 15 May 2006 (Table 2). Plots were seeded with a plot drill designed for small-seeded grasses and legumes with six inch row centers, and plot dimensions were 15x30 feet. The experimental design was a randomized complete block design with four replications. All sites were managed under dryland conditions, with the exception of Williston, which included all treatments under both dryland and irrigated conditions.

Following establishment, plots were sprayed and mowed at least once at all sites except Hettinger, where they received only chemical applications. Due to poor stands from exceptionally dry conditions, plots were reseeded at Hettinger in 2007. Additional information on plot establishment, management, and biomass harvest may be reviewed elsewhere (NDSU-CGREC, 2012).

Soil samples were collected between 27 April and 18 May in 2006 prior to seeding of treatments, and again in 2011 between 3 May and 27 September. Excessive soil moisture during the 2011 growing season severely restricted plot access. During each sampling, soil samples were collected near the center of each plot using a Giddings hydraulic probe (Giddings Machine Company, Windsor, CO) with an inner tip diameter of 3.54 cm. Depth increments sampled were 0-0.05, 0.05-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.6, 0.6-0.9, and 0.9-1.2 m. Within each sampled plot, six cores were composited from the 0-0.05 and 0.05-0.1 m depths, three cores from the 0.1-0.2, 0.2-0.3 m depths, and two cores from the 0.3-0.6, 0.6-0.9, and 0.9-1.2 m depths. Collection of cores at Minot, Streeter, and Williston was hampered by excessive gravel between 0.6-1.2 m which limited sample collection at lower depth increments. Once collected, samples were saved in double-lined plastic bags, placed in cold storage at 5ºC, and processed within 6-wk of collection.

Soil samples were dried at 35ºC for 3 to 4 d and then ground by hand to pass a 2.0 mm sieve. Identifiable plant material (>2.0 mm diameter, >10 mm length) was removed during sieving. Electrical conductivity and pH were estimated from a 1:1 soil-water mixture (Whitney, 1998; Watson and Brown, 1998). Plant-available soil P was estimated by bicarbonate extraction (Olson et al., 1954). Total soil C and N were determined by dry combustion on soil ground to pass a 0.106 mm sieve (Nelson and Sommers, 1996). Using the same fine-ground soil, inorganic C was measured on soils with a pH $\geq$7.2 by quantifying the amount of CO_2 produced using a volumetric calcimeter after application of dilute HCl stabilized with $FeCl_2$ (Loeppert and Suarez, 1996). Soil organic C was calculated as the difference between total C and inorganic C. Gravimetric data were converted to a volumetric basis for each sampling depth using field measured soil bulk density (Blake and Hartge, 1986). All data were expressed on an oven-dry basis.

To reduce the effects of sampling depth and soil bulk density on soil organic C, total N, and available P, data from the 2006 and 2011 samplings were recalculated on an equivalent mass

basis assuming soil profile masses of 3600, 7300, and 11300 Mg ha^{-1} following the method of Ellert and Bettany (1995). The three equivalent masses approximated soil within the 0-0.3, 0-0.6, and 0-0.9 m depths, respectively.

Soil attributes in 2011 were analyzed statistically to evaluate effects of harvest schedule and plant species using PROC MIXED in SAS (Littel et al., 1996). Harvest schedule comparisons (annual vs. biennial) were conducted for Sunburst switchgrass, Alkar tall wheatgrass, and a CRP mix (intermediate wheatgrass, tall wheatgrass, alfalfa, and sweetclover). Plant species comparisons were conducted using treatments subjected to the annual harvest schedule only. Differences in soil attributes due to harvest schedule and plant species in 2011 were negligible (reviewed below), so mean values of soil attributes across plant species were calculated and compared to baseline soil conditions in 2006 using a paired t-test. All statistical analyses were conducted by site and soil depth (or equivalent mass) using a significance criteria of $P \leq 0.05$.

Results

Initial conditions

Initial soil conditions at the five sites were not limiting to establishment and growth of perennial grasses (Table 3). Values for soil bulk density across sites were below critical threshold values for restriction of root growth (Jones, 1983). Soil pH within 0-30 cm depths varied from slightly acid to slightly alkaline (USDA, 1993), and fell within a range for successful switchgrass germination (Hanson and Johnson, 2005). Alkalinity increased with increasing depth at all sites due to presence of inorganic C. Initial available P levels were adequate for switchgrass establishment and growth (Brejda, 2000), though accumulation of P throughout the soil profile was apparent at Carrington due to previous livestock presence at the research site. Values for SOC and TN across sites were characteristic of soils with high inherent fertility in the northern Plains (Cihacek and Ulmer, 2002). At Williston, the irrigated site possessed greater SOC, TN, and available P compared to the dryland site as reflected by elevated biomass input in the former as a result of increased water availability.

Treatment effects on soil properties

Harvest schedule and plant species had negligible effects on soil properties in 2011 (Tables 4-7). Soil bulk density under switchgrass was greater for annual harvest at 0-0.05 and 0.1-0.2 m

compared to biennial harvest at the Williston dryland site (Table 4). Soil pH was greater under biennial harvest compared to annual harvest at the Minot (CRP mix; 0.3-0.6 m) and Williston irrigated (tall wheatgrass; 0.2-0.3 m) sites (Table 6), though values still fell within slightly to moderately alkaline pH ranges (NRCS, 1993). Effects of harvest schedule on SOC and TN were limited to switchgrass, where the biennial harvest contributed to greater SOC and TN at Hettinger (7300 Mg ha^{-1} soil mass for SOC; 11300 Mg ha^{-1} soil mass for TN) and greater SOC at Minot (11300 Mg ha^{-1} soil mass) (Table 7). At all sites and soil depths, harvest schedule had no effect on electrical conductivity or available P (Tables 5 and 7).

Plant species effects on soil bulk density, electrical conductivity, and soil pH were limited and inconsistent (Tables 8-10). Soil bulk density differed among treatments at Hettinger (0.9-1.2 m), Minot (0-0.05 m), Streeter (0.2-0.3 m), and Williston (0.1-0.2 m; irrigated only) (Table 8), though no one treatment was consistently lower or higher relative to other treatments across sites. Electrical conductivity was greatest at select depths within the CRP mix at Minot and Williston (dryland and irrigated), but least within the CRP mix at Streeter (Table 9). Where significant plant species effects on electrical conductivity were observed, all values fell within a non-saline category (NRCS, 1993). Plant species effects on soil pH were limited to Minot (0.1-0.2 m; CRP mix greatest, intermediate wheatgrass and switchgrass + tall wheatgrass least) and Williston (0.2-0.3 m; CRP mix and Trailblazer switchgrass greatest, switchgrass + tall wheatgrass least; irrigated only) (Table 10). Stocks of SOC, TN, and available P did not differ among plant species at the five sites (Table 11).

Changes in soil properties: 2006 to 2011

When averaged across annually harvested plant species treatments, changes in soil properties between the initial (2006) and 5-year (2011) samplings were subtle and varied by site (Tables 12-13). Among sites, changes in soil properties were most prevalent at the Williston dryland site (10 significant changes observed), followed by Williston irrigated (7), Carrington (3), Minot and Streeter (2 each), and Hettinger (0) sites. At select depths <0.3 m, soil bulk density was greater in 2011 than 2006 at Minot and Williston (dryland and irrigated), but the opposite was observed at Streeter (Table 12). Electrical conductivity consistently decreased between 2006 and 2011 at Carrington and Williston (dryland and irrigated), a change associated with a decline in

extractable N at both sites (data not shown). Soil pH did not significantly change between 2006 and 2011 at the five sites (Table 12).

Changes in stocks of SOC, TN, and available P over time were limited to the Williston site (Table 13). Soil organic C increased at the dryland site by 30 Mg C ha^{-1} between 2006 and 2011 (7300 Mg ha^{-1} soil mass). Total N increased at both the dryland and irrigated sites by 3.7 Mg N ha^{-1} (7300 Mg ha^{-1} soil mass) and 0.9 Mg N ha^{-1} (3600 Mg ha^{-1} soil mass), respectively. Between 2006 and 2011, available P nearly doubled within the 3600 Mg ha^{-1} soil mass of the dryland site (7 vs. 13 kg P ha^{-1}).

Comparisons between dryland and irrigated sites at Williston revealed plant species treatments under dryland conditions increased SOC and TN to an amount similar under irrigated conditions after 5-years (Fig. 2). Whereas SOC and TN were greater ($P \leq 0.1$) under irrigated conditions at the initiation of the study, there were no differences between the dryland and irrigated sites for either attribute in 2011 ($P = 0.23–0.86$).

Discussion

While differences in soil properties due to harvest schedule and plant species were observed in this study, their limited frequency across sites, coupled with a general lack of consistent trends, suggests both treatment effects were too subtle to impart functional changes in soil condition within a 5-year period. Compared to baseline conditions in 2006, the annually harvested plant species and species mixtures did change select soil properties by 2011, but changes were often small, and accordingly, of limited significance in the context of altering soil function (Andrews et al., 2004). These outcomes may be explained by site attributes associated with inherent soil properties and biomass production.

With the exception of Williston, soils at each of the sites were inherently fertile. Soils at Carrington, Hettinger, Minot, and Streeter were medium- to fine-textured, possessed deep (>0.2 m) mollic colors, and had high cation exchange capacity and base saturation (USDA-NRCS, 1999). Such inherent conditions may have served to mask subtle treatment effects throughout the soil profile, particularly for soil properties (e.g., SOC) that respond slowly to changes in management (Mikha et al., 2006). Furthermore, soil conditions at the sites were highly variable, where coefficients of variation ranged from 8-13% for soil bulk density, 33-149% for electrical

conductivity, 6-9% for soil pH, and 22-115% for SOC, TN, and available P (data not shown). Such variation in soil properties made it difficult to discern differences among treatments, as inherent 'background noise' likely overwhelmed treatment-induced changes.

Increasing the number of replications would have served to lower the variance of soil properties. However, replications (4) were fixed at the beginning of the study, and later reduced to three replications at Carrington, Minot, Streeter, and Williston in 2010 to eliminate potential confounding outcomes associated with non-randomized treatments in the first replicate. While understandable, the reduction in replicates decreased the likelihood of detecting treatment effects on soil properties in this study. Other studies in the region have used up to six replications to discriminate effects of perennial biofeedstocks on soil properties over time (Schmer et al., 2011; Lee et al., 2007; Frank et al., 2004).

Weather-induced challenges associated with establishing and maintaining treatments resulted in low aboveground biomass production at Hettinger (NDSU-CGREC, 2012). Accordingly, treatments at Hettinger were not expected to cause appreciable changes in soil condition within 5-years. Conversely, aboveground biomass production at the Williston irrigated site was greatest among all sites (5.4-7.3 ton ac^{-1} for the highest yielding treatments between 2007-2011) (NDSU-CGREC, 2012). Such high production, coupled with the less fertile sandy soil at Williston, would serve to increase the potential for altering soil properties through belowground biomass input over the course of the study. On a soil type similar to that evaluated at the Williston site, Frank et al. (2004) observed SOC accrual rates of 10.1 Mg C ha^{-1} yr^{-1} under switchgrass.

While aboveground biomass production at the dryland site was over five times less than under irrigation (NDSU-CGREC, 2012), enhanced root biomass and rhizodeposition under dryland conditions likely served to increase SOC and TN (Liebig et al., 2008). Moreover, since initial SOC and TN were lower under the dryland than irrigated site at Williston, there was greater capacity to accumulate organic matter in the former within edaphic limitations of the soil (Paustian et al., 1997). Such increases in SOC and TN on fragile soils contribute significantly to improving soil function, as near-surface (<0.3 m) increases in both attributes influence nutrient conservation, water infiltration, and erosion control (Franzluebbers, 2002), while increases in SOC below 0.3 m enhance the role of soil to serve as a repository for atmospheric CO_2, thereby contributing to a favorable GHG balance (Schmer et al., 2008).

Conclusions

Results from this study suggest perennial herbaceous crops have subtle short-term effects on soil properties in central and western North Dakota. Effects of harvest schedule and plant species on soil properties were infrequent and inconsistent across sites, and were unlikely to induce change in soil function. Inherently fertile soil conditions, high within-site variation in soil properties, and trends in biomass production among research sites likely contributed to observed results.

Changes in soil properties due to growth of perennial herbaceous crops were most prevalent at the Williston site, where the less fertile sandy soil and high biomass production contributed to increases in SOC, TN, and available P. Soil organic C increased at the Williston dryland site by 6 Mg C ha^{-1} yr^{-1}, supporting previous findings where perennial grasses managed for bioenergy production sequestered C within fragile, sandy soils.

Broad outcomes from this short-term study indicate perennial herbaceous crops can maintain or improve soil properties, depending on inherent soil conditions and site productivity. In that regard, coarse-textured soils have the greatest potential to respond positively in the short-term from the growth of perennial herbaceous crops. Such focused production – based on soil type – would not only improve the condition of fragile soils, but would also serve to improve wildlife habitat, decrease water pollution, and reduce wind and water erosion compared to annual row crop production.

References

Adler, P.R., S.J. Del Grosso, and W.J. Parton. 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecol. Appl. 17(3):675-691.

Andrews, S.S., D.L. Karlen, and C.A. Cambardella. 2004. The soil management assessment framework: A quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 68, 1945-1962.

Bailey, R.G. 1995. Description of the ecoregions of the United States. U.S. Govt. Printing Office, Washington, D.C.

Blake, G.R., and K.H. Hartge. 1986. Bulk density. P. 363-382. In: Klute, A. (Ed.), Methods of soil analysis. Part 1 – Physical and mineralogical methods. 2nd ed. Soil Science Society of America Book Series No. 5. Soil Science Society of America and American Society of Agronomy, Madison, WI.

Brejda, J.J. 2000. Fertilization of native warm-season grasses. P. 177–200. In: Moore, K.J., and B. Anderson (Eds.) Native warm-season grasses: Research trends and issues. CSSA Spec. Publ. 30. CSSA and ASA, Madison, WI.

Cihacek, L.J. and M.G. Ulmer. 2002. Effects of tillage on inorganic carbon storage in soils of the northern Great Plains of the U.S. P. 63-69. In: Kimble, J.M. et al. (Eds). Agricultural Practices and Policies for carbon sequestration in soil. Lewis Publishers, Boca Raton, FL.

Ellert, B.H. and Bettany, J.R. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75:529-528.

Frank, A.B., J.D. Berdahl, J.D. Hanson, M.A. Liebig, and H.A. Johnson. 2004. Biomass and carbon partitioning in switchgrass. Crop Sci. 44:1391-1396.

Garten, C.T. Jr, and S.D. Wullschleger. 2000. Soil carbon dynamics beneath switchgrass as indicated by stable isotope analysis. J. Environ. Qual. 29:645-653.

Hanson, J.D., and H.A. Johnson. 2005. Germination of switchgrass under various temperature and pH regimes. Seed Tech. 27(2):203-210.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proc. Nat. Acad. Sci. 103(30):11206-11210.

Jones, C.A. 1983. Effect of soil texture on critical bulk densities for root growth. Soil Sci. Soc. Am. J. 47:1208-1211.

Lee, D.K., V.N. Owens, and J.J. Doolittle. 2007. Switchgrass and soil carbon sequestration response to ammonium nitrate, manure, and harvest frequency on Conservation Reserve Program land. Agron J 99:462-468.

Liebig, M.A., M.R. Schmer, K.P. Vogel, and R. Mitchell. 2008. Soil carbon storage by switchgrass grown for bioenergy. Bioe. Res. 1: 215-222.

Liebig, M.A., H.A. Johnson, J.D. Hanson, and A.B. Frank. 2005. Soil carbon under switchgrass stands and cultivated cropland. Biom. Bioe. 28(4):347-354.

Littell, R.C., G.A. Milliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS system for mixed models. SAS Inst., Inc. Cary, NC.

Loeppert, R.H., and D.L. Suarez. 1996. Carbonate and gypsum. P. 437-474. In: Sparks, D.L. (Ed.), Methods of soil analysis. Part 3. Chemical methods. SSSA Book Series No. 5. SSSA and ASA, Madison, WI.

Ma, Z., C.W. Wood, and D.I. Bransby. 2000. Carbon dynamics subsequent to establishment of switchgrass. Biom. Bioe. 18:93-104.

McLaughlin, S.B. D.G. De La Torre Ugarte, C.T. Garten Jr., L.R. Lynd, M.A. Sanderson, V.R. Tolbert, and D.D. Wolf. 2002. High-value renewable energy from prairie grasses. Environ. Sci. Tech. 36(10):2122-2129.

Mikha, M.M., M.F. Vigil, M.A. Liebig, R.A. Bowman, B. McConkey, E.J. Deibert, J.L. Pikul Jr. 2006. Cropping system influences on soil chemical properties and soil quality in the Great Plains. Renew. Agric. Food Sys. 20(1): 26-35.

NDSU Central Grasslands Research Extension Center (CGREC). 2012. Biofuels research. http://www.ag.ndsu.edu/CentralGrasslandsREC/ (verified 13 March 2012).

Nelson, D.W., and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. P. 961-1010. In: Sparks, D.L. (Ed.), Methods of soil analysis. Part 3. Chemical methods. Soil Science Society of America Book Series No. 5. Soil Science Society of America and American Society of Agronomy, Madison, WI.

Olson, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA circ. 939. Washington, D.C.

Paustian, K., H.P Collins, and E.A. Paul. 1997. Management controls on soil carbon. P. 15-49. In: Paul, E.A. et al. (Eds.) Soil organic matter in temperate agroecosystems: Long-term experiments in North America. CRC Press, Boca Raton, FL.

Roth, A.B., D.W. Sample, C.A. Ribic, L. Paine, D.J. Undersander, and G.A. Bartelt. 2005. Grassland bird response to harvesting switchgrass as a biomass energy crop. Biom. Bioe. 28:490-498.

Scharlemann, J.P.W., and W.F. Laurance. 2008. How green are biofuels? Science 319:43-44.

Schmer, M.R., M.A. Liebig, K.P. Vogel, and R. Mitchell. 2011. Field-scale soil property changes under switchgrass managed for bioenergy. Global Change Biol. Bioe. 3:439-448.

Schmer, M.R., K.P. Vogel, R.B. Mitchell, and R.K. Perrin. 2008. Net energy of cellulosic ethanol from switchgrass. Proc. Nat. Acad. Sci. 105(2):464-469.

USDA Natural Resources Conservation Service (NRCS). 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin U.S. Department of Agriculture Handbook No. 296. U.S. Govt. Printing Office. Washington, D,C.

USDA Natural Resources Conservation Service (NRCS). 1999. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd Ed. USDA-NRCS Soil

Survey Staff. U.S. Dep. of Agric. Handbook No. 436. U.S. Govt. Printing Office. Washington, D.C.

USDA. 1993. Soil survey manual. USDA Soil Survey Division Staff. U.S. Dep. of Agric. Handbook No. 18. U.S. Govt. Printing Office. Washington, D.C.

Walsh, M.E. 1998. U.S. bioenergy crop economic analyses: status and needs. Biom. Bioe. 14:341-350.

Watson, M.E., and J.R. Brown. 1998. pH and lime requirement. P. 13-16. In: Brown, J.R. (Ed.), Recommended chemical soil test procedures for the North Central Region. North Central Region Publication 221 (revised). Missouri Agriculture Experiment Station Bulletin. SB1001.

Whitney, D.A. 1998. Soil salinity. P. 59-60. In: Brown, J.R. (Ed.), Recommended chemical soil test procedures for the North Central Region. North Central Region Publication 221 (revised). Missouri Agriculture Experiment Station Bulletin. SB1001.

Zan C., J. Fyles, P. Girouard, R. Samson, and M. Doan. 1997. Carbon storage in switchgrass and short-rotation willow plantations. P. 355-361. In: Overend, R.P., and E. Chornet (Eds.) Making a business from biomass in energy, environment, chemicals, fibers and materials. Vol. 1. Elsevier Science, Oxford, UK.

Table 1. Location, mean annual precipitation and temperature, prevalent soil type, and soil classification for sites included in study.

Site	MAP* (mm)	MAT† (ºC)	Prevalent soil type	Soil classification
Carrington, ND	505	5.0	Heimdal-Emrick loams, 0 to 3% slope	Coarse-loamy, Mixed, Superactive, Frigid Calcic and Pachic Hapludolls
Hettinger, ND	394	5.8	Belfield-Savage-Daglum silt loams, 3 to 6% slope	Fine, Smectitic, Frigid, Glossic and Vertic Natrustolls and Fine, Smectitic, Frigid, Vertic Argiustolls
Minot, ND	473	4.7	Bowbells-Tonka complex, 0 to 3% slope	Fine-Loamy, Mixed, Superactive, Frigid Pachic Argiustolls and Fine, Smectitic, Frigid Argiaquic Argialbolls
Streeter, ND	434	4.5	Barnes-Svea loams, 0 to 3% slope	Fine-Loamy, Mixed, Superactive, Frigid Calcic and Pachic Hapludolls
Williston, ND	381	5.6	Lihen loamy fine sand, 0 to 3% slope	Sandy, Mixed, Frigid, Entic Haplustolls

* MAP = Mean annual precipitation.
† MAT = Mean annual temperature.

Table 2. Species, seeding rates, and harvest schedule for biomass plots included in study.

Variety/species	Harvest schedule	Seeding rate (PLS ac^{-1})
Sunburst Switchgrass	Annual	10
Sunburst Switchgrass	Biennial	10
Trailblazer or Dakota Switchgrass†	Annual	10
Trailblazer or Dakota Switchgrass	Biennial	10
Alkar Tall Wheatgrass	Annual	11
Alkar Tall Wheatgrass	Biennial	11
Haymaker Intermediate Wheatgrass	Annual	10
Haymaker Intermediate Wheatgrass	Biennial	10
CRP mix (Intermediate + Tall Wheatgrass)	Annual	5 + 6
CRP mix (Intermediate + Tall Wheatgrass)	Biennial	5 + 6
CRP mix (Intermediate + Tall + Alfalfa + Sweetclover)	Annual	4+4.5+1+.5
CRP mix (Intermediate + Tall + Alfalfa + Sweetclover)	Biennial	4+4.5+1+.5
Sunburst Switchgrass + Tall Wheatgrass	Annual	5 +5
Sunburst Switchgrass + Tall Wheatgrass	Biennial	5 +5
Sunburst Switchgrass + Sunnyview Big Bluestem	Annual	7+2.5
Sunburst Switchgrass + Sunnyview Big Bluestem	Biennial	7+2.5
Sunburst Switchgrass + Mustang Altai Wildrye	Annual	7+11
Sunburst Switchgrass + Mustang Altai Wildrye	Biennial	7+11
Magnar Basin Wildrye + Mustang Altai Wildrye	Annual	5+11
Magnar Basin Wildrye + Mustang Altai Wildrye	Biennial	5+11

† Trailblazer was seeded at Carrington, Hettinger, and Streeter and Dakota at Williston and Minot.

Table 3. Initial soil conditions for sites included in study. Mean values and corresponding standard error are presented by site and depth.

Location/ Depth (m)	Soil bulk density (Mg m^{-3})	Electrical conductivity (dS m^{-1})	Soil pH (-log [H^+])	Available P (kg P ha^{-1})	Soil organic C (Mg C ha^{-1})	Soil inorganic C (Mg C ha^{-1})	Total N (Mg N ha^{-1})
Carrington							
0-0.05	1.17 (0.03)	0.38 (0.02)	7.02 (0.11)	55.8 (3.5)	20.2 (0.4)	--	1.8 (0.1)
0.05-0.1	1.36 (0.02)	0.28 (0.01)	6.45 (0.12)	35.1 (2.1)	19.1 (0.7)	--	1.7 (0.1)
0.1-0.2	1.35 (0.03)	0.29 (0.01)	6.61 (0.13)	40.7 (3.6)	33.6 (1.4)	--	3.0 (0.1)
0.2-0.3	1.32 (0.02)	0.33 (0.02)	6.82 (0.12)	30.4 (4.5)	26.9 (2.2)	--	2.5 (0.2)
0.3-0.6	1.32 (0.01)	0.30 (0.01)	7.22 (0.07)	65.1 (11.1)	49.7 (3.2)	0.5 (0.3)	4.9 (0.3)
0.6-0.9	1.39 (0.03)	0.22 (0.01)	7.59 (0.13)	40.2 (6.1)	28.5 (1.4)	9.7 (4.0)	2.8 (0.1)
0.9-1.2	1.55 (0.03)	0.19 (0.01)	7.66 (0.17)	33.9 (4.4)	25.1 (2.3)	12.2 (3.7)	1.8 (0.1)
Hettinger							
0-0.05	1.48 (0.04)	0.29 (0.02)	6.88 (0.14)	24.5 (1.5)	15.5 (0.4)	--	1.4 (0.1)
0.05-0.1	1.60 (0.03)	0.28 (0.02)	7.39 (0.13)	13.6 (1.0)	12.2 (0.8)	0.1 (0.1)	1.1 (0.1)
0.1-0.2	1.49 (0.02)	0.30 (0.01)	7.67 (0.12)	11.4 (0.5)	18.5 (0.8)	1.2 (0.4)	1.7 (0.1)
0.2-0.3	1.51 (0.02)	0.34 (0.01)	8.09 (0.09)	7.6 (1.0)	17.0 (0.9)	3.5 (0.8)	1.5 (0.1)
0.3-0.6	1.45 (0.01)	0.32 (0.01)	8.50 (0.03)	13.9 (1.1)	43.1 (2.0)	17.9 (2.3)	3.5 (0.1)
0.6-0.9	1.46 (0.02)	0.32 (0.01)	8.72 (0.03)	10.8 (0.7)	41.7 (4.8)	20.9 (2.2)	2.6 (0.1)
0.9-1.2	1.46 (0.03)	0.42 (0.03)	8.81 (0.04)	14.1 (1.4)	45.2 (8.7)	19.0 (1.6)	2.3 (0.2)

Table 3. Cont'd.

Location/ Depth (m)	Soil bulk density (Mg m^{-3})	Electrical conductivity (dS m^{-1})	Soil pH (-log [H^+])	Available P (kg P ha^{-1})	Soil organic C (Mg C ha^{-1})	Soil inorganic C (Mg C ha^{-1})	Total N (Mg N ha^{-1})
Minot							
0-0.05	1.20 (0.02)	0.22 (0.02)	6.31 (0.13)	14.3 (1.3)	14.6 (0.5)	--	1.3 (0.1)
0.05-0.1	1.37 (0.04)	0.24 (0.02)	6.16 (0.13)	14.0 (1.5)	14.4 (0.5)	--	1.4 (0.1)
0.1-0.2	1.50 (0.02)	0.28 (0.02)	6.48 (0.15)	19.6 (2.7)	22.6 (1.5)	--	2.3 (0.1)
0.2-0.3	1.53 (0.02)	0.41 (0.04)	7.20 (0.16)	12.3 (1.8)	15.2 (0.9)	1.3 (0.7)	1.6 (0.1)
0.3-0.6	1.59 (0.02)	1.43 (0.25)	7.89 (0.15)	29.7 (5.4)	38.6 (4.0)	23.9 (6.5)	3.1 (0.2)
0.6-0.9	1.65 (0.02)	2.34 (0.25)	8.28 (0.10)	36.8 (7.9)	33.1 (2.8)	34.2 (6.4)	2.0 (0.1)
0.9-1.2	1.63 (0.03)	2.54 (0.24)	8.36 (0.07)	39.7 (9.7)	34.4 (2.1)	28.7 (4.4)	1.7 (0.1)
Streeter							
0-0.05	1.20 (0.03)	0.33 (0.02)	7.14 (0.11)	5.6 (0.4)	20.1 (0.4)	0.1 (0.1)	1.9 (0.1)
0.05-0.1	1.38 (0.02)	0.34 (0.02)	7.20 (0.12)	3.7 (0.3)	20.1 (0.5)	0.1 (0.1)	1.9 (0.1)
0.1-0.2	1.30 (0.01)	0.34 (0.02)	7.28 (0.12)	3.5 (0.3)	28.3 (1.0)	0.5 (0.3)	2.7 (0.1)
0.2-0.3	1.39 (0.01)	0.36 (0.02)	7.53 (0.12)	2.3 (0.2)	22.4 (1.0)	2.1 (1.4)	2.1 (0.1)
0.3-0.6	1.37 (0.02)	0.52 (0.07)	8.15 (0.13)	4.5 (0.4)	56.4 (6.0)	38.5 (7.5)	4.4 (0.3)
0.6-0.9	1.46 (0.03)	0.79 (0.16)	8.50 (0.09)	7.5 (1.1)	45.1 (5.7)	78.6 (5.7)	2.3 (0.4)
0.9-1.2	1.59 (0.03)	0.82 (0.10)	8.59 (0.10)	7.3 (1.2)	57.9 (6.7)	54.4 (5.1)	1.2 (0.1)

Table 3. Cont'd.

Location/ Depth (m)	Soil bulk density (Mg m^{-3})	Electrical conductivity (dS m^{-1})	Soil pH (-log [H^+])	Available P (kg P ha^{-1})	Soil organic C (Mg C ha^{-1})	Soil inorganic C (Mg C ha^{-1})	Total N (Mg N ha^{-1})
Williston (dryland)							
0-0.05	1.27 (0.02)	0.31 (0.01)	7.51 (0.09)	2.7 (0.1)	13.3 (0.4)	0.1 (0.1)	1.2 (0.1)
0.05-0.1	1.50 (0.02)	0.27 (0.01)	7.48 (0.06)	1.9 (0.1)	13.0 (0.3)	0.1 (0.1)	1.2 (0.1)
0.1-0.2	1.55 (0.01)	0.22 (0.01)	7.59 (0.05)	1.5 (0.2)	19.7 (0.6)	0.1 (0.1)	1.8 (0.1)
0.2-0.3	1.50 (0.01)	0.23 (0.01)	7.87 (0.05)	1.3 (0.2)	15.5 (0.7)	0.2 (0.2)	1.4 (0.1)
0.3-0.6	1.46 (0.03)	0.25 (0.01)	8.43 (0.04)	4.8 (0.8)	53.6 (3.9)	20.2 (3.3)	3.2 (0.2)
0.6-0.9	1.54 (0.04)	0.26 (0.02)	8.83 (0.04)	20.7 (2.1)	78.9 (7.0)	30.8 (3.3)	3.0 (0.5)
0.9-1.2	--	--	--	--	--	--	--
Williston (irrigated)							
0-0.05	1.24 (0.02)	0.48 (0.01)	7.58 (0.06)	21.7 (2.0)	16.0 (0.4)	0.1 (0.1)	1.6 (0.1)
0.05-0.1	1.48 (0.03)	0.44 (0.02)	7.42 (0.09)	8.9 (0.5)	16.1 (0.5)	0.1 (0.1)	1.5 (0.1)
0.1-0.2	1.53 (0.02)	0.41 (0.02)	7.40 (0.09)	5.5 (0.4)	24.4 (1.1)	0.2 (0.1)	2.2 (0.1)
0.2-0.3	1.48 (0.02)	0.39 (0.02)	7.65 (0.12)	2.6 (0.3)	19.6 (0.4)	0.5 (0.2)	1.7 (0.1)
0.3-0.6	1.48 (0.02)	0.36 (0.03)	7.90 (0.15)	8.1 (1.1)	57.3 (3.5)	19.4 (4.9)	4.0 (0.2)
0.6-0.9	1.50 (0.03)	0.27 (0.02)	8.47 (0.15)	17.3 (3.4)	70.8 (5.5)	21.0 (4.3)	3.0 (0.3)
0.9-1.2	--	--	--	--	--	--	--

Table 4. Soil bulk density for annual and biennial harvests under switchgrass, tall wheatgrass, and CRP mix treatments in 2011.

Location/Depth (m)	Sunburst switchgrass		Alkar tall wheatgrass		CRP mix	
	Annual	Biennial	Annual	Biennial	Annual	Biennial
Carrington	Soil bulk density (Mg m^{-3})					
0-0.05	1.26 (0.08)†	1.33 (0.05)	1.28 (0.03)	1.27 (0.02)	1.31 (0.06)	1.20 (0.03)
0.05-0.1	1.54 (0.04)	1.55 (0.05)	1.50 (0.03)	1.50 (0.03)	1.45 (0.06)	1.47 (0.07)
0.1-0.2	1.54 (0.06)	1.52 (0.06)	1.49 (0.07)	1.50 (0.03)	1.54 (0.11)	1.44 (0.05)
0.2-0.3	1.40 (0.05)	1.42 (0.08)	1.44 (0.06)	1.43 (0.09)	1.49 (0.12)	1.47 (0.03)
0.3-0.6	1.36 (0.02)	1.39 (0.03)	1.39 (0.04)	1.39 (0.01)	1.33 (0.07)	1.40 (0.03)
0.6-0.9	1.37 (0.06)	1.47 (0.05)	1.58 (0.06)	1.42 (0.04)	1.45 (0.04)	1.47 (0.04)
0.9-1.2	1.76 (0.01)	1.70 (0.03)	1.70 (0.04)	1.67 (0.05)	1.70 (0.05)	1.60 (0.13)
Hettinger						
0-0.05	1.31 (0.03)	1.29 (0.02)	1.37 (0.05)	1.39 (0.01)	1.32 (0.03)	1.40 (0.04)
0.05-0.1	1.59 (0.06)	1.53 (0.04)	1.61 (0.05)	1.64 (0.02)	1.57 (0.06)	1.64 (0.02)
0.1-0.2	1.54 (0.03)	1.57 (0.02)	1.54 (0.05)	1.54 (0.05)	1.57 (003)	1.65 (0.03)
0.2-0.3	1.46 (0.04)	1.47 (0.02)	1.49 (0.04)	1.50 (0.05)	1.53 (0.07)	1.55 (0.03)
0.3-0.6	1.48 (0.04)	1.44 (0.02)	1.51 (0.05)	1.48 (0.05)	1.45 (0.06)	1.53 (0.03)
0.6-0.9	1.52 (0.04)	1.41 (0.04)	1.50 (0.02)	1.46 (0.03)	1.45 (0.03)	1.50 (0.04)
0.9-1.2	1.40 (0.03)	1.50 (0.02)	1.51 (0.01)	1.43 (0.03)	1.39 (0.04)	1.50 (0.04)
Minot						
0-0.05	1.52 (0.05)	1.48 (0.06)	1.46 (0.07)	1.42 (0.10)	1.30 (0.03)	1.41 (0.01)
0.05-0.1	1.57 (0.10)	1.59 (0.04)	1.52 (0.05)	1.67 (0.03)	1.53 (0.03)	1.56 (0.06)
0.1-0.2	1.60 (0.04)	1.57 (0.04)	1.61 (0.05)	1.59 (0.04)	1.52 (0.05)	1.54 (0.03)
0.2-0.3	1.52 (0.09)	1.52 (0.03)	1.52 (0.07)	1.63 (0.02)	1.54 (0.02)	1.53 (0.04)
0.3-0.6	1.72 (0.04)	1.67 (0.05)	1.65 (0.04)	1.60 (0.03)	1.58 (0.06)	1.68 (0.05)
0.6-0.9	1.76 (0.02)	1.73 (0.04)	1.73 (0.03)	1.80 (0.02)	1.76 (0.02)	1.78 (0.02)
0.9-1.2	1.78 (0.01)	1.81 (0.03)	1.78 (0.00)	1.78 (0.01)	1.77 (0.01)	1.81 (0.03)

Table 4. Cont'd.

Location/Depth (m)	Sunburst switchgrass Annual	Sunburst switchgrass Biennial	Alkar tall wheatgrass Annual	Alkar tall wheatgrass Biennial	CRP mix Annual	CRP mix Biennial
Streeter			Soil bulk density (Mg m^{-3})			
0-0.05	1.12 (0.02)	1.02 (0.04)	1.06 (0.02)	1.05 (0.04)	0.99 (0.06)	0.99 (0.06)
0.05-0.1	1.30 (0.06)	1.26 (0.03)	1.27 (0.04)	1.25 (0.08)	1.25 (0.03)	1.29 (0.02)
0.1-0.2	1.19 (0.05)	1.24 (0.04)	1.23 (0.05)	1.21 (0.04)	1.22 (0.03)	1.19 (0.06)
0.2-0.3	1.23 (0.05)	1.28 (0.03)	1.29 (0.01)	1.26 (0.05)	1.33 (0.01)	1.24 (0.07)
0.3-0.6	1.38 (0.02)	1.33 (0.02)	1.31 (0.04)	1.31 (0.02)	1.36 (0.04)	1.35 (0.04)
0.6-0.9	1.50 (0.04)	1.49 (0.01)	1.48 (0.09)	1.44 (0.07)	1.44 (0.03)	1.50 (0.08)
0.9-1.2	--	--	--	1.54 (0.04)	--	1.66 (0.11)
Williston (dryland)						
0-0.05	1.52 (0.05)	1.41 (0.06)*	1.53 (0.09)	1.42 (0.02)	1.44 (0.02)	1.48 (0.04)
0.05-0.1	1.63 (0.05)	1.59 (0.04)	1.59 (0.04)	1.62 (0.04)	1.64 (0.02)	1.63 (0.03)
0.1-0.2	1.71 (0.03)	1.65 (0.02)*	1.67 (0.05)	1.68 (0.03)	1.71 (0.02)	1.71 (0.01)
0.2-0.3	1.56 (0.04)	1.57 (0.05)	1.55 (0.02)	1.52 (0.03)	1.56 (0.03)	1.58 (0.04)
0.3-0.6	1.47 (0.01)	1.45 (0.04)	1.45 (0.07)	1.48 (0.03)	1.46 (0.05)	1.50 (0.08)
0.6-0.9	1.50 (0.09)	1.52 (0.08)	1.66 (0.02)	1.64 (0.06)	1.47 (0.09)	1.39 (0.15)
0.9-1.2	--	--	--	--	--	--
Williston (irrigated)						
0-0.05	1.48 (0.08)	1.48 (0.09)	1.46 (0.06)	1.41 (0.05)	1.42 (0.04)	1.36 (0.09)
0.05-0.1	1.60 (0.06)	1.58 (0.17)	1.55 (0.10)	1.62 (0.08)	1.68 (0.04)	1.57 (0.07)
0.1-0.2	1.64 (0.07)	1.56 (0.09)	1.60 (0.05)	1.66 (0.06)	1.65 (0.05)	1.56 (0.02)
0.2-0.3	1.57 (0.02)	1.54 (0.04)	1.56 (0.04)	1.56 (0.03)	1.58 (0.04)	1.55 (0.07)
0.3-0.6	1.47 (0.02)	1.49 (0.03)	1.49 (0.01)	1.50 (0.03)	1.41 (0.04)	1.43 (0.05)
0.6-0.9	1.48 (0.07)	1.61 (0.07)	1.52 (0.07)	1.64 (0.15)	1.52 (0.06)	1.52 (0.06)
0.9-1.2	--	--	--	--	--	--

† Values in parentheses represent standard error of the mean. * Comparison between annual and biennial treatment within a depth significant at $P \leq 0.05$.

Table 5. Electrical conductivity for annual and biennial harvests under switchgrass, tall wheatgrass, and CRP mix treatments in 2011.

	Sunburst switchgrass		Alkar tall wheatgrass		CRP mix	
Location/Depth (m)	Annual	Biennial	Annual	Biennial	Annual	Biennial
Carrington	---------- Electrical conductivity (dS m^{-1}) ----------					
0-0.05	0.26 (0.03)†	0.31 (0.02)	0.26 (0.01)	0.31 (0.04)	0.27 (0.03)	0.35 (0.04)
0.05-0.1	0.20 (0.02)	0.21 (0.02)	0.20 (0.02)	0.22 (0.03)	0.21 (0.02)	0.25 (0.01)
0.1-0.2	0.16 (0.03)	0.16 (0.03)	0.17 (0.01)	0.16 (0.02)	0.16 (0.01)	0.17 (0.01)
0.2-0.3	0.15 (0.02)	0.15 (0.03)	0.14 (0.02)	0.15 (0.02)	0.15 (0.01)	0.14 (0.01)
0.3-0.6	0.19 (0.03)	0.17 (0.03)	0.19 (0.03)	0.16 (0.03)	0.14 (0.01)	0.15 (0.01)
0.6-0.9	0.22 (0.04)	0.22 (0.01)	0.25 (0.05)	0.27 (0.07)	0.22 (0.04)	0.22 (0.05)
0.9-1.2	0.17 (0.03)	0.18 (0.02)	0.19 (0.06)	0.14 (0.04)	0.21 (0.06)	0.22 (0.01)
Hettinger						
0-0.05	0.36 (0.10)	0.35 (0.11)	0.42 (0.10)	0.34 (0.07)	0.36 (0.09)	0.38 (0.09)
0.05-0.1	0.28 (0.03)	0.25 (0.05)	0.25 (0.04)	0.23 (0.03)	0.25 (0.02)	0.26 (0.03)
0.1-0.2	0.27 (0.02)	0.25 (0.04)	0.25 (0.03)	0.21 (0.02)	0.25 (0.01)	0.25 (0.03)
0.2-0.3	0.27 (0.02)	0.23 (0.05)	0.23 (0.03)	0.27 (0.03)	0.28 (0.02)	0.24 (0.03)
0.3-0.6	0.26 (0.02)	0.25 (0.03)	0.27 (0.01)	0.26 (0.02)	0.25 (0.01)	0.24 (0.02)
0.6-0.9	0.30 (0.01)	0.26 (0.03)	0.31 (0.01)	0.37 (0.06)	0.32 (0.04)	0.32 (0.01)
0.9-1.2	0.48 (0.04)	0.44 (0.08)	0.5 (0.14)	0.42 (0.02)	0.35 (0.03)	0.45 (0.07)
Minot						
0-0.05	0.17 (0.01)	0.21 (0.01)	0.27 (0.05)	0.25 (0.05)	0.35 (0.02)	0.32 (0.01)
0.05-0.1	0.16 (0.01)	0.16 (0.01)	0.28 (0.10)	0.22 (0.04)	0.45 (0.20)	0.22 (0.01)
0.1-0.2	0.40 (0.17)	0.26 (0.07)	0.38 (0.20)	0.22 (0.07)	0.79 (0.27)	0.31 (0.06)
0.2-0.3	0.37 (0.12)	0.28 (0.07)	0.65 (0.34)	0.30 (0.03)	1.34 (0.48)	0.54 (0.21)
0.3-0.6	1.68 (0.94)	0.42 (0.02)	1.99 (0.84)	1.17 (0.62)	3.19 (0.83)	0.47 (0.04)
0.6-0.9	2.90 (0.51)	1.18 (0.39)	4.60 (1.29)	2.52 (0.83)	3.26 (0.98)	2.04 (0.64)
0.9-1.2	3.01 (0.80)	1.5 (0.77)	4.27 (1.34)	4.42 (1.11)	2.05 (0.55)	2.88 (1.68)

Table 5. Cont'd.

Location/Depth (m)	Sunburst switchgrass Annual	Sunburst switchgrass Biennial	Alkar tall wheatgrass Annual	Alkar tall wheatgrass Biennial	CRP mix Annual	CRP mix Biennial
Streeter	- - - Electrical conductivity (dS m^{-1}) - - -					
0-0.05	0.32 (0.05)	0.27 (0.02)	0.30 (0.04)	0.35 (0.01)	0.30 (0.02)	0.37 (0.07)
0.05-0.1	0.27 (0.06)	0.23 (0.02)	0.32 (0.10)	0.29 (0.03)	0.23 (0.01)	0.29 (0.04)
0.1-0.2	0.26 (0.04)	0.23 (0.04)	0.27 (0.06)	0.30 (0.04)	0.20 (0.01)	0.32 (0.05)
0.2-0.3	0.28 (0.02)	0.34 (0.06)	0.31 (0.07)	0.39 (0.09)	0.28 (0.01)	0.39 (0.08)
0.3-0.6	0.59 (0.08)	0.48 (0.11)	0.71 (0.18)	0.53 (0.09)	0.40 (0.05)	0.42 (0.07)
0.6-0.9	0.68 (0.03)	0.98 (0.56)	0.83 (0.53)	0.88 (0.16)	0.57 (0.23)	0.44 (0.10)
0.9-1.2	--	--	--	1.87 (0.73)	--	0.61 (0.24)
Williston (dryland)						
0-0.05	0.21 (0.01)	0.21 (0.01)	0.24 (0.02)	0.19 (0.01)	0.22 (0.01)	0.24 (0.01)
0.05-0.1	0.16 (0.01)	0.14 (0.01)	0.16 (0.03)	0.13 (0.02)	0.17 (0.01)	0.16 (0.02)
0.1-0.2	0.13 (0.04)	0.13 (0.01)	0.14 (0.01)	0.13 (0.01)	0.14 (0.02)	0.13 (0.01)
0.2-0.3	0.16 (0.05)	0.15 (0.02)	0.13 (0.02)	0.14 (0.01)	0.15 (0.02)	0.15 (0.01)
0.3-0.6	0.20 (0.02)	0.21 (0.02)	0.15 (0.04)	0.21 (0.01)	0.24 (0.01)	0.24 (0.01)
0.6-0.9	0.30 (0.05)	0.17 (0.03)	0.15 (0.02)	0.11 (0.01)	0.19 (0.02)	0.25 (0.01)
0.9-1.2	--	--	--	--	--	--
Williston (irrigated)						
0-0.05	0.25 (0.01)	0.28 (0.02)	0.27 (0.01)	0.26 (0.01)	0.29 (0.01)	0.32 (0.01)
0.05-0.1	0.20 (0.01)	0.21 (0.02)	0.22 (0.01)	0.23 (0.01)	0.24 (0.01)	0.24 (0.02)
0.1-0.2	0.17 (0.01)	0.19 (0.02)	0.20 (0.01)	0.19 (0.01)	0.2 (0.01)	0.19 (0.01)
0.2-0.3	0.18 (0.02)	0.18 (0.03)	0.21 (0.02)	0.23 (0.03)	0.22 (0.02)	0.24 (0.08)
0.3-0.6	0.21 (0.03)	0.18 (0.01)	0.20 (0.02)	0.45 (0.17)	0.27 (0.04)	0.25 (0.06)
0.6-0.9	0.24 (0.07)	0.14 (0.04)	0.36 (0.11)	0.65 (0.17)	0.55 (0.18)	0.24 (0.08)
0.9-1.2	--	--	--	--	--	--

† Values in parentheses represent standard error of the mean.

Table 6. Soil pH for annual and biennial harvests under switchgrass, tall wheatgrass, and CRP mix treatments in 2011.

Location/Depth (m)	Sunburst switchgrass		Alkar tall wheatgrass		CRP mix	
	Annual	Biennial	Annual	Biennial	Annual	Biennial
Carrington	- Soil pH (-log [H^+]) -					
0-0.05	6.73 (0.26)†	7.00 (0.17)	7.10 (0.25)	7.10 (0.25)	6.77 (0.23)	6.97 (0.23)
0.05-0.1	6.60 (0.44)	6.70 (0.15)	7.03 (0.30)	6.73 (0.37)	6.70 (0.44)	6.90 (0.26)
0.1-0.2	6.80 (0.26)	6.27 (0.09)	6.97 (0.32)	6.30 (0.23)	6.60 (0.42)	6.53 (0.19)
0.2-0.3	7.00 (0.17)	6.60 (0.10)	7.23 (0.23)	6.50 (0.21)	6.90 (0.20)	6.70 (0.15)
0.3-0.6	7.27 (0.18)	7.10 (0.26)	7.53 (0.28)	6.93 (0.27)	7.20 (0.06)	6.97 (0.23)
0.6-0.9	7.67 (0.39)	7.57 (0.48)	7.73 (0.23)	7.27 (0.34)	7.60 (0.32)	7.47 (0.45)
0.9-1.2	7.87 (0.43)	7.80 (0.60)	7.97 (0.28)	7.40 (0.80)	7.77 (0.44)	8.25 (0.05)
Hettinger						
0-0.05	6.75 (0.29)	6.55 (0.15)	6.30 (0.45)	6.40 (0.37)	6.60 (0.27)	6.80 (0.29)
0.05-0.1	7.20 (0.32)	6.93 (0.33)	6.88 (0.40)	6.90 (0.30)	7.10 (0.33)	7.38 (0.31)
0.1-0.2	7.68 (0.25)	7.23 (0.29)	7.30 (0.31)	7.33 (0.30)	7.60 (0.27)	7.65 (0.26)
0.2-0.3	8.13 (0.19)	7.63 (0.23)	7.63 (0.34)	7.95 (0.18)	8.20 (0.12)	8.05 (0.14)
0.3-0.6	8.40 (0.14)	8.15 (0.21)	8.35 (0.09)	8.40 (0.01)	8.48 (0.05)	8.43 (0.05)
0.6-0.9	8.60 (0.08)	8.50 (0.09)	8.58 (0.07)	8.55 (0.06)	8.60 (0.05)	8.55 (0.05)
0.9-1.2	8.70 (0.11)	8.58 (0.10)	8.60 (0.15)	8.73 (0.09)	8.78 (0.05)	8.60 (0.07)
Minot						
0-0.05	6.07 (0.09)	6.33 (0.20)	6.53 (0.38)	6.80 (0.53)	6.70 (0.10)	6.77 (0.07)
0.05-0.1	5.80 (0.06)	6.00 (0.15)	6.33 (0.29)	6.70 (0.55)	6.50 (0.25)	6.47 (0.23)
0.1-0.2	6.43 (0.09)	6.67 (0.38)	6.40 (0.12)	6.87 (0.54)	7.07 (0.23)	7.13 (0.17)
0.2-0.3	7.10 (0.61)	7.63 (0.32)	7.10 (0.40)	7.93 (0.38)	7.47 (0.29)	7.50 (0.45)
0.3-0.6	7.90 (0.40)	8.47 (0.26)	7.77 (0.29)	8.40 (0.35)	8.03 (0.03)	8.50 (0.12)*
0.6-0.9	8.37 (0.30)	8.70 (0.36)	8.10 (0.40)	8.80 (0.36)	8.37 (0.12)	8.30 (0.06)
0.9-1.2	8.40 (0.15)	8.90 (0.30)	8.33 (0.23)	8.53 (0.09)	8.30 (0.10)	8.25 (0.05)

Table 6. Cont'd.

Location/Depth (m)	Sunburst switchgrass Annual	Sunburst switchgrass Biennial	Alkar tall wheatgrass Annual	Alkar tall wheatgrass Biennial	CRP mix Annual	CRP mix Biennial
Streeter	------------------------------ Soil pH (-log [H^+]) ------------------------------					
0-0.05	7.03 (0.39)	6.47 (0.12)	6.77 (0.32)	7.17 (0.20)	6.83 (0.03)	7.10 (0.38)
0.05-0.1	7.07 (0.41)	6.70 (0.25)	7.03 (0.39)	7.37 (0.24)	6.87 (0.07)	7.27 (0.41)
0.1-0.2	7.03 (0.43)	6.77 (0.27)	7.00 (0.38)	7.43 (0.38)	6.93 (0.15)	7.43 (0.47)
0.2-0.3	7.43 (0.44)	7.00 (0.44)	7.07 (0.54)	7.57 (0.19)	7.07 (0.30)	7.60 (0.45)
0.3-0.6	8.23 (0.34)	7.50 (0.46)	7.67 (0.29)	8.13 (0.12)	0.87 (0.19)	7.97 (0.34)
0.6-0.9	8.63 (0.18)	8.13 (0.23)	8.40 (0.00)	8.43 (0.19)	8.40 (0.10)	8.53 (0.12)
0.9-1.2	--	--	--	8.23 (0.12)	--	8.60 (0.01)
Williston (dryland)						
0-0.05	7.33 (0.03)	7.33 (0.15)	7.47 (0.29)	7.17 (0.12)	7.37 (0.07)	7.13 (0.15)
0.05-0.1	7.30 (0.15)	7.33 (0.18)	7.57 (0.26)	7.10 (0.06)	7.17 (0.09)	6.97 (0.19)
0.1-0.2	7.70 (0.10)	7.43 (0.12)	7.67 (0.13)	7.47 (0.03)	7.53 (0.17)	7.33 (0.07)
0.2-0.3	8.00 (0.20)	7.73 (0.15)	7.87 (0.07)	7.70 (0.01)	7.77 (0.09)	7.70 (0.06)
0.3-0.6	8.37 (0.07)	8.23 (0.09)	8.20 (0.15)	8.33 (0.03)	8.27 (0.09)	8.17 (0.15)
0.6-0.9	8.90 (0.00)	8.70 (0.12)	8.55 (0.05)	8.85 (0.25)	8.60 (0.00)	8.45 (0.15)
0.9-1.2	--	--	--	--	--	--
Williston (irrigated)						
0-0.05	7.50 (0.00)	7.43 (0.12)	7.50 (0.06)	7.57 (0.09)	7.70 (0.06)	7.37 (0.23)
0.05-0.1	7.33 (0.03)	7.33 (0.18)	7.53 (0.09)	7.57 (0.09)	7.80 (0.06)	7.50 (0.29)
0.1-0.2	7.47 (0.07)	7.37 (0.19)	7.73 (0.15)	7.83 (0.09)	7.97 (0.09)	7.63 (0.29)
0.2-0.3	7.73 (0.12)	7.47 (0.32)	7.87 (0.12)	8.03 (0.09)*	8.17 (0.07)	7.70 (0.38)
0.3-0.6	8.00 (0.25)	7.57 (0.43)	8.03 (0.23)	8.27 (0.03)	8.47 (0.03)	7.80 (0.53)
0.6-0.9	8.30 (0.20)	7.05 (0.25)	8.07 (0.46)	8.30 (0.32)	8.00 (0.20)	7.93 (0.62)
0.9-1.2	--	--	--	--	--	--

† Values in parentheses represent standard error of the mean. * Comparison between annual and biennial treatment within a depth significant at P≤0.05.

Table 7. Soil organic C, total N, and available P for annual and biennial harvests under switchgrass, tall wheatgrass, and CRP mix treatments in 2011. Results provided for three soil masses approximately equivalent to 0-0.3, 0-0.6, and 0-0.9 m depths.

Location/Soil mass	Sunburst switchgrass		Alkar tall wheatgrass		CRP mix	
	Annual	Biennial	Annual	Biennial	Annual	Biennial
Carrington	- Soil organic C (Mg C ha^{-1}) -					
3600 Mg ha^{-1}	95 (21)†	99 (18)	100 (23)	104 (14)	108 (18)	101 (9)
7300 Mg ha^{-1}	170 (60)	146 (29)	146 (34)	147 (22)	208 (66)	141 (13)
11300 Mg ha^{-1}	224 (77)	204 (35)	217 (33)	183 (34)	324 (150)	178 (6)
Hettinger						
3600 Mg ha^{-1}	61 (3)	66 (6)	60 (4)	64 (3)	62 (3)	68 (5)
7300 Mg ha^{-1}	99 (5)	122 (5)*	107 (5)	106 (7)	106 (6)	113 (7)
11300 Mg ha^{-1}	130 (4)	166 (8)	140 (8)	143 (7)	138 (6)	145 (5)
Minot						
3600 Mg ha^{-1}	69 (8)	71 (3)	76 (6)	72 (8)	77 (2)	74 (5)
7300 Mg ha^{-1}	101 (4)	112 (2)*	119 (7)	104 (11)	120 (5)	112 (8)
11300 Mg ha^{-1}	--	--	--	--	--	--
Streeter						
3600 Mg ha^{-1}	96 (3)	96 (2)	95 (3)	97 (8)	96 (3)	100 (10)
7300 Mg ha^{-1}	156 (9)	148 (6)	152 (11)	197 (37)	148 (14)	161 (19)
11300 Mg ha^{-1}	--	--	--	--	--	--
Williston (dryland)						
3600 Mg ha^{-1}	74 (5)	77 (4)	79 (12)	70 (4)	72 (3)	75 (3)
7300 Mg ha^{-1}	127 (6)	129 (8)	141 (20)	146 (15)	132 (3)	126 (6)
11300 Mg ha^{-1}	--	--	--	--	--	--
Williston (irrigated)						
3600 Mg ha^{-1}	82 (5)	92 (7)	86 (1)	87 (4)	84 (7)	89 (9)
7300 Mg ha^{-1}	135 (0.1)	143 (3)	146 (16)	157 (28)	137 (9)	154 (5)
11300 Mg ha^{-1}	--	--	--	--	--	--

Table 7. Cont'd.

Location/Soil mass	Sunburst switchgrass Annual	Sunburst switchgrass Biennial	Alkar tall wheatgrass Annual	Alkar tall wheatgrass Biennial	CRP mix Annual	CRP mix Biennial
	Total N (Mg N ha^{-1})					
Carrington						
3600 Mg ha^{-1}	8.6 (1.7)	8.9 (1.4)	8.9 (1.9)	9.3 (1.0)	9.6 (1.5)	9.1 (0.8)
7300 Mg ha^{-1}	15.2 (5.0)	13.4 (2.4)	13.3 (2.9)	13.4 (1.8)	18.4 (5.3)	13.1 (1.2)
11300 Mg ha^{-1}	19.3 (7.0)	17.6 (4.4)	19.4 (3.6)	17.0 (3.1)	28.2 (12.1)	14.5 (0.1)
Hettinger						
3600 Mg ha^{-1}	5.5 (0.4)	6.0 (0.4)	5.5 (0.5)	5.9 (0.5)	5.8 (0.3)	6.0 (0.6)
7300 Mg ha^{-1}	8.8 (0.5)	10.5 (0.2)	9.1 (0.9)	9.4 (0.8)	8.9 (0.3)	9.6 (0.9)
11300 Mg ha^{-1}	11.2 (0.4)	13.7 (0.3)*	11.5 (1.0)	12.2 (0.9)	11.3 (0.3)	12.0 (0.8)
Minot						
3600 Mg ha^{-1}	6.6 (0.7)	6.5 (0.5)	7.0 (0.5)	6.6 (0.8)	7.3 (0.1)	6.9 (0.5)
7300 Mg ha^{-1}	9.2 (1.6)	9.1 (1.1)	10.6 (1.3)	9.1 (1.2)	10.5 (0.1)	9.4 (0.4)
11300 Mg ha^{-1}	--	--	--	--	--	--
Streeter						
3600 Mg ha^{-1}	8.7 (0.5)	8.9 (0.1)	8.8 (0.3)	9.0 (0.6)	9.0 (0.3)	9.1 (0.6)
7300 Mg ha^{-1}	13.1 (1.6)	13.7 (0.6)	12.7 (0.8)	14.5 (1.6)	13.7 (0.9)	14.3 (1.5)
11300 Mg ha^{-1}	--	--	--	--	--	--
Williston (dryland)						
3600 Mg ha^{-1}	6.9 (0.4)	7.2 (0.4)	7.1 (0.8)	6.6 (0.2)	6.7 (0.3)	7.2 (0.1)
7300 Mg ha^{-1}	10.9 (0.3)	11.5 (0.8)	12.4 (1.6)	11.4 (0.1)	11.3 (0.4)	11.3 (0.1)
11300 Mg ha^{-1}	--	--	--	--	--	--
Williston (irrigated)						
3600 Mg ha^{-1}	7.5 (0.5)	8.4 (0.6)	8.0 (0.2)	8.0 (0.3)	7.7 (0.6)	8.2 (0.8)
7300 Mg ha^{-1}	11.5 (1.1)	13.5 (0.2)	12.4 (0.3)	12.7 (0.8)	11.6 (9)	12.6 (1.5)
11300 Mg ha^{-1}	--	--	--	--	--	--

Table 7. Cont'd.

Location/Soil mass	Sunburst switchgrass Annual	Sunburst switchgrass Biennial	Alkar tall wheatgrass Annual	Alkar tall wheatgrass Biennial	CRP mix Annual	CRP mix Biennial
Carrington	Available P (kg P ha^{-1})					
3600 Mg ha^{-1}	116 (48)	120 (22)	104 (33)	115 (17)	112 (47)	112 (12)
7300 Mg ha^{-1}	181 (107)	129 (25)	145 (69)	123 (20)	213 (135)	133 (13)
11300 Mg ha^{-1}	238 (160)	165 (7)	216 (109)	110 (4)	303 (221)	145 (37)
Hettinger						
3600 Mg ha^{-1}	39 (10)	50 (12)	40 (13)	49 (12)	42 (10)	41 (11)
7300 Mg ha^{-1}	41 (11)	52 (20)	49 (12)	53 (12)	55 (1)	47 (9)
11300 Mg ha^{-1}	46 (15)	54 (21)	55 (20)	75 (29)	56 (1)	59 (16)
Minot						
3600 Mg ha^{-1}	22 (8)	22 (9)	17 (1)	19 (4)	11 (1)	11 (2)
7300 Mg ha^{-1}	30 (6)	30 (13)	23 (2)	27 (8)	15 (2)	27 (9)
11300 Mg ha^{-1}	--	--	--	--	--	--
Streeter						
3600 Mg ha^{-1}	26 (9)	99 (8)	17 (4)	19 (1)	15 (1)	17 (3)
7300 Mg ha^{-1}	47 (12)	122 (9)	31 (3)	33 (5)	25 (2)	26 (3)
11300 Mg ha^{-1}	--	--	--	--	--	--
Williston (dryland)						
3600 Mg ha^{-1}	10 (5)	9 (5)	13 (1)	10 (5)	14 (1)	13 (1)
7300 Mg ha^{-1}	15 (12)	20 (2)	16 (1)	17 (15)	24 (1)	18 (5)
11300 Mg ha^{-1}	--	--	--	--	--	--
Williston (irrigated)						
3600 Mg ha^{-1}	36 (8)	35 (3)	33 (6)	31 (4)	29 (4)	31 (4)
7300 Mg ha^{-1}	46 (16)	54 (15)	49 (11)	47 (7)	43 (16)	51 (6)
11300 Mg ha^{-1}	--	--	--	--	--	--

† Values in parentheses represent standard error of the mean. * Comparison between annual and biennial treatment within a depth significant at $P \leq 0.05$.

Table 8. Soil bulk density for seven perennial grass treatments in 2011.

Location/Depth (m)	Sunburst switchgrass	Trailblazer switchgrass	Tall wheatgrass	Intermediate wheatgrass	CRP mix	Switchgrass + Tall wheatgrass	Switchgrass + Big bluestem
Carrington	Soil bulk density (Mg m^{-3})						
0-0.05	1.26 (0.08)†	1.31 (0.02)	1.28 (0.03)	1.28 (0.06)	1.31 (0.06)	1.38 (0.09)	1.25 (0.09)
0.05-0.1	1.54 (0.04)	1.51 (0.05)	1.50 (0.03)	1.46 (0.06)	1.45 (0.06)	1.51 (0.08)	1.50 (0.06)
0.1-0.2	1.54 (0.06)	1.44 (0.04)	1.49 (0.07)	1.47 (0.06)	1.54 (0.11)	1.48 (0.08)	1.46 (0.10)
0.2-0.3	1.40 (0.05)	1.38 (0.03)	1.44 (0.06)	1.41 (0.13)	1.49 (0.12)	1.39 (0.09)	1.44 (0.08)
0.3-0.6	1.36 (0.02)	1.37 (0.02)	1.39 (0.04)	1.40 (0.01)	1.33 (0.07)	1.36 (0.02)	1.36 (0.06)
0.6-0.9	1.37 (0.06)	1.45 (0.04)	1.58 (0.06)	1.40 (0.07)	1.45 (0.04)	1.45 (0.07)	1.41 (0.05)
0.9-1.2	1.76 (0.01)	1.70 (0.05)	1.70 (0.04)	1.72 (0.01)	1.70 (0.05)	1.72 (0.03)	1.68 (0.03)
Hettinger							
0-0.05	1.31 (0.03)	1.34 (0.04)	1.37 (0.05)	1.33 (0.02)	1.32 (0.03)	1.34 (0.03)	1.36 (0.03)
0.05-0.1	1.59 (0.06)	1.56 (0.04)	1.61 (0.05)	1.62 (0.03)	1.57 (0.07)	1.60 (0.02)	1.62 (0.01)
0.1-0.2	1.54 (0.03)	1.58 (0.04)	1.54 (0.05)	1.60 (0.03)	1.57 (0.03)	1.57 (0.03)	1.58 (0.03)
0.2-0.3	1.46 (0.04)	1.50 (0.03)	1.49 (0.04)	1.45 (0.04)	1.53 (0.07)	1.56 (0.04)	1.58 (0.02)
0.3-0.6	1.48 (0.04)	1.48 (0.01)	1.51 (0.05)	1.50 (0.05)	1.45 (0.06)	1.52 (0.05)	1.51 (0.03)
0.6-0.9	1.52 (0.04)	1.49 (0.02)	1.50 (0.02)	1.51 (0.05)	1.45 (0.03)	1.55 (0.02)	1.59 (0.04)
0.9-1.2*	1.40 (0.03)	1.49 (0.05)	1.51 (0.01)	1.49 (0.03)	1.39 (0.04)	1.44 (0.06)	1.49 (0.02)
Minot							
0-0.05	1.52 (0.05)	1.43 (0.6)	1.46 (0.07)	1.29 (0.03)	1.30 (0.03)	1.31 (0.04)	1.43 (0.06)
0.05-0.1	1.57 (0.10)	1.56 (0.08)	1.52 (0.05)	1.50 (0.02)	1.53 (0.03)	1.50 (0.04)	1.62 (0.06)
0.1-0.2	1.60 (0.04)	1.55 (0.01)	1.61 (0.05)	1.55 (0.02)	1.52 (0.05)	1.60 (0.06)	1.59 (0.05)
0.2-0.3*	1.52 (0.09)	1.51 (0.04)	1.52 (0.07)	1.58 (0.03)	1.54 (0.02)	1.52 (0.11)	1.53 (0.05)
0.3-0.6	1.72 (0.04)	1.67 (0.03)	1.65 (0.04)	1.68 (0.03)	1.58 (0.06)	1.63 (0.01)	1.64 (0.02)
0.6-0.9	1.76 (0.02)	1.73 (0.06)	1.73 (0.03)	1.74 (0.05)	1.76 (0.02)	1.75 (0.06)	1.79 (0.02)
0.9-1.2	1.78 (0.01)	1.77 (0.03)	1.78 (0.00)	1.78 (0.00)	1.77 (0.01)	1.72 (0.06)	1.80 (0.02)

Table 8. Cont'd.

Location/Depth (m)	Sunburst switchgrass	Trailblazer switchgrass	Tall wheatgrass	Intermediate wheatgrass	CRP mix	Switchgrass + Tall wheatgrass	Switchgrass + Big bluestem
Streeter	- -		Soil bulk density (Mg m^{-3}) -				
0-0.05	1.12 (0.02)	1.08 (0.02)	1.06 (0.02)	1.08 (0.02)	0.99 (0.06)	1.00 (0.04)	1.03 (0.01)
0.05-0.1	1.30 (0.06)	1.27 (0.03)	1.27 (0.04)	1.24 (0.04)	1.25 (0.03)	1.26 (0.03)	1.27 (0.01)
0.1-0.2	1.19 (0.05)	1.21 (0.02)	1.23 (0.05)	1.24 (0.04)	1.22 (0.03)	1.26 (0.03)	1.21 (0.06)
0.2-0.3*	1.23 (0.05)	1.19 (0.02)	1.29 (0.01)	1.27 (0.02)	1.33 (0.01)	1.32 (0.04)	1.35 (0.06)
0.3-0.6	1.38 (0.02)	1.31 (0.02)	1.31 (0.04)	1.34 (0.01)	1.36 (0.04)	1.34 (0.04)	1.32 (0.01)
0.6-0.9	1.50 (0.04)	1.40 (0.02)	1.48 (0.09)	1.49 (0.06)	1.44 (0.03)	1.48 (0.02)	1.47 (0.03)
0.9-1.2	--	1.50 (0.16)	--	1.57 (0.05)	--	1.52 (0.09)	1.64 (0.04)
Williston (dryland)							
0-0.05	1.52 (0.05)	1.50 (0.04)	1.53 (0.09)	1.45 (0.09)	1.44 (0.02)	1.44 (0.02)	--
0.05-0.1	1.63 (0.05)	1.56 (0.02)	1.59 (0.04)	1.54 (0.03)	1.64 (0.02)	1.61 (0.01)	1.50 (0.17)
0.1-0.2	1.71 (0.03)	1.65 (0.04)	1.67 (0.05)	1.59 (0.01)	1.71 (0.02)	1.70 (0.03)	1.64 (0.04)
0.2-0.3	1.56 (0.04)	1.58 (0.02)	1.55 (0.02)	1.52 (0.01)	1.56 (0.03)	1.55 (0.05)	1.54 (0.01)
0.3-0.6	1.47 (0.01)	1.44 (0.07)	1.45 (0.07)	1.46 (0.06)	1.46 (0.05)	1.41 (0.06)	1.49 (0.08)
0.6-0.9	1.50 (0.09)	1.58 (0.06)	1.66 (0.02)	1.67 (0.03)	1.47 (0.09)	--	--
0.9-1.2	--	--	--	--	--	--	--
Williston (irrigated)							
0-0.05	1.48 (0.08)	1.50 (0.02)	1.46 (0.06)	1.42 (0.04)	1.42 (0.04)	1.45 (0.08)	1.50 (0.05)
0.05-0.1	1.60 (0.06)	1.73 (0.05)	1.55 (0.10)	1.61 (0.03)	1.68 (0.04)	1.56 (0.06)	1.65 (0.02)
0.1-0.2*	1.64 (0.07)	1.72 (0.06)	1.60 (0.05)	1.67 (0.03)	1.65 (0.05)	1.52 (0.05)	1.62 (0.03)
0.2-0.3	1.57 (0.02)	1.54 (0.03)	1.56 (0.04)	1.57 (0.04)	1.58 (0.04)	1.51 (0.01)	1.57 (0.02)
0.3-0.6	1.47 (0.02)	1.55 (0.03)	1.49 (0.01)	1.54 (0.01)	1.41 (0.04)	1.54 (0.01)	1.52 (0.05)
0.6-0.9	1.48 (0.07)	--	1.52 (0.07)	1.50 (0.07)	1.52 (0.06)	1.66 (0.06)	1.64 (0.10)
0.9-1.2	--	--	--	--	--	--	--

† Values in parentheses represent standard error of the mean. * Comparison within depth significant at P≤0.05.

Table 9. Electrical conductivity for seven perennial grass treatments in 2011.

Location/Depth (m)	Sunburst switchgrass	Trailblazer switchgrass	Tall wheatgrass	Intermediate wheatgrass	CRP mix	Switchgrass + Tall wheatgrass	Switchgrass + Big bluestem
Carrington	------------------------------ Electrical conductivity (dS m^{-1}) ------------------------------						
0-0.05	0.26 0.03)†	0.27 (0.02)	0.26 (0.01)	0.30 (0.02)	0.27 (0.03)	0.28 (0.01)	0.28 (0.01)
0.05-0.1	0.20 (0.02)	0.19 (0.02)	0.20 (0.02)	0.22 (0.01)	0.21 (0.02)	0.20 (0.02)	0.21 (0.03)
0.1-0.2	0.16 (0.03)	0.16 (0.01)	0.17 (0.01)	0.18 (0.01)	0.16 (0.01)	0.17 (0.01)	0.16 (0.02)
0.2-0.3	0.15 (0.02)	0.16 (0.01)	0.14 (0.02)	0.17 (0.01)	0.15 (0.01)	0.16 (0.02)	0.14 (0.01)
0.3-0.6	0.19 (0.03)	0.13 (0.02)	0.19 (0.03)	0.15 (0.02)	0.14 (0.01)	0.17 (0.03)	0.14 (0.01)
0.6-0.9	0.22 (0.04)	0.19 (0.03)	0.25 (0.05)	0.25 (0.06)	0.22 (0.04)	0.20 (0.05)	0.23 (0.04)
0.9-1.2	0.17 (0.03)	0.17 (0.03)	0.19 (0.06)	0.22 (0.06)	0.21 (0.06)	0.18 (0.05)	0.20 (0.03)
Hettinger							
0-0.05	0.36 (0.10)	0.36 (0.06)	0.42 (0.10)	0.32 (0.04)	0.36 (0.09)	0.35 (0.01)	0.37 (0.06)
0.05-0.1	0.28 (0.03)	0.27 (0.02)	0.25 (0.04)	0.25 (0.03)	0.25 (0.02)	0.23 (0.03)	0.26 (0.02)
0.1-0.2	0.27 (0.02)	0.26 (0.03)	0.25 (0.03)	0.26 (0.01)	0.25 (0.01)	0.24 (0.05)	0.26 (0.02)
0.2-0.3	0.27 (0.02)	0.23 (0.02)	0.23 (0.03)	0.25 (0.04)	0.28 (0.02)	0.25 (0.03)	0.25 (0.02)
0.3-0.6	0.26 (0.02)	0.25 (0.02)	0.27 (0.01)	0.28 (0.02)	0.25 (0.01)	0.24 (0.01)	0.24 (0.02)
0.6-0.9	0.30 (0.01)	0.32 (0.03)	0.31 (0.01)	0.32 (0.02)	0.32 (0.04)	0.33 (0.04)	0.35 (0.03)
0.9-1.2	0.48 (0.04)	0.35 (0.03)	0.50 (0.14)	0.37 (0.04)	0.35 (0.03)	0.37 (0.02)	0.62 (0.13)
Minot							
0-0.05*	0.17 (0.01)	0.24 (0.04)	0.27 (0.05)	0.21 (0.01)	0.35 (0.02)	0.18 (0.02)	0.23 (0.02)
0.05-0.1	0.16 (0.01)	0.20 (0.04)	0.28 (0.10)	0.19 (0.01)	0.45 (0.20)	0.16 (0.01)	0.17 (0.02)
0.1-0.2	0.40 (0.17)	0.19 (0.04)	0.38 (0.20)	0.18 (0.02)	0.79 (0.27)	0.18 (0.02)	0.17 (0.02)
0.2-0.3*	0.37 (0.12)	0.21 (0.05)	0.65 (0.34)	0.28 (0.10)	1.34 (0.48)	0.18 (0.03)	0.34 (0.16)
0.3-0.6	1.68 (0.94)	0.57 (0.09)	1.99 (0.84)	0.96 (0.56)	3.19 (0.83)	1.30 (0.96)	1.89 (0.58)
0.6-0.9	2.90 (0.51)	2.91 (0.77)	4.60 (1.29)	2.38 (0.68)	3.26 (0.98)	3.64 (1.72)	2.91 (0.38)
0.9-1.2	3.01 (0.80)	3.67 (0.99)	4.27 (1.34)	1.89 (0.52)	2.05 (0.55)	2.87 (1.82)	2.74 (0.45)

Table 9. Cont'd.

Location/Depth(m)	Sunburst switchgrass	Trailblazer switchgrass	Tall wheatgrass	Intermediate wheatgrass	CRP mix	Switchgrass + Tall wheatgrass	Switchgrass + Big bluestem
Streeter	Electrical conductivity (dS m^{-1})						
0-0.05	0.32 (0.05)	0.28 (0.02)	0.30 (0.04)	0.31 (0.01)	0.30 (0.02)	0.34 (0.02)	0.29 (0.01)
0.05-0.1	0.27 (0.06)	0.25 (0.01)	0.32 (0.10)	0.25 (0.02)	0.23 (0.01)	0.26 (0.01)	0.28 (0.03)
0.1-0.2*	0.26 (0.04)	0.23 (0.02)	0.27 (0.06)	0.7 (0.02)	0.20 (0.01)	0.29 (0.03)	0.22 (0.01)
0.2-0.3	0.28 (0.02)	0.30 (0.04)	0.31 (0.07)	0.49 (0.14)	0.28 (0.01)	0.34 (0.05)	0.29 (0.02)
0.3-0.6	0.59 (0.08)	0.51 (0.07)	0.71 (0.18)	0.87 (0.37)	0.40 (0.05)	0.56 (0.07)	0.56 (0.04)
0.6-0.9	0.68 (0.03)	0.54 (0.07)	0.83 (0.53)	1.16 (0.72)	0.57 (0.23)	0.80 (0.32)	1.02 (0.43)
0.9-1.2	--	1.39 (.96)	--	1.91 (1.41)	--	0.67 (0.37)	0.78 (0.10)
Williston(dryland)							
0-0.05	0.21 (0.01)	0.16 (0.02)	0.24 (0.02)	0.21 (0.01)	0.22 (0.01)	0.21 (0.01)	0.22 (0.01)
0.05-0.1	0.16 (0.01)	0.19 (0.02)	0.16 (0.03)	0.16 (0.01)	0.17 (0.01)	0.17 (0.01)	0.13 (0.01)
0.1-0.2	0.13 (0.04)	0.12 (0.01)	0.14 (0.01)	0.15 (0.03)	0.14 (0.02)	0.15 (0.02)	0.11 (0.01)
0.2-0.3	0.16 (0.05)	0.12 (0.02)	0.13 (0.02)	0.11 (0.01)	0.15 (0.02)	0.14 (0.02)	0.13 (0.01)
0.3-0.6	0.20 (0.02)	0.21 (0.03)	0.15 (0.04)	0.20 (0.02)	0.24 (0.01)	0.23 (0.02)	0.21 (0.01)
0.6-0.9*	0.30 (0.05)	0.21 (0.02)	0.15 (0.02)	0.16 (0.01)	0.19 (0.02)	--	--
0.9-1.2	--	--	--	--	--	--	--
Williston(irrigated)							
0-0.05*	0.25 (0.01)	0.24 (0.01)	0.27 (0.01)	0.26 (0.01)	0.29 (0.01)	0.27 (0.01)	0.27 (0.01)
0.05-0.1*	0.20 (0.01)	0.19 (0.01)	0.22 (0.01)	0.22 (0.01)	0.24 (0.01)	0.24 (0.01)	0.22 (0.01)
0.1-0.2	0.17 (0.01)	0.19 (0.03)	0.20 (0.01)	0.19 (0.02)	0.20 (0.01)	0.20 (0.01)	0.19 (0.01)
0.2-0.3	0.18 (0.02)	0.20 (0.02)	0.21 (0.02)	0.18 (0.01)	0.22 (0.02)	0.21 (0.05)	0.19 (0.02)
0.3-0.6	0.21 (0.03)	0.23 (0.03)	0.20 (0.02)	0.22 (0.03)	0.27 (0.04)	0.19 (0.05)	0.22 (0.01)
0.6-0.9	0.24 (0.07)	--	0.36 (0.11)	0.44 (0.15)	0.55 (0.18)	0.18 (0.06)	0.26 (0.05)
0.9-1.2	--	--	--	--	--	--	--

† Values in parentheses represent standard error of the mean. * Comparison within depth significant at P≤0.05.

Table 10. Soil pH for seven perennial grass treatments in 2011.

Location/Depth(m)	Sunburst switchgrass	Trailblazer switchgrass	Tall wheatgrass	Intermediate wheatgrass	CRP mix	Switchgrass + Tall wheatgrass	Switchgrass + Big bluestem
Carrington	- Soil pH (-log [H^+]) -						
0-0.05	6.73 0.26)†	6.93 (0.13)	7.10 (0.25)	7.17 (0.20)	6.77 (0.23)	7.03 (0.20)	7.00 (0.31)
0.05-0.1	6.60 (0.44)	6.73 (0.30)	7.03 (0.30)	7.00 (0.25)	6.70 (0.44)	6.80 (0.44)	6.73 (0.43)
0.1-0.2	6.80 (0.26)	6.80 (0.29)	6.97 (0.32)	6.93 (0.32)	6.60 (0.42)	6.90 (0.42)	6.83 (0.46)
0.2-0.3	7.00 (0.17)	7.00 (0.12)	7.23 (0.23)	7.20 (0.17)	6.90 (0.20)	7.13 (0.28)	7.13 (0.20)
0.3-0.6	7.27 (0.18)	7.07 (0.12)	7.53 (0.28)	7.37 (0.07)	7.20 (0.06)	7.43 (0.35)	7.40 (0.20)
0.6-0.9	7.67 (0.39)	7.47 (0.30)	7.73 (0.23)	7.67 (0.26)	7.60 (0.32)	7.40 (0.53)	7.67 (0.30)
0.9-1.2	7.87 (0.43)	7.73 (0.42)	7.97 (0.28)	7.60 (0.25)	7.77 (0.44)	7.67 (0.53)	7.87 (0.39)
Hettinger							
0-0.05	6.75 (0.29)	6.75 (0.25)	6.30 (0.45)	7.18 (0.59)	6.60 (0.27)	6.70 (0.23)	6.85 (0.32)
0.05-0.1	7.20 (0.32)	7.10 (0.35)	6.88 (0.40)	7.20 (0.32)	7.10 (0.33)	7.20 (0.31)	7.33 (0.31)
0.1-0.2	7.68 (0.25)	7.50 (0.32)	7.30 (0.31)	7.75 (0.23)	7.60 (0.27)	7.63 (0.16)	7.73 (0.26)
0.2-0.3	8.13 (0.19)	7.78 (0.34)	7.63 (0.34)	8.13 (0.15)	8.20 (0.12)	8.05 (0.22)	7.95 (0.30)
0.3-0.6	8.40 (0.14)	8.20 (0.22)	8.35 (0.09)	8.48 (0.05)	8.48 (0.05)	8.45 (0.05)	8.43 (0.08)
0.6-0.9	8.60 (0.08)	8.38 (0.19)	8.58 (0.07)	8.70 (0.10)	8.60 (0.05)	8.60 (0.07)	8.50 (0.04)
0.9-1.2	8.70 (0.11)	8.68 (0.14)	8.60 (0.15)	8.83 (0.08)	8.78 (0.05)	8.70 (0.06)	8.48 (0.11)
Minot							
0-0.05	6.07 (0.09)	6.60 (0.30)	6.53 (0.38)	6.27 (0.09)	6.70 (0.10)	6.07 (0.09)	6.30 (0.20)
0.05-0.1	5.80 (0.06)	6.40 (0.40)	6.33 (0.29)	5.97 (0.12)	6.50 (0.25)	5.80 (0.06)	6.07 (0.19)
0.1-0.2*	6.43 (0.09)	6.33 (0.23)	6.40 (0.12)	6.00 (0.06)	7.07 (0.23)	6.03 (0.23)	6.53 (0.32)
0.2-0.3	7.10 (0.61)	6.70 (0.46)	7.10 (0.40)	6.33 (0.12)	7.47 (0.29)	6.33 (0.20)	6.97 (0.38)
0.3-0.6	7.90 (0.40)	7.60 (0.40)	7.77 (0.29)	7.27 (0.46)	8.03 (0.03)	6.83 (0.68)	7.77 (0.27)
0.6-0.9	8.37 (0.30)	8.07 (0.09)	8.10 (0.40)	7.80 (0.46)	8.37 (0.12)	7.97 (0.37)	8.33 (0.22)
0.9-1.2	8.40 (0.15)	8.13 (0.09)	8.33 (0.23)	8.37 (0.18)	8.30 (0.10)	8.23 (0.32)	8.43 (0.17)

Table 10. Cont'd.

Location/Depth(m)	Sunburst switchgrass	Trailblazer switchgrass	Tall wheatgrass	Intermediate wheatgrass	CRP mix	Switchgrass + Tall wheatgrass	Switchgrass + Big bluestem
Streeter	- Soil pH (-log [H^+]) -						
0-0.05	7.03 (0.39)	6.70 (0.12)	6.77 (0.32)	7.07 (0.19)	6.83 (0.03)	7.20 (0.12)	7.03 (0.19)
0.05-0.1	7.07 (0.41)	6.90 (0.12)	7.03 (0.39)	7.13 (0.33)	6.87 (0.07)	7.47 (0.12)	7.13 (0.20)
0.1-0.2	7.03 (0.43)	7.07 (0.17)	7.00 (0.38)	7.23 (0.42)	6.93 (0.15)	7.57 (0.26)	7.40 (0.21)
0.2-0.3	7.43 (0.44)	7.07 (0.09)	7.07 (0.54)	7.57 (0.39)	7.07 (0.30)	7.80 (0.15)	7.57 (0.17)
0.3-0.6	8.23 (0.34)	7.80 (0.21)	7.67 (0.29)	8.17 (0.13)	0.87 (0.19)	8.33 (0.07)	8.27 (0.32)
0.6-0.9	8.63 (0.18)	8.53 (0.23)	8.40 (0.00)	8.53 (0.32)	8.40 (0.10)	8.63 (0.15)	8.57 (0.46)
0.9-1.2	--	8.20 (0.00)	--	8.30 (0.10)	--	8.40 (0.00)	8.80 (0.60)
Williston (dryland)							
0-0.05	7.33 (0.03)	7.43 (0.12)	7.47 (0.29)	7.27 (0.20)	7.37 (0.07)	7.50 (0.25)	7.15 (0.05)
0.05-0.1	7.30 (0.15)	7.60 (0.21)	7.57 (0.26)	7.27 (0.12)	7.17 (0.09)	7.53 (0.20)	7.10 (0.06)
0.1-0.2	7.70 (0.10)	7.73 (0.07)	7.67 (0.13)	7.53 (0.09)	7.53 (0.17)	7.83 (0.15)	7.43 (0.09)
0.2-0.3	8.00 (0.20)	7.90 (0.06)	7.87 (0.07)	7.77 (0.03)	7.77 (0.09)	8.00 (0.15)	7.80 (0.06)
0.3-0.6	8.37 (0.07)	8.23 (0.03)	8.20 (0.15)	8.17 (0.12)	8.27 (0.09)	8.30 (0.10)	8.33 (0.03)
0.6-0.9	8.90 (0.00)	8.60 (0.06)	8.55 (0.05)	8.50 (0.10)	8.60 (0.00)	--	--
0.9-1.2	--	--	--	--	--	--	--
Williston(irrigated)							
0-0.05	7.50 (0.00)	7.57 (0.03)	7.50 (0.06)	7.47 (0.03)	7.70 (0.06)	7.50 (0.21)	7.47 (0.07)
0.05-0.1	7.33 (0.03)	7.57 (0.09)	7.53 (0.09)	7.60 (0.00)	7.80 (0.06)	7.50 (0.20)	7.40 (0.15)
0.1-0.2	7.47 (0.07)	7.90 (0.10)	7.73 (0.15)	7.90 (0.06)	7.97 (0.09)	7.60 (0.26)	7.57 (0.22)
0.2-0.3*	7.73 (0.12)	8.17 (0.07)	7.87 (0.12)	8.03 (0.03)	8.17 (0.07)	7.70 (0.26)	7.80 (0.21)
0.3-0.6	8.00 (0.25)	8.37 (0.03)	8.03 (0.23)	8.37 (0.03)	8.47 (0.03)	7.67 (0.44)	7.80 (0.32)
0.6-0.9	8.30 (0.20)	--	8.07 (0.46)	8.20 (0.15)	8.00 (0.20)	7.47 (0.62)	8.30 (0.30)
0.9-1.2	--	--	--	--	--	--	--

† Values in parentheses represent standard error of the mean. * Comparison within depth significant at $P \leq 0.05$.

Table 11. Soil organic C, total N, and available P for seven perennial grass treatments in 2011. Results provided for three soil masses approximately equivalent to 0-0.3, 0-0.6, and 0-0.9 m depths.

Location / Soil mass (Mg ha^{-1})	Sunburst switchgrass	Trailblazer switchgrass	Tall wheatgrass	Intermediate wheatgrass	CRP mix	Switchgrass + Tall wheatgrass	Switchgrass + Big bluestem
Carrington	- - - - - - - - - - - - - - - Soil organic C (Mg C ha^{-1}) - - - - - - - - - - - - - - -						
3600 Mg ha^{-1}	95 (21)†	99 (20)	100 (23)	102 (18)	108 (18)	105 (13)	96 (16)
7300 Mg ha^{-1}	170 (60)	161 (46)	146 (34)	151 (26)	208 (66)	159 (21)	157 (41)
11300 Mg ha^{-1}	224 (77)	231 (60)	217 (33)	209 (5)	324 (150)	197 (22)	195 (47)
Hettinger							
3600 Mg ha^{-1}	61 (3)	56 (4)	60 (4)	64 (3)	62 (3)	66 (2)	55 (4)
7300 Mg ha^{-1}	99 (5)	97 (10)	107 (5)	108 (4)	106 (6)	110 (2)	96 (5)
11300 Mg ha^{-1}	130 (4)	131 (16)	140 (8)	141 (7)	138 (6)	145 (5)	138 (7)
Minot							
3600 Mg ha^{-1}	69 (8)	88 (13)	76 (6)	72 (12)	77 (2)	79 (17)	75 (8)
7300 Mg ha^{-1}	101 (4)	134 (20)	119 (7)	113 (5)	120 (5)	131 (18)	123 (11)
11300 Mg ha^{-1}	--	--	--	--	--	162 (21)	171 (24)
Streeter							
3600 Mg ha^{-1}	96 (3)	101 (1)	95 (3)	89 (3)	96 (3)	87 (10)	101 (4)
7300 Mg ha^{-1}	156 (9)	174 (10)	152 (11)	140 (9)	148 (14)	139 (8)	158 (9)
11300 Mg ha^{-1}	--	236 (2)	--	167 (17)	--	168 (1)	183 (24)
Williston (dryland)							
3600 Mg ha^{-1}	74 (5)	80 (12)	79 (12)	72 (9)	72 (3)	74 (9)	--
7300 Mg ha^{-1}	127 (6)	133 (11)	141 (20)	167 (20)	132 (3)	--	--
11300 Mg ha^{-1}	--	--	--	--	--	--	--
Williston (irrigated)							
3600 Mg ha^{-1}	82 (5)	94 (5)	86 (1)	85 (2)	84 (7)	89 (9)	80 (8)
7300 Mg ha^{-1}	135 (0.1)	--	146 (16)	132 (12)	137 (9)	137 (7)	130 (11)
11300 Mg ha^{-1}	--	--	--	--	--	--	--

Table 11. Cont'd.

Location / Soil mass (Mg ha^{-1})	Sunburst switchgrass	Trailblazer switchgrass	Tall wheatgrass	Intermediate wheatgrass	CRP mix	Switchgrass + Tall wheatgrass	Switchgrass + Big bluestem
Carrington	------------------------------ Total N (Mg N ha^{-1})					--------------------------------	
3600 Mg ha^{-1}	8.6 (1.7)	8.8 (1.7)	8.9 (1.9)	9.1 (1.5)	9.6 (1.5)	9.4 (1.0)	8.6 (1.3)
7300 Mg ha^{-1}	15.2 (5.0)	14.4 (3.8)	13.3 (2.9)	13.7 (2.1)	18.4 (5.3)	14.3 (1.9)	14.4 (3.5)
11300 Mg ha^{-1}	19.3 (7.0)	20.9 (5.5)	19.4 (3.6)	18.8 (1.2)	28.2 (12.1)	17.4 (2.3)	18.1 (4.3)
Hettinger							
3600 Mg ha^{-1}	5.5 (0.4)	5.5 (0.5)	5.5 (0.5)	5.7 (0.2)	5.8 (0.3)	6.1 (0.2)	5.2 (0.5)
7300 Mg ha^{-1}	8.8 (0.5)	9.1 (1.2)	9.1 (0.9)	9.1 (0.4)	8.9 (0.3)	9.6 (0.3)	8.1 (0.5)
11300 Mg ha^{-1}	11.2 (0.4)	11.8 (1.2)	11.5 (1.0)	11.6 (0.8)	11.3 (0.3)	12.0 (1.0)	11.0 (0.5)
Minot							
3600 Mg ha^{-1}	6.6 (0.7)	8.2 (1.0)	7.0 (0.5)	7.8 (0.1)	7.3 (0.1)	7.5 (1.3)	7.0 (0.6)
7300 Mg ha^{-1}	9.2 (1.6)	12.3 (2.6)	10.6 (1.3)	10.9 (0.2)	10.5 (0.1)	11.7 (2.5)	9.8 (0.8)
11300 Mg ha^{-1}	--	--	--	--	--	14.6 (3.4)	11.2 (0.9)
Streeter							
3600 Mg ha^{-1}	8.7 (0.5)	9.3 (0.2)	8.8 (0.3)	8.6 (0.4)	9.0 (0.3)	8.2 (0.6)	9.3 (0.1)
7300 Mg ha^{-1}	13.1 (1.6)	15.4 (0.7)	12.7 (0.8)	13.0 (0.5)	13.7 (0.9)	11.9 (1.0)	13.9 (0.7)
11300 Mg ha^{-1}	--	18.4 (0.9)	--	15.1 (0.7)	--	13.2 (1.6)	15.3 (1.1)
Williston(dryland)							
3600 Mg ha^{-1}	6.9 (0.4)	7.4 (0.9)	7.1 (0.8)	6.7 (0.8)	6.7 (0.3)	6.8 (0.6)	--
7300 Mg ha^{-1}	10.9 (0.3)	11.8 (1.1)	12.4 (1.6)	14.6 (2.2)	11.3 (0.4)	--	--
11300 Mg ha^{-1}	--	--	--	--	--	--	--
Williston(irrigated)							
3600 Mg ha^{-1}	7.5 (0.5)	8.1 (0.2)	8.0 (0.2)	7.8 (0.1)	7.7 (0.6)	8.4 (0.7)	7.4 (0.6)
7300 Mg ha^{-1}	11.5 (1.1)	--	12.4 (0.3)	11.5 (0.1)	11.6 (9)	12.6 (1.0)	12.3 (0.7)
11300 Mg ha^{-1}	--	--	--	--	--	--	--

Table 11. Cont'd.

Location / Soil mass (Mg ha^{-1})	Sunburst switchgrass	Trailblazer switchgrass	Tall wheatgrass	Intermediate wheatgrass	CRP mix	Switchgrass + Tall wheatgrass	Switchgrass + Big bluestem
Carrington	Available P (kg P ha^{-1})						
3600 Mg ha^{-1}	116 (48)	105 (35)	104 (33)	99 (19)	112 (47)	107 (15)	103 (34)
7300 Mg ha^{-1}	181 (107)	151 (74)	145 (69)	112 (25)	213 (135)	131 (24)	150 (73)
11300 Mg ha^{-1}	238 (160)	235 (141)	216 (109)	145 (35)	303 (221)	144 (28)	183 (100)
Hettinger							
3600 Mg ha^{-1}	39 (10)	35 (11)	40 (13)	29 (10)	42 (10)	37 (10)	43 (12)
7300 Mg ha^{-1}	41 (11)	40 (10)	49 (12)	35 (17)	55 (1)	41 (11)	41 (17)
11300 Mg ha^{-1}	46 (15)	43 (10)	55 (20)	58 (4)	56 (1)	--	46 (18)
Minot							
3600 Mg ha^{-1}	22 (8)	44 (21)	17 (1)	17 (1)	11 (1)	48 (25)	15 (2)
7300 Mg ha^{-1}	30 (6)	67 (56)	23 (2)	28 (5)	15 (2)	70 (37)	29 (10)
11300 Mg ha^{-1}	--	--	--	--	--	106 (56)	38 (13)
Streeter							
3600 Mg ha^{-1}	26 (9)	15 (4)	17 (4)	15 (3)	15 (1)	19 (2)	20 (5)
7300 Mg ha^{-1}	47 (12)	73 (40)	31 (3)	25 (3)	25 (2)	34 (4)	38 (5)
11300 Mg ha^{-1}	--	161 (98)	--	39 (7)	--	44 (1)	54 (19)
Williston(dryland)							
3600 Mg ha^{-1}	10 (5)	15 (1)	13 (1)	11 (2)	14 (1)	14 (3)	--
7300 Mg ha^{-1}	15 (12)	36 (15)	16 (1)	16 (3)	24 (1)	--	--
11300 Mg ha^{-1}	--	--	--	--	--	--	--
Williston(irrigated)							
3600 Mg ha^{-1}	36 (8)	32 (5)	33 (6)	33 (2)	29 (4)	31 (4)	26 (3)
7300 Mg ha^{-1}	46 (16)	--	49 (11)	44 (5)	43 (16)	46 (6)	36 (2)
11300 Mg ha^{-1}	--	--	--	--	--	--	--

† Values in parentheses represent standard error of the mean.

Table 12. Soil bulk density, electrical conductivity, and soil pH during the initial and 5-year samplings under annually harvested plant species treatments.

Location/Depth (m)	Soil bulk density (Mg m^{-3})		Electrical conductivity (dS m^{-1})		Soil pH (-log [H^+])	
	2006	2011	2006	2011	2006	2011
Carrington						
0-0.05	1.17 (0.03)†	1.30 (0.02)	0.38 (0.02)	0.27 (0.01)	7.02 (0.11)	6.96 (0.08)
0.05-0.1	1.36 (0.02)	1.50 (0.02)	0.28 (0.01)	0.20 (0.01)	6.45 (0.12)	6.80 (0.12)
0.1-0.2	1.35 (0.03)	1.49 (0.02)	0.29 (0.01)	0.17 (0.01)*	6.61 (0.13)	6.83 (0.12)
0.2-0.3	1.32 (0.02)	1.42 (0.03)	0.33 (0.02)	0.15 (0.01)*	6.82 (0.12)	7.09 (0.07)
0.3-0.6	1.32 (0.01)	1.37 (0.01)	0.30 (0.01)	0.16 (0.01)*	7.22 (0.07)	7.32 (0.07)
0.6-0.9	1.39 (0.03)	1.44 (0.02)	0.22 (0.01)	0.22 (0.02)	7.59 (0.13)	7.60 (0.11)
0.9-1.2	1.55 (0.03)	1.71 (0.01)	0.19 (0.01)	0.19 (0.02)	7.66 (0.17)	7.78 (0.13)
Hettinger						
0-0.05	1.48 (0.04)	1.34 (0.01)	0.29 (0.02)	0.36 (0.03)	6.88 (0.14)	6.73 (0.13)
0.05-0.1	1.60 (0.03)	1.60 (0.02)	0.28 (0.02)	0.25 (0.01)	7.39 (0.13)	7.14 (0.11)
0.1-0.2	1.49 (0.02)	1.57 (0.01)	0.30 (0.01)	0.25 (0.01)	7.67 (0.12)	7.60 (0.09)
0.2-0.3	1.51 (0.02)	1.51 (0.02)	0.34 (0.01)	0.25 (0.01)	8.09 (0.09)	7.98 (0.09)
0.3-0.6	1.45 (0.01)	1.49 (0.02)	0.32 (0.01)	0.25 (0.01)	8.50 (0.03)	8.40 (0.04)
0.6-0.9	1.46 (0.02)	1.51 (0.01)	0.32 (0.01)	0.32 (0.01)	8.72 (0.03)	8.56 (0.04)
0.9-1.2	1.46 (0.03)	1.46 (0.02)	0.42 (0.03)	0.43 (0.03)	8.81 (0.04)	8.68 (0.04)
Minot						
0-0.05	1.20 (0.02)	1.39 (0.02)*	0.22 (0.02)	0.23 (0.02)	6.31 (0.13)	6.36 (0.08)
0.05-0.1	1.37 (0.04)	1.54 (0.02)*	0.24 (0.02)	0.23 (0.03)	6.16 (0.13)	6.12 (0.09)
0.1-0.2	1.50 (0.02)	1.57 (0.01)	0.28 (0.02)	0.33 (0.07)	6.48 (0.15)	6.40 (0.10)
0.2-0.3	1.53 (0.02)	1.53 (0.02)	0.41 (0.04)	0.48 (0.11)	7.20 (0.16)	6.86 (0.15)
0.3-0.6	1.59 (0.02)	1.65 (0.01)	1.43 (0.25)	1.66 (0.29)	7.89 (0.15)	7.60 (0.16)
0.6-0.9	1.65 (0.02)	1.75 (0.01)	2.34 (0.25)	3.22 (0.35)	8.28 (0.10)	8.14 (0.11)
0.9-1.2	1.63 (0.03)	1.77 (0.01)	2.54 (0.24)	2.97 (0.38)	8.36 (0.07)	8.32 (0.07)

Table 12. Cont'd.

Location/Depth(m)	Soil bulk density (Mg m^{-3}) 2006	Soil bulk density (Mg m^{-3}) 2011	Electrical conductivity (dS m^{-1}) 2006	Electrical conductivity (dS m^{-1}) 2011	Soil pH (-log [H^+]) 2006	Soil pH (-log [H^+]) 2011
Streeter						
0-0.05	1.20 (0.03)	1.05 (0.01)	0.33 (0.02)	0.31 (0.01)	7.14 (0.11)	6.95 (0.08)
0.05-0.1	1.38 (0.02)	1.26 (0.01)*	0.34 (0.02)	0.27 (0.02)	7.20 (0.12)	7.09 (0.09)
0.1-0.2	1.30 (0.01)	1.22 (0.01)	0.34 (0.02)	0.26 (0.01)	7.28 (0.12)	7.18 (0.11)
0.2-0.3	1.39 (0.01)	1.28 (0.02)*	0.36 (0.02)	0.33 (0.03)	7.53 (0.12)	7.37 (0.12)
0.3-0.6	1.37 (0.02)	1.34 (0.01)	0.52 (0.07)	0.60 (0.06)	8.15 (0.13)	8.05 (0.09)
0.6-0.9	1.46 (0.03)	1.47 (0.02)	0.79 (0.16)	0.81 (0.14)	8.50 (0.09)	8.54 (0.09)
0.9-1.2	1.59 (0.03)	1.58 (0.04)	0.82 (0.10)	1.29 (0.36)	8.59 (0.10)	8.41 (0.12)
Williston (dryland)						
0-0.05	1.27 (0.02)	1.50 (0.03)*	0.31 (0.01)	0.21 (0.01)*	7.51 (0.09)	7.37 (0.06)
0.05-0.1	1.50 (0.02)	1.59 (0.02)	0.27 (0.01)	0.16 (0.01)*	7.48 (0.06)	7.36 (0.07)
0.1-0.2	1.55 (0.01)	1.67 (0.01)*	0.22 (0.01)	0.13 (0.01)*	7.59 (0.05)	7.63 (0.05)
0.2-0.3	1.50 (0.01)	1.55 (0.01)	0.23 (0.01)	0.13 (0.01)*	7.87 (0.05)	7.87 (0.04)
0.3-0.6	1.46 (0.03)	1.45 (0.02)	0.25 (0.01)	0.21 (0.01)*	8.43 (0.04)	8.27 (0.03)
0.6-0.9	1.54 (0.04)	1.59 (0.03)	0.26 (0.02)	0.20 (0.02)	8.83 (0.04)	8.61 (0.04)
0.9-1.2	--	--	--	--	--	--
Williston(irrigated)						
0-0.05	1.24 (0.02)	1.46 (0.02)*	0.48 (0.01)	0.26 (0.01)*	7.58 (0.06)	7.53 (0.03)
0.05-0.1	1.48 (0.03)	1.63 (0.02)	0.44 (0.02)	0.22 (0.01)*	7.42 (0.09)	7.53 (0.05)
0.1-0.2	1.53 (0.02)	1.63 (0.02)	0.41 (0.02)	0.19 (0.01)*	7.40 (0.09)	7.73 (0.06)
0.2-0.3	1.48 (0.02)	1.56 (0.01)	0.39 (0.02)	0.20 (0.01)*	7.65 (0.12)	7.92 (0.06)
0.3-0.6	1.48 (0.02)	1.50 (0.01)	0.36 (0.03)	0.22 (0.01)*	7.90 (0.15)	8.10 (0.10)
0.6-0.9	1.50 (0.03)	1.55 (0.03)	0.27 (0.02)	0.33 (0.05)	8.47 (0.15)	8.03 (0.16)
0.9-1.2	--	--	--	--	--	--

† Values in parentheses represent standard error of the mean. * Change from initial sampling within a depth significant at $P \leq 0.05$.

Table 13. Soil organic C, total N, and available P during the initial and 5-year samplings under annually harvested plant species treatments.

	Soil organic C (Mg C ha^{-1})		Total N (Mg N ha^{-1})		Available P (kg P ha^{-1})	
Location/Soil mass	2006	2011	2006	2011	2006	2011
Carrington						
3600 Mg ha^{-1}	99 (4)	101 (6)	8.9 (0.3)	9.0 (0.5)	161 (8)	106 (11)
7300 Mg ha^{-1}	147 (7)	162 (14)	13.6 (06)	14.6 (1.2)	222 (19)	152 (24)
11300 Mg ha^{-1}	169 (9)	224 (22)	15.8 (0.8)	19.9 (1.9)	225 (22)	205 (40)
Hettinger						
3600 Mg ha^{-1}	62 (3)	61 (1)	5.7 (0.2)	5.6 (0.1)	57 (3)	38 (4)
7300 Mg ha^{-1}	104 (4)	104 (2)	9.1 (0.3)	9.0 (0.2)	70 (3)	43 (4)
11300 Mg ha^{-1}	144 (8)	137 (3)	11.5 (0.4)	11.5 (0.2)	81 (3)	51 (4)
Minot						
3600 Mg ha^{-1}	66 (3)	77 (4)	6.5 (0.2)	7.3 (0.3)	62 (8)	25 (6)
7300 Mg ha^{-1}	104 (5)	121 (4)	9.5 (0.5)	10.7 (0.5)	90 (14)	37 (9)
11300 Mg ha^{-1}	135 (6)	160 (8)	11.4 (0.6)	12.9 (0.9)	125 (21)	59 (17)
Streeter						
3600 Mg ha^{-1}	90 (2)	95 (2)	8.6 (0.2)	8.9 (0.1)	15 (1)	18 (2)
7300 Mg ha^{-1}	146 (7)	153 (4)	12.9 (0.5)	13.4 (0.4)	19 (2)	40 (7)
11300 Mg ha^{-1}	190 (9)	187 (10)	15.0 (0.8)	15.5 (0.7)	26 (3)	71 (21)
Williston (dryland)						
3600 Mg ha^{-1}	61 (1)	75 (3)	5.4 (0.1)	6.9 (0.2)	7 (1)	13 (1)*
7300 Mg ha^{-1}	112 (3)	142 (6)*	8.5 (0.3)	12.2 (0.6)*	12 (1)	25 (4)
11300 Mg ha^{-1}	--	--	--	--	--	--
Williston (irrigated)						
3600 Mg ha^{-1}	75 (2)	86 (2)	6.9 (0.2)	7.8 (0.2)*	39 (2)	31 (2)
7300 Mg ha^{-1}	130 (3)	136 (5)	10.8 (0.3)	12.0 (0.3)	46 (3)	44 (3)
11300 Mg ha^{-1}	--	--	--	--	--	--

† Values in parentheses represent standard error of the mean. * Change from initial sampling within a depth significant at $P \leq 0.05$.

Figure 1. Approximate location of sites included in study.

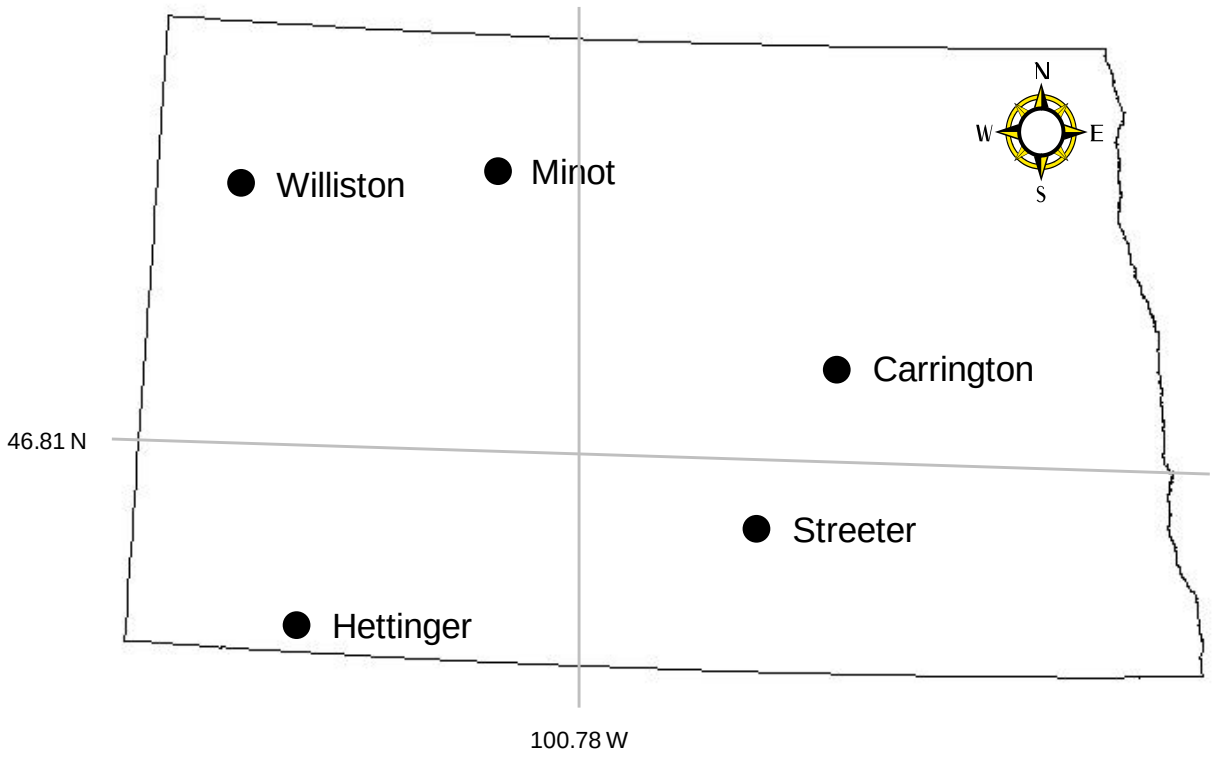
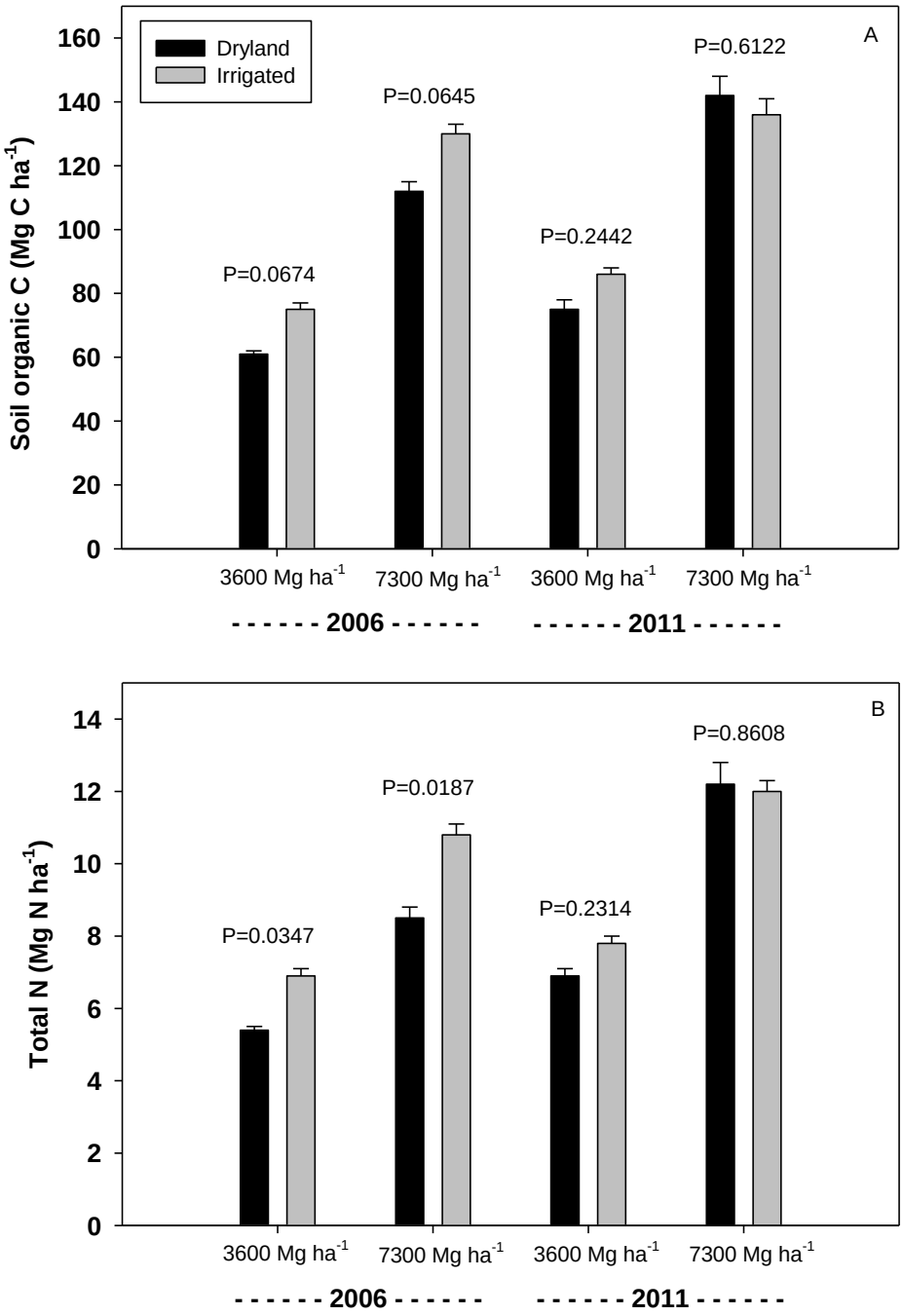


Figure 2. Soil organic C (A) and total N (B) for Williston dryland and irrigated plant species treatments at two soil masses (3600 and 7300 Mg ha^{-1}) in 2006 and 2011.



Evaluation of Perennial Herbaceous Biomass Crops in North Dakota– Impacts on Surface Soil Properties 2006-2011

Kristine Nichols, USDA-ARS, Northern Great Plains Research Laboratory, Mandan, ND

Abstract

The energy source for all animals, whether it has been food or fuel, comes from plants converting sunlight into carbon-based fuels. Because fossil fuels are a finite energy source and economic and social concerns exist in obtaining these fuels, alternative energy sources are being sought such as biofuels from perennial biomass. This project was designed to identify regionally appropriate and consistent high biomass perennials for the cold, semi-arid northern Great Plains. The environmental impacts, particularly soil parameters, of this production will be assessed. In this report, soil aggregation and glomalin production are reported. Soil aggregation is a major component of soil functions, such as water infiltration, water holding capacity, gas exchange, and nutrient cycling. The pore space provided between aggregates impacts water and gas movement whereas the aggregates themselves act as microbial habitats for nutrient cycling. Arbuscular mycorrhizal (AM) fungi provide nutrients to plants in exchange for carbon compounds by directly connecting plant roots and soil aggregates. Soil aggregates are formed and stabilized by AM fungi through the production of hyphae (i.e. fine threads) and glomalin, a sticky glycoprotein. Analysis showed that across all sites, treatments, and aggregate size classes only site and aggregate site class had significant differences between samples. For water-stable aggregation (WSA) and glomalin (measured as Bradford-reactive soil protein, BRSP) values, the Williston Dryland and Minot sites had the highest values in 2006 while in 2011 Carrington and Minot had the highest values. Within each site, only aggregate size class was significantly different. The differences between the aggregate size classes showed a shift from smaller aggregates to larger aggregates over the five years of production in this study.

Introduction

At the beginning of the last century, America's transportation system was fueled by biomass in the form of horses and mules to pull buggies, haul wagons, and drag plows. In the turn of the new century, biomass may again fuel America's transportation, but this time in the form of liquid fuels. Rather than converting corn into ethanol, dedicated warm and cool season perennial grasses, i.e. switchgrass, provide a carbohydrate source for ethanol conversion.

The increased use of agricultural commodities, corn, soybeans and their byproducts, for energy production results in resources moving away from feed and food production. Grasses for potential biofuel conversion have a low feed and food value and provide no competition on its final use. Additionally, because grasses can be grown in much more diverse areas, a dedicated energy crop like switchgrass offers a wider geographical impact than corn or soybeans and a perennial production system.

Based on a 1999 study of biomass feedstock availability in the United States, North Dakota ranks first in potential energy crops, such as switchgrass and other prairie grasses. North Dakota has over seven million acres of highly erodible crop land, with some counties in the western part of the state having as high as 91 percent of the crop land as highly erodible. Perennial energy crops would achieve more long-term sustainability on these lands by reducing

erosion, adding organic matter, reducing greenhouse gases, and sequestering carbon. Increases in amounts and stability of macroaggregates (i.e. aggregates ≥0.25 mm) improve soil sustainability by increasing water movement, gas exchange, nutrient cycling, and organic matter stability. When smaller soil particles are combined into soil aggregates, they resist wind or water erosive forces.

The North Dakota (ND) Natural Resources Trust has joined with the North Dakota State University (NDSU) Extension Service Research Experiment Stations, Northern Prairie Wildlife Research Center, USDA-ARS Northern Great Plains Research Laboratory in Mandan, ND, and ND Commerce Department on a dedicated bioenergy crop study to determine the appropriate grass species, harvest methods, and management practices to maintain productive stands. Surface (0-10 cm) soil properties were evaluated. These properties include the proportion of soil by weight in three aggregate size classes (1-2, 0.25-1, and 0.053-0.25 mm), the proportion of aggregates which are water stable, and the levels of Bradford-reactive protein in each size class.

Twenty different research plots were established at five research extension stations throughout central and western North Dakota with two locations – dryland and irrigated – at one location. The treatments include five grass species or mixes (two Switchgrass cultivars – Sunburst and Trailblazer, Tall Wheatgrass, Intermediate Wheatgrass, and the CRP mix); two harvest (annual or bi-annual); and with or without alfalfa. The individual grass species are two switchgrass *(Panicum virgatum)* cultivars – "Sunburst" and "Trailblazer" or "Dakota", "Alkar" tall wheatgrass *(Agropyron elongatum)*, and "Haymaker" intermediate wheatgrass *(Agropyron intermedium).* The mixes include: 1. a CRP mix with tall and intermediate wheatgrass; 2. a CRP mix with tall and intermediate wheatgrass plus alfalfa *(Medicago sativa)* and sweetclover *(Melilotus officinalis);* 3. "Sunburst" Switchgrass and tall wheatgrass; 4. "Sunburst" Switchgrass and "Sunnyview" big bluestem *(Andropogon gerardii)*; 5. "Sunburst" Switchgrass and "Mustang" alti wildrye *(Leymus angustus)*; and 6. "Mustang" alti wildrye and "Magnar" basin wildrye *(Leymus cinereus)*. This project is the first year of a ten year demonstration and research project. Soil samples were collected in 2006 for baseline measurement. In 2011, soil samples were again collected and analyzed.

The objective of this cooperative research project was to develop economically and environmentally sustainable uses for North Dakota's natural resources by comparing the productivity of perennial warm and cool season potential bioenergy grasses at the western edge of the historic switchgrass range. The results discussed here are for soil samples collected prior to seeding the plots in 2006 and after five years of growth in 2011.

Materials and Methods:

Twenty treatment plots replicated four times were established at NDSU Extension Service research experiment stations in Hettinger, Williston, Minot, Carrington, and Streeter (Table 1). The Williston location included both dryland and irrigated plots. Treatments were established in a split, split-plot design with ten main plot treatments including one of five plant species or mixes (two Switchgrass cultivars – Sunburst and Trailblazer, Tall Wheatgrass, Intermediate Wheatgrass, and CRP mix), and the sub-plots being two harvests (annual or bi-annual) and with or without alfalfa (Table 2). Plots are maintained and weeds controlled by NDSU staff at each location. Annually or bi-annually, above-ground biomass is harvested, weighed, cleaned, and analyzed for carbon and nitrogen concentration.

Soil analysis

Surface soil samples were collected from 0-10 cm with a garden trowel. The samples were air dried and then separated into size classes using a series of screens (2, 1, 0.25, and 0.053 mm) into dry aggregate size distribution (DASD). Aggregates were weighed and subsamples were removed for water-stable aggregation (WSA) (Nichols and Toro, 2011). Glomalin was extracted from another set of subsamples using an alkaline pyrophosphate solution with 1-hour long extractions at 121°C (Wright et al, 2006). Total protein was measured colorimetrically using the Bradford assay to give Bradford-reactive soil protein (BRSP) values (Rillig, 2004; Wright et al., 2006). Measurements from 2011 will be subtracted from the 2006 samples and are labeled DIFF. Soils data from the various treatments will be compared within and across location using PROC MIXED in SAS (SAS Institute, 1990). Multivariate analyses will be used to identify inherent and treatment-related factors contributing to enhanced soil quality under bioenergy crops. Analysis will be conducted across and within sites and aggregate size classes.

Results and Discussion

Surface (0-10 cm) soil samples were collected from three replicate plots at six sites (Table 1) with 20 perennial biomass crops (treatments, Table 2). These samples were collected in 2006 prior to the first planting and in 2011 after five years of growth. Soil aggregates were separated from these samples by passing the soil through a series of screens. These aggregates were tested for water stability and extracted for glomalin which is measured as BRSP. Mean values and standard errors (SE) are found for all the data collected in Appendices A-G.

Multivariate analysis was performed using site, treatment, and ASC as variable. Results of these analysis are found in Table 3. The data showed that there was no significant differences could be detected between samples for the site by treatment, treatment by ASC, and site by treatment by ASC interactions. Significant differences could be measured based and ASC and on site, except for the DASD data, and the interaction between site and ASC was also significant for all measurements. When trying to determine difference between treatments, only WSA values in 2006 and 2011 were significant. Multivariate analysis was also performed within each site to determine difference between treatments, ASC, and the interaction of treatment by ACS (Table 4). This data should that ASC again provided the most significant differences between samples.

For all sites and treatments, the middle ASC (0.25-1 mm) had the highest DASD and WSA values during both sampling periods, but the largest aggregate size class had the greatest increase over the five years of production (Table 5). The BRSP values did not follow this same pattern but rather the smallest size class had the highest values. Over the five production years, the BRSP in the 1-2 mm aggregates increased by 12%.

For each parameter measured, there was a significant difference between the sites (Table 6). Overall, the Minot site had the highest WSA values in both 2006 and 2011, but the Williston dryland and Minot sites had the highest BRSP values in 2006 sites. In 2011, the highest BRSP values were at the Carrington site.

When statistical analysis was performed without examining any interactions between the variables, treatment did not have a significant difference from any of the measurements (Table 7). Although a significant difference could not be detected by treatments, in 2006 WSA was highest in treatments 15 and 19 and BRSP was highest in 5 and 13. In 2011, WSA values were highest in 18 and 19 and BRSP in 2 and 12. The greatest increases in values were in treatments 4

and 19 for WSA and 9 and 11 for BRSP values. These data indicated no real trend between treatments.

Since ASC had the most influence on differences between treatments, data which combined ASC and site and ASC and treatment were examined more closely for DASD and WSA treatments in Tables 8-11 and Figures 1-4. Figures 1 and 3 showed that most values increased over the five year production period. Figures 2 and 4 showed a clearly visible shift from smaller aggregates into larger aggregates. The hierarchical theory of aggregate formation states that smaller aggregates may be combined by AM hyphae and fine roots into larger aggregates which is supported by the data presented here.

Conclusions:

- A significant difference could not be detected between treatments across all six sites for the DASD (Figure 1) and WSA (Figure 2) values (Table 3). A site difference was detected for the WSA and BRSP values.
- A difference was found between the three ASC (1-2, 0.25-1, and 0.053-0.25 mm) across all the sites and within each site (Table 3). This difference was detected in both baseline samples collected in 2006 and in samples collected 2011 after 5 years of growth as well as the difference between these two sampling periods.
- The data showed that over the five years of growth more soil was distributed into the largest ASC while it declined in the two smaller sizes.
- In 2006, the BRSP amounts of glomalin also differed by ASC rather than treatment. However, in 2011, because the main difference in aggregation was the shift to the largest ASC and no treatment difference was detected between treatments, BRSP was only extracted from the largest ASC. A site difference was detected but a treatment difference was not.
- Combined this data indicates that perennial growth may improve soil quality. Larger aggregates increase pore space which improves air and water movement and reduces compaction. Larger aggregates act as microbial habitats for increased nutrient cycling.

References:

Adler, P.R., S.J. Del Grosso, and W.J. Parton. 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecol. Appl. 17(3):675-691.

Andrews, S.S., D.L. Karlen, and C.A. Cambardella. 2004. The soil management assessment framework: A quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 68, 1945-1962.

Frank, A.B., J.D. Berdahl, J.D. Hanson, M.A. Liebig, and H.A. Johnson. 2004. Biomass and carbon partitioning in switchgrass. Crop Sci. 44:1391-1396.

Garten, C.T. Jr, and S.D. Wullschleger. 2000. Soil carbon dynamics beneath switchgrass as indicated by stable isotope analysis. J. Environ. Qual. 29:645-653.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proc. Nat. Acad. Sci. 103(30):11206-11210.Nichols, K.A., Toro, M. 2011. A whole soil stability index (WSSI) for evaluating soil aggregation. Soil Till. Res. 111:99-104.

Liebig, M.A., M.R. Schmer, K.P. Vogel, and R. Mitchell. 2008. Soil carbon storage by switchgrass grown for bioenergy. Bioe. Res. 1: 215-222.

Liebig, M.A., H.A. Johnson, J.D. Hanson, and A.B. Frank. 2005. Soil carbon under switchgrass stands and cultivated cropland. Biom. Bioe. 28(4):347-354.

Littell, R.C., G.A. Milliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS system for mixed models. SAS Inst., Inc. Cary, NC.

Ma, Z., C.W. Wood, and D.I. Bransby. 2000. Carbon dynamics subsequent to establishment of switchgrass. Biom. Bioe. 18:93-104.

McLaughlin, S.B. D.G. De La Torre Ugarte, C.T. Garten Jr., L.R. Lynd, M.A. Sanderson, V.R. Tolbert, and D.D. Wolf. 2002. High-value renewable energy from prairie grasses. Environ. Sci. Tech. 36(10):2122-2129.

NDSU Central Grasslands Research Extension Center (CGREC). 2012. Biofuels research. http://www.ag.ndsu.edu/CentralGrasslandsREC/ (verified 13 March 2012).

Nichols, K.A. 2008. Indirect contributions of AM fungi and soil aggregation to plant growth and protection. In: Z.A. Siddiqui, M. S. Akhtar, and K. Futai (eds.) Mycorrhizae: Sustainable Agriculture and Forestry. Springer, The Netherlands. pp. 177-194.

Nichols, K.A., Wright, S.F. 2004. Contributions of soil fungi to organic matter in agricultural soils. In: Soil Organic Matter in Sustainable Agriculture. F. Magdoff and R. Weil (Eds.). CRC Press.

Rillig, M.C. 2004. Arbuscular mycorrhizae, glomalin, and soil aggregation. Can. J. Soil Sci. 84: 355-363.

Scharlemann, J.P.W., and W.F. Laurance. 2008. How green are biofuels? Science 319:43-44.

Schmer, M.R., M.A. Liebig, K.P. Vogel, and R. Mitchell. 2011. Field-scale soil property changes under switchgrass managed for bioenergy. Global Change Biol. Bioe. 3:439-448.

Schmer, M.R., K.P. Vogel, R.B. Mitchell, and R.K. Perrin. 2008. Net energy of cellulosic ethanol from switchgrass. Proc. Nat. Acad. Sci. 105(2):464-469.

USDA Natural Resources Conservation Service (NRCS). 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin U.S. Department of Agriculture Handbook No. 296. U.S. Govt. Printing Office. Washington, D,C.

USDA Natural Resources Conservation Service (NRCS). 1999. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd Ed. USDA-NRCS Soil Survey Staff. U.S. Dep. of Agric. Handbook No. 436. U.S. Govt. Printing Office. Washington, D.C.

USDA. 1993. Soil survey manual. USDA Soil Survey Division Staff. U.S. Dep. of Agric. Handbook No. 18. U.S. Govt. Printing Office. Washington, D.C.

Walsh, M.E. 1998. U.S. bioenergy crop economic analyses: status and needs. Biom. Bioe. 14:341-350.

Wright, S.F., K.A. Nichols, and W.F. Schmidt. 2006. Comparison of efficacy of three extractants to solubilize glomalin on hyphae and in soil. Chemosphere. 64 (7): 1219-1224.

Xue, Q., Nyren, P.E., Wang, G., Eriksmoen, E., Bradbury, G., Halverson, M., Aberle, E., Nichols, K., Liebig, M. 2011. Biomass composition of perennial grasses for biofuel production in North Dakota, USA. Biofuels. 2(5): 515-528.

Table 1. List of sites

Site	Site Description
1	Carrington
2	Hettinger
3	Streeter
4	Minot
5	Williston – Dryland
6	Williston- Irrigated

Table 2. List of treatments

Treatment ID	Plant Mix	Harvest
1	Sunburst Switchgrass	Annual
2		Biennial
3	Trailblazer or Dakota Switchgrass	Annual
4		Biennial
5	Alkar Tall Wheatgrass	Annual
6		Biennial
7	Haymaker Intermediate Wheatgrass	Annual
8		Biennial
9	CRP Mix 1 (Intermediate and Tall Wheatgrass)	Annual
10		Biennial
11	CRP Mix 2 (Wheatgrass, Alfalfa, and Sweet Clover)	Annual
12		Biennial
13	Sunburst Switchgrass and Tall Wheatgrass	Annual
14		Biennial
15	Sunburst Switchgrass and Sunnyview Big Bluestem	Annual
16		Biennial
17	Sunburst Switchgrass and Mustang Alti Wildrye	Annual
18		Biennial
19	Magnar Basin and Mustang Alti Wildrye	Annual
20		Biennial

Table 3. Statistical analysis results across sites, treatments (TRT), and aggregate size classes (ASC) for dry aggregate size distribution (DASD), water-stable aggregation (WSA), and Bradford-reactive soil protein (BRSP) for both the 2006 and 2011 sampling periods and the difference (Diff) between these two sampling periods. Significant differences can be distinguished at a Prob>F≤0.05.

		Site	Trt	Site X Trt	ACS	Site X ACS	Trt X ASC	Site X Trt X ACS
	DASD	1.0000	1.0000	1.0000	<0.0001	<0.0001	0.9611	1.0000
2006	**WSA**	<0.0001	0.0260	0.9620	<0.0001	<0.0001	0.6302	1.0000
	BRSP	<0.0001	0.1552	0.9999	<0.0001	<0.0001	0.9043	1.0000
	DASD	1.0000	1.0000	1.0000	<0.0001	<0.0001	0.0784	0.0109
2011	**WSA**	<0.0001	0.0179	0.1104	<0.0001	<0.0001	0.6237	0.9986
	BRSP	<0.0001	0.9326	1.0000	NA	NA	NA	NA
	DASD	1.0000	1.0000	1.0000	<0.0001	<0.0001	0.9879	0.9391
Diff	**WSA**	<0.0001	0.1886	0.4087	<0.0001	<0.0001	0.5883	0.9977
	BRSP	<0.0001	0.7437	1.0000	NA	NA	NA	NA

NA = Data not available

Table 4. Statistical analysis of within site variation for a multi-variate model using treatment (TRT) and aggregate size class (ASC) for dry aggregate size distribution (DASD), water-stable aggregation (WSA), and Bradford-reactive soil protein (BRSP) in 2006 and 2011 and the difference (Diff) between these two sampling periods.

Value	Analysis	Carrington	Hettinger	Minot	Streeter	Williston - Dryland	Williston - Irrigated
DASD 2006	TRT	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	ACS	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	TRT X ACS	0.9999	0.7697	0.8881	0.1767	0.0419	1.0000
DASD 2011	TRT	1.0000	1.0000	1.0000	1.0000	1.0000	0.7415
	ACS	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	TRT X ACS	0.1435	0.0667	0.0564	0.3549	0.7882	0.0321
DASD DIFF	TRT	1.0000	1.0000	1.0000	1.0000	1.0000	0.9775
	ACS	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	TRT X ACS	0.9753	0.5072	0.0297	0.4368	0.9635	0.8454
WSA 2006	TRT	0.3281	0.0046	0.4542	0.0041	0.9696	0.8569
	ACS	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	TRT X ACS	0.7015	0.6009	0.8948	0.7734	0.9578	0.9966
WSA 2011	TRT	<0.0001	0.2125	0.6610	0.2257	0.4889	0.2559
	ACS	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	TRT X ACS	0.0885	0.9608	0.5551	0.6861	0.9199	0.9971
WSA DIFF	TRT	0.0554	<0.0001	0.7802	0.3810	0.7963	0.5518
	ACS	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	TRT X ACS	0.3875	0.0076	0.8116	0.8461	0.9783	0.7707
BRSP 2006	TRT	0.7187	0.3533	0.5832	0.3803	<0.0001	0.9648
	ACS	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	TRT X ACS	1.0000	1.0000	0.9998	0.9987	<0.0001	1.0000

Table 5. The dry aggregate size distribution (DASD) for each aggregate size class (ASC) for baseline samples collected in 2006 and samples collected in 2011 and the differences (Diff) between these values. Values are means ± standard errors. Values in a row followed by a different letter are significantly different at Prob>F ≤ 0.05.

	ASC			
Measurement	**1**	**2**	**3**	**Prob>F**
DASD 2006	23.168 ±0.277[b]	56.267 ±0.308[a]	20.565 ±0.282[c]	<0.001
DASD 2011	36.248±0.458[b]	48.663±0.466[a]	15.115±0.273[c]	<0.001
DASD Diff	12.630±0.425[a]	-6.940±0.322[c]	-5.660±0.393[b]	<0.001
WSA 2006	41.530±0.729[c]	70.264±0.488[a]	60.357±0.341[b]	<0.001
WSA 2011	59.736±1.045[b]	72.156±0.942[a]	59.273±0.875[b]	<0.001
WSA Diff	19.083±0.616[a]	1.303±0.490[b]	-1.526±0.798[c]	<0.001
BRSP 2006	3.894±0.074[b]	3.748±0.058[b]	6.760±0.097[a]	<0.001
BRSP 2011	4.408±0.065	NA	NA	NA
BRSP Diff	0.469±0.106	NA	NA	NA

Table 6. The percentage of water-stable aggregates (WSA) and Bradford-reactive soil protein (BRSP) for each site (Table 1) for baseline samples collected in 2006 and samples collected in 2011 and the differences (Diff) between these values. Values are means ± standard errors. Values in a column followed by a different letter are significantly different at Prob>F ≤ 0.05.

Site	WSA 2006	WSA 2011	WSA Diff	BRSP 2006	BRSP 2011	BRSP Diff
1	58.554 ±0.968[b]	64.341 ±1.020[b]	5.788 ±1.158[b]	4.489 ±0.102[b]	6.039 ±0.151[a]	2.672 ±0.230[a]
2	54.140 ±1.629[c]	55.448 ±1.612[c]	1.308 ±0.325[c]	4.401 ±0.109[b]	3.430 ±0.072[e]	-0.005 ±0.245[c]
3	49.249 ±1.363[s]	57.623 ±0.690[c]	20.259 ±1.142[c]	4.500 ±0.095[b]	4.257 ±0.089[c]	-0.366 ±0.211[d]
4	66.040 ±0.866[a]	86.764 ±0.719[a]	20.551 ±0.555[a]	4.688 ±0.094[b]	5.038 ±0.057[b]	0.630 ±0.135[b]
5	58.896 ±0.307[b]	51.849 ±0.992[b]	-7.983 ±1.219[d]	5.714 ±0.104[a]	3.412 ±0.048[e]	0.789 ±0.051[b]
6	57.422 ±0.415[b]	64.013 ±0.988[b]	5.942 ±0.898[b]	4.161 ±0.167[c]	3.727 ±0.081[d]	-1.642 ±0.180[e]
Prob> F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Table 7. The percentage of water-stable aggregates (WSA) and Bradford-reactive soil protein (BRSP) for each site (Table 1) for baseline samples collected in 2006 and samples collected in 2011 and the differences (Diff) between these values. Values are means ± standard errors.

Trt	WSA 2006	WSA 2011	WSA Diff	BRSP 2006	BRSP 2011	BRSP Diff
1	55.918 ±1.983	63.174 ±2.577	7.924 ±2.126	4.918 ±0.257	4.332 ±0.341	0.494 ±0.463
2	57.905 ±1.995	63.421 ±2.581	5.730 ±2.163	5.024 ±0.277	4.635 ±0.334	0.268 ±0.576
3	58.093 ±2.041	64.064 ±2.615	6.757 ±2.161	4.847 ±0.265	4.446 ±0.301	0.647 ±0.473
4	56.114 ±2.046	62.845 ±2.556	8.061 ±2.149	4.739 ±0.241	4.284 ±0.298	0.283 ±0.503
5	56.323 ±2.009	62.579 ±2.643	7.197 ±2.051	5.060 ±0.306	4.527 ±0.333	0.601 ±0.510
6	57.601 ±2.047	61.510 ±2.786	4.570 ±1.982	4.597 ±0.233	4.229 ±0.321	0.285 ±0.496
7	58.318 ±1.936	65.024 ±2.555	7.344 ±2.047	4.776 ±0.245	4.505 ±0.299	0.527 ±0.438
8	57.275 ±2.038	63.864 ±2.639	7.183 ±2.500	4.598 ±0.250	4.416 ±0.272	0.452 ±0.484
9	56.509 ±1.994	62.971 ±2.505	7.142 ±1.992	4.677 ±0.271	4.510 ±0.360	0.830 ±0.522
10	57.821 ±2.000	62.945 ±2.671	5.423 ±2.154	4.569 ±0.250	4.486 ±0.226	0.575 ±0.457
11	57.372 ±1.971	63.074 ±2.670	6.673 ±2.230	4.5448 ±0.237	4.598 ±0.333	1.063 ±0.443
12	57.465 ±1.982	62.728 ±2.676	6.548 ±2.203	4.671 ±0.234	4.694 ±0.332	0.673 ±0.533
13	57.264 ±2.045	62.033 ±2.524	5.283 ±1.978	5.048 ±0.301	4.542 ±0.328	0.490 ±0.486
14	57.698 ±1.970	62.336 ±2.579	5.204 ±1.881	4.648 ±0.240	4.410 ±0.301	0.320 ±0.442
15	58.624 ±1.950	64.234 ±2.604	5.974 ±2.103	4.850 ±0.283	4.162 ±0.279	0.408 ±0.423
16	57.383 ±2.010	62.442 ±2.569	5.676 ±2.150	4.524 ±0.242	4.258 ±0.244	0.306 ±0.498
17	57.279 ±2.107	63.051 ±2.626	6.406 ±2.032	5.004 ±0.281	4.442 ±0.258	0.374 ±0.482

Table 7 Con’t

18	57.826 ±1.972	64.579 ±2.605	6.786 ±2.066	4.712 ±0.256	4.224 ±0.275	-0.003 ±0.513
19	58.251 ±1.888	65.851 ±2.614	8.279 ±2.171	4.678 ±0.274	4.349 ±0.226	0.430 ±0.422
20	56.633 ±2.021	62.833 ±2.656	6.869 ±2.185	4.304 ±0.230	4.103 ±0.241	0.352 ±0.450

Table 8. The dry aggregate size distribution (DASD) for each site (Table 1) and aggregate size class (ACS) for baseline samples collected in 2006 and samples collected in 2011 and the differences (Diff) between these values. Values are means ± standard errors.

	DASD 2006			DASD 2011			DASD Diff		
Site	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	23.464 ±0.423	47.152 ±0.342	29.385 ±0.687	42.675 ±0.829	42.849 ±0.378	14.476 ±0.585	19.212 ±1.132	-4.303 ±0.376	-14.909 ±1.155
2	30.882 ±0.544	53.715 ±0.372	15.403 ±0.314	42.224 ±0.634	45.703 ±0.544	12.073 ±0.305	11.342 ±0.643	-8.012 ±0.624	-3.330 ±0.359
3	21.745 ±0.318	55.373 ±0.275	22.882 ±0.277	38.975 ±0.628	38.262 ±0.461	22.764 ±0.654	17.263 ±0.769	-17.084 ±0.384	-0.179 ±0.754
4	26.506 ±0.344	53.227 ±0.231	20.266 ±0.300	36.940 ±0.622	46.853 ±0.626	16.207 ±0.509	10.648 ±0.675	-6.755 ±0.693	-3.893 ±0.625
5	14.726 ±0.179	63.288 ±0.229	21.986 ±0.260	23.041 ±0.500	61.696 ±0.356	15.263 ±0.549	8.628 ±0.517	-1.581 ±0.399	-7.047 ±0.627
6	21.683 ±0.455	64.847 ±0.442	13.469 ±0.193	29.498 ±0.948	59.541 ±0.720	11.134 ±0.305	6.945 ±1.235	-4.451 ±0.653	-2.322 ±0.377

Table 9. The percentage of water-stable aggregates (WSA) for each site (Table 1) and aggregate size class (ACS) for baseline samples collected in 2006 and samples collected in 2011 and the differences (Diff) between these values. Values are means ± standard errors.

	WSA 2006			WSA 2011			WSA Diff		
Site	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	42.553 ±0.622	76.150 ±0.483	56.958 ±0.741	68.052 ±0.888	79.935 ±0.412	45.036 ±0.719	25.500 ±1.086	3.785 ±0.814	-11.922 ±1.180
2	20.421 ±0.492	79.244 ±0.348	62.756 ±0.632	23.263 ±0.568	82.251 ±0.317	60.830 ±0.770	2.841 ±0.627	3.007 ±0.457	-1.926 ±0.398
3	22.084 ±0.407	72.856 ±0.376	52.806 ±0.373	53.238 ±1.056	NA	62.008 ±0.364	31.002 ±1.061	NA	9.517 ±0.469
4	48.764 ±0.543	79.695 ±0.305	69.663 ±0.370	74.413 ±0.868	92.096 ±0.208	93.783 ±0.100	25.824 ±0.893	12.479 ±0.331	23.350 ±0.432
5	55.484 ±0.447	58.465 ±0.323	62.739 ±0.468	68.592 ±0.841	47.104 ±0.628	39.850 ±0.536	11.989 ±0.996	-11.246 ±0.684	-24.693 ±0.623
6	59.875 ±0.453	55.172 ±0.817	57.219 ±0.742	80.244 ±0.489	53.438 ±0.986	58.358 ±0.879	20.614 ±0.651	-2.904 ±0.626	0.117 ±0.986

Table 10. The dry aggregate size distribution (DASD) for each treatment (Trt, Table 2) and aggregate size class (ACS) for baseline samples collected in 2006 and samples collected in 2011 and the differences (Diff) between these values. Values are means ± standard errors.

	DASD 2006			DASD 2011			DASD Diff		
TRT	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	22.693 ±1.075	55.941 ±1.348	21.365 ±1.343	34.311 ±1.790	48.081 ±2.009	16.449 ±1.251	11.080 ±1.356	-7.250 ±1.709	-4.990 ±1.773
2	23.407 ±1.082	55.278 ±1.214	21.315 ±1.218	39.457 ±2.115	46.355 ±2.180	14.218 ±1.247	15.757 ±2.126	-8.607 ±1.589	-7.121 ±1.737
3	23.711 ±1.420	56.167 ±1.431	20.122 ±1.251	36.324 ±2.072	48.929 ±2.235	15.272 ±1.097	12.309 ±1.763	-6.760 ±1.344	-5.024 ±1.480
4	23.161 ±1.218	55.657 ±1.518	21.182 ±1.371	35.772 ±2.310	48.142 ±1.963	15.823 ±1.676	12.228 ±2.386	-6.814 ±1.611	-5.677 ±2.440
5	22.617 ±1.070	56.689 ±1.331	20.694 ±1.110	36.233 ±2.083	49.018 ±2.294	15.169 ±1.027	13.097 ±2.106	-6.787 ±1.588	-5.890 ±1.675
6	23.548 ±1.487	56.649 ±1.672	19.803 ±1.406	37.321 ±2.021	49.151 ±2.123	13.947 ±1.330	13.325 ±1.940	-6.762 ±1.660	-6.144 ±1.985
7	22.642 ±1.231	56.809 ±1.397	20.550 ±1.104	34.542 ±2.082	50.641 ±1.955	15.104 ±1.078	11.608 ±1.710	-5.582 ±1.377	-5.740 ±1.192
8	22.158 ±1.087	56.256 ±1.374	21.586 ±1.379	35.611 ±2.315	48.049 ±2.265	15.277 ±1.246	13.078 ±2.070	-7.510 ±1.214	-6.631 ±1.983
9	22.828 ±1.199	56.770 ±1.454	20.402 ±1.320	36.988 ±1.673	50.126 ±2.121	13.761 ±0.993	13.724 ±1.373	-5.872 ±1.197	-6.978 ±1.429
10	22.941 ±1.254	56.276 ±1.335	20.783 ±1.244	35.977 ±2.155	48.824 ±2.041	14.946 ±1.474	12.266 ±1.977	-6.682 ±1.475	-5.837 ±2.063
11	22.560 ±1.057	57.001 ±1.433	20.438 ±1.304	34.525 ±2.221	50.604 ±2.502	15.833 ±1.027	11.488 ±1.779	-5.772 ±1.706	-4.754 ±1.688
12	23.464 ±1.279	56.425 ±1.226	20.111 ±1.159	34.823 ±2.865	48.959 ±2.192	15.060 ±1.088	10.963 ±2.510	-6.891 ±1.584	-5.231 ±1.829
13	23.240 ±1.278	56.478 ±1.363	20.282 ±1.210	36.389 ±1.895	48.401 ±2.109	15.259 ±1.026	12.695 ±1.832	-7.406 ±1.629	-5.239 ±1.463
14	23.261 ±1.358	56.741 ±1.503	19.998 ±1.565	36.054 ±2.010	48.868 ±2.171	15.227 ±1.493	12.361 ±1.931	-6.752 ±1.491	-5.459 ±2.301
15	23.312 ±1.187	56.546 ±1.358	20.142 ±1.147	35.811 ±1.971	48.870 ±1.955	15.130 ±1.190	12.233 ±1.582	-7.147 ±1.347	-5.274 ±1.433
16	23.612 ±1.397	56.167 ±1.467	20.221 ±1.413	37.621 ±2.463	47.106 ±2.163	15.653 ±1.630	13.680 ±2.366	-8.423 ±1.212	-4.877 ±2.231
17	23.562 ±1.264	55.992 ±1.472	20.446 ±1.147	36.206 ±1.741	48.460 ±2.004	15.070 ±1.131	12.479 ±1.909	-6.906 ±1.405	-5.837 ±1.335

Table 10 Con't

18	23.646 ±1.338	55.868 ±1.359	20.485 ±1.3031	37.331 ±1.917	46.975 ±1.963	14.955 ±1.353	12.747 ±1.688	-8.113 ±1.370	-5.373 ±1.867
19	23.748 ±1.336	55.860 ±1.333	20.392 ±1.274	36.815 ±1.733	48.562 ±2.018	15.967 ±1.117	12.608 ±1.731	-6.652 ±1.392	-4.611 ±1.431
20	23.241 ±1.434	55.772 ±1.386	20.987 ±1.305	36.846 ±2.119	49.144 ±2.036	14.177 ±1.113	12.943 ±2.029	-6.180 ±1.216	-6.596 ±1.903

Table 11. The percentage of water-stable aggregates (WSA) for each treatment (Trt, Table 2) and aggregate size class (ACS) for baseline samples collected in 2006 and samples collected in 2011 and the differences (Diff) between these values. Values are means ± standard errors.

	WSA 2006			WSA 2011			WSA Diff		
Trt	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	38.484 ±3.068	69.375 ±1.779	59.896 ±1.440	58.326 ±4.614	71.975 ±4.478	60.541 ±3.885	20.414 ±2.638	2.328 ±2.680	0.191 ±3.621
2	41.766 ±3.371	70.344 ±2.119	61.604 ±1.534	60.075 ±4.739	73.297 ±3.817	58.372 ±4.098	18.894 ±2.781	1.400 ±1.785	-3.753 ±3.820
3	43.038 ±3.497	71.365 ±2.450	59.875 ±1.641	63.087 ±4.714	71.937 ±4.592	58.351 ±3.948	20.847 ±2.839	-0.166 ±2.171	-1.449 ±3.417
4	38.988 ±3.335	69.417 ±2.111	59.938 ±1.457	58.546 ±4.547	72.703 ±4.145	58.765 ±3.962	20.911 ±2.964	3.497 ±2.234	-0.910 ±3.456
5	40.198 ±3.378	69.063 ±2.193	59.708 ±1.513	57.985 ±4.861	72.048 ±4.303	59.124 ±4.006	19.053 ±3.001	2.548 ±2.309	-0.851 ±3.278
6	42.481 ±3.521	70.365 ±2.436	59.958 ±1.791	56.683 ±5.277	70.688 ±4.552	58.534 ±4.130	15.056 ±2.847	-0.194 ±2.195	-1.866 ±3.531
7	43.696 ±3.210	71.125 ±2.389	60.132 ±1.454	63.244 ±4.766	72.332 ±4.466	60.592 ±3.776	20.290 ±2.747	0.156 ±2.105	0.508 ±3.301
8	39.939 ±3.301	70.250 ±2.108	61.635 ±1.367	61.956 ±4.751	71.701 ±4.213	59.111 ±4.368	22.829 ±2.931	0.848 ±2.315	-3.077 ±4.455
9	41.047 ±3.493	68.688 ±2.279	59.792 ±1.456	59.000 ±4.557	71.481 ±4.186	59.707 ±3.843	19.200 ±2.395	1.996 ±2.125	-0.543 ±3.525
10	42.016 ±3.313	70.427 ±2.227	61.021 ±1.699	59.287 ±5.172	72.229 ±3.942	58.711 ±4.066	18.100 ±2.986	0.405 ±2.228	-2.989 ±3.633
11	42.802 ±3.359	69.938 ±2.472	59.375 ±1.524	61.532 ±4.835	71.007 ±4.844	57.875 ±3.916	20.026 ±2.923	0.639 ±2.619	-1.550 ±3.710
12	41.425 ±3.241	69.802 ±2.300	61.167 ±1.480	59.284 ±4.719	72.140 ±4.447	58.172 ±4.247	19.409 ±3.079	2.626 ±2.034	-2.978 ±3.760
13	41.432 ±3.542	70.194 ±2.234	60.167 ±1.627	57.344 ±4.278	71.321 ±4.420	58.828 ±3.957	16.281 ±2.182	1.145 ±2.263	-2.197 ±3.789
14	42.083 ±3.154	71.135 ±2.253	59.875 ±1.506	57.228 ±4.472	72.450 ±4.319	58.846 ±3.992	15.465 ±2.454	1.318 ±2.080	-1.754 ±3.443
15	43.905 ±3.200	71.844 ±2.265	60.125 ±1.652	61.342 ±5.053	72.696 ±4.132	59.934 ±3.821	17.500 ±3.275	0.372 ±2.186	-0.791 ±3.507
16	41.186 ±3.373	69.719 ±2.199	61.243 ±1.590	58.418 ±4.146	72.491 ±4.502	57.925 ±4.160	18.426 ±2.700	2.226 ±2.272	-4.141 ±3.700

Table 11 con’t

17	41.021 ±3.446	69.920 ±1.994	60.896 ±1.675	57.781 ±4.773	72.549 ±4.188	60.247 ±4.082	17.768 ±2.360	1.990 ±2.459	-1.203 ±3.753
18	42.050 ±3.248	70.156 ±2.311	61.271 ±1.481	60.465 ±4.882	73.284 ±4.066	61.295 ±4.059	19.554 ±2.336	0.931 ±2.055	-1.005 ±3.748
19	43.043 ±2.856	72.063 ±2.051	59.646 ±1.467	63.117 ±5.161	73.296 ±4.278	62.259 ±3.754	20.698 ±3.083	0.931 ±2.372	2.134 ±3.674
20	40.003 ±3.244	70.083 ±2.138	59.813 ±1.552	60.019 ±4.887	71.504 ±4.601	58.278 ±3.916	20.933 ±2.954	1.107 ±2.178	-2.297 ±3.416

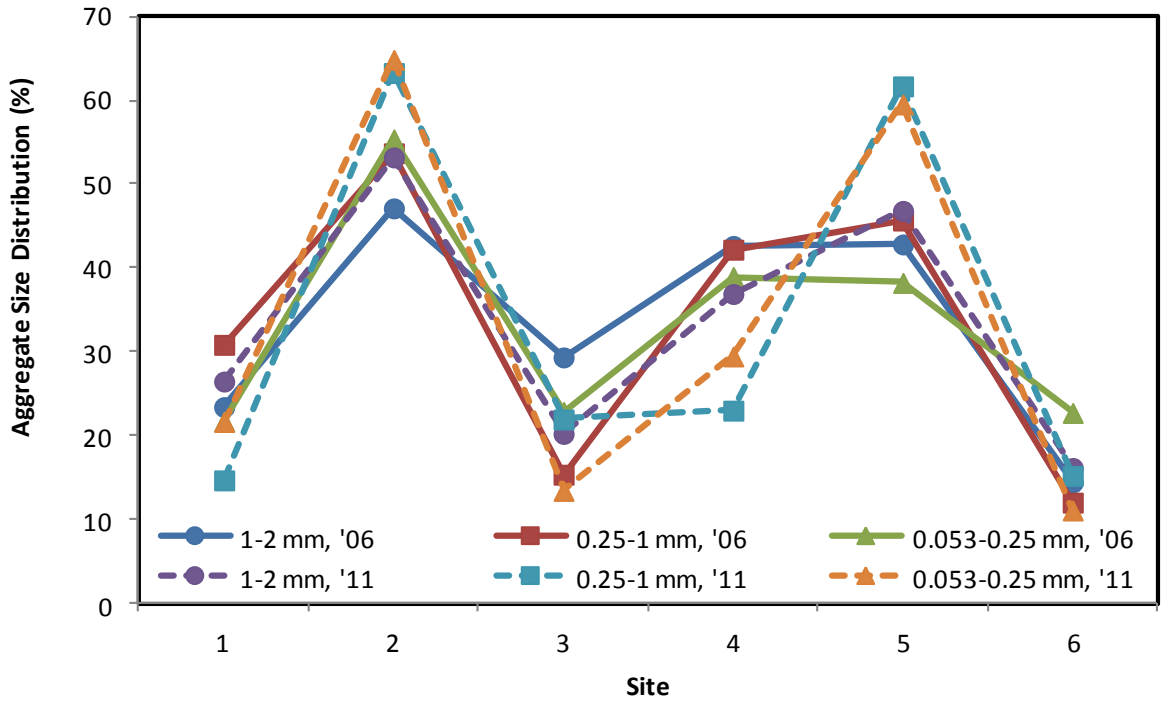


Figure 1. The dry aggregate size distribution (DASD) in each aggregate size classes [1-2 (circles), 0.25-1 (squares), and 0.053-0.25 (triangles) mm] for samples collected in 2006 and 2011.

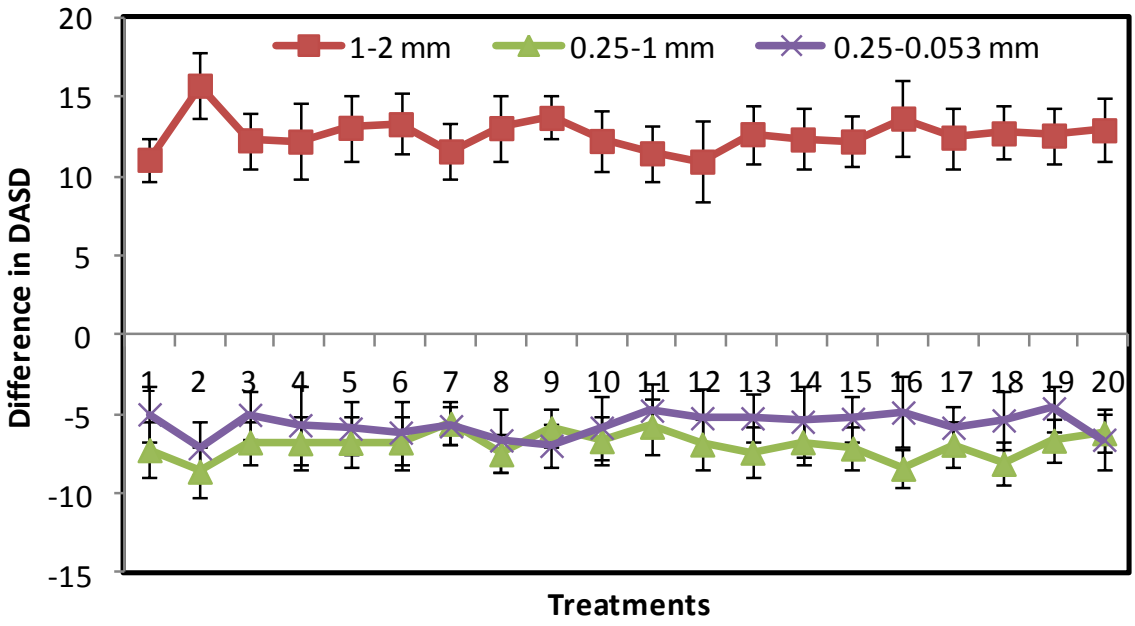


Figure 2. The differences in dry aggregate size distribution (DASD) between the baseline soil collection in 2006 and after five years of growth in 2011 for each of the three aggregate size classes (1-2, 0.25-1, and 0.053-0.25 mm).

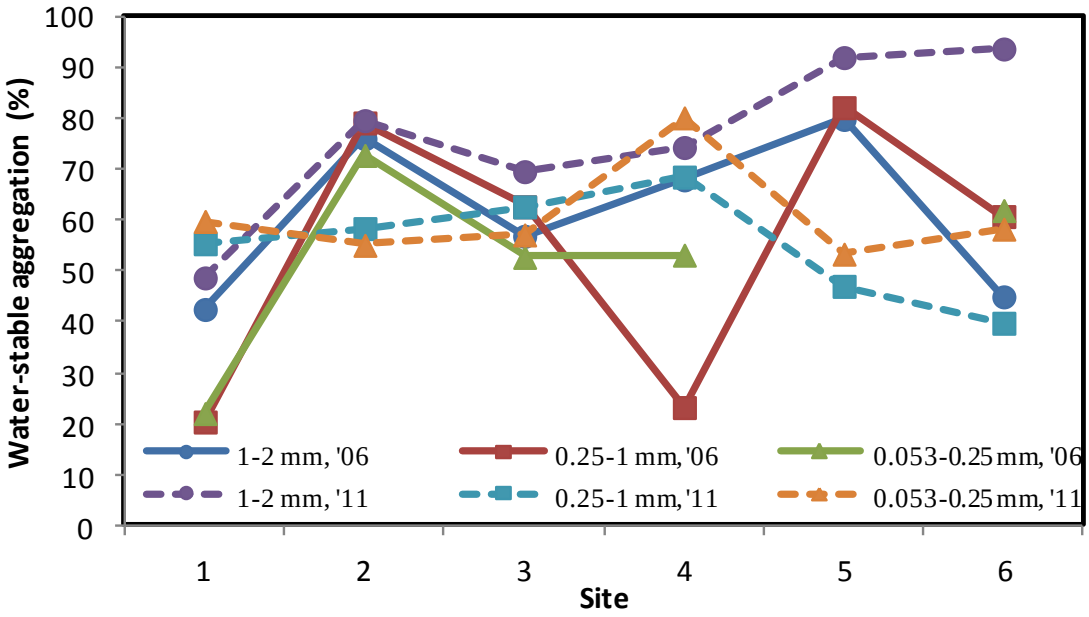


Figure 3. The percentages of water-stable aggregation (WSA) for aggregates from each of three size classes [1-2 (circles), 0.25-1 (squares), and 0.053-0.25 (triangles) mm] measured in samples collected in 2006 (solid lines) and 2011 (dotted lines).

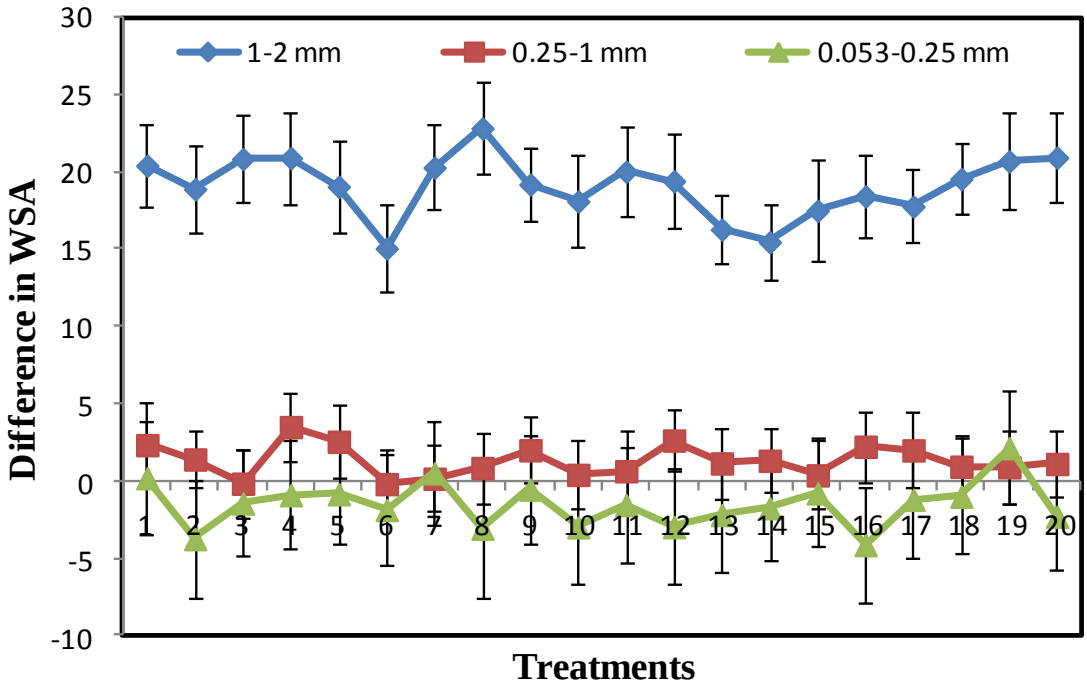


Figure 2. The differences in water-stable aggregation (WSA) between the baseline soil collection in 2006 and after five years of growth in 2011 for each of the three aggregate size classes (1-2, 0.25-1, and 0.053-0.25 mm).

Appendix A. Proportion of soil (Dry Aggregate Size Distribution, DASD) in each of the three aggregate size classes (ASC): 1. 1-2, 2. 0.25-1, and 3. 0.053-0.25 mm for baseline values in 2006 for six sites (Table 1) and twenty treatments (Table 2) per site. Values are means and standard errors (SE).

		1-2 mm		0.25-1 mm		0.053-0.25 mm	
Site	Trt	Mean	SE	Mean	SE	Mean	SE
1	1	22.938	1.795	46.277	2.537	30.785	4.089
1	2	24.782	1.894	47.107	1.515	28.112	3.132
1	3	23.883	1.842	47.217	1.448	28.9	3.191
1	4	22.655	2.135	46.741	2.632	30.604	4.669
1	5	24.109	1.189	48.161	1.665	27.73	2.838
1	6	24.121	4.289	46.348	2.392	29.531	5.234
1	7	24.384	0.369	48.089	1.144	27.527	1.326
1	8	21.366	1.539	46.676	2.033	31.957	3.569
1	9	24.094	2.535	45.693	0.87	30.213	3.186
1	10	23.866	1.711	46.549	1.727	29.585	2.623
1	11	22.225	2.077	47.279	1.085	30.496	3.107
1	12	25.112	2.555	48.416	0.889	26.472	3.353
1	13	24.048	1.694	48.663	1.24	27.289	2.676
1	14	22.227	2.73	46.701	2.927	31.072	5.642
1	15	23.653	2.041	47.755	0.786	28.592	2.807
1	16	22.429	2.308	46.124	1.046	31.447	3.291
1	17	24.344	0.803	46.909	1.165	28.747	1.525
1	18	21.982	1.294	47.513	1.595	30.505	2.693
1	19	24.618	1.989	46.897	1.539	28.485	3.435
1	20	22.433	1.877	47.922	1.44	29.645	2.979
2	1	29.741	2.305	54.162	1.209	16.097	1.33
2	2	27.981	3.084	53.967	1.663	18.051	1.753
2	3	33.612	3.276	51.863	2.045	14.524	1.428
2	4	30.922	2.687	52.962	3.406	16.116	1.31
2	5	27.041	1.063	56.05	1.468	16.909	0.884
2	6	32.065	3.147	53.02	2.04	14.915	1.274
2	7	29.303	3.062	54.036	1.309	16.661	2.299
2	8	28.254	1.723	55.429	0.867	16.318	1.995
2	9	31.32	1.897	54.493	1.431	14.187	0.813
2	10	30.105	2.199	54.902	1.367	14.993	0.925
2	11	28.581	1.657	54.038	1.073	17.38	1.548
2	12	30.375	1.541	54.233	0.473	15.392	1.593
2	13	31.831	1.985	53.11	1.577	15.06	1.991
2	14	32.205	2.545	53.773	1.229	14.022	1.446
2	15	31.325	2.57	54.026	2.132	14.649	1.292

2	16	32.278	2.066	54.091	1.271	13.63	0.92
2	17	31.029	2.42	53.607	2.043	15.365	1.361
2	18	32.948	3.233	52.615	1.936	14.437	1.378
2	19	32.518	3.863	52.707	2.895	14.776	1.098
2	20	34.201	3.133	51.219	2.015	14.579	1.629
3	1	22.228	1.014	55.096	1.427	22.677	1.167
3	2	21.288	1.067	53.59	1.289	25.122	1.369
3	3	21	0.565	56.155	0.723	22.845	1.124
3	4	23.003	1.25	55.907	0.757	21.09	0.916
3	5	21.808	1.6	54.692	1.471	23.5	1.633
3	6	21.671	0.853	56.736	1.748	21.594	0.95
3	7	20.049	0.498	55.026	1.316	24.924	0.963
3	8	21.509	1.794	54.584	1.615	23.908	0.704
3	9	20.721	1.068	56.206	0.699	23.073	1.067
3	10	20.87	0.951	56.081	0.319	23.049	0.677
3	11	22.123	1.619	55.512	1.692	22.364	1.298
3	12	21.839	1.611	57.314	0.63	20.847	1.834
3	13	20.926	1.464	55.189	1.102	23.885	1.332
3	14	22.548	1.286	55.919	1.611	21.533	1.397
3	15	22.505	1.282	55.616	1.369	21.878	0.66
3	16	21.87	1.864	54.806	1.502	23.324	0.494
3	17	22.821	2.251	54.351	1.643	22.828	1.404
3	18	22.538	0.971	55.474	1.59	21.988	1.214
3	19	22.105	3.417	54.584	1.368	23.311	2.417
3	20	21.474	2.193	54.628	1.237	23.898	1.025
4	1	24.593	0.967	53.913	1.645	21.494	1.915
4	2	27.151	0.531	52.744	1.27	20.106	1.61
4	3	28.39	0.872	53.31	0.754	18.3	0.253
4	4	25.802	1.244	51.379	2.173	22.819	1.318
4	5	26.654	1.945	53.782	0.614	19.564	1.35
4	6	28.612	1.131	51.628	0.544	19.759	0.737
4	7	26.062	1.729	53.339	0.88	20.599	0.962
4	8	26.297	1.387	53.467	0.572	20.236	1.288
4	9	24.665	1.537	54.032	0.952	21.303	1.088
4	10	27.023	2.14	53.114	0.26	19.862	2.146
4	11	26.107	1.354	54.881	1.019	19.013	1.023
4	12	27.38	1.107	52.702	1.347	19.918	1.079
4	13	25.56	1.311	53.397	0.892	21.042	0.979
4	14	26.78	2.237	54.579	1.08	18.641	1.166
4	15	25.813	1.69	53.256	0.919	20.931	1.062
4	16	29.263	1.573	53.275	1.504	17.462	0.832

4	17	27.067	1.774	51.772	0.604	21.161	1.368
4	18	27.454	1.719	52.633	0.768	19.913	1.721
4	19	23.73	1.551	54.794	0.613	21.477	1.48
4	20	25.725	2.485	52.548	0.658	21.728	2.151
5	1	14.58	0.761	62.341	1.027	23.078	1.033
5	2	15.206	1.46	61.331	0.676	23.463	1.265
5	3	14.485	1.225	62.699	1.837	22.817	0.81
5	4	14.797	0.518	62.771	1.326	22.432	1.823
5	5	14.784	1.297	62.892	1.099	22.325	1.694
5	6	14.735	0.244	64.82	1.326	20.445	1.191
5	7	13.453	0.561	66.13	0.566	20.417	0.929
5	8	14.589	0.302	62.366	0.444	23.045	0.717
5	9	14.694	0.561	64.794	0.36	20.512	0.893
5	10	14.224	0.865	62.797	0.944	22.978	0.696
5	11	15.693	0.899	63.758	1.278	20.549	1.991
5	12	13.931	1.262	61.692	0.345	24.377	1.529
5	13	14.38	0.222	63.764	1.185	21.855	1.373
5	14	14.564	0.994	63.347	1.065	22.089	1.179
5	15	15.084	0.771	64.082	0.808	20.833	0.791
5	16	14.376	1.006	63.616	1.002	22.008	0.454
5	17	14.086	0.276	64.623	0.424	21.291	0.45
5	18	15.349	0.381	62.56	0.877	22.091	1.169
5	19	16.314	0.476	62.633	0.6	21.053	0.738
5	20	15.193	1.059	62.743	0.731	22.064	1.186
6	1	22.081	1.489	63.859	1.219	14.06	0.459
6	2	24.033	0.954	62.932	1.164	13.035	0.781
6	3	20.895	1.597	65.757	1.712	13.348	0.64
6	4	21.787	2.567	64.182	2.068	14.03	0.675
6	5	21.305	2.856	64.559	3.288	14.136	0.943
6	6	20.085	2.725	67.34	2.242	12.575	0.948
6	7	22.599	2.567	64.23	1.903	13.172	0.735
6	8	20.935	2.401	65.014	2.536	14.051	0.958
6	9	21.473	1.573	65.405	1.187	13.122	0.969
6	10	21.556	2.825	64.213	2.321	14.231	1.739
6	11	20.633	2.392	66.54	2.085	12.827	1.17
6	12	22.145	2.7	64.195	2.92	13.659	0.347
6	13	22.695	3.131	64.745	3.119	12.56	0.973
6	14	21.241	2.324	66.127	2.577	12.632	0.603
6	15	21.491	1.222	64.539	2.066	13.971	0.898
6	16	21.456	2.455	65.09	2.685	13.454	0.685
6	17	22.025	2.225	64.69	2.152	13.285	1.132

6	18	21.606	2.624	64.415	2.285	13.978	1.197
6	19	23.201	1.895	63.547	1.537	13.252	0.633
6	20	20.42	1.248	65.57	0.496	14.01	1.185

Appendix B. Proportion of soil (Dry Aggregate Size Distribution, DASD) in each of the three aggregate size classes (ASC): 1. 1-2, 2. 0.25-1, and 3. 0.053-0.25 mm after five years of treatment in 2011 for six sites (Table 1) and twenty treatments (Table 2) per site. Values are means and standard errors (SE).

		1-2 mm		0.25-1 mm		0.053-0.25 mm	
Site	Trt	Mean	SE	Mean	SE	Mean	SE
1	1	38.964	2.806	44.291	0.599	16.745	2.226
1	2	50.131	5.739	38.661	3.442	11.208	2.303
1	3	39.897	2.872	42.464	0.502	17.639	2.669
1	4	45.402	3.979	43.324	2.191	11.274	1.843
1	5	42.54	3.573	43.396	1.023	14.064	2.959
1	6	40.641	2.743	45.322	1.382	14.036	1.947
1	7	39.042	2.822	44.281	0.715	16.676	2.723
1	8	43.637	4.261	42.507	1.752	13.857	2.553
1	9	39.729	2.816	43.135	0.716	17.136	3.119
1	10	44.514	5.231	42.211	2.149	13.275	3.275
1	11	36.014	2.393	45.918	1.073	18.068	3.418
1	12	48.288	4.679	40.026	3.308	11.686	1.764
1	13	41.011	3.466	43.94	0.723	15.049	2.838
1	14	43.679	3.844	43.862	1.775	12.458	2.306
1	15	39.508	3.347	43.257	0.573	17.235	3.827
1	16	47.162	4.844	40.752	2.145	12.086	2.759
1	17	42.586	3.607	41.258	0.657	16.156	3.131
1	18	44.419	3.598	42.387	1.475	13.195	2.952
1	19	41.397	3.267	42.529	1.646	16.074	2.044
1	20	44.943	3.386	43.464	1.261	11.593	2.22
2	1	39.174	3.605	45.754	3.787	15.071	2.66

2	2	36.242	2.766	51.324	1.881	12.435	1.443
2	3	44.69	2.785	43.552	2.607	11.758	0.961
2	4	40.083	2.89	45.812	2.304	14.105	0.597
2	5	37.534	2.898	49.507	2.708	12.959	1.535
2	6	48.219	2.282	42.73	1.865	9.051	0.644
2	7	43.439	1.892	45.18	1.623	11.381	0.619
2	8	44.433	3.252	43.975	3.435	11.591	0.564
2	9	44.075	2.536	45.831	2.411	10.094	0.551
2	10	42.041	2.619	46.073	2.049	11.886	1.674
2	11	44.864	1.703	43.761	2.546	11.375	0.857
2	12	39.535	1.06	48.763	1.117	11.702	0.325
2	13	41.307	3.305	45.841	1.85	12.853	1.693
2	14	41.101	1.706	46.691	0.585	12.208	2.153
2	15	43.883	4.692	43.702	4.196	12.415	1.16
2	16	44.104	3.558	44.539	2.678	11.358	1.337
2	17	39.615	0.882	46.916	2.599	13.469	2.193
2	18	44.111	1.941	43.612	1.648	12.277	0.75
2	19	41.19	3.91	46.385	3.011	12.425	1.212
2	20	44.839	2.561	44.116	2.37	11.045	1.588
3	1	38.289	2.332	37.187	0.832	24.524	3.055
3	2	41.506	1.021	35.482	0.485	23.012	1.418
3	3	41.229	3.201	39.149	3.584	19.622	0.57
3	4	36.312	6.762	36.574	0.571	27.114	7.207
3	5	44.104	0.553	35.036	0.694	20.861	1.065
3	6	36.406	2.598	38.119	0.518	25.474	2.747

3	7	40.335	4.014	39.357	3.964	20.309	3.249
3	8	35.007	1.158	41.21	3.508	23.782	2.484
3	9	41.624	2.334	40.94	2.625	17.436	0.881
3	10	35.926	3.463	38.696	0.762	25.378	2.904
3	11	41.093	0.893	38.645	1.397	20.262	2.26
3	12	40.608	3.207	36.893	1.366	22.498	3.005
3	13	41.532	2.069	36.998	2.428	21.47	1.732
3	14	36.023	2.368	36.654	0.598	27.324	2.69
3	15	40.578	3.563	41.096	3.454	18.326	0.524
3	16	35.787	3.101	37.08	0.356	27.133	3.236
3	17	41.517	1.457	39.189	2.482	19.294	1.95
3	18	35.717	1.548	37.998	1.23	26.286	1.929
3	19	36.067	1.034	39.64	3.046	24.293	2.246
3	20	39.832	2.407	39.293	2.42	20.876	3.885
4	1	37.609	0.348	46.304	1.84	16.086	2.002
4	2	43.646	3.367	39.507	2.366	16.846	4.216
4	3	34.619	1.289	47.826	2.318	17.555	2.65
4	4	34.576	2.488	48.221	1.977	17.203	3.554
4	5	38.18	3.956	45.021	4.418	16.799	2.236
4	6	38.646	2.672	48.721	2.374	12.632	1.009
4	7	32.202	2.561	50.621	2.003	17.178	3.285
4	8	36.45	3.805	46.923	3.436	16.627	3.074
4	9	34.848	1.895	48.838	3.529	16.314	1.855
4	10	37.673	0.52	47.861	3.317	14.467	2.834
4	11	37.283	5.102	47.658	4.286	15.06	0.825

4	12	35.523	2.449	49.599	0.486	14.877	2.924
4	13	37.432	3.155	44.8	4.608	17.767	1.483
4	14	39.409	2.771	44.688	1.28	15.903	3.696
4	15	32.395	1.91	49.252	1.878	18.353	2.814
4	16	38.784	1.09	44.002	2.016	17.214	2.704
4	17	34.706	5.041	46.532	3.936	18.762	2.163
4	18	40.116	1.205	45.084	2.572	14.8	1.769
4	19	38.989	1.915	45.691	3.368	15.32	1.511
4	20	35.72	2.348	49.906	1.441	14.374	0.912
5	1	21.975	1.92	61.607	0.608	16.418	2.527
5	2	26.215	0.872	60.25	0.951	13.535	1.797
5	3	21.858	3.621	62.36	2.907	15.782	3.499
5	4	22.192	0.671	61.216	2.715	16.591	3.069
5	5	21.823	2.401	62.195	0.723	15.982	2.772
5	6	26.036	3.438	61.591	0.825	12.374	2.67
5	7	21.611	2.745	65.099	0.677	13.291	2.165
5	8	23.384	3.873	60.646	0.574	15.97	3.623
5	9	25.543	2.266	63.122	0.899	11.335	1.385
5	10	24.47	4.455	60.084	2.13	15.446	4.675
5	11	21.406	2.921	63.108	1.225	15.486	2.871
5	12	21.087	0.456	62.048	1.98	16.865	2.367
5	13	22.752	2.157	63.141	1.347	14.107	1.252
5	14	21.295	0.926	63.731	0.838	14.973	1.286
5	15	24.01	1.632	61.424	0.294	14.567	1.806
5	16	19.958	1.731	61.541	2.885	18.501	4.597

5	17	24.58	0.45	61.073	2.085	14.347	1.896
5	18	23.193	2.328	61.641	2.484	15.166	1.881
5	19	24.358	2.898	58.742	1.085	16.9	2.904
5	20	23.068	1.23	59.307	0.72	17.625	1.886
6	1	26.681	1.77	55.38	5.431	10.209	1.382
6	2	36.514	1.786	53.815	0.827	9.868	0.803
6	3	31.673	5.555	62.169	1.427	9.657	0.749
6	4	31.419	7.785	56.089	3.025	10.736	1.636
6	5	30.68	5.574	60.663	3.805	11.454	1.393
6	6	29.237	4.843	61.841	3.469	11.72	0.95
6	7	26.157	4.084	63.246	1.965	12.505	0.567
6	8	25.136	5.106	56.241	4.393	11.536	1.079
6	9	32.831	2.954	62.65	1.123	10.345	0.956
6	10	26.37	2.564	61.138	2.218	10.804	0.969
6	11	22.549	2.01	68.377	1.292	15.489	1.06
6	12	17.836	1.716	59.466	2.595	14.977	0.955
6	13	31.123	3.403	58.026	0.848	11.182	1.68
6	14	30.595	4.595	59.977	3.679	10.425	1.609
6	15	30.572	2.756	58.085	0.525	10.084	1.46
6	16	34.589	6.814	57.695	3.701	10.249	1.998
6	17	30.967	2.296	58.706	1.008	8.566	0.343
6	18	31.811	2.346	53.778	5.063	9.486	0.959
6	19	35.904	4.222	61.124	3.235	11.939	0.395
6	20	27.31	1.923	62.349	3.713	11.454	0.96

Appendix C. Differences in proportion of soil (Dry Aggregate Size Distribution, DASD) in each of the three aggregate size classes (ASC): 1. 1-2, 2. 0.25-1, and 3. 0.053-0.25 mm between baseline values in 2006 and after five years of treatment in 2011 for six sites (Table 1) and twenty treatments (Table 2) per site. Values are means and standard errors (SE).

		1-2 mm		0.25-1 mm		0.053-0.25 mm	
Site	Trt	Mean	SE	Mean	Std Error	Mean	Std Error
1	1	16.026	3.966	-1.987	1.953	-14.039	5.911
1	2	25.349	7.574	-3.808	0.644	-10.851	3.526
1	3	16.013	4.257	-4.723	1.055	-12.24	5.394
1	4	22.747	6.03	-4.368	0.988	-12.411	5.169
1	5	18.431	4.73	-6.543	3.421	-3.95	2.391
1	6	16.52	6.167	-10.277	3.171	-6.006	2.107
1	7	14.658	3.129	-6.691	4.021	-1.896	2.078
1	8	22.27	5.8	-16.728	3.439	-3.463	1.686
1	9	15.635	5.064	-15.032	1.824	-6.236	0.862
1	10	20.648	6.015	-14.645	2.508	-3.013	0.064
1	11	13.789	4.16	-8.807	2.669	-4.406	2.115
1	12	23.176	7.152	-3.524	2.019	-3.841	2.585
1	13	16.962	4.895	-9.089	5.557	-3.882	2.535
1	14	21.452	6.534	-9.403	3.768	-4.943	0.313
1	15	15.855	4.841	-0.987	2.045	-6.411	4.788
1	16	24.732	6.913	-0.121	2.594	-6.451	2.127
1	17	18.242	4.299	-3.564	2.049	-7.051	2.296
1	18	22.437	4.848	-3.652	1.41	-3.675	1.262
1	19	16.779	4.84	-2.115	1.259	-1.967	0.771
1	20	22.51	5.169	-6.572	2.693	-3.915	0.987
2	1	9.434	2.588	-8.445	2.526	-16.904	5.365
2	2	8.26	4.059	-4.17	0.544	-18.101	6.118
2	3	11.078	1.89	-2.838	1.694	-18.613	7.922
2	4	9.161	1.944	-4.458	0.842	-18.052	5.1
2	5	10.493	3.304	-10.29	3.098	-5.864	1.687
2	6	16.154	4.421	-5.47	1.39	-3.69	1.391
2	7	14.136	3.909	-9.003	3.003	-2.161	0.869
2	8	16.18	2.093	-19.833	0.552	5.924	7.249
2	9	12.755	1.427	-17.126	0.967	2.695	3.516
2	10	11.936	3.073	-17.105	1.887	3.678	3.887
2	11	16.283	2.021	-14.36	2.098	-1.752	3.697
2	12	9.16	1.364	-6.727	3.174	-3.085	4.32
2	13	9.476	3.072	-10.483	2.151	-3.496	2.559
2	14	8.897	1.008	-2.924	2.28	-5.942	3.205

2	15	12.558	3.697	-3.15	1.763	-8.097	3.902
2	16	11.825	1.576	0.476	2.388	-8.757	3.599
2	17	8.587	3.205	-1.533	2.575	-5.954	0.995
2	18	11.163	3.859	-7.743	0.922	-2.726	2.139
2	19	8.672	3.827	-1.806	4.246	-2.208	0.953
2	20	10.638	3.042	-6.205	2.339	-3.49	1.643
3	1	15.248	1.96	-4.753	1.437	-11.26	5.615
3	2	20.089	0.885	-2.558	1.507	-13.076	6.135
3	3	20.191	3.983	-4.498	0.924	-11.357	5.76
3	4	13.909	7.673	-8.408	4.268	-1.025	2.102
3	5	22.216	2.8	-8.856	2.88	-5.28	1.909
3	6	15.036	3.723	-7.269	2.905	-2.207	1.355
3	7	19.981	3.578	-6.321	3.832	-2.351	0.271
3	8	12.958	1.261	-18.56	0.801	-3.656	2.145
3	9	21.268	1.037	-17.133	1.128	-0.95	1.674
3	10	14.431	4.398	-16.223	1.183	-4.658	2.135
3	11	18.082	2.775	-5.889	2.116	-0.77	2.307
3	12	17.777	4.998	-5.56	2.54	-5.816	1.024
3	13	20.416	0.111	-4.427	0.984	-3.055	4.153
3	14	12.917	3.344	-0.902	2.028	-7.214	3.686
3	15	17.658	2.454	-0.922	1.277	-7.788	1.338
3	16	13.427	5.645	-0.244	1.025	-8.303	2.933
3	17	20.881	1.226	-3.679	0.56	-3.947	2.642
3	18	12.586	0.515	-1.893	3.016	-3.417	1.49
3	19	16.762	3.016	1.676	1.768	3.827	0.925
3	20	19.419	4.759	-4.245	2.24	-5.51	1.457
4	1	13.213	1.103	-3.418	1.748	-19.329	6.467
4	2	16.112	3.376	-4.338	1.066	-16.31	5.48
4	3	6.659	0.247	-5.371	1.158	-19.361	5.912
4	4	8.95	3.566	-2.644	3.163	-5.617	1.012
4	5	11.026	4.005	-11.453	3.782	-4.727	1.939
4	6	10.13	1.7	-7.083	1.536	-1.814	1.085
4	7	7.365	0.883	-7.103	1.953	-3.535	2.566
4	8	9.812	2.856	-19.142	2.501	4.105	2.052
4	9	11.376	1.595	-20.19	0.622	2.413	5.074
4	10	11.576	2.471	-17.188	1.724	4.602	2.217
4	11	10.925	3.523	-2.348	4.722	-6.601	4.491
4	12	8.385	1.819	-5.491	3.453	-6.085	5.493
4	13	12.972	3.357	-10.379	2.771	-0.047	3.841
4	14	13.979	0.48	-1.431	1.332	-11.034	2.097
4	15	7.482	3.199	-1.408	0.32	-7.453	3.59

4	16	10.426	2.908	1.291	1.423	-8.072	1.576
4	17	7.928	7.485	-3.794	1.62	-3.643	2.696
4	18	11.432	0.619	-4.822	2.343	-1.237	1.776
4	19	14.346	3.455	-4.525	1.811	1.272	0.515
4	20	8.866	5.478	-8.607	4.328	-4.995	1.459
5	1	8.116	1.658	-4.765	1.586	-13.666	5.743
5	2	12.465	1.005	-1.361	2.043	-12.428	6.132
5	3	8.262	3.17	-5.651	1.765	-12.591	3.861
5	4	7.401	0.981	-8.311	1.233	-2.767	1.344
5	5	7.398	3.45	-8.662	1.266	-4.094	0.272
5	6	11.247	3.101	-10.325	4.624	-2.233	1.394
5	7	8.71	2.605	-17.449	1.344	2.201	2.019
5	8	8.861	3.909	-15.607	2.389	-4.375	3.63
5	9	11.086	2.55	-18.555	1.06	-1.861	1.095
5	10	9.994	4.514	-15.88	1.674	-0.881	3.467
5	11	6.572	2.573	-8.73	3.834	-2.296	3.946
5	12	8.28	1.246	-7.382	2.948	-3.543	1.269
5	13	8.546	2.35	-5.551	4.617	-2.377	3.772
5	14	6.781	0.55	-1.381	3.909	-6.88	4.469
5	15	9.298	2.439	-1.481	0.591	-9.605	2.062
5	16	6.377	2.503	-2.241	0.703	-7.057	1.782
5	17	10.615	0.394	-7.313	5.934	-3.761	1.966
5	18	7.487	2.461	-0.274	2.16	-0.754	1.191
5	19	7.626	3.112	-5.498	4.484	-1.616	0.867
5	20	7.437	1.816	-1.133	2.145	-1.285	0.585
6	1	3.345	0.669	-1.026	2.703	-15.494	6.918
6	2	11.569	1.682	-8.39	2.622	-14.786	4.836
6	3	10.826	7.81	-5.126	0.456	-17.311	5.13
6	4	8.713	10.155	-7.15	2.622	-2.011	1.576
6	5	8.107	9.095	-8.829	2.55	-3.107	1.954
6	6	8.857	8.121	-9.553	1.534	-2.273	0.785
6	7	2.935	4.275	-18.728	1.264	-1.361	0.401
6	8	4.286	7.388	-12.792	1.378	-0.166	2.578
6	9	9.909	2.978	-17.711	0.509	4.794	3.28
6	10	2.326	2.988	-16.049	1.121	-3.369	5.241
6	11	0.912	4.705	-2.879	1.725	-7.251	0.032
6	12	-4.468	3.503	-3.218	1.995	-5.168	1.814
6	13	7.445	7.597	-7.923	1.623	-3.509	2.238
6	14	8.262	6.959	-1.411	1.867	-5.99	2.4
6	15	9.228	4.303	-2.565	3.044	-7.429	5.395
6	16	12.228	9.521	-2.569	1.661	-3.807	4.161

6	17	7.995	5.092	-8.075	1.443	-3.298	1.411
6	18	8.677	3.115	-8.309	1.011	-3.064	2.097
6	19	11.384	6.148	-4.886	3.476	-2.38	0.955
6	20	6.367	1.501	-3.019	3.343	-2.235	2.458

Appendix D. The percentage of water stable aggregates (WSA) in each of the three aggregate size classes (ASC): 1. 1-2, 2. 0.25-1, and 3. 0.053-0.25 mm in 2006 for six sites (Table 1) and twenty treatments per site. Treatments (Trt) are described in Table 2 and included ten grasses or mixtures of grasses with biomass samples collected annually or biennially. Values are means and standard errors (SE).

		1-2 mm		0.25-1 mm		0.053-0.25 mm	
Site	Trt	Mean	SE	Mean	SE	Mean	SE
1	1	38.594	1.675	75.188	1.733	55.25	2.847
1	2	41.688	2.187	77.563	2.654	60.375	4.125
1	3	45.5	0.47	77.063	2.846	54.875	4.492
1	4	37.25	2.58	75.438	3.013	56.5	4.392
1	5	40.5	2.525	75.125	1.583	55.875	2.267
1	6	45.292	4.124	78.25	1.287	57.875	4.145
1	7	44.052	2.724	77.5	2.248	56.417	3.499
1	8	37.344	1.747	75.188	2.199	59.125	4.205
1	9	41.031	1.562	74.313	2.72	56.375	2.703
1	10	42.938	1.518	76.688	2.315	58.375	4.038
1	11	46.406	2.989	77	2.034	56.25	3.562
1	12	40.781	3.192	75.063	2.433	56.875	4.165
1	13	41	3.019	74.813	3.145	57.375	4.012
1	14	44.094	3.077	76.875	3.58	57.875	4.007
1	15	49.094	4.312	77.188	2.107	55.625	3.158
1	16	38.708	2.902	76.563	0.664	58.25	2.78
1	17	43.563	1.849	74.875	2.561	54.125	4.18
1	18	43.281	2.957	74.938	2.939	57.375	3.037
1	19	47.094	1.19	77.5	2.588	56.25	4.352
1	20	42.844	2.458	75.875	0.696	58.125	2.882
2	1	18	1.623	75.188	1.344	64.125	1.533
2	2	21.469	2.15	79.938	0.8	61.625	2.824
2	3	20.406	1.545	83.188	0.472	62	1.208
2	4	21.656	1.84	78	1.418	61.125	4.269
2	5	17.938	3.894	76.063	0.695	60.5	3.048
2	6	20.344	1.823	79.313	0.68	62.75	3.326
2	7	24.531	0.428	82.563	0.534	60.875	4.17
2	8	20.417	2.906	78.625	1.21	62.375	3.436
2	9	17.031	2.262	76.875	0.462	64.125	1.749
2	10	21.438	1.512	81.313	1.751	63.75	1.051
2	11	18.719	1.66	80.25	1.862	60.75	3.031
2	12	20	1.549	76.625	1.833	63.375	1.197
2	13	16.594	2.478	78.188	1.101	60.125	4.125
2	14	22.094	1.496	78.75	0.884	61.125	1.39

2	15	24.271	2.227	83.375	0.462	65.75	3.597
2	16	20.479	1.832	77.875	1.048	66.25	2.905
2	17	17.438	1.908	76.188	1.023	65.5	4.444
2	18	21.958	2.459	81.688	0.921	66.625	1.983
2	19	25.406	2.335	82.5	0.51	62	3.247
2	20	18.24	1.696	78.375	0.753	60.375	3.799
3	1	21.875	2.111	71.313	1.697	51.625	1.737
3	2	21.906	1.194	70	1.199	53.5	1.732
3	3	21.5	1.218	74.188	0.624	53.25	0.595
3	4	17.375	1.269	72	1.923	52.25	0.924
3	5	22.281	0.913	71.875	2.39	52.625	1.375
3	6	21.469	0.626	72.438	1.077	52	2.121
3	7	23.219	2.199	72.063	1.438	55.75	1.887
3	8	20.25	2.492	73.563	1.666	56.5	1.339
3	9	21.438	1.158	70.625	1.509	52.75	1.762
3	10	21.406	2.509	70.563	2.55	51.75	1.963
3	11	24.906	0.926	73.938	1.441	52.125	0.688
3	12	23.438	1.416	74.813	0.812	53.125	0.657
3	13	23.688	3.17	73.5	2.827	54.25	2.788
3	14	22.406	2.345	74.688	0.687	53.25	2.287
3	15	23.313	0.911	74.688	1.441	51.625	2.741
3	16	22.75	1.492	73.438	1.948	51.125	0.591
3	17	20.563	1.766	72.438	2.027	53.25	0.829
3	18	22.125	2.377	70.875	2.427	51.875	2.322
3	19	24.688	2.262	76	0.621	51.625	1.068
3	20	21.094	2.27	74.125	0.505	51.875	2.436
4	1	42.719	0.845	78.125	1.628	69	1.671
4	2	46.438	1.481	79.313	1.284	70.625	0.966
4	3	52.854	3.898	81.75	1.396	71.875	1.344
4	4	44.094	2.06	77.625	2.123	67.875	1.248
4	5	47.094	3.279	79.813	1.179	70.25	1.315
4	6	47.375	3.107	81.063	0.943	72	2.227
4	7	51.219	0.699	81.625	0.688	71	0.89
4	8	48.031	3.185	79.625	1.301	67.25	1.639
4	9	52	2.339	80.063	0.504	69.5	1.208
4	10	49.688	2.844	78.938	2.132	72	1.061
4	11	48.75	2.238	78.5	0.685	69.25	1.436
4	12	51.188	1.441	81.125	1.033	70.5	1.541
4	13	50.875	2.356	81	0.408	69.25	1.614
4	14	49.563	0.947	81.625	1.277	70.875	1.546
4	15	50.438	1.826	79.188	0.766	67.75	1.601

4	16	46.344	1.857	78.25	0.924	70.25	1.031
4	17	52.438	1.797	79.646	2.04	69.625	2.719
4	18	48.813	1.09	79.188	1.927	67.25	2.586
4	19	49.448	3.755	78.188	2.125	67.375	2.536
4	20	45.906	1.013	79.25	1.229	69.75	1.831
5	1	53.25	1.119	60.188	0.329	62.875	2.322
5	2	54.969	2.51	57.75	1.735	64.625	2.014
5	3	55.625	1.912	57.938	1.063	62.25	2.57
5	4	53.375	1.497	58.375	1.844	62.75	1.362
5	5	53.846	3.364	59.063	0.759	60.875	2.553
5	6	58.25	2.363	59.125	0.681	61	1.339
5	7	56.656	1.175	58.688	1.569	61.375	1.39
5	8	55	1.675	57.625	2.223	63.813	3.03
5	9	55.875	1.965	57.938	1.033	61.625	2.875
5	10	57.781	2.232	58.5	1.95	63.5	2.208
5	11	57.5	2.261	59.563	1.201	63.375	2.503
5	12	52.875	1.592	57.875	1.333	63.375	2.23
5	13	54.875	2.334	58.042	1.639	62.5	2.669
5	14	56.5	2.012	58.125	1.375	60.5	2.646
5	15	57.406	2.268	60	0.586	62.125	3.023
5	16	56.344	2.157	56.875	0.781	63.333	2.151
5	17	54.094	2.564	60.063	2.006	64.875	1.519
5	18	54.875	0.928	55.938	1.899	62.75	2.097
5	19	55.906	2.701	59.75	2.191	63.25	2.087
5	20	54.688	2.079	57.875	2.233	64	2.282
6	1	56.469	1.663	56.25	0.586	56.5	1.814
6	2	64.125	1.575	57.5	3.157	58.875	4.492
6	3	62.344	1.767	54.063	2.913	55	3.335
6	4	60.177	3.065	55.063	3.412	59.125	2.802
6	5	59.531	2.411	52.438	3.931	58.125	4.539
6	6	62.156	1.111	52	5.169	54.125	4.784
6	7	62.5	2.181	54.313	3.501	55.375	1.663
6	8	58.594	0.626	56.875	3.381	60.75	4.404
6	9	58.906	1.687	52.313	4.752	54.375	2.304
6	10	58.844	1.006	56.563	4.088	56.75	4.867
6	11	60.531	1.788	50.375	4.916	54.5	3.007
6	12	60.271	3.015	53.313	4.079	59.75	3.683
6	13	61.563	2.273	55.625	4.078	57.5	5.012
6	14	57.844	1.043	56.75	4.386	55.625	2.954
6	15	58.906	3.045	56.625	5.472	57.875	4.422
6	16	62.49	2.602	55.313	4.973	58.25	4.136

6	17	58.031	1.509	56.313	3.744	58	2.475
6	18	61.25	1.516	58.313	5.431	61.75	3.8
6	19	55.719	0.648	58.438	0.724	57.375	2.135
6	20	57.25	1.55	55	3.067	54.75	2.046

Appendix E. The percentage of water stable aggregates (WSA) in each of the three aggregate size classes (ASC): 1. 1-2, 2. 0.25-1, and 3. 0.053-0.25 mm in 2011 for six sites (Table 1) and twenty treatments per site. Treatments (Trt) are described in Table 2 and included ten grasses or mixtures of grasses with biomass samples collected annually or biennially. Values are means and standard errors (SE).

		1-2 mm		0.25-1 mm		0.053-0.25 mm	
Site	Trt	Mean	SE	Mean	SE	Mean	SE
1	1	65.359	6.009	80.716	1.752	49.375	3.037
1	2	68.605	1.749	80	1.031	39.824	2.13
1	3	74.639	2.81	81.375	2.333	50.074	4.226
1	4	62.113	4.631	79.627	1.488	42.25	1.652
1	5	62.675	5.97	79.454	2.715	45.074	4.425
1	6	58.426	1.601	78.625	1.184	41.625	2.641
1	7	74.314	1.193	80.86	1.907	51.375	3.891
1	8	70.32	2.716	79.513	1.642	44.25	1.051
1	9	65.985	2.428	78.438	1.566	45.25	1.315
1	10	71.066	2.667	80.154	1.989	39.875	2.839
1	11	74.47	2.809	81.188	2.526	47	4.108
1	12	71.775	4.33	79.701	1.348	38.625	3.138
1	13	64.98	2.389	79.483	2.456	48.375	3.287
1	14	61.523	5.05	80.262	1.744	42.5	2.7
1	15	72.312	3.336	79.438	3.289	49.25	3.425
1	16	64.376	2.558	79.875	2.078	40.75	1.051
1	17	65.098	5.694	79.813	1.929	45.375	3.777
1	18	67.471	3.713	79.125	2.695	43.125	2.478
1	19	75.078	2.591	80.75	2.43	50.25	3.192
1	20	70.459	1.483	80.313	1.637	46.5	0.612

2	1	24.084	0.221	82.863	2.427	63.955	2.687
2	2	22.52	3.402	81.761	0.234	59.659	3.089
2	3	26.763	3.27	82.481	1.247	55.556	3.072
2	4	26.274	3	82.049	1.31	60.948	4.322
2	5	20.561	3.325	82.5	0.973	58.921	3.837
2	6	16.677	1.877	80.987	1.747	59.296	3.448
2	7	25.784	2.221	82.989	1.149	58.959	3.89
2	8	23.927	3.158	79.84	2.643	61.804	3.614
2	9	25.455	3.078	81.482	1.972	59.533	3.474
2	10	19.965	2.408	79.943	2.06	62.303	1.59
2	11	21.47	2.042	81.216	1.114	54.374	4.289
2	12	22.801	2.663	83.082	0.977	62.985	1.843
2	13	25.551	1.919	81.883	0.649	59.891	3.381
2	14	25.896	3.386	82.964	1.244	60.105	1.594
2	15	21.022	2.49	81.893	1.566	62.171	4.407
2	16	25.649	3.27	85.523	1.742	64.252	3.826
2	17	23.305	0.878	83.147	0.866	62.359	5.665
2	18	24.633	0.903	82.956	0.594	67.35	3.577
2	19	22.723	1.819	83.757	1.272	64.168	3.019
2	20	20.197	1.041	81.706	0.565	58.014	3.878
3	1	52.5	3.073	NA	NA	62.667	1.014
3	2	55.625	2.653	NA	NA	61.833	1.302
3	3	58.417	5.586	NA	NA	62.167	2.351
3	4	50.583	8.198	NA	NA	62.833	0.928

3	5	54.083	5.335	NA	NA	58.167	2.682
3	6	47.042	1.355	NA	NA	61.333	1.093
3	7	54.75	5.953	NA	NA	64	0.577
3	8	58.458	4.167	NA	NA	65.167	0.441
3	9	50.917	5.565	NA	NA	61.833	2.848
3	10	49.5	5.233	NA	NA	59	1.155
3	11	59.083	1.001	NA	NA	60.333	0.167
3	12	54.292	2.919	NA	NA	60.333	1.302
3	13	51.167	5.408	NA	NA	62.167	0.441
3	14	47.5	6.788	NA	NA	61.833	0.441
3	15	58.333	2.592	NA	NA	61.167	1.167
3	16	56.667	3.016	NA	NA	59.833	1.202
3	17	47.417	7.544	NA	NA	64.167	0.833
3	18	47.25	4.906	NA	NA	63.833	0.667
3	19	54.917	7.343	NA	NA	65.167	0.928
3	20	56.25	4.226	NA	NA	62.333	3.087
4	1	69.792	8.335	91.5	0.722	93.833	0.333
4	2	71.333	4.48	91.5	0.804	94.167	0.167
4	3	79.292	4.853	92.583	0.917	93.667	0.441
4	4	72.333	5.397	92.833	0.795	93.5	0.764
4	5	74.208	0.512	91	0.382	94	0.289
4	6	78.083	2.311	92.25	0.382	94	0.5
4	7	80.083	1.646	92.75	0.764	93.167	0.601
4	8	76.833	1.949	92.083	2.043	93.5	0.764

4	9	75.167	0.522	91.667	0.726	93.667	0.601
4	10	74.583	3.819	90.917	1.59	93.833	0.667
4	11	77.5	1.938	93.5	0.5	93.333	0.601
4	12	76.25	1.502	93.083	0.464	94.333	0.333
4	13	65.417	5.802	91	1.465	93.667	0.167
4	14	69.875	3.573	91.417	1.093	93.667	0.167
4	15	74.333	4.647	92.667	0.961	93.5	0.5
4	16	71.417	3.253	91.333	1.176	93.833	0.601
4	17	74.042	6.212	90.917	0.795	93.667	0.167
4	18	74.625	1.233	92.167	0.464	94.167	0.441
4	19	76.917	4.693	93.5	0.661	94	0.5
4	20	76.167	2.616	93.25	0.144	94.167	0.601
5	1	67.667	4.271	45.333	3.144	39.833	0.833
5	2	71	4.392	50.25	0.722	41.5	1.893
5	3	67.5	6.709	48.417	2.709	39.667	2.421
5	4	69.25	5.321	48.25	2.046	42.167	0.726
5	5	67.958	2.063	45.167	2.587	40.833	1.691
5	6	73.875	1.566	46.833	6.126	40.667	2.404
5	7	73.625	1.337	47	2.765	39	1.528
5	8	70.333	3.004	47.833	2.931	32.833	7.167
5	9	62.375	2.884	48.833	3.964	41.333	1.424
5	10	65.917	2.146	48.917	4.096	41.833	2.682
5	11	69.917	1.158	44.583	3.607	39.333	2.315
5	12	61.708	6.045	46.75	1.953	39.333	3.087

5	13	63.917	2.468	45	3.929	37	1
5	14	68.583	6.076	45.167	1.991	39.833	2.906
5	15	68.708	6.043	50.333	2.103	41.167	2.205
5	16	64	2.268	46.167	1.543	39.667	1.093
5	17	68	1.843	45.417	4.459	38.333	1.74
5	18	74.625	2.392	46.75	2.673	41.167	2.167
5	19	75.083	0.651	50.167	1.158	40.667	2.186
5	20	67.792	1.543	44.917	3.411	40.833	1.856
6	1	79.625	3.289	52.917	4.851	56.167	7.055
6	2	81.042	2.301	57.917	5.459	59	3.253
6	3	80.167	1.97	48.167	5.272	52.667	6.966
6	4	80.292	0.855	55.333	4.835	55.667	3.167
6	5	79.333	2.204	56.167	6.279	62.5	4.933
6	6	78.75	2.457	48.667	4.542	59.667	7.167
6	7	79.708	1.3	51.667	4.381	60.667	3.42
6	8	81.75	2.482	53.917	6.083	61.167	4.343
6	9	82.958	2.5	51.333	1.856	61.5	2.93
6	10	83.875	3.027	56	3.003	60.5	3.329
6	11	75.792	1.173	47.75	4.901	57.667	2.028
6	12	76.875	2.438	51.917	4.775	58.333	0.928
6	13	81.083	1.917	53	5.346	55	3.786
6	14	79	1.252	56.333	5.924	60.167	3.06
6	15	83.125	0.591	53.833	5.288	55.167	4.969
6	16	77.333	3.088	52.75	5.662	52.833	3.444

6	17	77.875	3.054	57.5	2.376	61.833	1.014
6	18	83.792	0.356	60.25	5.15	62.167	3.06
6	19	83.458	0.292	52.333	3.423	62.667	2.892
6	20	79.042	0.561	51	4.583	51.833	3.087

Appendix F. Differences in the percentages of water stable aggregates (WSA) in each of the three aggregate size classes (ASC): 1. 1-2, 2. 0.25-1, and 3. 0.053-0.25 mm between 2006 and 2011 for six sites (Table 1) and twenty treatments per site. Treatments (Trt) are described in Table 2 and included ten grasses or mixtures of grasses with biomass samples collected annually or biennially. Values are means and standard errors (SE).

		1-2 mm		0.25-1 mm		0.053-0.25 mm	
Site	Trt	Mean	Std Error	Mean	Std Error	Mean	Std Error
1	1	26.765	6.436	5.529	3.43	-5.875	5.569
1	2	26.917	3.248	2.438	3.43	-20.551	2.617
1	3	29.139	2.749	4.312	5.177	-4.801	7.289
1	4	24.863	6.496	4.189	4.193	-14.25	3.7
1	5	22.175	8.466	4.329	3.751	-10.801	4.978
1	6	13.134	5.63	0.375	2.193	-16.25	6.578
1	7	30.262	2.569	3.36	3.875	-5.042	6.874
1	8	32.976	3.395	4.325	3.591	-14.875	4.616
1	9	24.953	2.387	4.125	4.251	-11.125	3.76
1	10	28.129	3.923	3.466	3.618	-18.5	3
1	11	28.064	5.463	4.187	4.487	-9.25	7.25
1	12	30.994	7.107	4.639	2.988	-18.25	3.854
1	13	23.98	4.373	4.67	5.494	-9	6.693
1	14	17.429	6.587	3.387	5.23	-15.375	3.782
1	15	23.218	4.975	2.25	5.241	-6.375	6.189
1	16	25.668	3.17	3.312	2.664	-17.5	3.41
1	17	21.535	4.615	4.938	4.445	-8.75	7.261
1	18	24.19	5.04	4.188	5.091	-14.25	5.487
1	19	27.984	2.021	3.25	4.807	-6	6.931
1	20	27.615	3.654	4.438	2.274	-11.625	2.331

2	1	6.084	1.722	7.676	2.922	-0.17	1.574
2	2	1.051	4.803	1.824	0.914	-1.966	1.028
2	3	6.356	3.102	-0.706	1.548	-6.444	2.514
2	4	4.618	1.26	4.049	0.991	-0.177	0.766
2	5	2.623	3.446	6.438	1.08	-1.579	0.845
2	6	-3.667	2.861	1.675	1.774	-3.454	0.682
2	7	1.252	2.088	0.426	0.718	-1.916	0.918
2	8	3.51	3.149	1.215	2.408	-0.571	0.823
2	9	8.424	1.235	4.607	1.651	-4.592	2.078
2	10	-1.473	2.239	-1.369	2.697	-1.447	1.651
2	11	2.751	0.752	0.966	0.996	-6.376	1.26
2	12	2.801	1.409	6.457	2.244	-0.39	1.827
2	13	8.957	1.112	3.695	1.729	-0.234	1.815
2	14	3.803	3.174	4.214	0.676	-1.02	1.434
2	15	-3.249	2.085	-1.482	1.583	-3.579	1.746
2	16	5.17	2.103	7.648	1.596	-1.998	2.305
2	17	5.867	1.138	6.959	1.569	-3.141	1.35
2	18	2.674	1.915	1.268	1.298	0.725	2.108
2	19	-2.683	3.802	1.257	1.604	2.168	2.15
2	20	1.958	2.28	3.331	0.711	-2.361	1.759
3	1	28.958	2.134	NA	NA	11	2.021
3	2	32.833	3.717	NA	NA	8.667	3.655
3	3	36.958	6.556	NA	NA	9.333	2.92
3	4	32.75	9.153	NA	NA	9.833	1.093

3	5	31.625	4.109	NA	NA	6.333	1.167
3	6	25.458	0.491	NA	NA	11	0.866
3	7	29.708	6.344	NA	NA	8.667	2.333
3	8	36.083	2.807	NA	NA	8.833	2.048
3	9	30.25	6.664	NA	NA	10.167	0.928
3	10	26.458	2.729	NA	NA	8.833	2.242
3	11	34.625	1.665	NA	NA	8	1.041
3	12	29.583	3.364	NA	NA	7.833	1.59
3	13	26.083	1.63	NA	NA	7	4.093
3	14	23.667	6.155	NA	NA	7.833	2.619
3	15	34.875	3.442	NA	NA	10.5	2.93
3	16	34.917	4.24	NA	NA	9	1.756
3	17	28.25	8.758	NA	NA	11.667	0.333
3	18	27.417	4.556	NA	NA	11.833	3.087
3	19	32.375	6.59	NA	NA	13.833	2.315
3	20	37.167	4.707	NA	NA	10.167	0.441
4	1	26.75	7.825	14	1.422	24.667	2.242
4	2	25.583	2.682	11.833	0.961	22.833	0.882
4	3	24.903	1.997	10.583	1.083	20.667	1.093
4	4	29.875	5.17	16.75	1.5	26.167	1.093
4	5	28.667	4.554	12.25	0.75	23.833	2.128
4	6	31.167	2.167	11.5	1.01	20.667	2.048
4	7	29.5	1.803	11.667	0.441	21.333	1.014
4	8	30.125	3.047	13.167	1.722	26.667	2.906

4	9	25.417	1.044	12.083	0.846	24.333	2.088
4	10	27.542	2.606	13	1.09	21	1.323
4	11	30.75	3.301	14.917	0.982	23.333	2.315
4	12	26.292	2.558	11.667	1.862	23	2.021
4	13	12.5	7.3	10.333	1.557	23.667	2.128
4	14	19.375	3.429	10	0.722	21.5	1.258
4	15	22.333	3.336	13.5	1.732	24.667	1.167
4	16	24.333	1.011	13.167	0.87	23	1.041
4	17	20.667	4.763	10.083	1.59	22.5	3.055
4	18	25.208	2.227	11.25	1.233	25	2.646
4	19	25.667	1.242	14.583	2.315	25.333	3.563
4	20	29.833	2.534	13.25	1.377	22.833	1.59
5	1	13.417	4.981	-14.75	2.788	-24.333	3.087
5	2	14.25	3.341	-8.083	3.032	-25	1.756
5	3	10.458	6.293	-10.25	3.467	-24.667	0.667
5	4	15.042	5.887	-8.917	3.371	-21.333	2.048
5	5	12.497	4.499	-14.083	2.963	-21.667	1.878
5	6	13.708	0.751	-12.083	5.955	-21.333	3.114
5	7	16.208	1.74	-12.333	3.321	-23.333	2.744
5	8	13.917	1.745	-10.75	5.346	-33.25	7.915
5	9	5.125	4.01	-8.583	3.941	-22.667	3.321
5	10	6.958	4.677	-10.667	4.95	-23.833	2.744
5	11	10.917	1.693	-13.833	3.104	-26.5	2.363
5	12	9.125	7.635	-10.5	0.52	-25.833	2.421

5	13	8.125	5.204	-11.417	4.124	-28	1.803
5	14	10.25	7.181	-11.583	1.991	-23	3.055
5	15	10.417	8.941	-9.583	1.387	-23.333	1.641
5	16	7.333	5.232	-11.417	1.965	-25.778	1.115
5	17	12.25	4.547	-15.417	3.404	-28	1.323
5	18	19.625	1.092	-10.417	0.795	-23	0.764
5	19	18.167	2.907	-8.75	3.175	-24	1.323
5	20	12	0.992	-11.5	3.538	-25	2.021
6	1	23.167	3.546	-3.667	4.174	-2	7.697
6	2	16	0.904	-1.5	2.179	-1.5	6.506
6	3	19.333	3.229	-6.083	1.557	0	3.606
6	4	22.431	2.755	1	2.646	-1.5	3.014
6	5	21.167	3.18	1.917	2.022	2.333	1.302
6	6	17.417	2.092	-3.25	4.446	3.5	2.754
6	7	17.833	1.815	-3.5	0.901	6	2.466
6	8	23.417	3.031	-5	2.376	-2.167	8.477
6	9	22.708	1.465	-3.833	3.941	5.5	4.311
6	10	24.167	2.301	-2.833	2.113	0.667	7.384
6	11	16.125	2.955	-4.333	5.525	5.667	1.965
6	12	19.333	4.187	-1.083	3.097	0	5.008
6	13	17.917	3.552	-3.583	1.21	-5	6.449
6	14	21.5	2.629	-1.083	1.96	3.833	4.285
6	15	22.417	3.076	-2.833	2.485	-3.833	3.346
6	16	15.139	3.711	-3.75	4.347	-7.833	3.193

6	17	20.75	2.223	0.75	2.898	1.667	2.048
6	18	22.292	2.394	-2.833	1.481	-2.5	4.583
6	19	28.042	1.052	-6.75	3.884	4.167	2.167
6	20	21.125	2.202	-5.833	1.158	-4.667	1.74

Appendix G. Concentration of glomalin measured as Bradford-reactive soil protein (BRSP) in 1-2 mm aggregates in 2006 and 2011 and the difference between 2006 and 2011 values (Diff) for six sites (Table 1) and twenty treatments per site. Treatments (Trt) are described in Table 2 and included ten grasses or mixtures of grasses with biomass samples collected annually or biennially.

		BRSP 2006		BRSP 2011		Diff	
Site	Trt	Mean	SE	Mean	SE	Mean	SE
1	1	3.35	0.404	6.247	0.98	2.897	1.367
1	2	3.591	0.583	6.506	0.88	2.915	1.429
1	3	3.252	0.442	5.997	0.88	2.745	1.315
1	4	2.993	0.414	5.835	0.849	2.842	1.263
1	5	3.263	0.272	6.419	0.931	3.156	1.115
1	6	3.5	0.644	6.431	0.522	2.931	1.099
1	7	3.714	0.479	6.272	0.777	2.558	1.235
1	8	3.406	0.589	5.902	0.777	2.496	1.347
1	9	3.262	0.387	6.572	1.1	3.310	1.414
1	10	3.141	0.329	5.771	0.48	2.631	0.601
1	11	3.131	0.318	6.474	0.89	3.342	1.194
1	12	3.272	0.538	6.454	0.918	3.182	1.436
1	13	3.692	0.401	6.259	0.71	2.568	1.07
1	14	3.745	0.528	5.848	0.708	2.103	1.016
1	15	3.431	0.334	5.708	0.617	2.277	0.951
1	16	2.994	0.529	5.593	0.375	2.600	0.874
1	17	3.374	0.397	6.041	0.379	2.667	0.774
1	18	3.754	0.779	5.412	0.709	1.658	1.451
1	19	3.385	0.41	5.544	0.343	2.159	0.739
1	20	3.096	0.565	5.492	0.414	2.397	0.851
2	1	4.299	1.224	3.322	0.252	-0.132	1.116
2	2	5.124	1.485	3.843	0.351	-0.526	1.458
2	3	3.756	1.109	3.799	0.617	0.982	1.44
2	4	4.498	1.168	3.356	0.076	-0.327	1.124
2	5	4.246	1.445	3.39	0.396	-0.103	1.517
2	6	3.952	0.985	3.251	0.165	-0.175	1.338
2	7	3.595	0.848	3.429	0.015	0.125	1.116
2	8	3.768	0.823	3.584	0.192	0.244	1.167
2	9	3.384	0.808	3.256	0.323	0.335	1.245
2	10	4.308	1.613	3.503	0.436	-0.526	1.932
2	11	3.38	0.816	3.492	0.26	0.545	1.209
2	12	4.156	1.379	3.438	0.436	-0.579	1.516
2	13	3.391	0.701	3.523	0.097	0.247	1.071
2	14	4.174	1.407	3.774	0.701	-0.32	1.455

2	15	3.696	1	3.131	0.246	0.246	1.067
2	16	3.509	0.974	3.085	0.174	0.019	1.156
2	17	3.703	1.077	3.574	0.051	-0.065	1.542
2	18	3.563	0.904	2.944	0.422	-0.373	0.836
2	19	3.517	0.966	3.504	0.481	-0.001	1.172
2	20	3.268	0.683	3.396	0.406	0.287	1.121
3	1	4.624	0.706	4.289	0.579	-0.335	0.89
3	2	5.858	1.326	4.017	0.702	-1.84	1.319
3	3	4.398	1.195	4.426	0.435	0.029	0.861
3	4	4.662	1.255	3.898	0.656	-0.764	1.045
3	5	4.345	1.122	4.416	0.292	0.07	1.01
3	6	4.752	1.206	3.613	0.247	-1.14	1.132
3	7	4.222	0.942	4.504	0.1	0.282	0.961
3	8	5.378	1.59	4.359	0.084	-1.02	1.514
3	9	3.659	0.676	3.966	0.37	0.307	1
3	10	4.082	1.046	4.079	0.124	-0.003	1.126
3	11	3.86	0.746	4.806	0.2	0.946	0.935
3	12	4.08	0.755	4.644	0.507	0.564	1.243
3	13	4.362	0.839	4.654	0.662	0.292	1.028
3	14	4.827	0.976	4.262	0.531	-0.565	0.615
3	15	4.231	0.453	4.128	0.4	-0.103	0.841
3	16	4.774	0.447	4.474	0.15	-0.3	0.584
3	17	4.799	1.193	4.593	0.368	-0.206	1.013
3	18	5.373	1.186	3.991	0.346	-1.382	0.972
3	19	5.143	0.94	4.511	0.331	-0.632	1.108
3	20	5.046	0.863	3.518	0.406	-1.528	0.9
4	1	4.432	0.488	4.87	0.354	0.404	0.341
4	2	4.313	0.358	5.275	0.385	1.048	0.167
4	3	4.627	0.656	4.953	0.403	0.201	0.565
4	4	4.389	0.464	5.037	0.313	0.729	0.37
4	5	4.567	0.513	5.134	0.038	0.677	0.676
4	6	4.644	0.499	4.863	0.23	0.381	0.625
4	7	4.791	0.419	5.168	0.064	0.353	0.652
4	8	4.413	0.352	4.987	0.416	0.827	0.569
4	9	4.473	0.525	5.047	0.343	0.809	0.911
4	10	4.587	0.53	5.05	0.109	0.658	0.739
4	11	4.493	0.404	5.208	0.202	0.797	0.658
4	12	4.878	0.539	5.198	0.031	0.242	0.726
4	13	4.786	0.483	5.304	0.24	0.575	0.909
4	14	4.529	0.469	5.29	0.243	0.947	0.851
4	15	4.593	0.642	4.846	0.092	0.472	0.762

4	16	4.549	0.527	4.882	0.135	0.569	0.8
4	17	4.62	0.409	4.996	0.109	0.405	0.617
4	18	4.359	0.38	4.927	0.396	0.566	0.897
4	19	3.914	0.436	4.976	0.417	1.074	0.893
4	20	3.895	0.308	4.739	0.507	0.865	0.897
5	1	2.484	0.025	3.171	0.113	0.691	0.079
5	2	2.766	0.168	3.671	0.264	0.785	0.248
5	3	2.659	0.125	3.517	0.059	0.829	0.162
5	4	2.822	0.097	3.299	0.131	0.445	0.209
5	5	2.567	0.137	3.38	0.381	0.781	0.482
5	6	2.491	0.064	2.972	0.069	0.531	0.099
5	7	2.736	0.2	3.467	0.169	0.666	0.204
5	8	2.635	0.201	3.366	0.068	0.693	0.24
5	9	2.481	0.131	3.459	0.191	0.986	0.058
5	10	2.809	0.102	3.815	0.108	0.98	0.141
5	11	2.588	0.043	3.293	0.359	0.702	0.418
5	12	2.808	0.142	3.583	0.197	0.689	0.244
5	13	2.507	0.074	3.285	0.405	0.83	0.463
5	14	2.62	0.122	3.46	0.283	0.758	0.158
5	15	2.524	0.103	3.42	0.226	0.838	0.14
5	16	2.595	0.116	3.569	0.207	0.879	0.29
5	17	2.515	0.079	3.203	0.121	0.675	0.156
5	18	2.438	0.071	3.349	0.247	0.873	0.319
5	19	2.453	0.145	3.524	0.167	1.078	0.222
5	20	2.367	0.151	3.438	0.283	1.062	0.078
6	1	4.541	0.578	3.453	0.125	-1.366	0.423
6	2	4.997	1.318	3.876	0.415	-1.659	1.169
6	3	4.929	0.79	3.464	0.148	-1.605	0.52
6	4	5.799	1.06	3.764	0.245	-2.081	0.848
6	5	4.952	1.569	3.795	0.254	-1.828	0.801
6	6	4.68	1.238	3.509	0.169	-1.703	0.602
6	7	4.677	0.95	3.599	0.111	-1.499	0.553
6	8	4.334	0.995	3.804	0.27	-1.21	0.543
6	9	4.682	1.493	4.075	0.151	-1.592	0.932
6	10	4.586	1.121	4.273	0.374	-0.976	0.853
6	11	4.112	0.625	3.691	0.168	-0.716	0.324
6	12	4.827	1.039	4.263	0.647	-0.899	1.153
6	13	4.898	1.887	3.654	0.711	-2.268	1.066
6	14	4.536	1.248	3.348	0.518	-1.6	0.975
6	15	4.429	1.346	3.225	0.554	-1.905	0.831
6	16	5.702	2.014	3.499	0.61	-2.698	1.338

6	17	5.085	1.602	3.709	0.253	-1.997	1.272
6	18	5.541	1.761	4.325	0.615	-1.912	1.736
6	19	4.705	1.101	3.638	0.156	-1.675	0.583
6	20	4.896	0.957	3.572	0.144	-1.65	0.501

ANALYSIS REPORT:

CHEMICAL AND HEAT VALUE CHARACTERIZATION OF PERENNIAL HERBACEOUS BIOMASS MIXTURES

Submitted to:

Karen Kreil
North Dakota Natural Resources Trust
1605 E. Capitol Avenue, Suite 101
Bismarck, ND 58501

Sandra Broekema
Great River Energy
12300 Elm Creek Boulevard
Maple Grove, MN 55369-4718

Submitted by:

Steve Benson
Margaret Laumb
Microbeam Technologies, Inc.

September 9, 2010

MTI Report 1164 - final

This report was prepared by Microbeam Technologies, Inc., on behalf of the North Dakota Natural Resources Trust pursuant to an agreement with the Industrial Commission of ND, which partially funded the report. None of the North Dakota Natural Resources Trust or its partners or any of its subcontractors, the Industrial Commission of North Dakota or any person acting on behalf of any of them:

(A) Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights; or

(B) Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Industrial Commission of North Dakota. The views and opinions of authors expressed herein do not necessarily state or reflect those of the Industrial Commission of North Dakota.

ANALYSIS REPORT: CHEMICAL AND HEAT VALUE CHARACTERIZATION OF PERENNIAL HERBACEOUS BIOMASS MIXTURES

EXECUTIVE SUMMARY

North Dakota National Resources Trust (NDNRT) and Great River Energy (GRE) contacted Microbeam Technologies Inc. (MTI) regarding characterization of biomass samples for use in a circulating fluidized bed combustion (CFBC) system. The biomass will be co-fired with North Dakota lignite. Biomass fuel provides a renewable fuel source that is carbon neutral and will decrease the carbon footprint by replacing lignite firing in the CFB boiler. Biomass fuels are highly reactive with high carbon conversion efficiencies due to high volatile matter and low fixed carbon contents. The biomass can also contain relatively high moisture content that decreases the heat production efficiency and increases the bulk gas flow through the system. Biomass can contain alkali (K and Na), phosphorus, chlorine, and amorphous silicon that can contribute to ash bonding and system corrosion. Chlorine can contribute to corrosion problems in boilers and air pollution control devices.

Twenty blends of biomass fuels composed of grasses from two study sites, along with six replicate blends, were submitted to MTI for characterization. The samples were received in two sets – one set of sixteen (composited into six samples) and one set of forty-two (composited to produce fourteen samples). The first set of six composite samples was split into duplicate samples for analysis. The biomass fuel samples were characterized using standard ASTM bulk analysis methods proximate, ultimate, ash composition, chlorine, and heating value analyses. Partial chemical fractionation was performed to differentiate between water-soluble and organically-associated potassium and sodium.

Proximate, Ultimate and Ash Composition

Fuel analyses are compared using conventional (weight percent-in-fuel or weight percent-in-ash) basis, and on a pound-per-million-BTU (lb/MMBTU) basis to reflect actual ladings. Proximate and ultimate analysis results are summarized as follows:

- Moisture
  - Ranged from 5.6 wt% to 13 wt% (as-received or "wet" basis)
  - Lb/MMBTU basis:
    - Ranged from 7 lb/MMBTU (Carrington-Magnar Basin/Mustang alti. Wildrye) sample to about 20 lb/MMBTU (Carrington tall wheatgrass)
  - Samples from the first set (of sixteen) had higher moisture contents
    - Carrington samples had moisture contents of 13 wt%
    - Streeter samples had moisture contents of 8 – 10 wt%
    - The duplicates that were split from these first six samples all had lower moisture contents
- Ash content
  - Ranged from 4.4 wt% (Carrington switchgrass) to 9.2 wt% (Streeter – Trailblazer switchgrass) (dry basis)
  - Streeter grass samples had higher overall ash contents, with an average ash content of 7.8 wt% (dry basis)

        - Switchgrass samples had lowest ash content (5.8 wt% dry basis)
        - Trailblazer switchgrass had highest ash (9.2 wt% or 12 lb/MMBTU)
    - Carrington grass samples average ash was 5.2 wt% (dry basis)
        - CRP mixes had the highest ash content of site at about 6.2 wt% (dry basis)
        - Carrington switchgrass had lowest ash content on lb/MMBTU basis.
- Volatile matter
    - Ranged from 73 wt% to 77 wt% dry basis.
    - Indicates that during combustion most of the biomass materials will volatilize and burn as a gas in the system
- Fixed carbon
    - Ranged from 16.2 wt% to 19.6 wt% (dry basis)
    - Carrington grasses generally had higher fixed carbon contents than Streeter grasses
        - Carrington average fixed carbon was 18.5 wt% (dry basis)
        - Streeter average fixed carbon was 17.4 wt% (dry basis)
    - Fixed carbon will produce a char and burn as solid material in combustion system
- Total sulfur
    - Ranged from 0.01 wt% (Streeter – Sunburst switchgrass and Sunnyview Big Blues blend) to 0.12 wt% (Streeter – Sunburst switchgrass and tall wheatgrass blend) (dry basis)
- Heating value
    - Ranged from 7,650 BTU/lb (dry basis, for Streeter Trailblazer switchgrass) to 8,180 BTU/lb (dry basis, Carrington – Sunburst switchgrass and Mustang Alti. Wildrye blend)
    - No obvious trend for heating values based on grass type or plot location
- Chlorine content
    - Streeter site grasses ranged from 92.2 µg/g (switchgrass) to 1,150 µg/g (Sunburst switchgrass/Mustang Alti. Wildrye blend)
        - Average Streeter grass chlorine content was 413 µg/g
    - Carrington site grasses chlorine content ranged from 1,420 µg/g (Trailblazer switchgrass) to 4,160 µg/g or 0.5 lb/MMBTU (tall wheatgrass)
        - Average Carrington grass chlorine content was 2,750 µg/g
        - Tall wheatgrass had highest chlorine content on lb/MMBTU basis

Ash composition analysis showed the grasses contained varying levels of silicon (as SiO_2), calcium (CaO), magnesium (MgO), potassium (K_2O), sodium (Na_2O) and phosphorus (P_2O_5).

- Silica
    - Ranged from 45 wt% (Carrington Trailblazer switchgrass) to 77 wt% (Streeter intermediate wheatgrass)
    - Streeter grass samples had significantly more silica (average 72.5 wt%) than Carrington grasses (average 58.2 wt%).
- Calcium
    - Ranged from 4 wt% to 13 wt%.

    - Streeter grasses generally had lower levels of calcium in the ash (average 5.8 wt%, versus the 7.8 wt% average CaO in Carrington grasses),
        - Exception: Streeter CRP mix (wheatgrass, alfalfa, and sweet clover) contained 13 wt% CaO.
- Magnesium
    - Ranged from 2.1 wt% to 7.9 wt%
    - Carrington site grasses had slightly higher average magnesium contents, with an average MgO content of 4.8 wt%
    - Streeter grasses average MgO content was 3.4 wt%
- Potassium
    - The alkali components of the ash are known to contribute to bed agglomeration and convective pass fouling
    - Ranged from 7.7 wt% (Streeter intermediate wheatgrass) to 15.5 wt% (Carrington Trailblazer switchgrass)
    - Grasses from the Carrington site had significantly higher average potassium content (average 15.5 wt% K_2O) than Streeter grasses (9.7 wt% K_2O)
    - The Carrington switchgrass and blends generally had higher potassium levels than the other grass species
- Sodium
    - The alkali components of the ash are known to contribute to bed agglomeration and convective pass fouling
    - Ranged from less than 1 wt% in ash (Streeter grasses) to 4.7 wt% (Carrington wheatgrass)
    - Carrington grass samples contained an average of 2.74 wt% Na_2O in the ash
    - Streeter grass samples had an average of 1.24 wt% Na_2O in the ash
- Phosphorus
    - Can contribute to the formation of phases that cause bonding of bed particles and ash materials in a fluidized bed
    - Ranged from 1.5 wt% in ash (Streeter intermediate wheatgrass) to 8.1 wt% (Carrington – Magnar Basin, Mustang alti. wildrye blend)
    - Carrington grasses contained significantly more phosphorus in the ash, at 6.3 wt%, than Streeter grasses (2.2 wt%)

Duplicates of six samples were analyzed. Percent difference between the two sets of analyses was calculated on a dry basis only. Dry basis analyses were used due to differences in moisture contents. Volatile matter, carbon, heating value, and silica in ash had less than 10% difference between duplicate samples. Variability between analyses for other constituents was mainly due to low quantities of nitrogen, total sulfur, and, in some cases, alkali and alkaline earth components.

Partial Chemical Fractionation

Partial chemical fractionation was performed to quantify the water-soluble alkali components and the ion-exchangeable or organically-associated alkali components. Results are summarized as follows:

- Potassium
  - Initial quantities ranged from 3,980 µg/g (Streeter switchgrass) to 8,474 µg/g (Streeter Sunburst switchgrass)
  - Water-soluble potassium:
    - 79% to 97% was water-soluble
    - Average 92% water-soluble potassium in Streeter site samples
    - Average 91% water-soluble potassium in Carrington site samples
  - Organically-associated potassium
    - Similar levels between Streeter and Carrington grasses, average 7-8%
    - Carrington Sunburst switchgrass-Sunnyview Big Blues blend had highest level of organically-associated potassium at 20%
      - Same blend from Streeter contained 11% organically-associated potassium
- Sodium
  - Initial quantities ranged from 291 µg/g (Streeter intermediate wheatgrass) to 1,280 µg/g (Carrington tall wheatgrass)
  - Water-soluble sodium:
    - Ranged from none-detected to 86% (Carrington wheatgrass)
    - Average 41% water-soluble potassium in Streeter site samples
    - Average 66% water-soluble potassium in Carrington site samples
      - Sunburst switchgrass blends had lower water-soluble sodium than other Carrington fuels, at 25-27%
  - Organically-associated sodium
    - Ranged from none-detected to 41% (Carrington Sunburst switchgrass-Sunnyview Big Blues blend)

Performance Predictions – Blends with Design Coal

MTI made performance predictions using GRE-provided ASTM analyses for Spiritwood design coal. The design coal is a dried coal (Falkirk Mine enhanced using the DryFining™ process). GRE anticipates up to 10% co-firing or 109.2 MMBTU/hour input basis. MTI used the highest blend ratio, 10% on a BTU basis, to calculate blend compositions for the biomass with the "typical" or design lignite enhanced with the DryFining™ process.[1]

MTI's performance indices were developed for pulverized and cyclone-fired boilers, but may be interpreted relative to the formation of agglomerates and deposits in fluidized bed systems. Indices calculated included the following:

- *Strength index*
  - *Used for interpreting potential for bed agglomeration*
    - *Ability of ash materials to produce low-viscosity phases on silicate and aluminosilicate bed materials, resulting in agglomeration*
  - *Deposit strength index is used to predict the strength of deposited material*
    - *Combined with wall slagging and silication indices to assess deposit characteristics (size and tenacity of deposits)*
  - *Baseline (100%) lignite and the blends with biomass all had low-to-moderate strength index values of 0.27-0.28*
- *Sulfation (low-temperature fouling)*
  - *Ability to produce sulfate-rich bonding phases*
  - *Temperature range 1000-1750°F*
  - *Based on the availability of alkali and alkaline earth elements to react with gas-phase SO_2 and SO_3 to form sulfates*
    - *Cause particle-to-particle bonding in high-calcium situations*
    - *Thermodynamically stable below about 1650°F.*
  - *Baseline coal – low sulfation index*
    - Biomass blends had slightly higher sulfation index due to increased level of alkali and alkaline earth elements
- *Silication (high temperature fouling) index*
  - *Related to formation of high-temperature bed agglomerates and deposits on heat exchangers*
  - Temperature excursions in bed can result in silicate bonding, especially in sand bed with high available quartz
  - Indicates propensity to form high-temperature silicate-based deposits (1600-2400°F)

---

[1] Note: in addition to ultimate and ash composition analyses, CCSEM data on mineral size, composition and abundance is required to make performance predictions. CCSEM analysis was not performed on the biomass samples, and a sample of lignite enhanced with the DryFining™ process was not provided for analysis using CCSEM. To make performance predictions, a high-mineral-content (15.5 wt% as-received ash) Falkirk Mine lignite CCSEM analysis was used along with the design coal ultimate and ash composition. The impact of mineral/inorganic constituents in the biomass was neglected.

    - Baseline coal – high silication index
        - Blending with biomass increased silication index
- Slagging index
    - Provides indication of impact of coal minerals, organically-associated elements on performance
    - Baseline coal had low-moderate index value
        - Biomass blends had moderate slagging index
- *T_{250}*
    - *Temperature at which materials become molten – viscosity 250 poise*
    - Baseline coal T_{250} was 2315°F (based on Urbain viscosity-temperature relationship)
        - Addition of Carrington biomass did not significantly change T_{250} for baseline coal
        - Streeter biomass slightly increased T_{250} (by ~15°F)
- Viscosity of silicate-based phases
    - At design bed temperature of 1600°F, calculated viscosity for all blends is between that of initial sticking and particle bonding initiation.

TABLE OF CONTENTS

INTRODUCTION **135**

BACKGROUND **137**
CFBC systems **137**
Biomass characteristics **137**
Bonding phase properties **138**
Bed agglomeration process **143**

METHODS **145**
ASTM methods **145**
Partial chemical fractionation **145**

RESULTS AND DISCUSSION **149**
ASTM analyses **149**
Select ASTM data on heating-value-input basis **159**
Chemical fractionation **162**
Predicted performance for blends with Falkirk coal **166**
Viscosity-temperature relationships for silicate-based bonding materials **175**
Sulfate-based bonding **186**
Low-temperature bonding in ash handling equipment **189**

REFERENCES **190**

INTRODUCTION

North Dakota National Resources Trust (NDNRT) and Great River Energy (GRE) contacted Microbeam Technologies Inc. (MTI) regarding characterization of biomass samples for use in a circulating fluidized bed combustion (CFBC) system. The biomass will be co-fired with North Dakota lignite. Biomass fuel provides a renewable fuel source that is carbon neutral and will decrease the carbon footprint by replacing lignite firing in the CFB boiler.

NDNRT and GRE submitted twenty blends of biomass fuels composed of grasses from two study sites, along with six replicate blends. MTI performed the following analyses on the samples:

- Proximate (moisture, ash, volatile matter and fixed carbon) ;
- Ultimate (carbon, hydrogen, nitrogen, sulfur, and oxygen by difference) ;
- Heating value;
- Chlorine;
- Ash composition (major elemental constituents in ash including Na, Mg, Al, Si, P, S, K, Ca, Ti, and Fe); and
- Alkali (Na and K) forms (inorganically-associated, salts, organically-associated).

The samples submitted and analyses requested are listed in Table 1. The information gained from the analyses was used along with lignite composition data provided by GRE to assess potential ash-related issues associated with co-firing the grass and lignite in a CFBC system.

Table 1. Biomass (grass) samples submitted and analyses requested.

MTI ID	Description	Proximate	Ultimate	Chlorine	Heating Value (BTU/lb)	Partial Chemical Fractionation (Na,K)
10-081	Carrington - Sunburst switchgrass, Sunnyview Big Blues	X	X	x	x	x
10-082	Carrington - CRP mix (wheatgrass, alfalfa, sweet clover)	X	X	x	x	x
10-083	Carrington - Sunburst switchgrass, Mustang alti. wildrye	X	X	x	x	x
10-084	Carrington - Trailblazer switchgrass	X	X	x	x	x
10-085	Carrington - CRP mix (intermediate, tall wheatgrass)	X	X	x	x	x
10-086	Carrington - Sunburst switchgrass, tall wheatgrass	X	X	x	x	x
10-087	Carrington - Magnar Basin, Mustang alti. wildrye	X	X	x	x	x
10-088	Streeter - Sunburst switchgrass, Sunnyview Big Blues	X	X	x	x	x
10-089	Streeter - Trailblazer switchgrass	X	X	x	x	x
10-090	Streeter - CRP mix (intermediate, tall wheatgrass)	X	X	x	x	x
10-091	Streeter - Magnar Basin, Mustang Alti. Wildrye	X	X	x	x	x
10-092	Streeter - Sunburst switchgrass, tall wheatgrass	X	X	x	x	x
10-093	Streeter - Sunburst switchgrass, Mustang Alti. Wildrye	X	X	x	x	x
10-094	Streeter - CRP mix (wheatgrass, alfalfa, sweet clover)	X	X	x	x	x
10-098	Carrington - intermediate wheatgrass	X	X	x	x	x
10-099	Carrington - tall wheatgrass	X	X	x	x	x
10-100	Carrington - switchgrass	X	X	x	x	x
10-101	Streeter - intermediate wheatgrass	X	X	x	x	x
10-102	Streeter - tall wheatgrass	X	X	x	x	x
10-103	Streeter - switchgrass	X	X	x	x	x
10-056c	Carrington - intermediate wheatgrass (replicate)	X	X	x	x	
10-059c	Streeter - intermediate wheatgrass (replicate)	X	X	x	x	
10-061c	Carrington - switchgrass (replicate)	X	X	x	x	
10-063	Streeter – switchgrass (replicate)	X	X	x	x	
10-065c	Carrington - tall wheatgrass (replicate)	X	X	x	x	
10-068c	Streeter - tall wheatgrass (replicate)	X	X	x	x	

BACKGROUND

CFBC Systems

CFBC systems are typically designed to operate at temperatures between 1500°F and 1800°F. Bed materials can consist of limestone, dolomite, sintered clay, sand, olivine, and other materials. Bed materials such as limestone and dolomite are often used to aid in sulfur capture (these materials will capture sulfur oxide species in the bed). Bed material selection must be based on fuel composition. Significant problems can occur if inappropriate bed materials are used. For example, it is well-known that sand beds containing high levels of quartz (SiO_2) should not be used with fuels containing high levels of alkali (Na and K) (Hajicek and others, 1985). Sodium reacts with silicon to produce very low melting point phases that create bed agglomeration problems.

Ash-related challenges in fluidized bed combustion systems include bed agglomeration, ash deposition on heat transfer and other surfaces in the boiler, and deposition in cyclones. These problems are largely attributed to the formation of low melting-point sulfates and silicates. In some case, chlorides and phosphates can also produce low melting-point bonding phases.

GRE is having a Babcock and Wilcox (B&W) Internal Recirculation (IR) CFB boiler installed. A schematic diagram of the boiler is illustrated in Figure 1. The B&W design does not include a large cyclone between the furnace and convective pass to separate particles for recirculation in the system. The B&W design relies on a two-stage solids collection system. The first stage is a U-beam particle separator shown in Figure 1 (following page). In this stage, the particles impact the U-beam surface and travel down the channel back to the bed. The second stage of the solids collection system is a multi-cyclone dust collector (MDC) that is located downstream of the horizontal convection pass.

Biomass characteristics

Biomass fuels are highly reactive fuels with high carbon conversion efficiencies due to high volatile matter and low fixed carbon contents. The biomass can also contain relatively high moisture content that decreases the heat production efficiency and increases the bulk gas flow through the system. Biomass can contain alkali (K and Na), phosphorus, chlorine, and amorphous silicon that can contribute to ash bonding and system corrosion. Chlorine can contribute to corrosion problems in boilers and air pollution control devices.

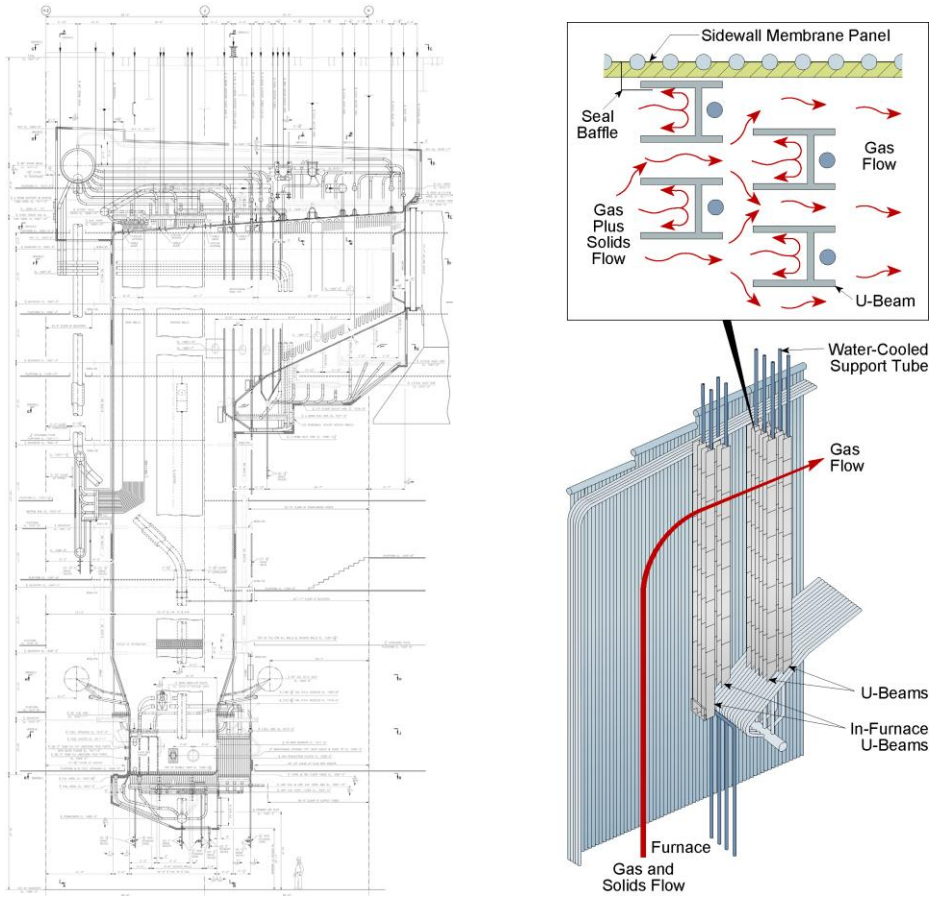


Figure 1. Cross section of GRE CFB system (Maryamchik and Wietzke, 2009).

Bonding phase properties

Figure 2 shows the general type of phases responsible for deposit or agglomerate bonding as a function of temperature. Typically, sulfate bonding is dominant at lower temperatures (below about 900°C or 1650°F), while silicate phases cause bonding at higher temperatures. In fluidized bed combustion systems most of the challenges are associated with the bonding of agglomerates with sulfate based liquid phases. However, if high quartz (SiO_2)-containing sand bed are used along with high alkali (sodium and potassium) containing fuels the silicate based bonding materials will contribute to agglomeration and fouling problems because the silicate liquid phase melting temperature and viscosity are significantly depressed by the alkali.

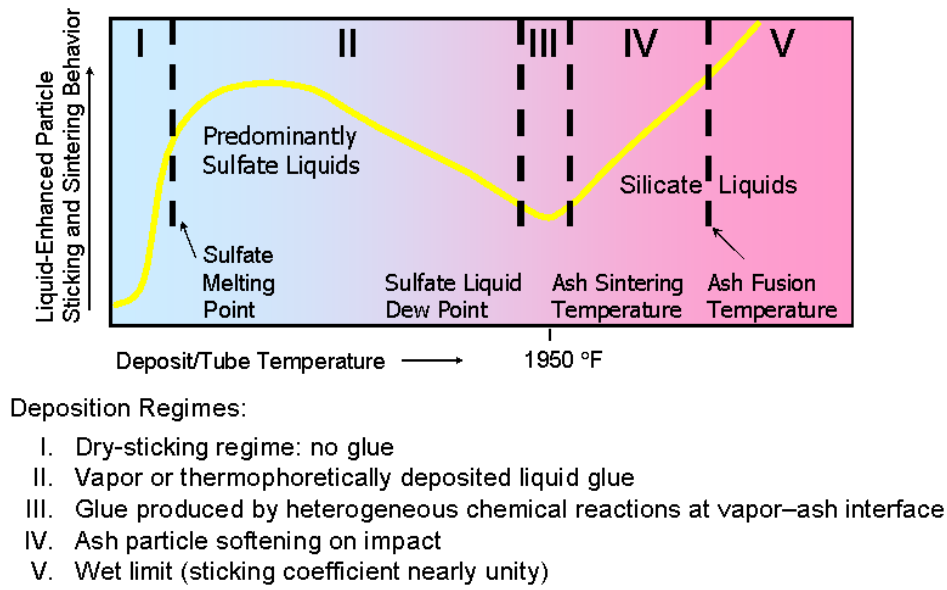


Figure 2. Bonding phases in ash deposits.

Formation of liquid bonding phases during the combustion of North Dakota lignite is directly related to the formation of low-melting point alkali- and alkaline earth-aluminosilicates and sulfates. Some North Dakota lignites contains significant quantities of sodium, which will volatilize upon combustion, become dispersed throughout the gas stream, and will later condense on bed materials, other ash particles, and on metal surfaces. Sodium and potassium compounds in coal ash-related systems melt at relatively low temperatures. The melting points of sulfate-based materials are on the order of 1200°F (650°C). Phase diagrams for select sodium- and potassium silicate and sulfate systems are shown in Figures 3 through 7.

Information derived from examination of phase diagrams will aid in identifying potential problems associated with high-sodium North Dakota lignite. This information can be used to identify optimum compositions and temperatures that will allow for the minimization of agglomeration and deposition problems.

Phase diagrams for sodium silicate and sodium aluminosilicate-based liquid phases are shown in Figures 3 and 4. Sodium silicate ($Na_2Si_2O_5$) was found to be thermodynamically more stable than sulfates at temperatures from 2200°F to 2900°F (1200°C to 1600°C), but at lower temperatures, sodium sulfate is more likely to form (Wibberly and Wall, 1982). Sodium sulfate is stable below 2000°F (1100°C). Vapor-phase sodium and potassium hydroxides or chlorides were found to be present in significant amounts at temperatures exceeding 1750°F (950°C) (Scandrett and Clift, 1984). Below 1750°F (950°C), these alkalis are present mainly as condensed sulfates. Reactions of alkali sulfates with aluminosilicates begin at about 1350°F (730°C).

At temperatures below 1650°F, sulfate-based bonding is the dominant mechanism. Phase diagrams for sulfate-based liquid phases are shown in Figures 5 through 7. Formation of sulfate-based bonding phases is related to the abundance of alkali, chlorine, and sulfur in the system.

The level of chlorine in biomass has a significant impact on the volatility of alkali elements (sodium and potassium). Volatile alkali chlorides will condense on cooled surfaces, and will rapidly sulfate in the presence of gas-phase sulfur oxides. Higher levels of sulfur in the fuel will diminish the chloride-related ash deposition mechanism, by increasing the likelihood of forming alkali sulfates. However, formation of chloride bonding materials likely proceeds at a much faster rate than formation of sulfate bonding materials, because the two-step sulfation process requires the transformation of SO_2 to SO_3 before reaction with alkali or alkaline earth elements. The melting point of complex sulfates can be as low as 1,200°F.

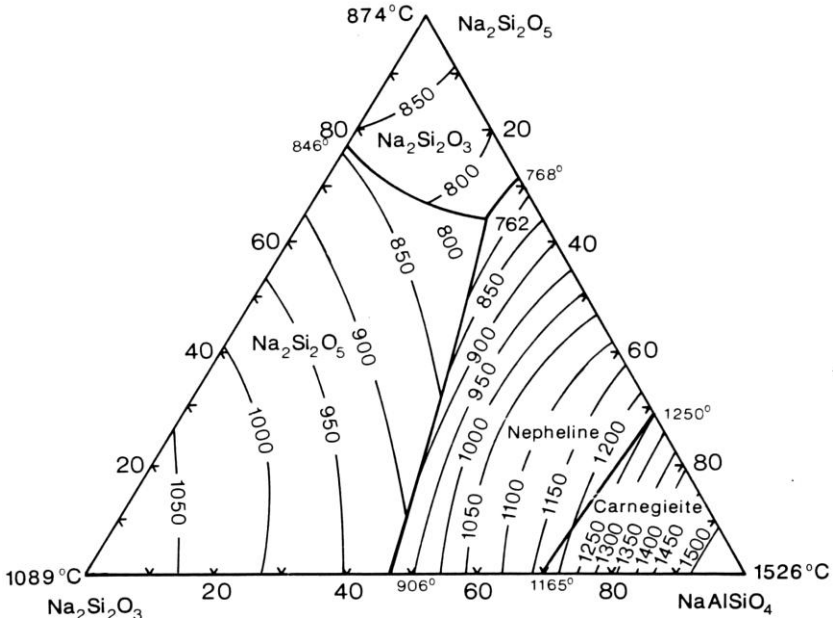


Figure 3. Sodium aluminosilicate phase diagram (Levin et al., 1964).

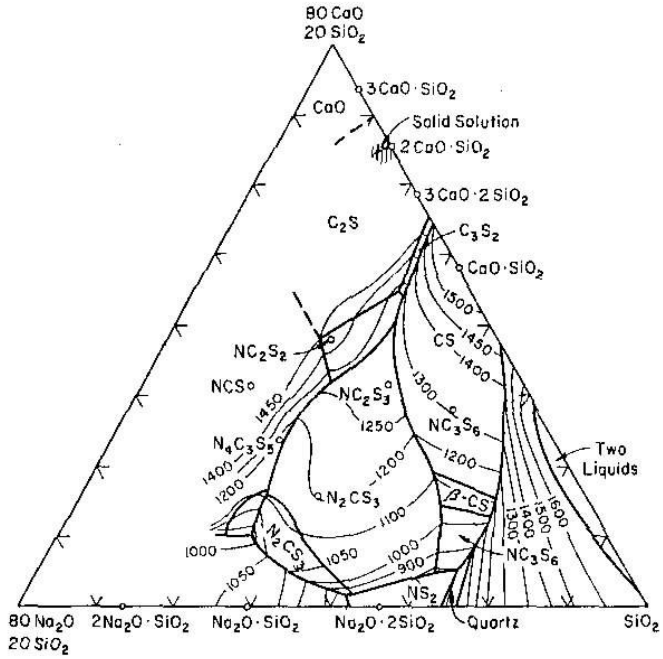


Figure 4. Phase diagram of sodium-calcium-silicate systems (temperatures °C) (Levin et al., 1964).

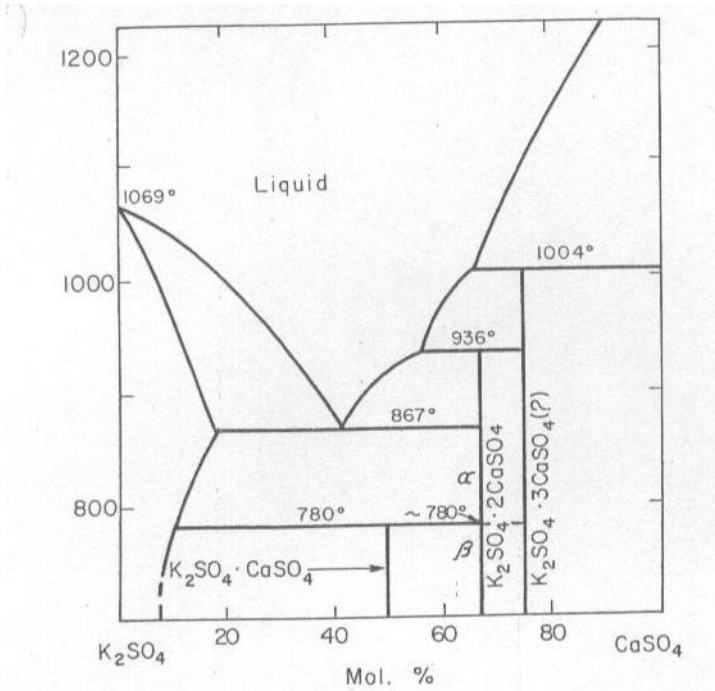


Figure 5. Phase diagrams of potassium sulfate-calcium sulfate systems (temperatures °C) (Mikimov et al., 1949).

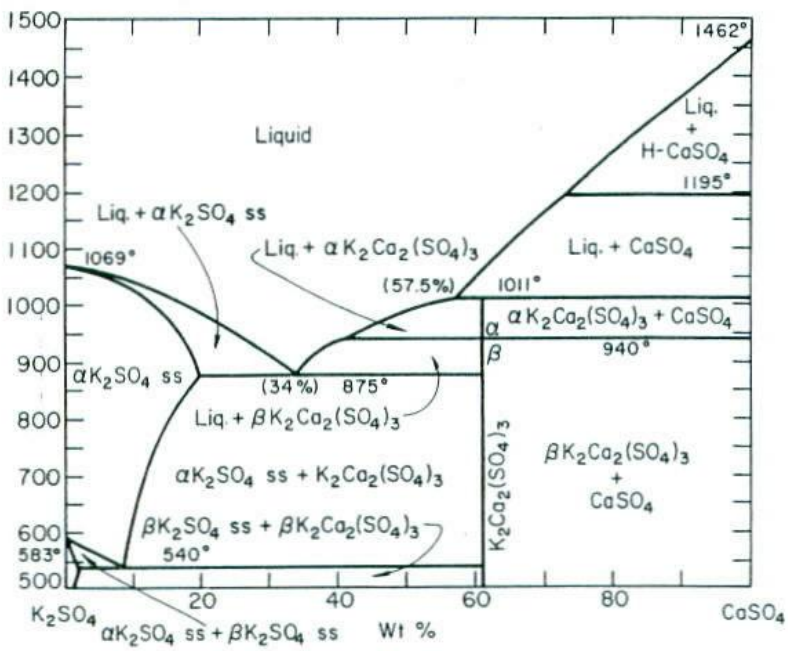


Figure 6. Phase diagram of potassium sulfate-calcium sulfate systems (temperatures °C) (Levin et al., 1964).

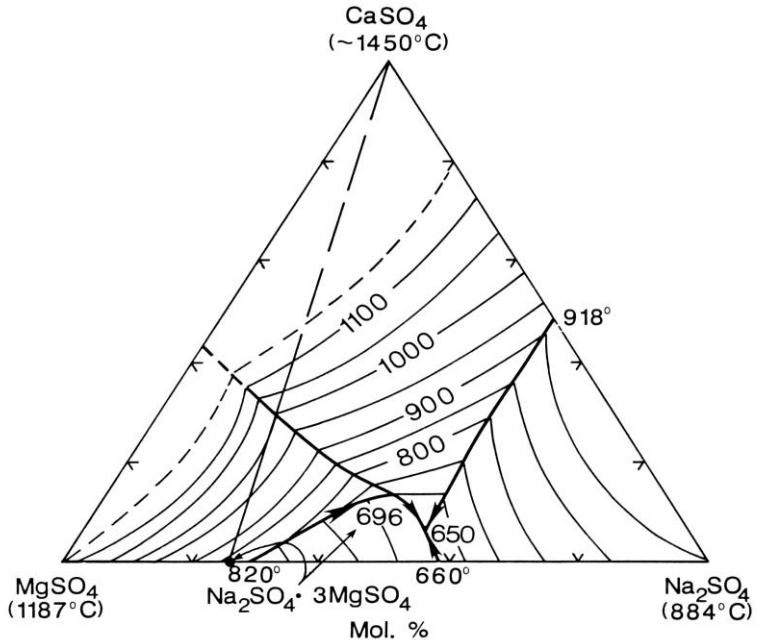


Figure 7. Sodium, calcium, and magnesium sulfate phase diagram (Levin et al., 1964).

Bed agglomeration process

Bed material agglomerates can be classified into four distinct categories. These categories include: small particle agglomerates; hollow egg-like agglomerates; high-temperature agglomerates; and sintered fly ash/sorbent agglomerates. The agglomerate types are described as follows:

- Small particle agglomerates – bed particles that are coated with ash particles. The bed material is reactive with coal ash, resulting in the formation of lower-melting-point phases that cause particle-to-particle bonding. This agglomerate type is typical of deposits produced from high-sodium lignite. The bonding phases consist of sodium, calcium, or potassium sulfates. Agglomerates of this type have solid cores.
- Hollow core agglomerates. These agglomerates form around burning coal particles. After the coal burns out, a hollow, egg-shaped agglomerate is formed. Agglomerates range in size from ½ to 3 inches in diameter.
- High-temperature agglomerates. These agglomerates form as a result of localized "hot spots" where the temperature has exceeded about 1700°F and are typically silicate-based. Temperatures capable of melting various ash materials may be attained in an operating CFBC. Typically this type of agglomerate is produced in localized zones of poor fluidization. They occur during startup and turndown.
- Sintered fly ash agglomerate. These agglomerates consist mainly of sintered fly ash with some bed material. These deposits are typically weaker and are commonly found in loop seals and other areas of low or stagnant flow.

The primary fuel components that have been known to contribute to agglomerate formation are the alkali elements (sodium and potassium). Other elements also associated with bed agglomeration include iron, vanadium, and calcium. Silicon will also participate in the bonding process.

The agglomeration mechanism for high-sodium or potassium-containing lignite begins with the combustion of the coal, which results in the release of the ash-forming components. Fine ash particles are produced along with vapor-phase species such as sodium, potassium, and sulfur. The vapor-phase species, through the process of heterogeneous condensation and formation of fine-grained liquid materials, stick to the surfaces of the bed particles, resulting in the build-up of a sticky layer on the particle surface. The sticky layer on the bed materials becomes thick enough to allow for particle-to-particle bonding and sintering. The material is continually swept with flue gas, such that continued reaction with sulfur oxides will cause the material to expand, leading to pore filling and increasing the amount of bonding and the rate of formation of liquid phases. The mechanism has been described in stages, as follows:

- Stage 1 – Coating of the bed materials with ash. Bed particles become coated with coal ash that is rich in sodium and calcium. These components are in the form of sulfates. The coating appears to be selectively enriched in sodium and calcium sulfates. The specific mechanisms of formation of the coatings are not fully understood, but there are two possible mechanisms. The first possible mechanism is that as the coal particle burns, the sodium and calcium-rich material on the coal particle surface come in contact with the bed particles and preferentially stick to the bed particles. This results in a coating on the surface. The second possible mechanism is described in Stage 2.

- Stage 2 – Sulfation of the sodium and calcium-rich particles on the surface to form sodium calcium sulfates by reaction with flue gas. This sodium calcium sulfate coating is continually impacted by small ash particles. The small ash particles are then captured in the sticky coating on the bed material. This process continues until the thickness of the sticky coating reaches approximately 10% of the total particle diameter. At this point, the coating becomes thick enough to bond with other coated ash particles, thus initiating the agglomeration process. Once bonded, the agglomerated materials will continue to react with the flue gas and other ash particles, resulting in pore filling and further particle bonding.
- Stage 3 – The sodium and calcium-rich materials on the surface of the bed particle can react with the bed particle itself, producing a liquid-phase material. If the bed material is silica sand, a low-melting-point sodium silicate glass material will form. Sodium silicate materials are extremely sticky, and rapid agglomeration can occur. The viscosity of the sodium silicates is very low, and will allow for further bonding of bed particles as well as increased flow and filling of pores.
- Stage 4 – Once larger agglomerates have formed, poor fluidization occurs, resulting in hot spots and complete fusing of the agglomerated materials. In some instances, massive fusing of the bed has resulted, requiring the unit to be shut down to remove the deposited materials.

The key factors that enhance agglomerate formation include: the composition of the coal ash; composition of the bed material; temperature of the bed; presence of localized reducing conditions in the bed; and the degree of fluidization.

The methods used to alleviate agglomeration and deposition will include careful design of the FBC, blending to optimize lignite quality, bed material selection, additives, optimizing plant operation, and management of sodium in the system (recycle rates, etc.).

METHODS

The samples were received in two sets – one set of sixteen that were composited into six samples (MTI 10-056c, -058c, -061c, -063c, -065c and -068c) and one set of forty-two replicates that were composited to produce fourteen samples. The first set of six composite samples was split into duplicate samples (MTI 10-098 to -103) for analysis. A complete list of samples received and composite sample identification is provided in Table 2.

ASTM methods

The biomass fuel samples were characterized using standard ASTM bulk analysis methods proximate, ultimate, ash composition, chlorine, and heating value analyses. Proximate analysis provides the following information: moisture; ash; volatile matter; fixed carbon. Ultimate analysis includes carbon, hydrogen, nitrogen, sulfur, and oxygen by difference. The ash composition analysis reports, on an equivalent oxide basis, the following major constituents: silicon; aluminum; titanium; iron; calcium; magnesium; potassium; sodium; sulfur; phosphorus; strontium; barium; and manganese. The chlorine content and heating value (BTU/lb) of the biomass samples was determined.

Partial Chemical Fractionation

Chemical fractionation analysis (Benson and Holm, 1985) provides an indication of the association of selected important inorganic components in the biomass fuel. The tendency to form volatile compounds under combustion conditions can be assumed from the analysis results. The water-soluble fraction consists of salts that are assumed to be more easily volatilized under combustion conditions, while the acetate-soluble fraction contains more organically-associated elements. The organically-associated elements are volatile but are more prone to react with other organically-associated species. A third step (acid-soluble) is used to identify carbonates or coordination complexes. The acid-soluble step is not performed on biomass samples. Residual material typically consists of minerals that are likely to remain in the char upon combustion and not volatilize.

The biomass fuel samples were ground to 100% passing 60 mesh (250 µm) for the partial chemical fractionation. Partial chemical fractionation was performed to differentiate between water-soluble and organically-associated potassium and sodium. Extractions were performed using room-temperature distilled water and hot (160°F) 1-molar ammonium acetate solution.

Table 2. Samples received and composite sample identification.

Sample Description	MTI ID	Date Received	Sample mass, gm
Composite - Carrington intermediate wheatgrass	10-056c		no data
Duplicate – Carrington intermediate wheatgrass composite	10-098		no data
Intermediate Carrington R3 T7	10-056	3/25/2010	
Intermediate WG Carrington R2 T7	10-057	3/25/2010	
Intermediate WG Carrington R4 T7	10-058	3/25/2010	
Composite - Streeter intermediate wheatgrass	10-059c	x	no data
Duplicate – Streeter intermediate wheatgrass composite	10-101		
Intermediate WG Streeter R3 T7	10-059	3/25/2010	x
Intermediate WG Streeter R4 T7	10-060	3/25/2010	x
Composite - Carrington wwitchgrass	10-061c	x	no data
Duplicate – Carrington switchgrass composite	10-100		
Switchgrass Carrington R2 T1	10-061	3/25/2010	x
Switchgrass Carrington R4 T1	10-062	3/25/2010	x
Switchgrass Sunburst Carrington R3 T1	10-064	3/25/2010	x
Switchgrass Streeter R2 T1	10-063	3/25/2010	no data
Duplicate – Streeter switchgrass	10-103		
Composite - Carrington tall wheatgrass	10-065c	x	no data
Duplicate – Carrington tall wheatgrass composite	10-099		
Tall WG Carrington R4 T5	10-065	3/25/2010	x
Tall WG Carrington R2 T5	10-066	3/25/2010	x
Tall WG Carrington R3 T5	10-067	3/25/2010	x
Composite - Streeter tall wheatgrass	10-068c	x	no data
Duplicate – Streeter tall wheatgrass composite	10-102		
Tall WG Streeter R4 T5	10-068	3/25/2010	x
Tall WG Streeter R2 T5	10-069	3/25/2010	x
Tall WG Streeter R3 T5	10-070	3/25/2010	x

Sample Description	MTI ID	Date Received	Sample mass, gm
Composite - Carrington Sunburst switchgrass, Sunnyview Big Blues	10-081	x	**859.1**
I12 WW 4 Carrington REP-2 TRT-15 Sunburst Switchgrass + Sunnyview Big Blues	-	4/8/2010	277.4
I24 SV 4 st. Carrington REP-3 TRT-15 Sunburst switchgrass + Sunnyview Big Blues	-	4/8/2010	332.4
M14 WW 4 Carrington REP-4 TRT-15 Sunburst switchgrass + Sunnyview Big Blues	-	4/8/2010	249.3
Composite - Carrington CRP mix (wheatgrass, alfalfa, sweet clover)	10-082	x	**817.6**
M27 P5 st. Carrington REP-2 TRT-11 CRP Mix (wheatgrass + Alfalfa + Swt Clover)	-	4/8/2010	313.4
I25 WS 4 Carrington REP-3 TRT-11 CRP Mix (wheatgrass + Alfalfa + Swt Clover)	-	4/8/2010	267.2
I12 WW 4 st. Carrington REP-4 TRT-11 CRP Mix (wheatgrass + Alfalfa + Swt Clover)	-	4/8/2010	237
Composite - Carrington Sunburst switchgrass, Mustang alti. Wildrye	10-083	x	**736.2**
I16 P4 st. Carrington REP-2 TRT-17 Sunburst switchgrass + Mustang Alti. Wildrye	-	4/8/2010	218.1
I17 WW 4 Carrington REP-3 TRT-17 Sunburst switchgrass + Mustang Alti. Wildrye	-	4/8/2010	231.6
M16 SV 4 st. Carrington REP-4 TRT-17 Sunburst switchgrass + Mustang Alti. Wildrye	-	4/8/2010	286.5
Composite - Carrington Trailblazer switchgrass	10-084	x	**765.6**
I22 WW 4 st. Carrington REP-2 TRT-3 Trailblazer Switchgrass	-	4/8/2010	346.7
I16 WW 4 Carrington REP-3 TRT-3 Trailblazer Switchgrass	-	4/8/2010	208.9
M22 SV 4 st. Carrington REP-4 TRT-3 Trailblazer Switchgrass	-	4/8/2010	210
Composite - Carrington CRP mix (intermediate, tall wheatgrass)	10-085	x	**678.2**
M15 WW 4 Carrington REP-2 TRT-9 CRP Mix (Intermediate + Tall wheatgrass)	-	4/8/2010	239.6
I25 WS 4 st. Carrington REP-3 TRT-9 CRP Mix (Intermediate + Tall wheatgrass)	-	4/8/2010	247.6
I23 WW 4 Carrington REP-4 TRT-9 CRP Mix (Intermediate + Tall wheatgrass)	-	4/8/2010	191
Composite - Carrington Sunburst switchgrass, tall wheatgrass	10-086	x	**856.2**
M21 P4 st. Carrington REP-2 TRT-13 Sunburst switchgrass + Tall wheatgrass	-	4/8/2010	319.9
I14 P4 st. Carrington REP-3 TRT-13 Sunburst switchgrass + Tall wheatgrass	-	4/8/2010	261.5
M21 SV 4 st. Carrington REP-4 TRT-13 Sunburst switchgrass + Tall wheatgrass	-	4/8/2010	274.8
Composite - Carrington Magnar Basin, Mustang alti. Wildrye	10-087	x	**633.2**
I17SV 4 st. Carrington REP-3 TRT-19 Magnar Basin + Mustang Alti. Wildrye	-	4/8/2010	210.9
M22 SB 4 Carrington REP-4 TRT-19 Magnar Basin + Mustang Alti. Wildrye	-	4/8/2010	181.9
M42 P4 st. Carrington REP-4 TRT-19 Magnar Basin + Mustang Alti. Wildrye	-	4/8/2010	240.4
Composite - Streeter Sunburst switchgrass, Sunnyview Big Blues	10-088	x	**484.45**
Streeter REP-2 TRT-15 Sunburst switchgrass + Sunnyview Big Blues (no BBS)	-	4/8/2010	99.25
Streeter REP-3 TRT-15 Sunburst switchgrass + Sunnyview Big Blues (20% SWG + 80% WG)	-	4/8/2010	136.1
Streeter REP-4 TRT-15 Sunburst switchgrass + Sunnyview Big Blues (no SWG, no BBS, WG &	-	4/8/2010	249.1

Sample Description	MTI ID	Date Received	Sample mass, gm
Weeds)			
Composite - Streeter Trailblazer switchgrass	10-089	x	**340.88**
Streeter REP-2 TRT-3 Trailblazer switchgrass (no SWG, WG & weeds)	-	4/8/2010	110.88
Streeter REP-3 TRT-3 Trailblazer switchgrass (no SWG, WG)	-	4/8/2010	120.9
Streeter REP-4 TRT-3 Trailblazer switchgrass (40% weeds, 40% WG)	-	4/8/2010	109.1
Composite - Streeter CRP mix (intermediate, tall wheatgrass)	10-090	x	**239.87**
Streeter REP-2 TRT-9 CRP Mix (Intermediate + Tall wheatgrass)	-	4/8/2010	80.4
Streeter REP-3 TRT-9 CRP Mix (Intermediate + Tall wheatgrass)	-	4/8/2010	77.2
Streeter REP-4 TRT-9 CRP Mix (Intermediate + Tall wheatgrass)	-	4/8/2010	82.27
Composite - Streeter Magnar Basin, Mustang alti. Wildrye	10-091	x	**332.6**
Streeter REP-2 TRT-19 Magnar Basin + Mustang Alti. Wildrye	-	4/8/2010	125.6
Streeter REP-3 TRT-19 Magnar Basin + Mustang Alti. Wildrye	-	4/8/2010	118
Streeter REP-4 TRT-19 Magnar Basin + Mustang Alti. Wildrye	-	4/8/2010	89
Composite - Streeter Sunburst switchgrass, tall wheatgrass	10-092	x	**473.2**
Streeter REP-2 TRT-13 Sunburst switchgrass + Tall wheatgrass (no SWG)	-	4/8/2010	91.8
Streeter REP-3 TRT-13 Sunburst switchgrass + Tall wheatgrass (no SWG)	-	4/8/2010	278.3
Streeter REP-4 TRT-13 Sunburst switchgrass + Tall wheatgrass (10% SWG + 90% WG)	-	4/8/2010	103.1
Composite - Streeter Sunburst switchgrass, Mustang alti. Wildrye	10-093	x	**267.1**
Streeter REP-2 TRT-17 Sunburst switchgrass + Mustang Alti. Wildrye (50% SWG)	-	4/8/2010	95.6
Streeter REP-3 TRT-17 Sunburst switchgrass + Mustang Alti. Wildrye (no Swg, no wildrye, 80% WG)	-	4/8/2010	87.8
Streeter REP-4 TRT-17 Sunburst switchgrass + Mustang Alti. Wildrye (no SWG)	-	4/8/2010	83.7
Composite - Streeter CRP mix (wheatgrass, alfalfa, sweet clover)	10-094	x	**235.3**
Streeter REP-2 TRT-11 CRP Mix (Wheatgrass + alfalfa + swt, Clover)	-	4/8/2010	73.1
Streeter REP-3 TRT-11 CRP Mix (Wheatgrass + alfalfa + swt, Clover)	-	4/8/2010	88.3
Streeter REP-4 TRT-11 CRP Mix (Wheatgrass + alfalfa + swt, Clover)	-	4/8/2010	73.9

RESULTS AND DISCUSSION

ASTM Analyses: Proximate; Ultimate; Ash Composition; Chlorine and Heating Value

Table 3 contains the results for the ASTM analyses of the fourteen biomass feedstock blends – analyses in Table 3a are for the Carrington site grasses, and analyses in table 3b are for the Streeter site grasses. Table 4 contains the ASTM analysis results of the six duplicate Carrington and Streeter samples. The percent difference between the reported ASTM results for the six duplicate samples was calculated as shown in Table 5.

The as-received moisture contents for the samples ranged from 5.6 wt% to 13 wt% (Tables 3 and 4). As shown in Table 4, three Carrington samples had moisture contents of 13 wt% and were the first set of samples received. The other three samples from the first set (MTI 10-059c, 063, -068c) were from the Streeter site and these also had higher moisture contents of 8 – 10 wt%. The duplicates that were split from these first six samples all had lower moisture contents (Table 4).

Ash content on a dry basis ranged from 4.4 wt% (Carrington switchgrass, Table 4) to 9.2 wt% (Streeter – Trailblazer switchgrass, Table 3b). Generally, Streeter grass samples had higher overall ash contents, with an average ash content of 7.8 wt% (dry). At about 5.8 wt%, Streeter switchgrass samples had the lowest ash content of all Streeter grasses. Grass samples from the Carrington site had average dry ash content of 5.2 wt%. The Carrington CRP mixes had the highest ash content of the Carrington site samples, at about 6.2 wt%.

Volatile matter ranged from 73 wt% to 77 wt% dry basis. Fixed carbon ranged from 16.2 wt% to 19.6 wt% (dry basis). Carrington grasses generally had higher fixed carbon contents than Streeter grasses. The average (dry) fixed carbon content for Carrington grasses was 18.5 wt% and the average fixed carbon for Streeter grasses was 17.4 wt%. The high volatile matter content indicates that during combustion most of the biomass materials will volatilize and burn as a gas in the system. The fixed carbon will produce a char and burn as a solid material in the combustion system.

Total sulfur was low for the grasses, ranging from 0.01 wt% (Streeter – Sunburst switchgrass and Sunnyview Big Blues blend) to 0.12 wt% (Streeter – Sunburst switchgrass and tall wheatgrass blend).

Heating values ranged from 7,650 BTU/lb (dry basis, for Streeter Trailblazer switchgrass) to 8,180 BTU/lb (Carrington – Sunburst switchgrass and Mustang Alti. Wildrye blend). There was no obvious trend for heating values based on grass type or plot location.

Chlorine content varied significantly for the sites. Streeter site grasses had lower overall chlorine contents, ranging from 92.2 µg/g (switchgrass) to 1,150 µg/g (Sunburst switchgrass/Mustang Alti. Wildrye blend). Carrington site grasses chlorine content ranged from 1,420 µg/g (Trailblazer switchgrass) to 4,160 µg/g (tall wheatgrass). Average Streeter grass

chlorine content was 413 µg/g and average Carrington grass chlorine content was 2,750 µg/g. Chlorine will vaporize during combustion and can condense on and react with heat transfer and other metal surfaces in combustion and air pollution control systems. The high levels of alkali and alkaline earth elements will help minimize the problem. In all cases, however, high levels of chlorine should be avoided because of its potential to contribute to corrosion of system components.

Ash composition analysis showed the grasses contained varying levels of silicon (as SiO_2), calcium (CaO), magnesium (MgO), potassium (K_2O), sodium (Na_2O) and phosphorus (P_2O_5). Results are reported on a weight percent in dry ash basis. Silica content ranged from 45 wt% in the Carrington Trailblazer switchgrass to 77 wt% in the Streeter intermediate wheatgrass. Overall, Streeter grass samples had significantly more silica (average 72.5 wt%), than Carrington grasses (average 58.2 wt%).

Calcium oxide (CaO) in the ash of the grass samples ranged from 4 wt% to 13 wt%. Streeter grasses generally had lower levels of calcium in the ash (average 5.8 wt%, versus the 7.8 wt% average CaO in Carrington grasses), with the exception of the Streeter CRP mix (wheatgrass, alfalfa, and sweet clover), which contained 13 wt% CaO.

Magnesium content in the grasses ranged from 2.1 wt% to 7.9 wt%. Grasses from the Carrington site had slightly higher average magnesium contents, with an average MgO content of 4.8 wt%. Streeter grasses average MgO content was 3.4 wt%.

The alkali components of the ash include potassium (K_2O) and sodium (Na_2O). Potassium ranged from 7.7 wt% (Streeter intermediate wheatgrass) to 15.5 wt% (Carrington Trailblazer switchgrass). The alkali components of the ash are known to contribute to bed agglomeration and convective pass fouling. Grasses from the Carrington site had significantly higher average potassium content (average 15.5 wt% K_2O) than Streeter grasses (9.7 wt% K_2O). The Carrington switchgrass and blends generally had higher potassium levels than the other grass species.

Sodium in the ash ranged from less than 1 wt% (Streeter grasses) to 4.7 wt% (Carrington wheatgrass). Carrington grass samples contained an average of 2.74 wt% Na_2O in the ash, and Streeter grass samples had an average of 1.24 wt% Na_2O in the ash.

Phosphorus, like chlorine, alkali components, and amorphous silica, can contribute to the formation of phases that cause bonding of bed particles and ash materials in a fluidized bed. The phosphorus content in the ash from the grass samples ranged from 1.5 wt% (Streeter intermediate wheatgrass) to 8.1 wt% (Carrington – Magnar Basin, Mustang alti. wildrye blend). Carrington grasses contained significantly more phosphorus in the ash, at 6.3 wt%, than Streeter grasses (2.2 wt%).

To evaluate the repeatability of the data, blind duplicates were created of the Carrington and Streeter switchgrass, intermediate wheatgrass, and tall wheatgrass samples and

proximate, ultimate, chlorine, heating value and ash composition analyses were performed on the duplicates. The two sets of analyses are shown in Table 4 and were discussed along with the other analyses above. Percent difference between the two sets of analyses was calculated on a dry basis only. Dry basis analyses were used due to differences in moisture contents; the duplicate samples were analyzed after the initial six analyses were performed.

As shown in Table 5, the proximate analyses were similar for the duplicate analyses. Data for volatile matter, carbon, heating value, and silica in ash had less than 10% difference between the two analyses. Variability between analyses was mainly due to low quantities of certain constituents, including nitrogen, total sulfur, and, in some cases, alkali and alkaline earth components.

Table 3a. ASTM analyses proximate, ultimate, ash composition, chlorine and heating value, for Carrington biomass feedstock blends (MTI 10-088 to 10-094).

Sample Description*:	Sunburst SG, Sunnyview Big Blues (MTI 10-081)	CRP mix (WG, alfalfa, sweet clover) (MTI 10-082)	Sunburst SG, Mustang alti. WR (MTI 10-083)	Trailblazer SG (MTI 10-084)	CRP mix (Int., tall WG) (MTI 10-085)	Sunburst SG, tall WG (MTI 10-086)	Magnar Basin, Mustang alti. WR (MTI 10-087)
Proximate (as-received)							
Total moisture	6.1	6.2	6.7	6.7	6.2	5.9	5.6
Ash	5.5	5.7	4.7	4.8	5.9	4.9	4.7
Volatile matter	71.5	71.6	71.0	71.0	70.7	71.3	71.2
Fixed carbon	16.9	16.6	17.6	17.5	17.1	17.8	18.5
Proximate (dry)							
Ash	5.8	6.0	5.0	5.2	6.3	5.2	4.9
Volatile matter	76.2	76.3	76.1	76.1	75.4	75.8	75.5
Fixed carbon	18.0	17.6	18.9	18.7	18.3	19.0	19.6
Ultimate (as-received)							
Carbon	43.6	43.6	44.0	43.8	43.0	43.6	43.8
Hydrogen	6.2	6.1	6.1	6.2	6.1	6.1	6.1
Nitrogen	0.8	0.5	0.6	0.7	0.7	0.6	0.9
Total sulfur	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Oxygen by diff.	43.9	44.1	44.5	44.4	44.2	44.7	44.5
Ultimate (dry)							
Carbon	46.4	46.5	47.2	47.0	45.9	46.3	46.4
Hydrogen	5.9	5.8	5.8	5.8	5.8	5.8	5.8
Nitrogen	0.8	0.5	0.7	0.8	0.7	0.6	0.9
Total sulfur	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Oxygen by diff.	41.0	41.1	41.3	41.2	41.3	41.9	41.8
Heating value, BTU/lb							
As-received	7645	7299	7639	7524	7420	7445	7416
Dry basis	8139	7781	8183	8061	7913	7912	7858
Chlorine, ppm in fuel							
As-received	1470	1960	1530	1330	2530	2990	3390
Dry basis	1570	2090	1640	1420	2700	3180	3590

Sample Description*:	Sunburst SG, Sunnyview Big Blues (MTI 10-081)	CRP mix (WG, alfalfa, sweet clover) (MTI 10-082)	Sunburst SG, Mustang alti. WR (MTI 10-083)	Trailblazer SG (MTI 10-084)	CRP mix (Int., tall WG) (MTI 10-085)	Sunburst SG, tall WG (MTI 10-086)	Magnar Basin, Mustang alti. WR (MTI 10-087)
Ash composition (dry basis)							
SiO_2	57.1	66.8	48.4	44.9	68.3	62.7	54.7
Al_2O_3	0.5	0.5	0.4	0.5	0.6	1.2	0.4
TiO_2	<0.03	<0.03	0.0	<0.03	<0.03	<0.03	<0.03
Fe_2O_3	<0.29	<0.29	0.3	<0.29	<0.29	<0.29	0.9
CaO	9.1	6.1	10.5	9.8	5.9	7.4	7.1
MgO	5.4	2.8	7.6	7.2	3.0	3.4	3.5
K_2O	15.9	13.3	20.7	22.4	10.6	12.2	17.2
Na_2O	1.1	2.6	2.2	2.3	2.2	2.9	3.9
SO_3**	2.3	1.3	2.4	2.5	1.8	2.3	2.3
P_2O_5	6.7	4.7	6.0	7.7	5.0	6.0	8.1
SrO	0.0	<0.02	0.0	0.0	<0.02	<0.02	0.0
BaO	0.1	0.1	0.0	0.0	0.1	0.0	0.1
MnO_2	0.1	0.1	0.2	0.2	0.1	0.1	0.1

*note: Switchgrass - SG, wheatgrass - WG, wildrye - WR, intermediate - Int.

**note: the minor amounts of SO_3 found in the ash may be derived from the ashing furnace during sample preparation. These ashing furnaces are used to ash sulfur-containing coals.

Table 3b. ASTM analyses proximate, ultimate, ash composition, chlorine and heating value, for Streeter biomass feedstock blends (MTI 10-088 to 10-094).

Sample Description*:	Sunburst SG, Sunnyview Big Blues (MTI 10-088)	Trailblazer SG (MTI 10-089)	CRP mix (Int., tall WG) (MTI 10-090)	Magnar Basin, Mustang Alti. WR (MTI 10-091)	Sunburst SG, tall WG (MTI 10-092)	Sunburst SG, Mustang Alti. WR (MTI 10-093)	CRP mix (WG, alfalfa, sweet clover) (MTI 10-094)
Proximate (as-received)							
Total moisture	5.7	6.8	7.0	7.0	6.3	6.3	6.9
Ash	7.5	8.6	7.5	8.2	7.5	8.3	7.1
Volatile matter	70.3	67.8	69.2	69.5	69.1	70.2	69.6
Fixed carbon	16.5	16.8	16.4	15.4	17.2	15.2	16.4
Proximate (dry)							
Ash	7.9	9.2	8.0	8.8	8.0	8.8	7.6
Volatile matter	74.6	72.8	74.3	74.7	73.7	75.0	74.8
Fixed carbon	17.5	18.1	17.6	16.5	18.3	16.2	17.6
Ultimate (as-received)							
Carbon	43.0	42.1	42.4	42.6	42.6	42.3	43.1
Hydrogen	6.1	6.1	6.1	6.1	6.0	6.0	6.1
Nitrogen	0.6	0.8	0.7	0.7	0.8	0.7	0.9
Total sulfur	0.0	0.1	0.1	0.1	0.1	0.1	0.0
Oxygen by diff.	42.9	42.4	43.3	42.4	43.1	42.7	42.8
Ultimate (dry)							
Carbon	45.6	45.1	45.6	45.8	45.5	45.1	46.3
Hydrogen	5.8	5.7	5.7	5.7	5.6	5.7	5.7
Nitrogen	0.6	0.9	0.7	0.8	0.8	0.7	1.0
Total sulfur	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Oxygen by diff.	40.1	39.0	39.9	38.9	40.0	39.6	39.4
Heating value, BTU/lb							
As-received	7349	7130	7492	7250	7245	7209	7313
Dry basis	7796	7652	8053	7794	7731	7697	7855
Chlorine, ppm in fuel							
As-received	248	328	484	578	529	1080	411
Dry basis	263	352	520	621	565	1150	441

Sample Description*:	Sunburst SG, Sunnyview Big Blues (MTI 10-088)	Trailblazer SG (MTI 10-089)	CRP mix (Int., tall WG) (MTI 10-090)	Magnar Basin, Mustang Alti. WR (MTI 10-091)	Sunburst SG, tall WG (MTI 10-092)	Sunburst SG, Mustang Alti. WR (MTI 10-093)	CRP mix (WG, alfalfa, sweet clover) (MTI 10-094)
Ash composition (dry basis)							
SiO_2	71.8	72.1	74.1	72.4	72.8	72.4	62.7
Al_2O_3	<0.38	<0.38	<0.38	<0.38	<0.38	<0.38	0.6
TiO_2	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.0
Fe_2O_3	0.8	0.5	1.7	1.7	0.5	1.4	0.8
CaO	6.0	5.1	4.9	5.4	4.4	5.3	13.1
MgO	3.3	2.4	2.8	2.6	2.6	2.9	4.4
K_2O	9.6	12.0	10.5	10.4	10.3	11.1	10.1
Na_2O	0.8	1.3	1.3	2.1	2.9	1.2	1.7
SO_3**	1.6	1.4	1.4	1.9	2.4	1.9	2.0
P_2O_5	2.2	2.7	1.8	1.7	2.1	2.2	2.7
SrO	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.1
BaO	0.1	0.0	0.0	0.0	0.0	0.0	0.1
MnO_2	0.2	0.1	0.1	0.2	0.1	0.1	0.2

*note: Switchgrass - SG, wheatgrass - WG, wildrye - WR, intermediate - Int.

**note: minor amounts of SO_3 found in the ash may be derived from the ashing furnace during sample preparation. These ashing furnaces are used to ash sulfur containing coals.

Table 4. ASTM analyses proximate, ultimate, ash composition, chlorine and heating value, for six replicate biomass feedstock blend samples.

Sample Description:	Carrington Switchgrass		Carrington Intermediate wheatgrass		Carrington Tall wheatgrass		Streeter Switchgrass		Streeter Intermediate wheatgrass		Streeter Tall wheatgrass	
MTI ID:	**10-061c**	**10-100**	**10-056c**	**10-098**	**10-065c**	**10-099**	**10-063c**	**10-103**	**10-059c**	**10-101**	**10-068c**	**10-102**
Proximate (as-received)												
Total moisture	13.0	7.2	13.2	8.5	13.6	7.9	9.8	7.1	8.5	6.1	8.0	5.8
Ash	4.2	4.0	4.2	5.0	4.2	4.7	5.2	5.5	7.1	7.2	7.4	7.7
Volatile matter	66.6	71.8	66.1	70.8	65.5	70.3	69.0	70.8	68.1	70.9	67.9	70.2
Fixed carbon	16.2	17.0	16.6	15.6	16.7	17.1	16.0	16.6	16.4	15.8	16.7	16.3
Proximate (dry)												
Ash	4.8	4.4	4.8	5.5	4.9	5.1	5.8	5.9	7.8	7.7	8.0	8.2
Volatile matter	76.6	77.4	76.1	77.4	75.8	76.3	76.5	76.2	74.4	75.5	73.8	74.5
Fixed carbon	18.7	18.3	19.1	17.1	19.3	18.6	17.7	17.9	17.9	16.8	18.2	17.3
Ultimate (as-received)												
Carbon	41.3	43.0	40.8	42.5	40.4	42.4	41.8	42.7	41.8	42.4	42.0	42.1
Hydrogen	6.0	6.2	6.1	6.2	6.2	6.2	5.7	6.1	5.9	6.0	5.7	5.9
Nitrogen	0.5	0.8	0.5	0.6	1.0	0.8	0.3	0.4	0.6	0.6	0.5	0.6
Total sulfur	0.06	0.06	0.06	0.05	0.08	0.07	0.04	0.03	0.05	0.06	0.09	0.08
Oxygen by diff.	48.0	46.0	48.4	45.6	48.2	45.7	47.0	45.3	44.6	43.8	44.4	43.5
Ultimate (dry)												
Carbon	47.5	46.3	46.9	46.4	46.7	46.0	46.3	46.0	45.7	45.2	45.6	44.7
Hydrogen	5.2	5.8	5.3	5.8	5.4	5.8	5.1	5.7	5.4	5.7	5.3	5.6
Nitrogen	0.6	0.8	0.6	0.7	1.1	0.9	0.7	0.4	0.6	0.6	0.5	0.7
Total sulfur	0.07	0.06	0.07	0.05	0.09	0.08	0.04	0.03	0.05	0.06	0.10	0.08
Oxygen by diff.	41.9	42.7	42.2	41.6	41.8	42.1	42.4	42.0	40.5	40.8	40.5	40.7
Heating value, BTU/lb												
As-received	6901	7524	6919	7225	6692	7166	7002	7378	7117	7220	7083	7353
Dry basis	7933	8107	7969	7900	7742	7779	7764	7941	7775	7689	7696	7805
Chlorine, ppm in fuel												
As-received	2170	2040	3050	3140	3600	3490	86	86	400	422	244	121
Dry basis	2490	2200	3510	3430	4160	3790	95	92	437	449	265	128

Ash composition (dry basis)												
SiO_2	51.6	51.6	67.0	65.0	61.8	57.1	71.9	73.4	77.3	76.9	71.3	73.2
Al_2O_3	<0.38	0.8	<0.38	0.7	<0.38	1.4	<0.38	1.1	<0.38	0.5	<0.38	0.6
TiO_2	0.0	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Fe_2O_3	0.7	<0.29	<0.29	<0.29	<0.29	0.5	<0.38	1.8	0.4	<0.29	<0.29	<0.29
CaO	9.3	8.5	7.6	7.1	6.9	6.6	6.8	4.0	4.6	4.8	4.6	7.0
MgO	6.8	6.4	3.9	3.8	3.5	3.2	5.8	2.1	3.4	3.1	3.8	5.0
K_2O	17.8	17.6	11.0	14.0	12.8	16.3	9.4	8.9	8.1	7.7	9.9	8.3
Na_2O	2.8	3.0	2.2	1.7	4.0	4.7	0.4	1.0	0.4	0.7	2.2	0.5
SO_3*	2.3	3.5	1.7	1.8	2.9	2.4	0.8	1.7	1.0	1.3	1.8	1.5
P_2O_5	6.7	7.0	5.7	5.2	6.9	6.2	2.0	2.5	1.6	1.5	3.0	1.9
SrO	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
BaO	0.1	0.0	0.1	0.1	0.1	0.0	<0.02	0.0	0.0	0.0	0.1	<0.02
MnO_2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.1

*note: minor amounts of SO_3 found in the ash may be derived from the ashing furnace during sample preparation. These ashing furnaces are used to ash sulfur containing coals.

Table 5. Percent difference between replicate sample ASTM analyses proximate, ultimate, ash composition, chlorine and heating value.

Site:	Carrington	Carrington	Carrington	Streeter	Streeter	Streeter
Type:	Switchgrass	Intermediate wheatgrass	Tall wheatgrass	Switchgrass	Intermediate wheatgrass	Tall Wheatgrass
Proximate (dry)						
Ash	9%	13%	4%	2%	1%	2%
Volatile matter	1%	2%	1%	0%	2%	1%
Fixed carbon	2%	11%	4%	1%	6%	5%
Ultimate (dry)						
Carbon	2%	1%	1%	1%	1%	2%
Hydrogen	11%	8%	7%	12%	5%	6%
Nitrogen	30%	9%	19%	50%	0%	27%
Total sulfur	15%	33%	12%	29%	18%	22%
Oxygen by diff.	2%	1%	1%	1%	1%	0%
BTU/lb (dry)	2%	1%	0%	2%	1%	1%
Chlorine (dry)	12%	2%	9%	3%	3%	70%
Ash composition (dry basis)						
SiO_2	0%	3%	8%	2%	1%	3%
Al_2O_3	-	-	-	-	-	-
TiO_2	-	-	-	-	-	-
Fe_2O_3	-	-	-	-	-	-
CaO	9%	7%	5%	51%	3%	41%
MgO	6%	3%	7%	94%	9%	29%
K_2O	1%	24%	24%	5%	6%	18%
Na_2O	5%	25%	15%	84%	56%	122%
SO_3*	39%	8%	19%	67%	30%	22%
P_2O_5	4%	8%	11%	23%	4%	44%
SrO	-	-	-	-	-	-
BaO	22%	0%	22%	-	0%	-
MnO_2	6%	5%	13%	25%	7%	77%

*note: minor amounts of SO_3 found in the ash may be derived from the ashing furnace during sample preparation. These ashing furnaces are used to ash sulfur containing coals.

Select ASTM Data on lb/MMBTU basis

Results of selected analyses for the biomass fuel samples are provided on a heating value basis (lb/MMBTU) in Figures 8 and 9. Figure 8 illustrates the range in moisture and ash contents for the biomass fuels. Biomass moisture contents ranged from 7 lb/MMBTU for the Carrington-Magnar Basin/Mustang alti. wildrye sample to about 20 lb/MMBTU for the Carrington tall wheatgrass. The Streeter Trailblazer switchgrass had high ash content, at about 12 lb/MMBTU and the Carrington switchgrass had the lowest ash content.

The Carrington tall wheatgrass had the highest chlorine content with about 0.5 lb chlorine/MMBTU. Several of the biomass samples had very low chlorine contents such as the samples from Streeter.

As shown in Figure 9, the biomass samples showed variability in the total alkali (sodium and potassium) ranging from around 0.7 lb/MMBTU for the Streeter switchgrass to nearly 1.4 lb/MMBTU for the Carrington and Streeter Trailblazer switchgrass samples.

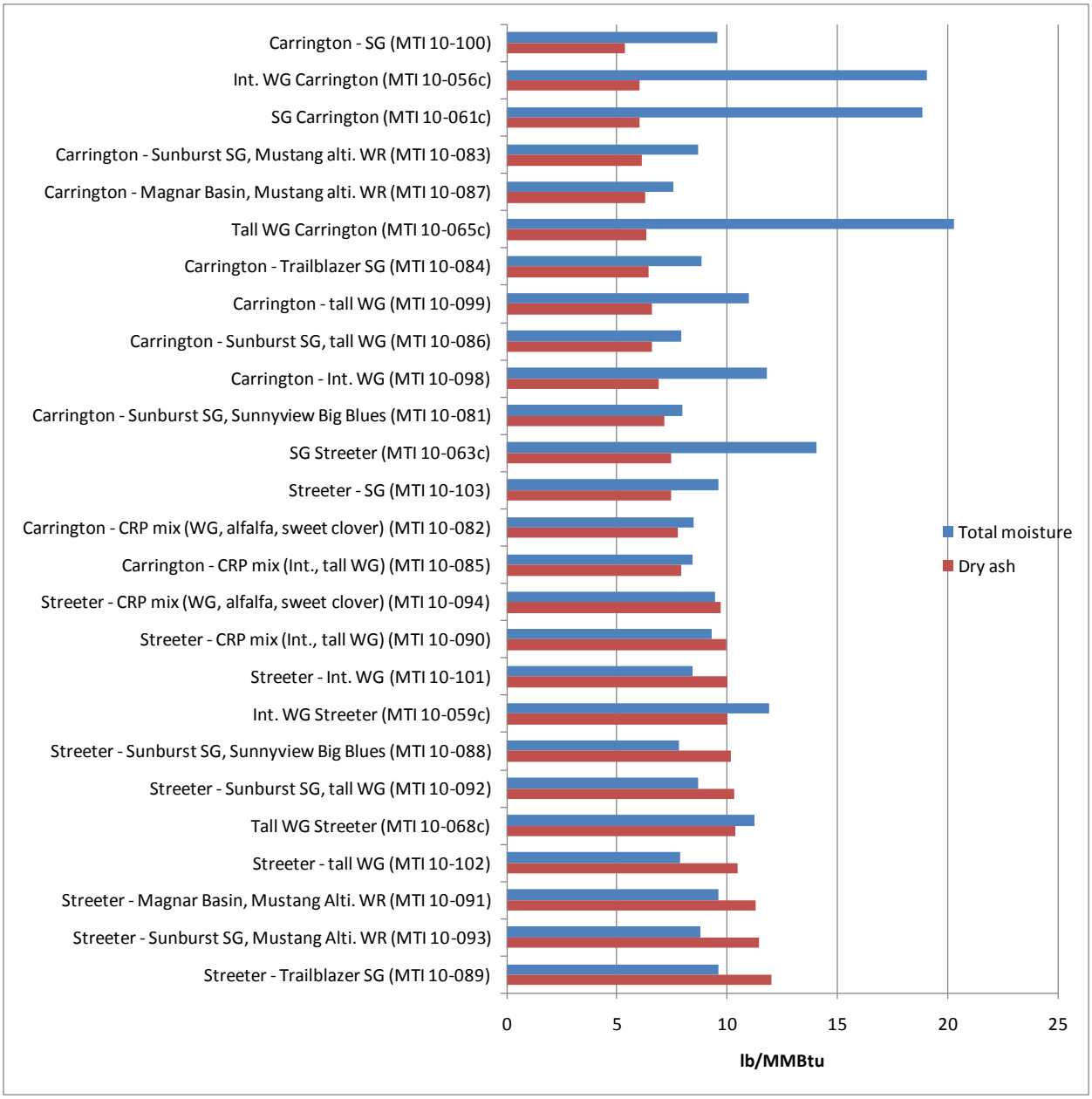


Figure 8. Moisture and ash in biomass fuels on lb/MMBTU basis.

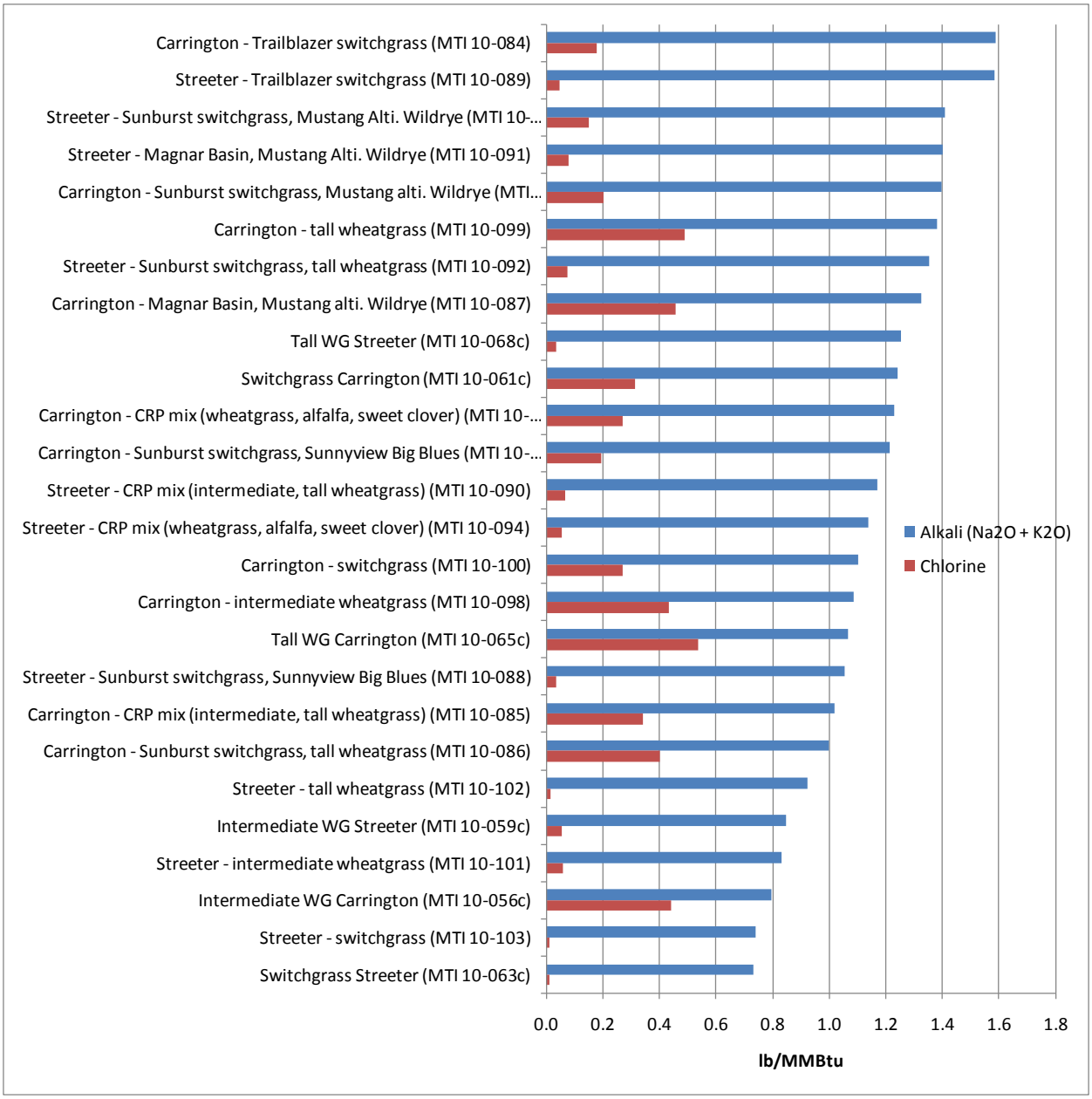


Figure 9. Total alkali (sodium and potassium) and chlorine in biomass fuels on lb/MMBTU basis.

Chemical Fractionation

Partial chemical fractionations for potassium and sodium were performed on the twenty biomass feedstock blends. Results are shown in Table 6.

The chemical fractionation method uses subsequent leaching with water and ammonium acetate (NH_4OAc) to remove water-soluble salts and organically-associated elements. Recovered solid material from each leaching step is analyzed for ash content, silica content, potassium and sodium. The ash and silica content are used to normalize the data from each leaching step; silica is not present as a salt nor organically-associated.

The first set of data in Table 6 shows the initial quantities of potassium and sodium, as ppm or µg/g, in the fuel samples. (This is reported differently than the data in Tables 3 and 4, in which potassium and sodium are reported as weight percent equivalent oxide in ash.) Potassium in the fuel ranged from 3,980 µg/g (Streeter switchgrass) to 8,474 µg/g (Streeter Sunburst switchgrass). Sodium in the fuel ranged from 291 µg/g (Streeter intermediate wheatgrass) to 1,280 µg/g (Carrington tall wheatgrass).

The second set of data in Table 6 shows the percentages of potassium and sodium removed during the water-leaching step. This is the water-soluble fraction of potassium and sodium. Potassium in the fuels was between 79% and 97% water-soluble. Average water-soluble potassium in the fuels was similar, at 92% in Streeter and 91% in Carrington. Water-soluble sodium ranged from none-detected (Streeter intermediate wheatgrass) to 86% (Carrington wheatgrass). The average fraction of water-soluble sodium in Streeter fuels was 41% and in Carrington fuels was 66%. Carrington Sunburst switchgrass blends had lower water-soluble sodium fractions than the other Carrington fuels, at 25-27%.

The organically-associated fraction of potassium and sodium are shown in the third set of data in Table 6. This is the fraction that is removable using ammonium acetate. Streeter and Carrington grasses had similar levels of organically-associated potassium, with averages of 7-8%. The Carrington Sunburst switchgrass-Sunnyview Big Blues blend had the highest quantity of organically-associated potassium, at 20%. The same blend from the Streeter site had the second-highest level of organically-associated potassium, at 11%. Organically-associated sodium ranged from 'none-detected' to 41%. The highest quantity of organically-associated sodium belonged to the Carrington Sunburst switchgrass-Sunnyview Big Blues blend (41%). This blend initially contained 969 µg/g sodium in the fuel. The Sunburst-Sunnyview blend from the Streeter site contained 25% organically-associated sodium (from the initial sodium content of 453 µg/g).

Solubility of sodium and potassium based on the partial chemical fractionation analysis is illustrated in Figures 10 and 11 (sorted by percent water-soluble). The organically-associated and water-soluble forms of sodium and potassium will likely be the most reactive form during combustion.

Table 6. Partial chemical fractionation analysis results for twenty biomass feedstock blends. Silicon was used as a tracer for normalization.

			Initial Quantity (ppm in fuel, dry basis)			Percent water-soluble (Removed by water)			Percent organically-associated (Removed by NH4OAc)		
Sample ID:	**Source:**	**Type*:**	**Silicon (Si)**	**Potassium (K)**	**Sodium (Na)**	**Silicon (Si)**	**Potassium (K)**	**Sodium (Na)**	**Silicon (Si)**	**Potassium (K)**	**Sodium (Na)**
10-081	Carrington	Sunburst SG, Sunnyview Big Blues	15,598	6,911	969	0%	79%	27%	0%	20%	41%
10-082	Carrington	CRP mix (WG, alfalfa, sweet clover)	22,321	5,236	1,089	0%	88%	81%	0%	10%	0%
10-083	Carrington	Sunburst SG, Mustang alti. WR	12,794	7,178	718	0%	92%	25%	0%	5%	11%
10-084	Carrington	Trailblazer SG	11,619	7,942	873	0%	97%	67%	0%	2%	9%
10-085	Carrington	CRP mix (Int., Tall WG)	19,991	6,127	801	0%	95%	73%	0%	5%	8%
10-086	Carrington	Sunburst SG, Tall WG	15,447	5,096	1,147	0%	91%	84%	0%	7%	1%
10-087	Carrington	Magnar Basin, Mustang alti. WR	14,550	8,007	878	0%	89%	73%	0%	10%	8%
10-088	Streeter	Sunburst SG, Sunnyview Big Blues	33,399	6,228	453	0%	88%	20%	0%	11%	25%
10-089	Streeter	Trailblazer SG	34,394	7,334	636	0%	91%	54%	0%	7%	0%
10-090	Streeter	CRP mix (Int., Tall WG)	28,673	5,626	518	0%	94%	54%	0%	4%	6%
10-091	Streeter	Magnar Basin, Mustang Alti. WR	29,542	7,009	577	0%	90%	49%	0%	9%	7%
10-092	Streeter	Sunburst SG, Tall WG	29,548	6,523	805	0%	93%	61%	0%	4%	0%
10-093	Streeter	Sunburst SG, Mustang Alti. WR	30,288	8,474	555	0%	93%	36%	0%	6%	25%
10-094	Streeter	CRP mix (WG, alfalfa, sweet clover)	24,283	7,681	685	0%	93%	65%	0%	5%	5%
10-098	Carrington	Int. WG	15,491	4,388	545	0%	88%	69%	0%	10%	3%
10-099	Carrington	Tall WG	14,146	5,586	1,276	0%	91%	86%	0%	6%	0%
10-100	Carrington	SG	10,688	6,428	656	0%	96%	72%	0%	2%	0%
10-101	Streeter	Int. WG	30,353	4,617	291	0%	92%	0%	0%	6%	25%
10-102	Streeter	Tall WG	28,843	6,759	437	0%	90%	33%	0%	8%	12%
10-103	Streeter	SG	19,513	3,983	388	0%	91%	42%	0%	6%	20%

*note: Switchgrass - SG, wheatgrass - WG, wildrye - WR, intermediate - Int.

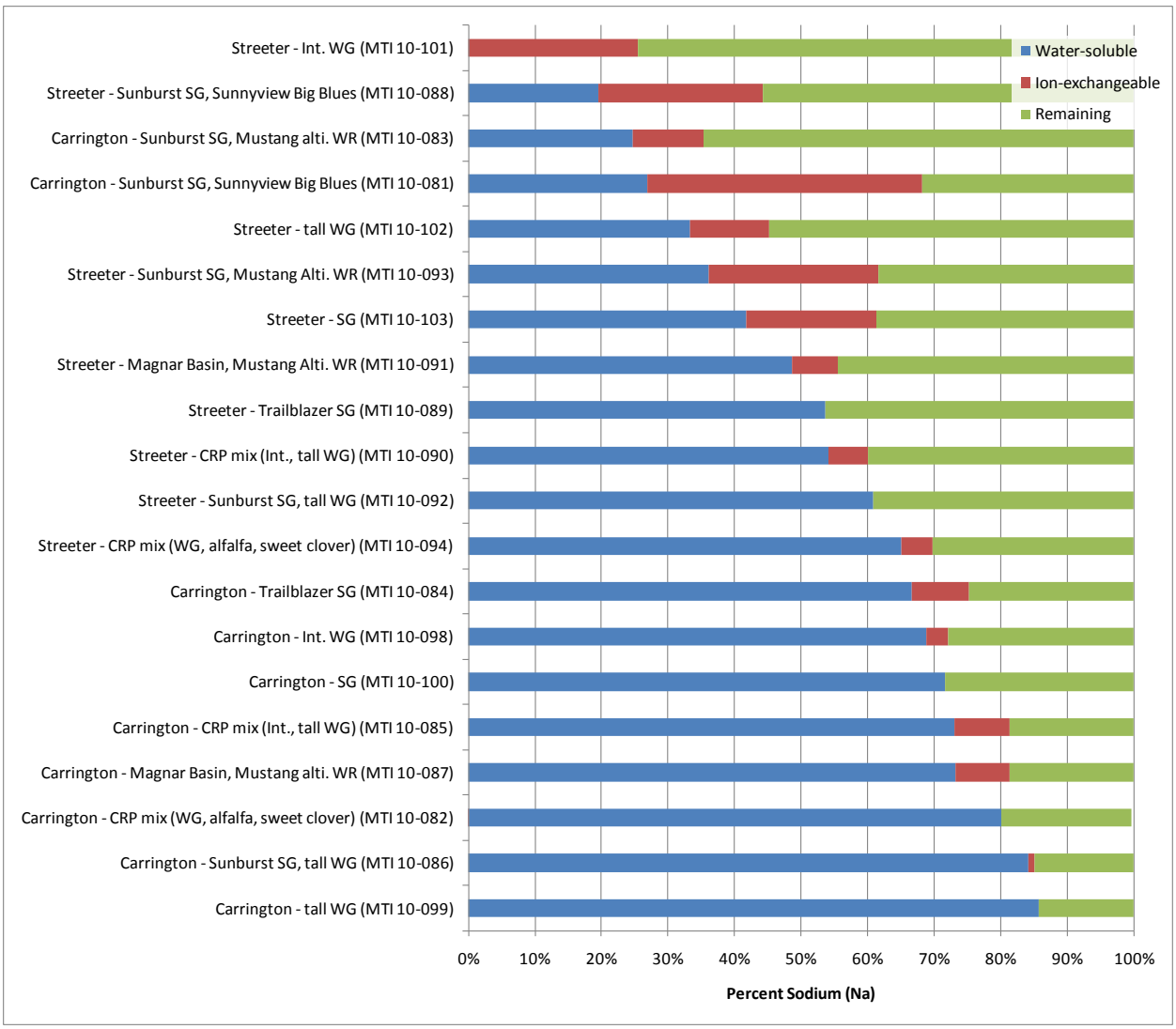


Figure 10. Percent sodium by association (water-soluble, ion exchangeable, or remaining) for twenty biomass fuel samples, sorted by percent water-soluble.

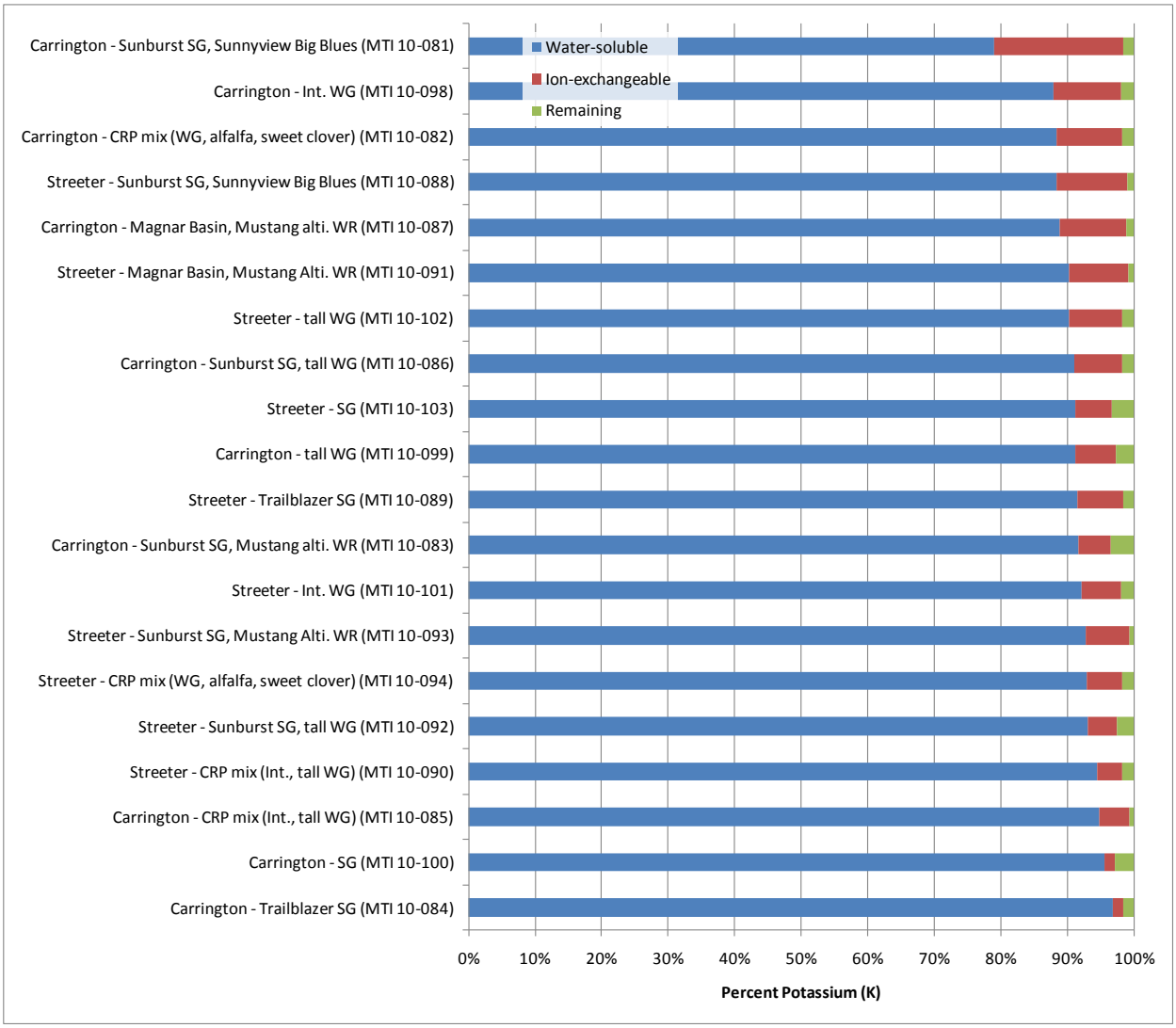


Figure 11. Percent potassium by association (water-soluble, ion exchangeable, or remaining) for twenty biomass fuel samples, sorted by percent water-soluble.

Predicted Performance for Blends with Falkirk Coal

GRE provided ASTM analyses for Spiritwood design coal, including proximate, ultimate, ash composition, sulfur forms, ash fusion temperatures, and trace elements. The design coal is a dried coal (Falkirk Mine enhanced using the DryFining™ process), and GRE provided raw lignite ASTM data for the coal. ASTM analyses for the enhanced coal are shown in Table 7.

Table 7. Ultimate and ash composition data for dried lignite, provided by GRE.

Quality Parameter	Typical (Mean value)	Standard Deviation	Typical 95% Range -2 Std Dev	+2 Std Dev
Proximate				
% Moisture	25.81	1.92	21.96	29.65
% Ash	13.38	1.09	12.17	16.54
% Volatile	30.45	0.67	29.11	31.79
% Fixed Carbon	30.36	0.83	27.73	31.05
BTU/lb	7500	138	7224	7776
MAFBTU	12333			
Dry BTU	10109			
% Sulfur	.078	0.09	0.67	1.03
Ultimate As-Received				
% Moisture	25.81	1.92		
% Carbon	44.14			
% Hydrogen	3.13			
% Nitrogen	0.56			
% Oxygen (by difference)	12.19			
Chlorine (as-received ug/g)	<16.9			
Fluorine in coal (as-received ug/g)	73.54	14.49	44.52	102.48
% Total Sulfur	0.79	0.09	0.67	1.03
% Ash	13.38	1.09	12.17	16.54
Total	100.00			
Mercury in coal (as-received ug/g)	0.075	0.009	0.057	0.093
Sulfur Forms				
Pyritic Sulfur (%)	0.25	0.04	0.17	0.33
Sulfate Sulfur (%)	0.04	0.01	0.02	0.06
Organic Sulfur (%)	0.49	0.06	0.37	0.61
Total Sulfur (%)	0.78	0.09	0.67	1.03
Mineral Analysis of Ash (wt %)				
Silicon Dioxide (Silica, SIO2)	45.86	2.65	40.57	51.16
Aluminum Oxide (Alumina, AI2O3)	13.61	0.41	12.79	14.44
Titanium Dioxide (Titania, TIO2)	0.57	0.03	.052	0.62
Iron oxide (Ferric Oxide, Fe2O3)	7.15	0.94	5.27	9.02
Calcium Oxide (Lime, CaO)	13.26	0.90	11.46	15.05
Magnesium Oxide (Magnesia, MgO)	4.06	0.21	3.64	4.49
Potassium Oxide (K2O)	1.77	0.09	1.59	1.94
Sodium Oxide (Na2O)	1.71	0.41	0.90	2.52
Sulfur Trioxide (SO3)	10.90	1.08	8.73	13.07

Quality Parameter	Typical (Mean value)	Standard Deviation	Typical 95% Range -2 Std Dev	+2 Std Dev
Phosphorous Pentoxide (P2O5)	0.35	0.05	0.26	0.44
Barium Oxide (BaO)	0.40	0.05	0.30	0.50
Manganese Oxide (Mn3O4)	0.05	0.00		
Base/Acid Ratio	0.47	0.05	0.37	.057
Base Value	27.94	1.88	24.18	31.70
Acid Value	60.05	2.99	54.07	66.03
Ash Fusion Temperatures				
Reducing (ºF)				
Initial	2115	23	2069	2161
Softening	2138	19	2100	2176
Hemispherical	2148	21	2106	2190
Fluid	2183	35	2113	2253
Oxidizing (ºF)				
Initial	2189	24	2151	2237
Softening	2195	23	2149	2241
Hemispherical	2204	23	2158	2250
Fluid	2235	28	2179	2291
Additional Analyses and Calculated Values				
T250 Temperature (ºF)	2014	118	1778	2250
Lbs, SO2 per Million BTUs	2.38	0.29	1.80	2.96
Size Fraction				
On ¼ inch Mesh	14.0%			
On 4 Mesh	10.7%			
On 8 Mesh	28.4%			
On 20 Mesh	21.8%			
On 40 Mesh	7.1%			
On 50 Mesh	3.0%			
On 70 Mesh	2.6%			
On 100 Mesh	2.6%			
Thru 100 Mesh	7.9%			
Trace Element Summery				
Parts per Million				
Air Dried Coal				
Antimony (Sb)	0.74	0.15	0.44	1.04
Arsenic (As)	6.53	0.93	4.67	8.39
Beryllium (Be)	0.60	0.14	0.32	0.88
Boron (B)	134.33	9.79	114.75	153.91
Cadmium (Cd)	<0.17			
Chromium (Cr)	5.19	0.51	4.17	6.21
Cobalt (Co)	1.88	0.21	1.46	2.30
Copper (Cu)	6.26	0.77	4.72	7.80
Lead (Pb)	3.13	0.40	2.33	3.93
Lithium (Li)	<8.00			
Molybdenum (Mo)	2.24	0.39	1.46	3.02
Nickel (Ni)	5.00	0.69	3.62	6.38
Selenium (Se)	1.15	0.13	0.89	1.41

Quality Parameter	Typical (Mean value)	Standard Deviation	Typical 95% Range -2 Std Dev	+2 Std Dev
Silver (Ag)	<0.17			
Strontium (Sr)	358.85	21.03	316.79	400.91
Tin (Sn)	<4.00			
Vandium (V)	10.22	3.64	2.94	17.50
Zirconium (Zr)	<16.00			
Zinc (Zn)	10.36	1.99	6.38	14.34

GRE anticipates up to 10% co-firing or 109.2 MMBTU/hr input basis. MTI used the highest blend ratio, 10% on a BTU basis, to calculate blend compositions for the biomass with the "typical" or average lignite enhanced with the DryFining™ process (Table 7). It should be noted that because average dry ash was not available for the enhanced lignite, as-received ash contents were used to calculate the blend ash compositions.

A sample calculation is shown below.

Blend: "typical" lignite enhanced with the DryFining™ process and Carrington Sunburst switchgrass/Sunnyview Big Blues (MTI 10-081)

Calculated feed rates:
Coal = 0.90*(1,092 MMBTU/hr)/7,500 BTU/lb coal/2000 lb/ton = 65.52 tons/hr
Biomass = 0.10*(1,092 MMBTU/hr)/7,645 BTU/lb biomass/2000 lb/ton = 7.14 tons/hr

Biomass mass percent of total feed:
% Biomass = 7.14 tons/hr biomass/(7.14 tons/hr biomass+65.52 tons/hr coal) = 9.83%

Average ash content (as-received) of blend:
% Ash = 9.83% biomass*5.48% ash/100 + 90.17% coal*13.38% ash/100 = 12.60% ash

Average SiO_2 in ash of blend:
% SiO_2 = (9.83% biomass*5.48% ash/100*57.1% SiO_2 + 90.17% coal*13.38% ash*45.86% SiO2)/12.60% ash = 46.4% SiO_2

Calculated ultimate and ash compositions for 10% biomass blends are shown in Tables 8a (Carrington blends) and 8b (Streeter blends). These data were used as input for MTI's predictive indices, along with CCSEM data for a high-ash Falkirk Mine coal.

Table 8a. Calculated biomass-"typical" lignite (enhanced with DryFining™ process) composition for 10% (BTU basis) blends of Carrington biomass samples with "typical" lignite. Note: dry-basis "typical" (average) data was not provided for lignite.

Blend - 90% coal (BTU basis) with:	Sunburst SG, Sunnyview Big Blues (MTI 10-081)	CRP mix (WG, alfalfa, sweet clover) (MTI 10-082)	Sunburst SG, Mustang alti. WR (MTI 10-083)	Trailblazer SG (MTI 10-084)	CRP mix (Int., tall WG) (MTI 10-085)	Sunburst SG, tall WG (MTI 10-086)	Magnar Basin, Mustang alti. WR (MTI 10-087)	Int. WG (MTI 10-098)	Tall WG (MTI 10-099)	SG (MTI 10-100)
% biomass	9.83%	10.25%	9.84%	9.97%	10.10%	10.07%	10.10%	10.34%	10.42%	9.97%
Proximate, as-received (no volatile matter data provided for coal)										
Total moisture	23.87	23.80	23.93	23.90	23.83	23.81	23.77	24.02	23.94	23.95
Ash	12.60	12.59	12.52	12.53	12.62	12.53	12.50	12.51	12.48	12.45
Fixed carbon	29.04	28.94	29.11	29.07	29.03	29.10	29.16	28.84	28.98	29.02
Total sulfur	0.72	0.71	0.72	0.72	0.72	0.72	0.72	0.71	0.71	0.72
Ultimate, as-received										
Carbon	44.09	44.08	44.13	44.11	44.03	44.08	44.11	43.97	43.96	44.02
Hydrogen	3.43	3.44	3.42	3.43	3.43	3.43	3.43	3.45	3.45	3.43
Nitrogen	0.58	0.55	0.57	0.57	0.57	0.56	0.59	0.57	0.59	0.58
Total sulfur	0.72	0.71	0.72	0.72	0.72	0.72	0.72	0.71	0.71	0.72
Oxygen by diff.	15.30	15.46	15.37	15.40	15.43	15.46	15.45	15.65	15.69	15.56
Heating value, BTU/lb										
As-received	7514	7479	7514	7502	7492	7494	7492	7472	7465	7502
Dry basis	9915	9870	9920	9905	9887	9888	9882	9881	9866	9909
Ash composition (no data for SrO, BaO or MnO2 in coal ash)										
SiO_2	46.34	46.82	45.95	45.82	46.92	46.52	46.19	46.65	46.30	46.05
Al_2O_3	13.05	13.01	13.12	13.10	13.00	13.12	13.11	13.08	13.13	13.20
TiO_2	0.55	0.55	0.55	0.55	0.54	0.55	0.55	0.55	0.55	0.55
Fe_2O_3	6.86	6.83	6.90	6.89	6.83	6.88	6.91	6.87	6.89	6.93
CaO	13.08	12.93	13.16	13.13	12.92	13.03	13.03	13.01	13.00	13.11
MgO	4.12	4.00	4.19	4.18	4.01	4.03	4.04	4.05	4.03	4.13
K_2O	2.37	2.30	2.46	2.56	2.19	2.18	2.35	2.27	2.34	2.28
Na_2O	1.68	1.75	1.73	1.73	1.73	1.76	1.79	1.71	1.83	1.75
SO_3	10.53	10.46	10.59	10.58	10.47	10.56	10.57	10.52	10.56	10.66
P_2O_5	0.62	0.55	0.56	0.63	0.57	0.57	0.64	0.55	0.58	0.56

*note: Switchgrass - SG, wheatgrass - WG, wildrye - WR, intermediate - Int.

Table 8b. Calculated biomass-"typical" lignite (enhanced with DryFining™ process) composition for 10% (BTU basis) blends of Streeter biomass samples with "typical" lignite. Note: dry-basis typical or average data was not provided for lignite.

Blend - 90% coal (BTU basis) with:	Sunburst SG, Sunnyview Big Blues (MTI 10-088)	Trailblazer SG (MTI 10-089)	CRP mix (Int., tall WG) (MTI 10-090)	Magnar Basin, Mustang Alti. WR (MTI 10-091)	Sunburst SG, tall WG (MTI 10-092)	Sunburst SG, Mustang Alti. WR (MTI 10-093)	CRP mix (WG, alfalfa, sweet clover) (MTI 10-094)	Int. WG (MTI 10-101)	Tall WG (MTI 10-102)	SG (MTI 10-103)
% Biomass blend	10.18%	10.46%	10.01%	10.31%	10.32%	10.36%	10.23%	10.35%	10.18%	10.15%
Proximate, as-received (no volatile matter data provided for coal)										
Total moisture	23.76	23.82	23.92	23.87	23.80	23.79	23.88	23.77	23.77	23.91
Ash	12.78	12.87	12.79	12.84	12.77	12.85	12.74	12.74	12.80	12.58
Fixed carbon	28.94	28.94	28.96	28.81	29.00	28.79	28.93	28.85	28.93	28.96
Total sulfur	0.71	0.72	0.72	0.72	0.72	0.72	0.72	0.71	0.72	0.71
Ultimate, as-received										
Carbon	44.02	43.92	43.97	43.98	43.98	43.95	44.03	43.96	43.94	43.99
Hydrogen	3.43	3.44	3.43	3.43	3.42	3.43	3.43	3.43	3.42	3.43
Nitrogen	0.56	0.59	0.57	0.58	0.58	0.57	0.60	0.56	0.57	0.54
Total sulfur	0.71	0.72	0.72	0.72	0.72	0.72	0.71	0.71	0.72	0.71
Oxygen by diff.	15.31	15.35	15.30	15.30	15.38	15.35	15.32	15.46	15.38	15.55
Heating value, BTU/lb										
As-received	7485	7461	7499	7474	7474	7470	7481	7471	7485	7488
Dry basis	9873	9852	9903	9870	9864	9859	9878	9859	9874	9889
Ash composition (no data for SrO, BaO or MnO2 in coal ash)										
SiO_2	47.41	47.69	47.51	47.61	47.48	47.63	46.82	47.68	47.53	47.09
Al_2O_3	12.82	12.69	12.84	12.74	12.81	12.73	12.87	12.84	12.81	13.05
TiO_2	0.54	0.53	0.54	0.53	0.54	0.53	0.54	0.54	0.54	0.55
Fe_2O_3	6.77	6.69	6.83	6.79	6.75	6.77	6.79	6.75	6.73	6.91
CaO	12.83	12.69	12.77	12.74	12.72	12.73	13.25	12.76	12.87	12.85
MgO	4.01	3.95	3.99	3.96	3.97	3.98	4.08	4.01	4.12	3.97
K_2O	2.23	2.48	2.28	2.34	2.28	2.39	2.24	2.11	2.17	2.09
Na_2O	1.65	1.68	1.68	1.73	1.78	1.68	1.71	1.65	1.64	1.68
SO_3	10.35	10.24	10.34	10.31	10.39	10.30	10.39	10.34	10.32	10.49
P_2O_5	0.46	0.51	0.44	0.44	0.46	0.47	0.49	0.42	0.45	0.45

*note: Switchgrass - SG, wheatgrass - WG, wildrye - WR, intermediate - Int.

A sample of lignite enhanced with the DryFining™ process was not provided for analysis using CCSEM. MTI used a high-mineral-content Falkirk Mine lignite CCSEM analysis for mineral data required for calculating advanced performance indices. The CCSEM analysis data used for the calculations is shown in Table 9. The coal contained 15.5 wt% ash (as-received).

Table 9. CCSEM analysis results for Coal CS Composite (MTI 09-629). Results expressed as weight percent on a mineral basis, normalized to 100%.

	Size bin, microns						
	1 to 2.2	**2.2 to 4.6**	**4.6 to 10**	**10 to 22**	**22 to 46**	**46 to 400**	**Total**
QUARTZ	1.5	2.8	2.7	4	2.1	7.2	20.3
IRON OXIDE	0	0	0	0	0	0	0
PERICLASE	0	0	0	0	0	0	0
RUTILE	0	0	0	0	0	0	0
ALUMINA	0	0	0	0	0	0	0
CALCITE	0	0	0	0	0	0.1	0.1
DOLOMITE	0	0	0.1	0.1	0	0	0.2
ANKERITE	0	0	0	0	0	0	0
KAOLINITE	0	0	0.1	0.4	0.2	0.2	1
MONTMORILLONITE	0.2	0.5	0.6	0.5	0.4	0	2.1
K AL-SILICATE	0.3	1.1	1.8	2.1	1	1.3	7.5
FE AL-SILICATE	0.1	0.5	0.2	0.4	0.3	1.6	3.1
CA AL-SILICATE	0.1	0.4	0.5	0.3	0.3	0.3	1.9
NA AL-SILICATE	0.1	0	0.1	0	0.1	0.3	0.6
ALUMINOSILICATE	0.3	0	0.7	0.3	0.3	1.1	2.8
MIXED AL-SILICATE	0.1	0.4	0.4	0.3	0.3	0.2	1.6
FE SILICATE	0	0	0	0	0	0	0
CA SILICATE	0	0.1	0	0	0	0	0.1
CA ALUMINATE	0	0	0	0	0	0	0
PYRITE	0.2	1.8	1.4	1.8	2.3	2.9	10.4
PYRRHOTITE	0	0.4	0.2	0.4	0	0	1.1
OXIDIZED PYRRHOTITE	0.1	0	0.2	0	0	0	0.3
GYPSUM	0	0	0	0	0	0	0
BARITE	0	0	0	0	0	0	0
APATITE	0	0	0	0	0	0	0
CA AL-P	0	0	0	0	0	0	0
KCL	0	0	0	0	0	0	0
GYPSUM/BARITE	0	0	0	0	0	0	0
GYPSUM/AL-SILICATE	0.1	0.1	0.1	0.1	0	0	0.4
SI-RICH	1.1	2	3.7	4.8	3.4	9.4	24.4
CA-RICH	0	0	0	0	0	0	0.1
CA-SI RICH	0	0	0	0	0	0	0.1
UNKNOWN	1.9	3.4	3.4	3.3	3.1	6.6	21.7
TOTALS	**6.2**	**13.5**	**16.5**	**18.8**	**13.8**	**31.1**	**100**

Performance predictions for the blends of biomass with coal were made using MTI's ash behavior indices. The ash behavior indices used ultimate and ash composition data for each blend and CCSEM data for a high-ash Falkirk Mine lignite. The ultimate and ash composition data were calculated based on a 10% blend (on heating value basis) using the biomass analyses and the "typical" lignite (enhanced with the DryFining™ process) analysis provided by GRE (Table 7). The blend compositions are shown in Tables 8a and 8b. The CCSEM data used was an analysis that had been performed on a Coal Creek Station lignite standard ("CS", MTI 09-629) and is used for mineral data (Table 9). This CCSEM data provides a rough estimate of behavior only – mineral or phase information is not known for the biomass samples.

MTI's performance indices were developed for pulverized and cyclone-fired boilers, but may be interpreted relative to the formation of agglomerates and deposits in fluidized bed systems. In coal-fired systems, potassium is typically not active in the fouling process (available for reaction with other elements to contribute to fouling). Based on the partial chemical fractionation results for the potassium in biomass, the potassium as well as the sodium is active and both have the potential to contribute to the formation of silicate and sulfate phases that produce bed agglomerates and convective pass fouling deposits. To fully assess the impacts of potassium and sodium, the total alkali (sodium and potassium) were used as input for sodium in the index calculations. The calculated performance indices for the baseline lignite enhanced with the DryFining™ process and the blends with biomass are shown in Table 10.

The strength index can be used for interpreting potential for bed agglomeration. Specifically, the strength index is related to the ability of the ash materials to produce low-viscosity phases on aluminosilicate bed materials, resulting in agglomeration. Deposit strength index is used to predict the strength of deposited material. It is used in conjunction with the wall slagging and the silication indices to assess deposit characteristics (size and tenacity of deposits). Index values less than 0.25 indicate weak deposits. Values of 0.25 to 0.34 indicate low-to-moderate-strength deposits, and values of 0.34 to 0.41 indicate strong deposits. Index values greater than 0.41 correspond to flowing slag. The baseline lignite and the blends with biomass all had low-to-moderate strength index values of 0.27-0.28.

The low temperature fouling (sulfation) index is related to the ability to produce sulfate-rich bonding phases. The low-temperature convective pass fouling (sulfation) index indicates the propensity to form low-temperature sulfate-based fouling deposits. These deposits form in the convective pass of a utility boiler at temperatures from 1000 to 1750°F. The index is based on the availability of alkali and alkaline earth elements to react with gas-phase SO_2 and SO_3 to form sulfates. Sulfates are the primary material causing particle-to-particle bonding in high-calcium coals and are thermodynamically stable at temperatures below about 1650°F. Sulfation index values range from 1 (low) to 10 (severe). The baseline coal had a low sulfation index of 2.71. The biomass blends with the coal had similar sulfation index values, of 2.67 to 2.81. These are all fairly low index values.

The high temperature fouling (silication) index and slagging indices are related to the formation of deposits on heat exchangers and high-temperature bed agglomerates. Temperature excursions in fluid bed systems can result in the formation of silicate bonding and the silication index will provide information on this type of bonding. This is especially important if the sand bed material used contains a high level of available quartz. The high-temperature (silication) index indicates the propensity to form high-temperature silicate-based fouling deposits. These types of deposits form at

temperatures from 1600-2400°F; in these deposits silicates are the primary accumulating materials and bonding component. The index is based on the size and abundance of minerals including quartz and clay, the availability of alkali and alkaline earth elements, and viscosity of silicate liquid phase. Index values range from 1 (low) to 300 (severe). Silication index for the baseline coal was high, at 170. The biomass-coal blends had calculated silication indices of 189 (Streeter intermediate wheatgrass) to 198 (Carrington Sunburst switchgrass/Mustang Alti. wildrye). Overall, Carrington site blends had slightly higher average silication indices than the Streeter site blends (average 196 vs. 193).

In the specific application of fluidized beds, the slagging index will provide an indication of the impact of coal minerals and organically-associated elements on performance. Wall slagging index indicates the propensity of deposits to accumulate on radiant walls, from 2000-3000°F. The index is based on the size of minerals (including illite, quartz and pyrite), the association of calcium (calcite can contribute to slagging) and the viscosity of the silicate-based liquid phase. The index values range from 1 (low) to 20 (severe). The slagging index was 3.55 for the baseline coal. Blending biomass with the coal increases the wall slagging index to 5. These are moderate wall slagging index values.

The temperature at which materials become molten (viscosity 250 poise) is known as "T_{250}". The T_{250} is calculated using several different methods, including the Sage and McIlroy method ("B&W") or by the Urbain method. The Sage and McIlroy method uses base-to-acid ratios to predict T_{250} and is considered valid for bituminous-type ash and for lignitic ash with acid content (SiO_2 + Al_2O_3 + TiO_2) over 60%. The biomass-coal blends analyzed in this work all had acid content of about 66-67%. The Urbain method categorizes slag constituents into three groups: "glass-formers", such as silicon and phosphorus, which form the initial solid structure in a molten slag; "modifiers" such as sodium, potassium, calcium, iron and titanium, which extend the solid structure over a larger range; and "amphoterics" such as aluminum, boron and iron, which influence the solid structure of slag. T_{250} is calculated based on the interactions of these three types of slag constituents. The Urbain method has become an accepted technique for predicting viscosity for silicate-rich materials. The biomass-coal blends all are rich in silica, with more than 50% SiO_2 in the ash.

T_{250} values calculated for the blends were similar using the two calculation methods (Urbain and B&W). The baseline coal (100% lignite enhanced with the DryFining™ process) had calculated T_{250}s of 2315°F (Urbain) and 2339°F (B&W). Addition of Carrington-site biomass did not significantly change predicted T_{250} for the coal. Average Carrington-site T_{250}s were 2306°F (Urbain) and 2349°F (B&W). Streeter-site biomass resulted in slightly higher calculated T_{250}s than the baseline coal, with values of 2329°F (Urbain) and 2363°F (B&W).

Table 10. Performance indices for calculated blends of biomass with dried coal (enhanced with DryFining™) and for 100% dried coal. Indices based on ultimate and ash composition analyses of biomass and dried coal, and CCSEM analysis of Falkirk lignite.

Blend - 90% coal (BTU basis) with*:	Mass % Biomass	Strength Index	Sulfation	Silication	Slagging	MTI T250	B&W T250
Baseline – 100% dried coal	**-**	**0.28**	**2.71**	**170.27**	**3.55**	**2315**	**2339**
Carrington biomass:							
Sunburst SG, Sunnyview Big Blues (MTI 10-081)	9.83%	0.27	2.77	194.71	5.12	2304	2348
CRP mix (WG, alfalfa, sweet clover) (MTI 10-082)	10.25%	0.27	2.72	195.24	5.14	2317	2356
Sunburst SG, Mustang alti. WR (MTI 10-083)	9.84%	0.27	2.8	197.67	5.23	2293	2341
Trailblazer SG (MTI 10-084)	9.97%	0.27	2.81	199.66	5.3	2291	2340
CRP mix (Int., tall WG) (MTI 10-085)	10.10%	0.27	2.71	192.93	5.05	2321	2358
Sunburst SG, tall WG (MTI 10-086)	10.07%	0.27	2.72	193.43	5.07	2312	2352
Magnar Basin, Mustang alti. WR (MTI 10-087)	10.10%	0.27	2.75	197.4	5.22	2304	2347
Int. WG (MTI 10-098)	10.34%	0.27	2.72	193.68	5.08	2313	2353
Tall WG (MTI 10-099)	10.42%	0.27	2.75	198.23	5.25	2306	2349
SG (MTI 10-100)	9.97%	0.27	2.75	194.97	5.13	2299	2345
Streeter biomass:							
Sunburst SG, Sunnyview Big Blues (MTI 10-088)	10.18%	0.27	2.72	191.7	5	2329	2363
Trailblazer SG (MTI 10-089)	10.46%	0.27	2.75	196.57	5.19	2335	2366
CRP mix (Int., tall WG) (MTI 10-090)	10.01%	0.27	2.72	193.18	5.06	2330	2363
Magnar Basin, Mustang Alti. WR (MTI 10-091)	10.31%	0.27	2.74	195.5	5.15	2331	2363
Sunburst SG, tall WG (MTI 10-092)	10.32%	0.27	2.73	195.77	5.16	2331	2364
Sunburst SG, Mustang Alti. WR (MTI 10-093)	10.36%	0.27	2.74	194.97	5.13	2332	2364
CRP mix (WG, alfalfa, sweet clover) (MTI 10-094)	10.23%	0.27	2.79	193.18	5.06	2308	2350
Int. WG (MTI 10-101)	10.35%	0.27	2.68	189.81	4.92	2337	2368
Tall WG (MTI 10-102)	10.18%	0.27	2.72	190.28	4.94	2328	2363
SG (MTI 10-103)	10.15%	0.27	2.67	190.04	4.93	2327	2362

*note: Switchgrass - SG, wheatgrass - WG, wildrye - WR, intermediate - Int.

Viscosity-temperature relationships for silicate-based bonding materials

The ability of particles to stick together, become bonded, and fuse with bed material to form agglomerates is dependent upon the viscosity of the liquid phase present. Above temperatures of about 1700°F, silicate-based bonding is the main bonding type. If temperature excursions above the design bed temperature of 1600°F occur, silicate-based bonding may result. The silicate liquid phase viscosity is calculated based on chemical composition as a function of temperature. In this case, the liquid phase components are concentrated on the surfaces of the bed particles and can cause initial bonding that leads to the formation of the agglomerate. The viscosity criteria for bonding are defined as follows:

- Initial sticking – 5.5 $\log_{10}$ poise
- Particle bonding initiation – 4.5 $\log_{10}$ poise
- Particle fusing – 3.5 $\log_{10}$ poise
- Molten material – 2.4 $\log_{10}$ poise

Bulk viscosity was calculated for each blend composition (Tables 8a and 8b) using a modified Urbain viscosity model. The results of the calculations are shown in Figures 12 through 21. Figures 12 and 13 show the viscosity-temperature relationships for the Carrington and Streeter sites, respectively. Figures 14 through 21 show the viscosity patterns for the Carrington and Streeter sites over the ranges for initial sticking (5.5 log10 poise, Figures 14 and 15), particle bonding initiation (4.5 log10 poise, Figures 16 and 17), particle fusing (3.5 log10 poise, Figures 18 and 19) and molten material (2.4 log10 poise, Figures 20 and 21).

Design bed temperature is 1600°F. At this temperature, the calculated viscosity for all blends is between that of initial sticking and particle bonding initiation.

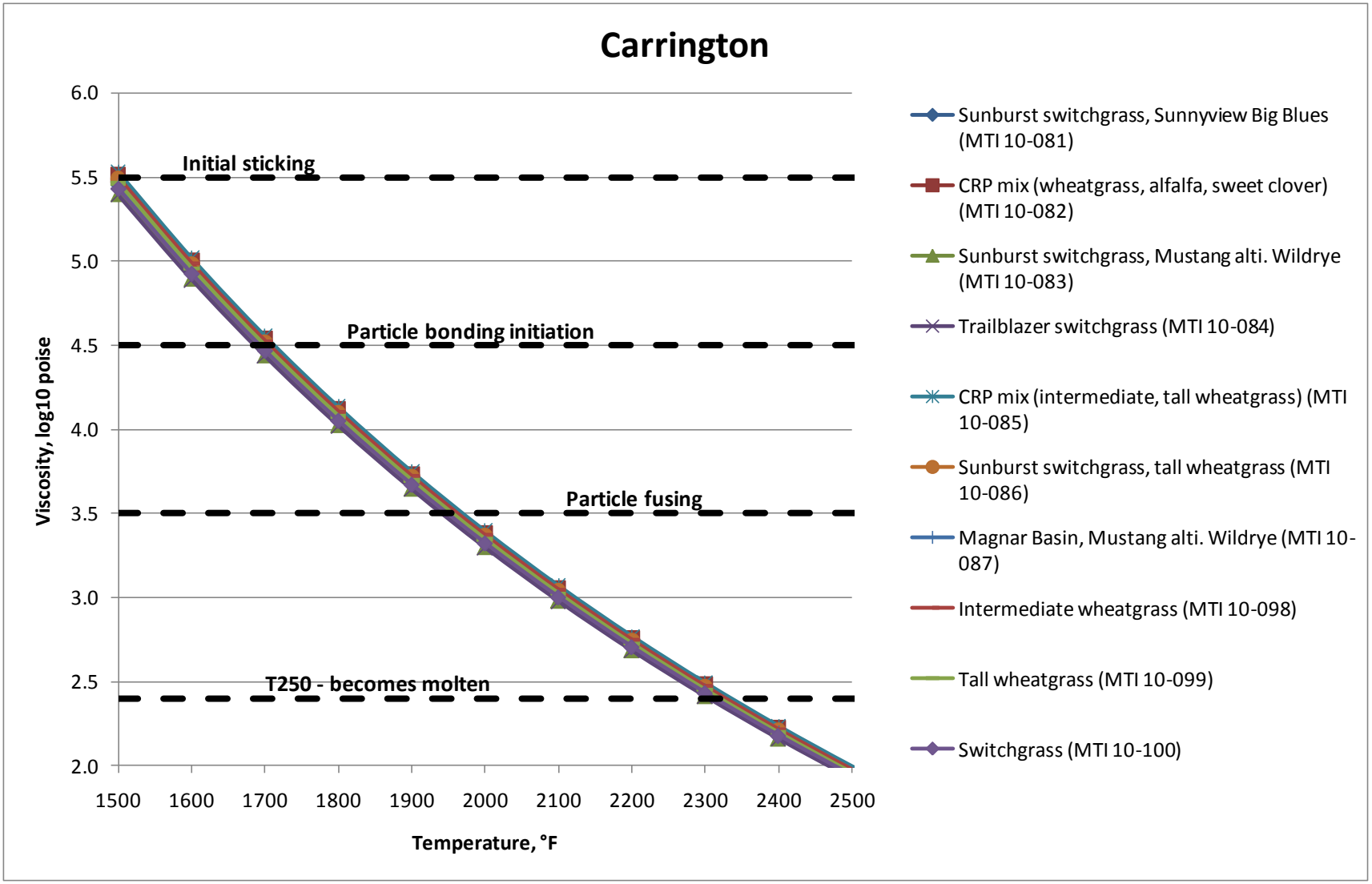


Figure 12. Predicted viscosity-temperature relationship for Carrington site biomass blends with coal, based on calculated compositions from Table 8a.

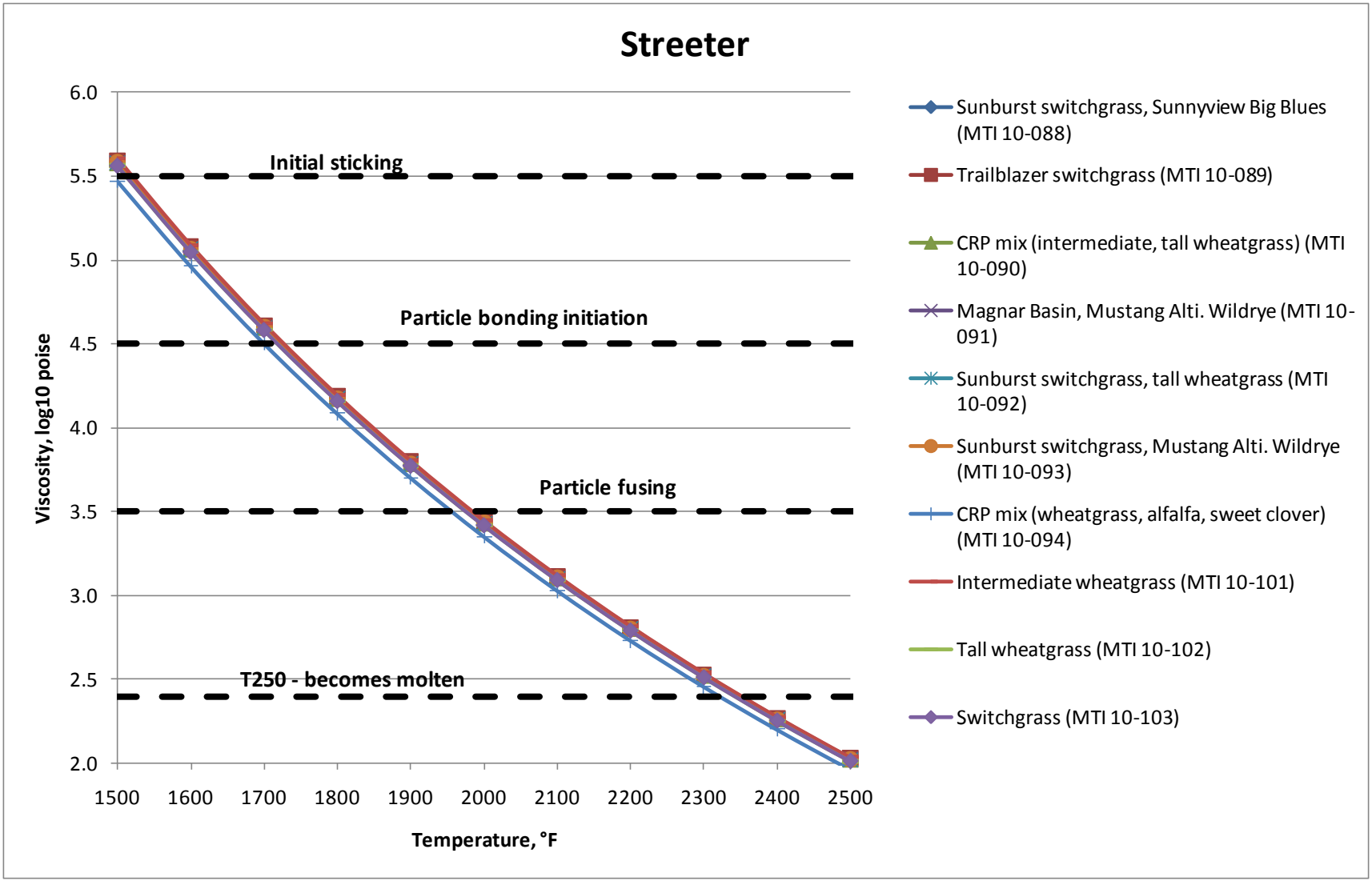


Figure 13. Predicted viscosity-temperature relationship for Streeter site biomass blends with coal, based on calculated compositions from Table 8b.

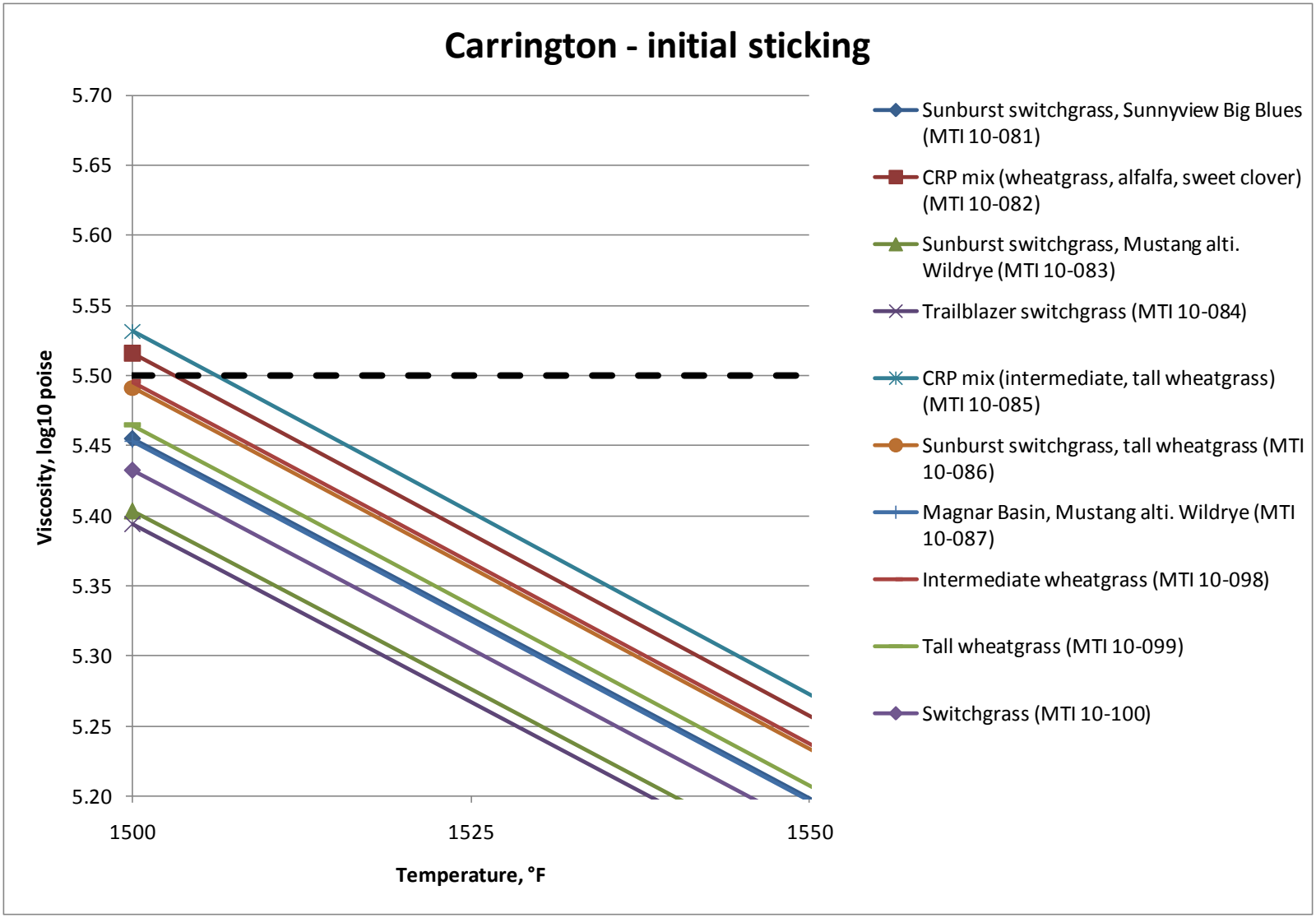


Figure 14. Predicted viscosity-temperature relationship for Carrington site biomass blends with coal, based on calculated compositions from Table 8a, showing temperatures at initial sticking (viscosity 5.5 log10 poise).

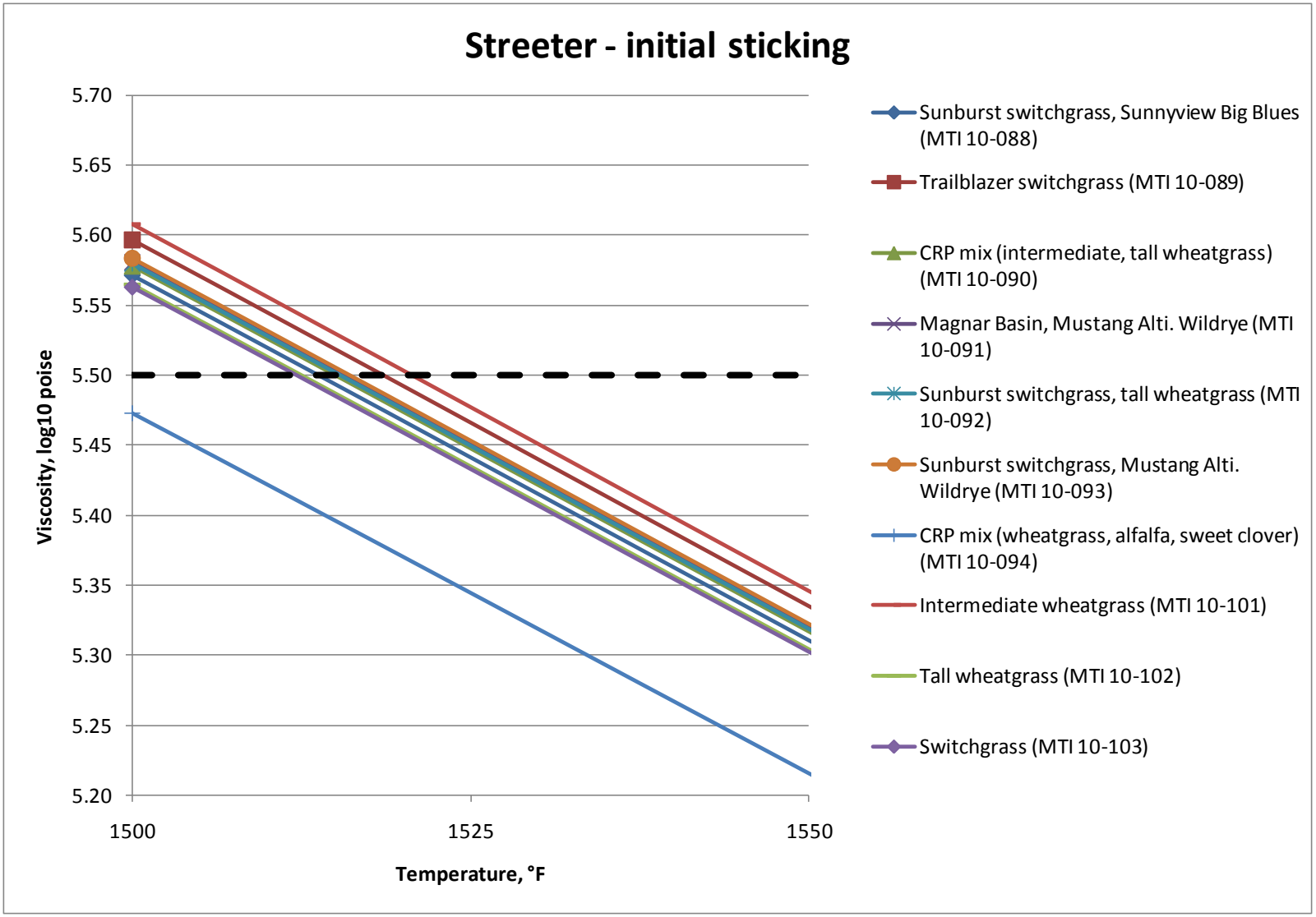


Figure 15. Predicted viscosity-temperature relationship for Streeter site biomass blends with coal, based on calculated compositions from Table 8b, showing temperatures at initial sticking (viscosity 5.5 log10 poise).

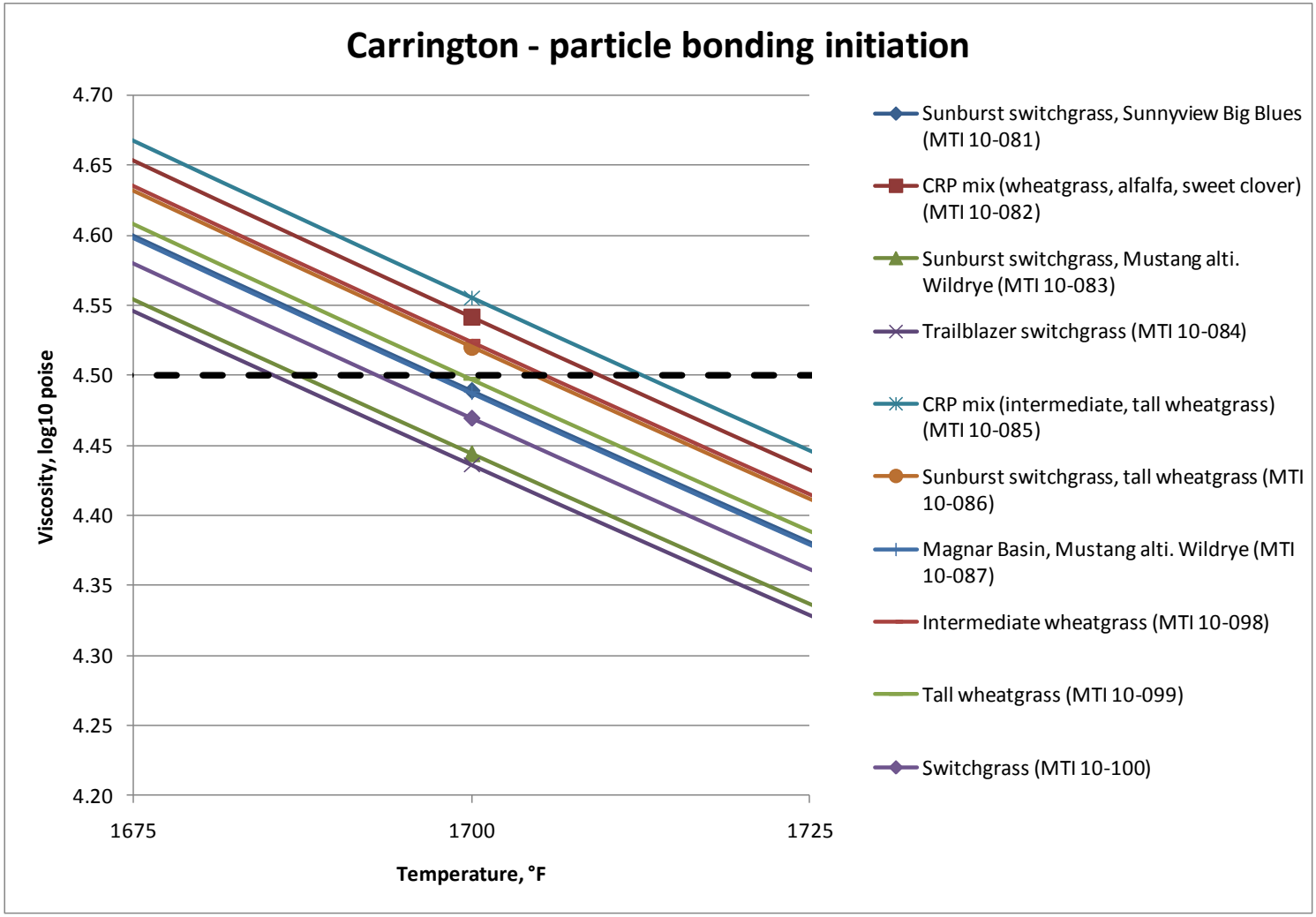


Figure 16. Predicted viscosity-temperature relationship for Carrington site biomass blends with coal, based on calculated compositions from Table 8a, showing temperatures at particle bonding initiation (viscosity 4.5 log10 poise).

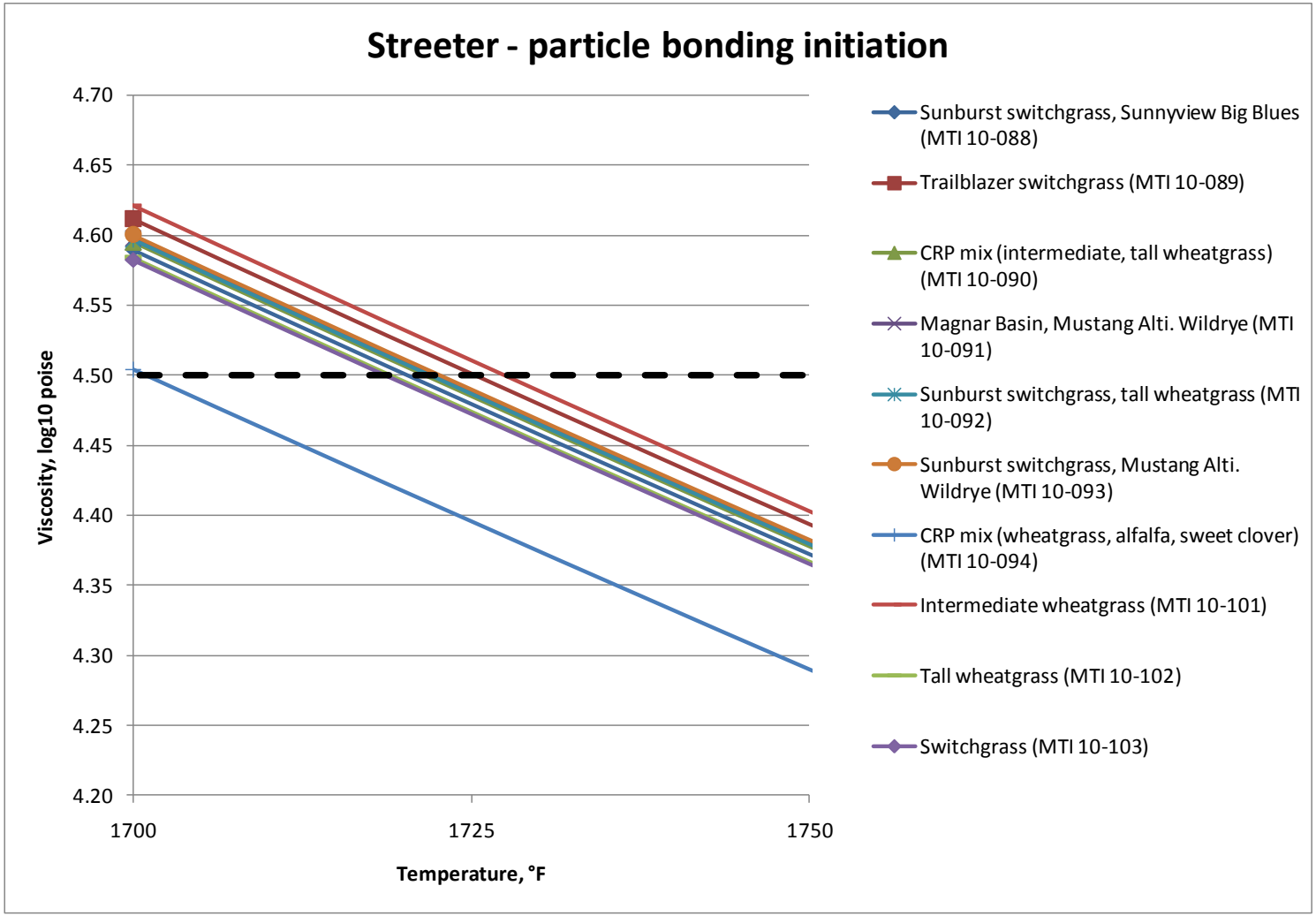


Figure 17. Predicted viscosity-temperature relationship for Streeter site biomass blends with coal, based on calculated compositions from Table 8b, showing temperatures at particle bonding initiation (viscosity 4.5 log10 poise).

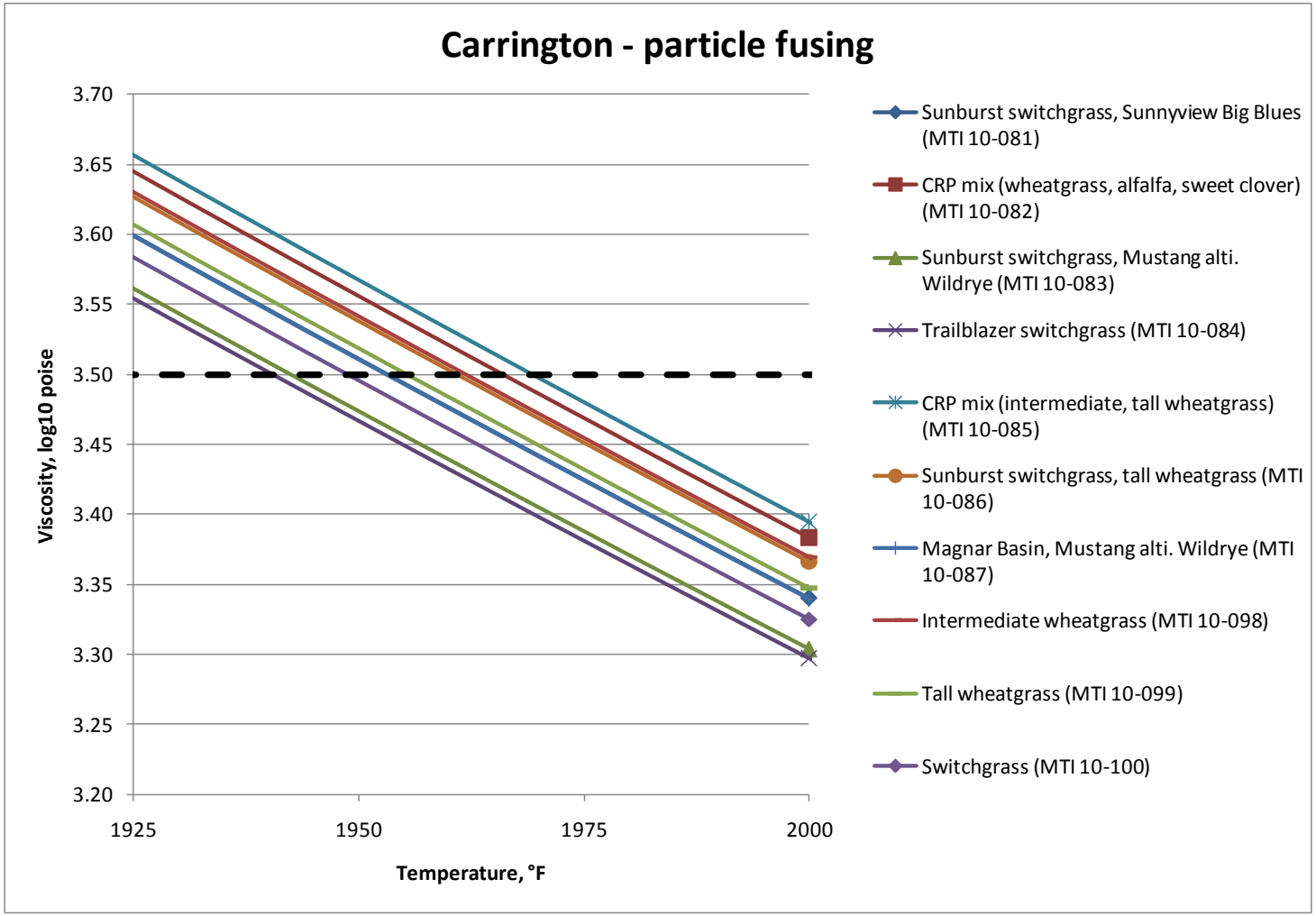


Figure 18. Predicted viscosity-temperature relationship for Carrington site biomass blends with coal, based on calculated compositions from Table 8a, showing temperatures at particle fusing (viscosity 3.5 log10 poise).

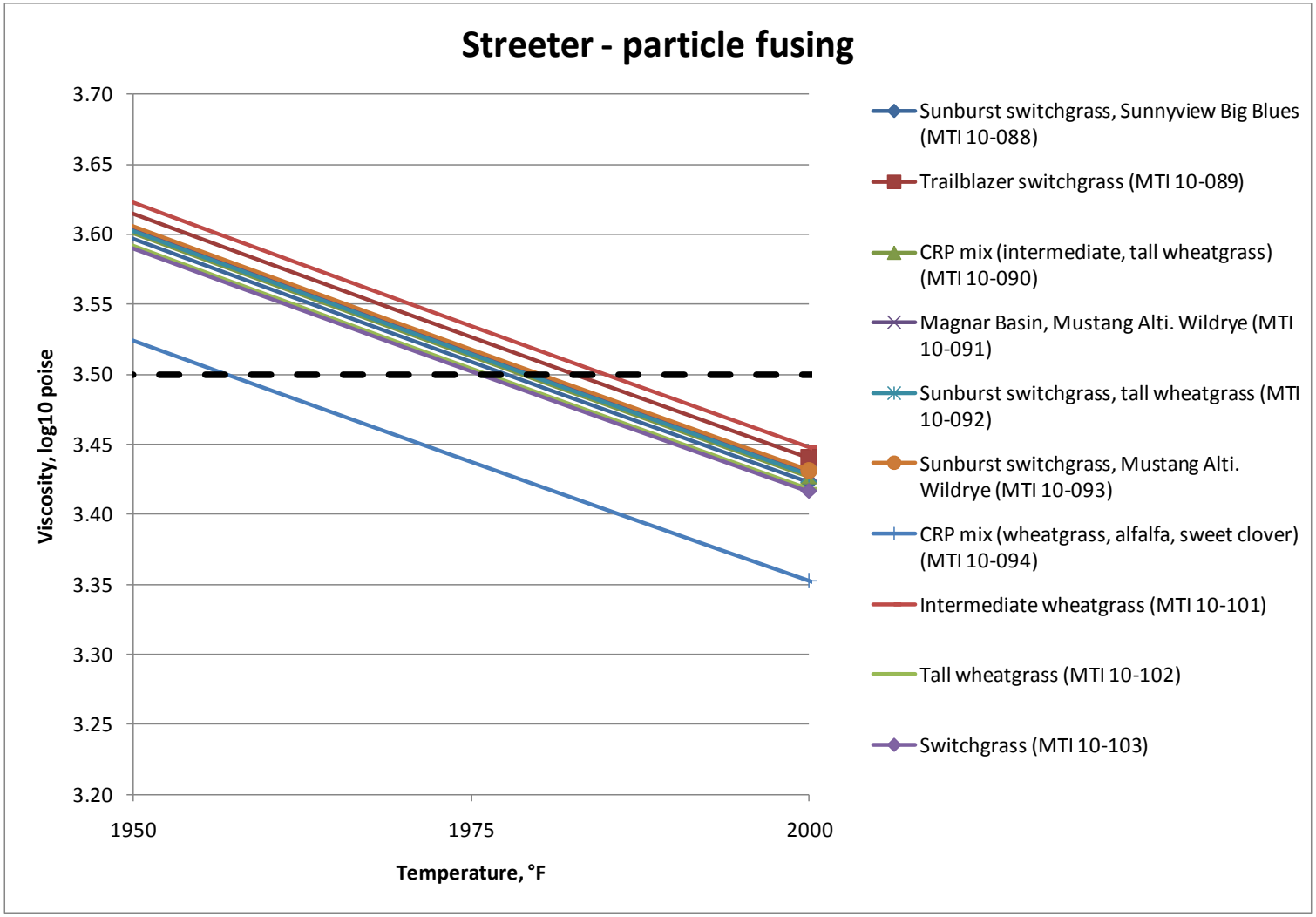


Figure 19. Predicted viscosity-temperature relationship for Streeter site biomass blends with coal, based on calculated compositions from Table 8b, showing temperatures at particle fusing (viscosity 3.5 log10 poise).

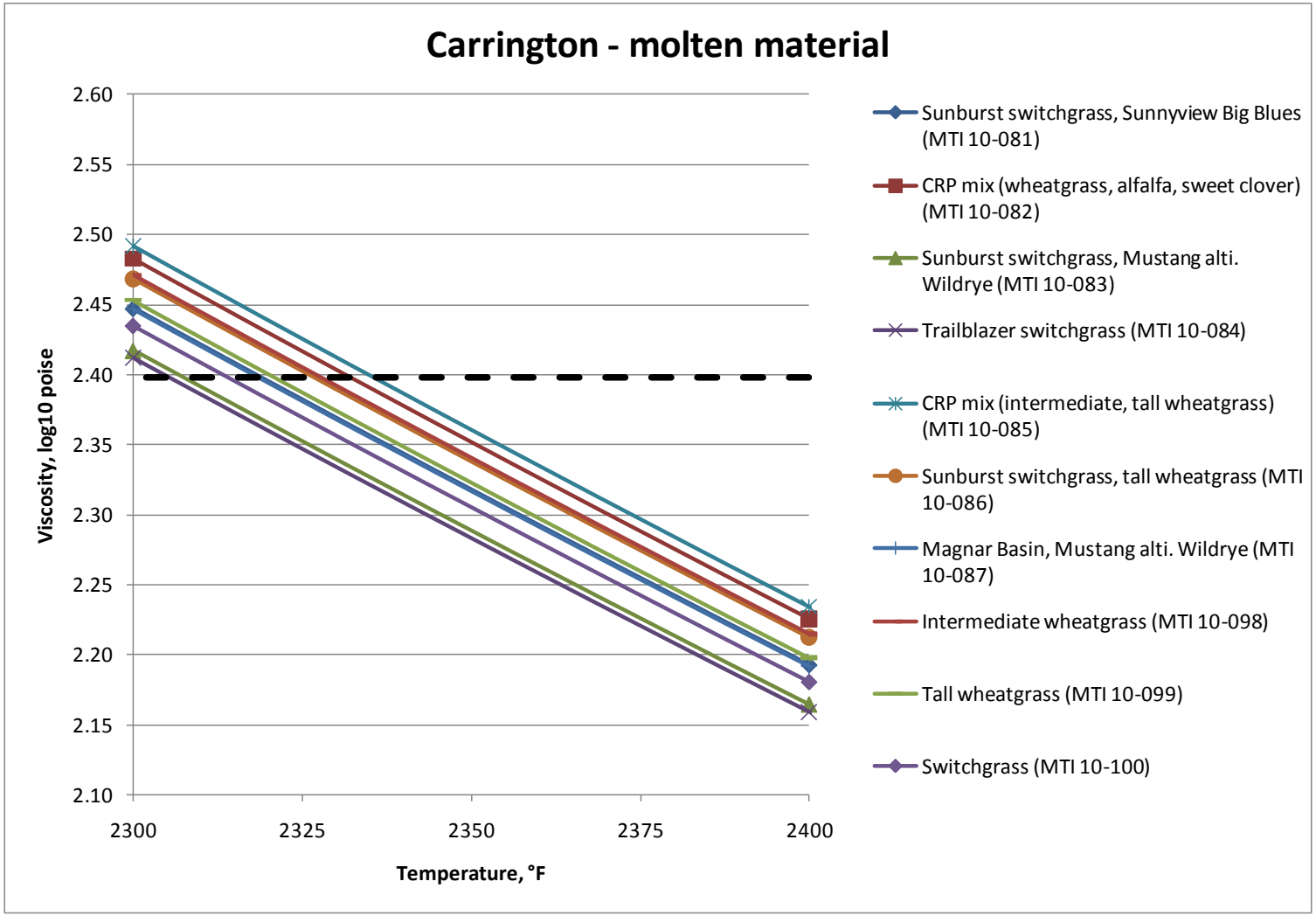


Figure 20. Predicted viscosity-temperature relationship for Carrington site biomass blends with coal, based on calculated compositions from Table 8a, showing temperatures at particle melting (viscosity 2.4 log10 poise).

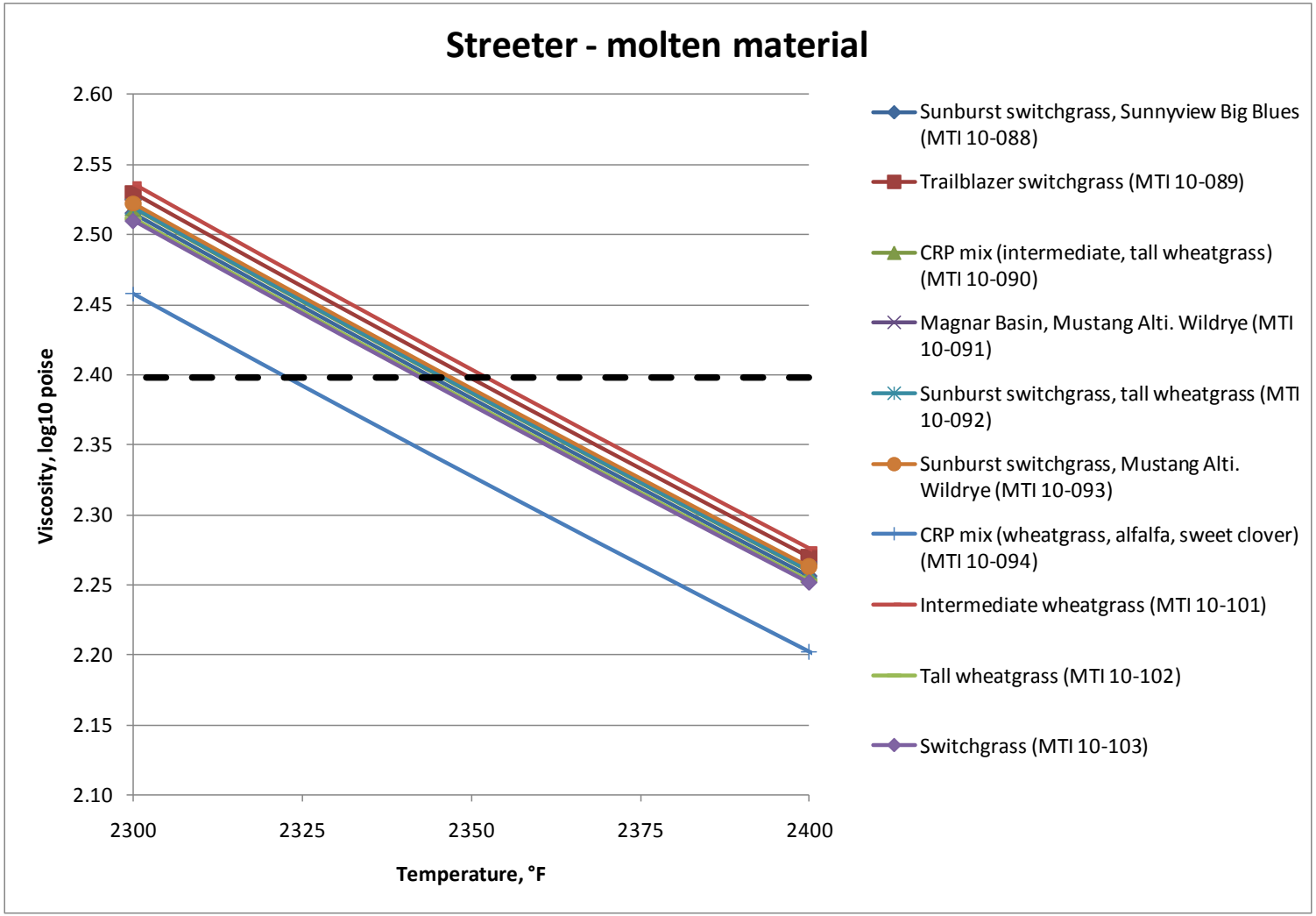


Figure 21. Predicted viscosity-temperature relationship for Streeter site biomass blends with coal, based on calculated compositions from Table 8b, showing temperatures at particle melting (viscosity 2.4 log10 poise).

Sulfate-based bonding

Sulfate-based bonding is related to the formation of low melting-point alkali and alkaline earth sulfate materials. Formation of the sulfate-based bonding phases is related to the abundance of alkali, chlorine, and sulfur in the system. The level of chlorine in the biomass has a significant impact on the volatility of alkali elements (sodium and potassium). Volatile alkali chlorides will condense on cooled surfaces, and will rapidly sulfate in the presence of gas-phase sulfur oxides. Higher levels of sulfur in the fuel will diminish the chloride-related ash deposition mechanism, by increasing the likelihood of forming alkali sulfates. However, formation of chloride bonding materials likely proceeds at a much faster rate than formation of sulfate bonding materials, because the two-step sulfation process requires the transformation of SO_2 to SO_3 before reaction with alkali or alkaline earth elements. The melting point of complex sulfates can be as low as 1,200°F.

Sulfation rates are a function of the availability of alkali and alkaline earth elements to react with the gas-phase sulfur (Hurley et al. 1991). Sulfation propensity is compared for the baseline coal and the biomass blends in Figures 22 (Carrington) and 23 (Streeter). The charts are unitless and show sulfation propensity for each blend relative to the baseline coal.

As shown in Figure 22, Carrington blends Trailblazer switchgrass, Sunburst switchgrass/Mustang alti. wildrye, and Sunburst switchgrass/Sunnyview Big Blues had the highest sulfation propensity. The baseline coal (no biomass) had the lowest. The Streeter CRP mix (wheatgrass, alfalfa, and sweet clover) had the highest sulfation propensity for all the Streeter blends (Figure 23).

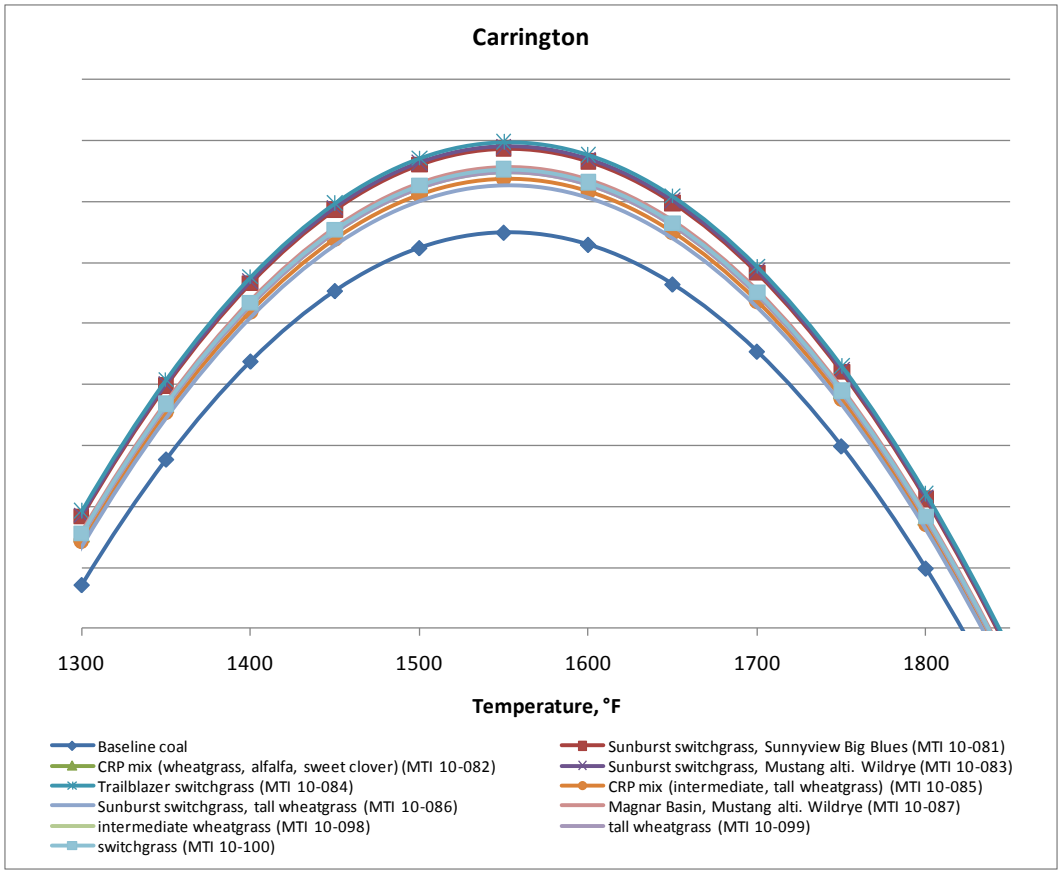


Figure 22. Sulfation propensity for Carrington biomass blends, relative to baseline coal, as a function of temperature.

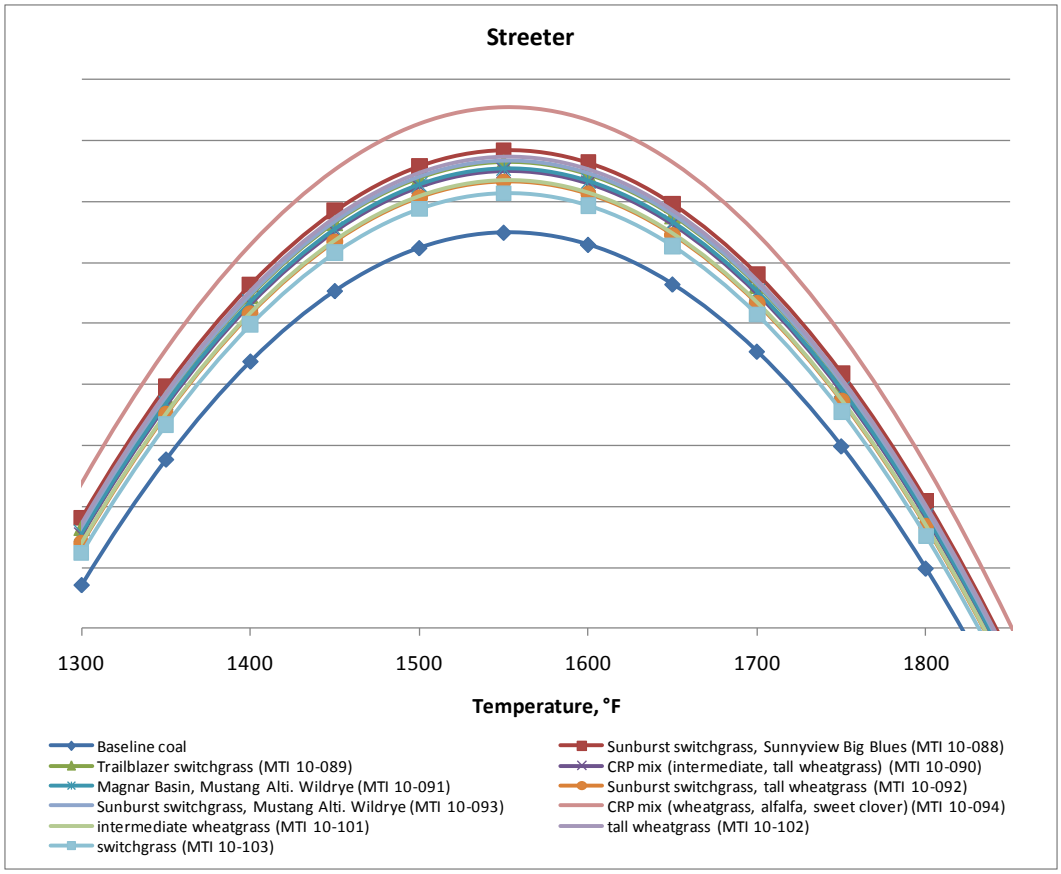


Figure 23. Sulfation propensity for Streeter biomass blends, relative to baseline coal, as a function of temperature.

Low temperature bonding in ash handling equipment

The cohesivity of the ash materials is a measure of their ability to bond together at low temperatures (< 400°F), where the cohesive properties are important relative to forming dust cakes on fabric filters and flow of the materials in hoppers and belts. Cohesive characteristics of ash from the various blends were calculated using relationships derived from Miller and Laudal (1986), which relate the composition of high-alkali and alkaline-earth ash to its cohesive strength. The calculated ash cohesive strengths are shown in Figure 24.

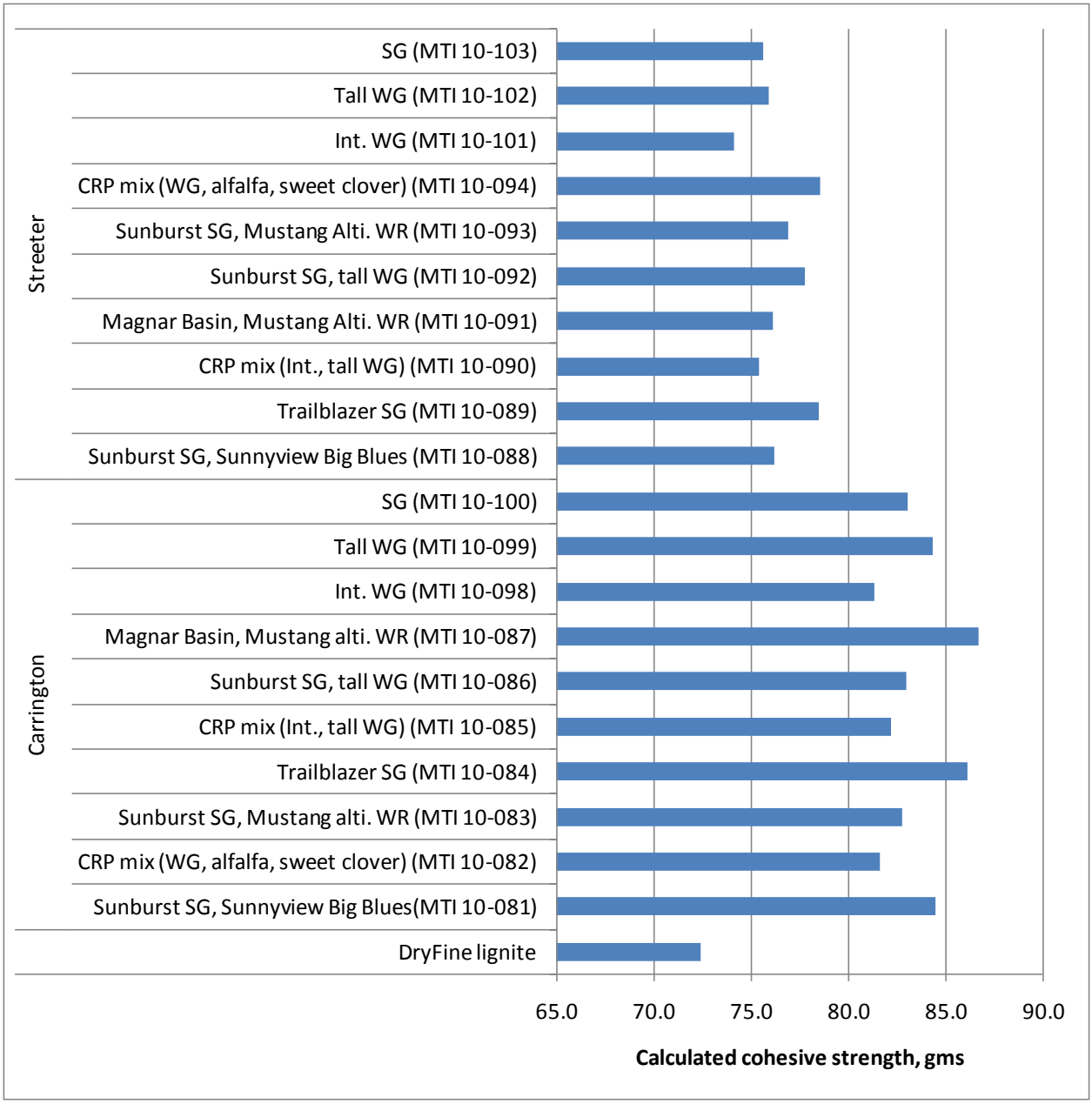


Figure 24. Cohesivity of ash materials derived from biomass.

REFERENCES

Benson, S.A.; Holm, P.L. "Comparison of Inorganic Constituents in Three Low-Rank Coals," Ind. Eng. Chem. Prod. Res. Dev., Vol. 24 (1985) p. 145.

Hajicek, D.R.; Zobeck, B.J.; Mann, M.D.; Miller, B.G.; Ellman, R.C.; Benson, S.A.; Goblirsch, G.M.; Cooper, J.L.; Guillory, J.L.; Eklund, A.G. *Performance of Low-Rank Coal in Atmospheric Fluidized-Bed Combustion*; Technology Transfer Report; DOE/FE/60181-1869; 1985.

Hurley, J.P.; Erickson, T.A.; Benson, S.A.; Brobjorg, J.N. Ash Deposition at Low Temperatures in Boilers Firing Western U.S. Coals. International Joint Power Generation Conference, San Diego, CA, 1991.

Levin, E.M., C.R. Robbins, and H.F. McMurdie, "Phase Diagrams for Ceramists", American Ceramics Society, Columbus, Ohio, 1964.

Maryamchik, M. and Wietzke, D.L., B&W IR-CFB: Operating Experience and New Developments, 20th International Conference on Fluidized Bed Combustion, Xian City, People's Republic of China, May 18-20, 2009, BW report BR-1820.

Mikimov, S.M., Kri'lova, N.I., and A. G. Bergman, *Akad. Nauk Uzbeksk. SSR, Tashkent. Inst. Khim. Trudy,* 2, 99 (1949).

Miller, S.J. and D.L. Laudal. Particulate Characterization. Final Report, DOE/FE/60181-2089, University of North Dakota Energy Research Center, Grand Forks, North Dakota, June 1986.

Scandrett, L.A. and Clift, R., "The Thermodynamics of Alkali Removal from Coal-Derived Gases," Journal of the Institute of Energy. 391, December, 1984.

Wibberly, L.J., and Wall, T.F., "Alkali-Ash Reactions and Deposit Formation in Pulverized Coal-Fired Boilers: The Thermodynamic Aspects Involving Silica, Sodium, Sulphur, and Chlorine," Fuel, 61, 87, 1982.